Spring 2020

Caltech magazine

These people are on a mission to build a sustainable world.

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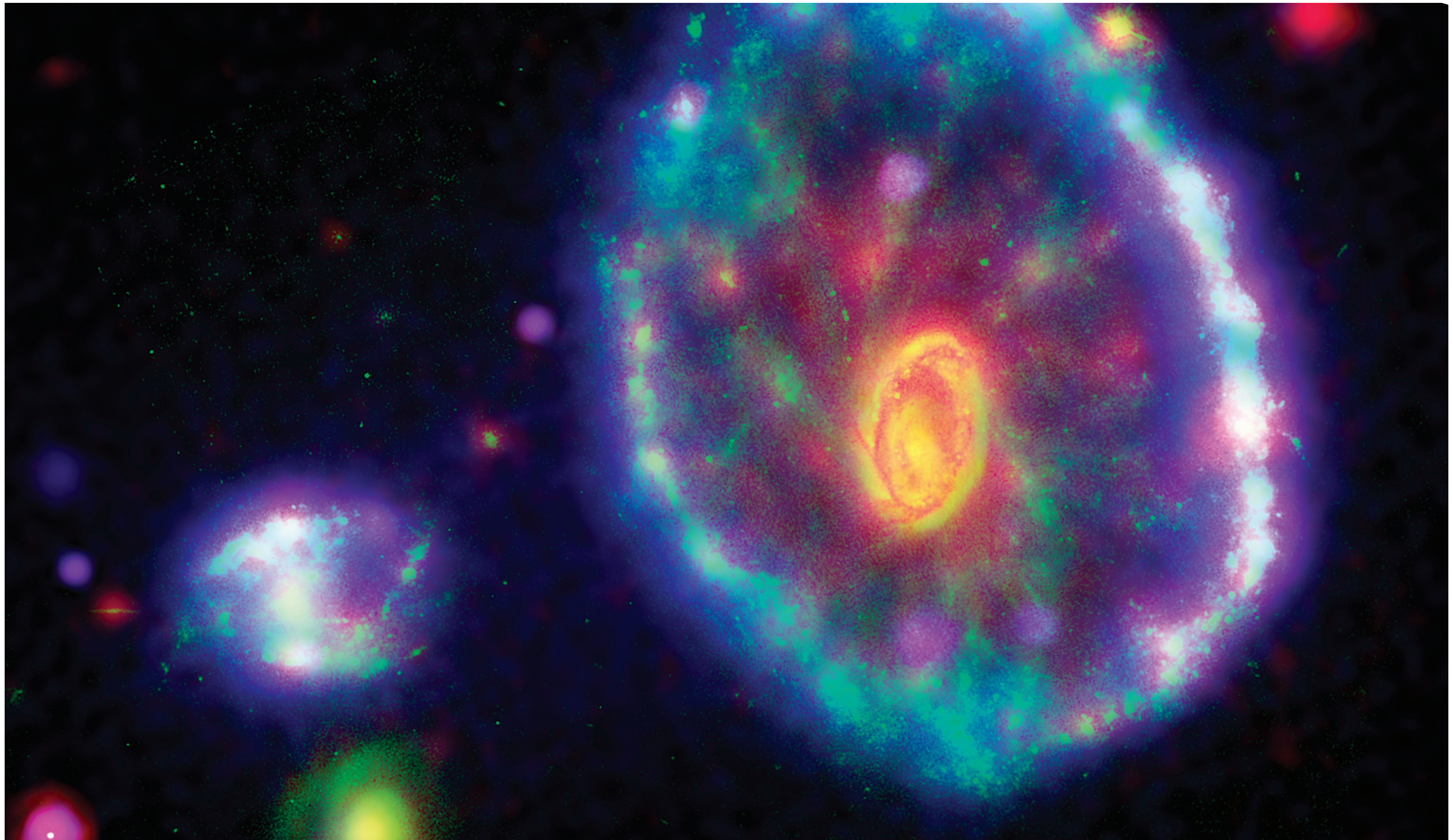

Departments

Left: This image of Messier 101, also known as the Pinwheel Galaxy, combines data from Spitzer and three other NASA space telescopes. The galaxy is approximately 70 percent larger than the Milky Way and sits at a distance of 21 million light-years from Earth. The red colors in the image show infrared light, as seen by Spitzer. These red areas reveal light emitted by dusty lanes in the galaxy where stars are forming.

Online

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An egret contemplates Millikan Pond on a sunny winter's day.

Letters

Still entangled?

That was a fascinating article about quantum entanglement ("Untangling Entanglement," Fall 2019). It mentioned how a single photon could upset a delicate experiment. But if quantum gravity and gravitons are real, why don't gravitons get entangled with experimental setups? Wouldn't gravitons be part of the environment? A curious mind wants to know.

Bill Holland (BS '77)

If a particle like an electron is in a superposition of two different positions, a single emitted photon could reveal the position of the particle, causing that delicate superposition to decohere. In principle, emission of a single graviton could have the same effect. In practice, however, gravity is such a weak force that we never need to worry about this source of decoherence in today's laboratory experiments. — John Preskill, Richard P. Feynman Professor of Theoretical Physics

As part of the article on quantum entanglement, I wish you had mentioned some of the history and the role played by Caltech alumni. The first experiment to demonstrate entanglement was done by my Caltech classmate John Clauser (BS '64). Following this original experiment, numerous more refined versions have been carried out.

The idea that spatially separated particles could be correlated, or entangled, such that a measurement of some property of one would be instantaneously reflected—faster than the speed of light—in the other had deeply troubled philosophically minded physicists from Einstein onward. John had already become interested in these ideas while at Caltech, but no one there, or at Columbia where he went to grad school, took any of it seriously.

After receiving his PhD in astrophysics at Columbia, John managed to get a postdoc at Lawrence Berkeley Labs with Nobel Laureate Charles Townes (PhD '39) who found the idea of experimentally testing entanglement intriguing. So John, together with graduate student Stuart Freedman, finally did the experiment at Berkeley. This represented the beginning of quantum entanglement as an experimental science.

Frank Winkler (BS '64)

The recent article on quantum entanglement misunderstood the nature of the perfect correlation between spin measurements of entangled particles with net zero spin (e.g., superposition of horizontal and vertical spin). If one particle is measured to have horizontal polarization when the polarizer is at angle alpha, its twin will instantly adopt vertical polarization if measured at the same angle. If the twin also adopted horizontal polarization, angular momentum would not be conserved.

Jerre Levy (PhD '70)

Nice job!

Great to see these colorful jobs, especially those of my friends Garnett Pessel and Bernie Schweitzer. To add to your list, I was (1) a roustabout in a Wisconsin carnival and (2), not to be outdone by the prominent foot model Bridget Landry, a New York hand model, shaking maracas for Gunther Beer.

Sam Phillips (BS '56, MS '57)

Mulling the myths

When I got to "Myth #7: Genetically modified food is unsafe" ("Humans Have Landed on Mars," Fall 2019), I was surprised to read the following: "In order for any of the resulting GMOs to go to market, they first have to be tested extensively by the USDA, the FDA, and the EPA."

Until I read Jane Goodall's book, *Seeds of Hope,* in 2015, I would have sworn on a stack of Feynman Lectures that the FDA did extensive testing on every GMO plant before it went to market. Ms. Goodall disabused me of that notion in chapter 14.

FDA does no independent testing. Neither does it require any testing by the developer. The FDA encourages developers to consult, but the consultation is entirely voluntary. And if a developer agrees to a consultation, the data that are used are generated by the developer.

D. J. Krajnovich

Regarding Myth #7, it is worth noting that the most prevalent genetic modification is resistance to Roundup, promoting widespread use of this herbicide. There is significant debate about whether or not the side effects of this are serious, especially when you include non-laboratory effects like promiscuous overspray affecting nearby vegetation and the as-yet-not-understood effects on the soil biome.

John Bloom (PhD '77)

Soaring

"Soaring" in the Fall 2019 issue brought back a fond memory from my days at Caltech. My friend Jim LaFleur was both a sailplane and power plane pilot. One time, we went out to El Mirage Dry Lake, where there was a sailplane operation. They had a 3,000-foot steel wire laying in an adjacent dirt road. We dragged that onto the dry lake and car-towed the sailplane to the dizzying height of 1,200 feet or so. It was a two-place plane so we non-pilots took turns riding with Jim and driving the tow car.

Every time we could rustle up $7 between us, we would run down to the Rosemead Airport (now the SoCal Edison headquarters) and rent a Piper Cub for an hour. Jim taught me to fly … unofficially, of course. I earned my license later.

Richard Kennon (BS '52)

"This is such an LA winter… I've been invited to go skiing and to the beach this weekend."

@overheardla

Errata:

— In the sidebar to the article "Soaring," it was erroneously stated that Bryan Allen works at JPL as a software engineer. As reader Jared Call pointed out, he retired from JPL in February of 2019.

— In "Humans Have Landed on Mars," Fall 2019, Myth #1 was erroneously titled "Solar energy is cheap and clean." The correct heading, requested by Cora Went, the researcher, is "Today's solar panels are as good as it gets."

SoCaltech

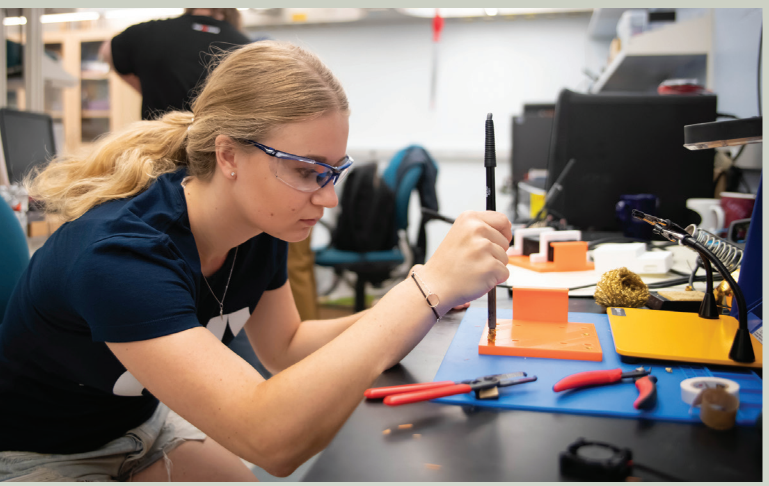
Off the Wall

Of all the murals adorning the hallways of Ruddock House, which include a Monopoly board and a giant depiction of an astronaut, the copy of M.C. Escher's woodcut *Metamorphose* is one of the most complex. Tom Berto (BS '83) recalls the process of painting it, which began at the start of his junior year: "I bought a copy, mail-order, of the woodcut as a very long, rolled-up poster and enlarged it by a factor calculated to allow it to fit within the available length. Because it is such a long, long woodcut, it was ideal for a long hallway. At the beginning, about four people worked on it, but within a week or two, after just a few feet, the help tailed off, and it was just me. The pattern started out geometric and was easy to enlarge and 'draft' onto the wall with rulers, compass, and pencil, but it quickly became more complicated, and I eventually settled on laying out important reference points on the wall, projecting close-up Kodachrome slides onto the wall, and painting the projected image. I don't think I got to the end of the first wall during my junior year, junior years being what they are at Caltech. In my senior year, my course load eased up, and so I was able to work on it more. I completed it in the last week or two before graduation. I think I spent about 230 hours on it. I painted myself into the mural: about 15 feet from the end there is a seaside village with a promenade, and I added myself, riding a bike. … I have had a long career as a mechanical engineer: at Hewlett-Packard, then Agilent, then Keysight Technologies. But the painting urge came out as a painting avocation that has been satisfying and durable, if not financially rewarding."

See more of Tom Berto's art at **sonic.net/~monicab/tom**

BALTO
Portrait of a Robot

Last summer, Balto, a robot designed and built by undergraduate and graduate students at Caltech in collaboration with robotics researchers at JPL, took to the field in the first phase of the Defense Advanced Research Projects Agency (DARPA) Subterranean (SubT) Challenge. This international competition advances technologies to autonomously map, navigate, and search underground environments. The Caltech-JPL team took second place in that contest and then, in February, claimed first place in the Urban Circuit phase of the competition. Balto, named after a famous rescue dog, was built atop a commercial radio control car and is one of a fleet of robots designed for the competition. Smaller, lighter, and faster than its peers, Balto is deployed primarily as a ground-based scout.



Caltech senior Alexandra Bodrova fabricates custom parts for Balto.

Length: 1 meter

Weight: 12 kilograms

Able to navigate slopes of up to 40 degrees.

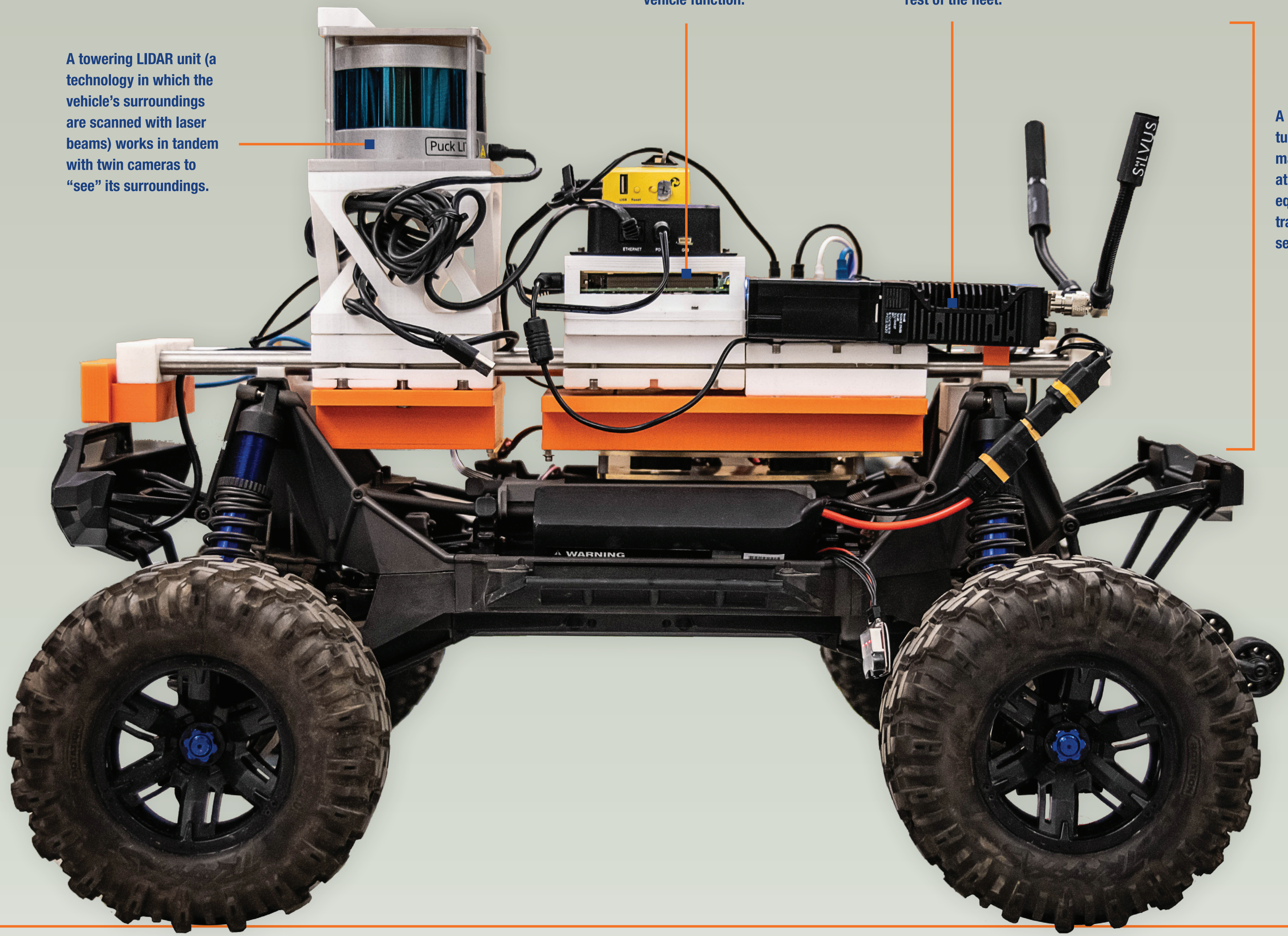
Can reach speeds of 55 miles per hour.

A towering LIDAR unit (a technology in which the vehicle's surroundings are scanned with laser beams) works in tandem with twin cameras to "see" its surroundings.

An onboard computer contains the program for autonomous vehicle function.

A radio receiver enables communication with the rest of the fleet.

A removable superstructure (built using milling machines and 3-D printers at Caltech) houses the equipment necessary to transform an R/C car into a self-guided robot explorer.



Class Act:

Volcanoes and Victorian Media

Last fall, Caltech undergraduates had the opportunity to take two new courses offered by Anne Sullivan, the Weisman Postdoctoral Instructor in Visual Culture.

The new classes, Volcanoes and Consuming Victorian Media, are part of the new Caltech-Huntington Program in Visual Culture, which was established in 2018 with a grant from the Andrew W. Mellon Foundation. The program is designed to expand Caltech students' exposure to different forms of artistic media through coursework, guest lectures, field trips, and artists-in-residence.

Collaborative classrooms

Sullivan says her classes are based on her own academic interests in 19th-century British literature and culture as well as previous experiences as a writing instructor at UC Riverside.

"When I'm designing classes, I find what I am really excited about but then make it relevant to everybody," she says. "What's great about working at Caltech and close to The Huntington is that I can enrich my own work in scientific literature and culture. These are collaborative classrooms where students learn from one another and the instructor, and the instructor learns from the students as well."

"Too scintillating"

The course on Victorian media looks at historical concerns around the consumption of media, which at that time included books, art, and live entertainment. The students read *Northanger Abbey* by Jane Austen, in which the main character becomes obsessed with Gothic novels. "Similar to the way we are concerned with screen time now and how we consume media, 19th-century people had concerns about media consumption, such as of Gothic novels, which were thought to be overly stimulating and too scintillating," she says. The students also read *Dracula* by Bram Stoker, which includes mentions of typewritten notes, telegrams, and phonograph recordings, items that, according to Sullivan, would have been considered new forms of media technology at the time.

Lava, bonfires, and fireworks

The volcanoes class focused on various forms of media that depict famous disasters brought on by the eruption of volcanoes, including Mount Vesuvius in AD 79, which destroyed the Italian city of Pompeii; Indonesia's Mount Tambora in 1815, one of the largest eruptions in recorded human history; and Mount Krakatoa, also in Indonesia, whose 1883 eruption changed the color of sunsets worldwide for some time afterward. Students studied "pyrodramas" of the 1880s and 1890s, big outdoor shows that dramatized the Vesuvius eruption for crowds of thousands of people; the shows used bonfires and fireworks along with water-pump systems to create the effects of lava. The course also included a field trip to the Getty Villa in Malibu to see the exhibit *Buried by Vesuvius: Treasures from the Villa dei Papiri.*

"I remember learning about these disasters as a kid and being horrified, but now I am fascinated," says Sullivan. "By examining literary and visual representations of disasters, students engaged with larger questions about how we perceive the past and how we conceptualize our relationship with nature."

Vesuvius from Portici by Joseph Wright of Derby, in the collection of The Huntington Library, Art Museum, and Botanical Gardens.

Three Questions for:

Kara Whatley

Caltech's new university librarian, Kara Whatley, came to the Institute from New York City, where she was head of science and engineering library services for NYU. *Caltech* magazine talked with Whatley about modern librarianship and her goals for supporting Caltech's researchers.

1. Why did Caltech seem like a good fit for you?

As a science librarian, this is the dream job. Also, even though I've always worked in large research institutions, I attended a small liberal arts college. This is the best of both those worlds: a small institution with an outsized research reputation. That means I can realistically accomplish my goal to meet all the faculty during my first year here, whereas I'm not sure that would have been possible at the other institutions I've worked in. So, the scale of this place and the ability to design library services to closely fit the needs of the researchers and students in almost a boutique kind of way was really appealing to me.

2. How have academic libraries changed since you were an undergraduate?

As the mode of communication has changed, the way libraries collect and provide access to information has changed, [but] the job is still, at its core, collecting and providing discoverability and access to research communications.

I think of libraries as having one foot in the 21st century and one in the 19th century because in many ways we are still supporting traditional formats and traditional access to those formats. There are certain disciplines, including mathematics and humanities, where the mode of communication is still a print book.

3. What are some of the challenges for librarians today?

I think grappling with what preservation means in a digital age is key. I was having a conversation with one of our division chairs earlier this week, and it turns out that division has lab notebooks from a famous Caltech scientist sitting on the shelves in one of its rooms. And so, of course, I'm interested in what we can do to help preserve those. But in some ways, that's an easy solution, because paper is a pretty good preservation format.

On the other hand, when I was cleaning out my desk at NYU, one of the things I found in the corner of my desk drawer was a stack of floppy disks held together with rubber bands. There were files on there, of course, but I didn't have any way to read them. That's the kind of challenge that we have with born-digital information.

"I did what I love to do: I started learning. ... I voraciously read files, conducted research in the Archives, and read (and indexed) the official records of the Board of Trustees, starting with 1891 and continuing through to today. I observed and emulated the behaviors and management styles of the people I admired. I reflected on the lessons that I had learned, the challenges that I met, and, most importantly, the mistakes that I made (and, yes, there have been plenty). Where better to be a lifelong learner than at Caltech?"

— Mary Webster (pictured with Caltech president Thomas Rosenbaum) on assuming the role of secretary of the Board of Trustees in 1987. Webster, who joined the Institute in 1966 as a clerk stenographer at JPL, retired in January 2020.

Daniel Mukasa (first-year graduate student)

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

Daniel Mukasa is a graduate student in materials science. He was introduced to Caltech through the WAVE Fellows program, which aims to foster diversity through increased participation of underrepresented students in science and engineering PhD programs.

"I was originally interested in combining medical technology with physics and materials science because my uncle, who is a professor, does work in medical engineering, specifically to help the nation of Uganda, where my family is from. I met Wei Gao [a Caltech assistant professor of medical engineering] and was really interested in how very innovative technology that would not be used necessarily in America can make a dramatic difference in developing countries. I wanted to follow that path. If you can apply technology [like his low-cost sweat-based diagnostics] in a developing country, you can make a substantial change to life expectancy just by being able to monitor people's health statistics and provide preventive care."

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

History Relocated

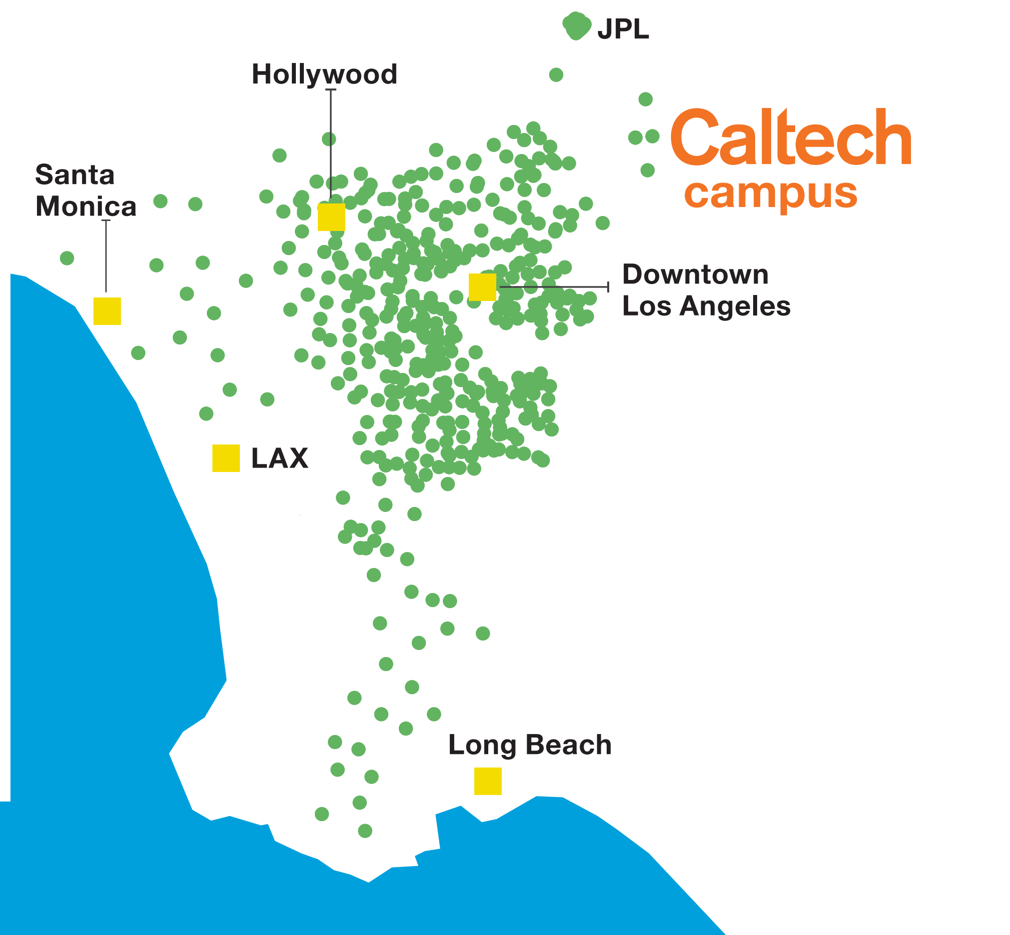
As part of the Tianqiao and Chrissy Chen Neuroscience Research Building construction project, the Wilson Court bungalows, originally located on the southeast corner of Del Mar Boulevard and Wilson Avenue, were transported in 2018 two blocks away to the northeast corner of Catalina Avenue and San Pasqual Street. Late in 2019, restoration of the exteriors of the historic bungalow court was completed. The Spanish Colonial Revival–style court was originally built in 1923, with five of the buildings arranged around a central landscaped courtyard. Two additional structures were built to one side of the main court, an unusual feature for a bungalow court and one that adds to its historical significance. As part of the relocation project, Caltech repaired and restored the terracotta tile parapets, lime plaster exterior walls, wooden window trim, French entry doors with arched transoms, and other historical features.

Quake Map

A decade ago, Caltech earthquake scientists and engineers rolled out a network of low-cost, easy-to-install seismometers. With around 800 sensors now in the L.A. area, the Community Seismic Network (CSN) recently expanded westward with another hundred, thanks to new funding from the Conrad N. Hilton Foundation and Computers & Structures, Inc.

Most of the sensors are situated on L.A. Unified School District campuses, which brings distinct advantages, says Monica Kohler (PhD '95), a research professor of mechanical and civil engineering. "When an earthquake happens and the waves propagate, we like to see this very coherent picture of what the wave is doing as it travels across the L.A. Basin. And having all of these stations roughly equidistant, at half a kilometer spacing, gives us that information."

In addition to the LAUSD sensors, the network also includes a 52-story tower in downtown L.A. and several other mid- and high-rise buildings with instruments on every floor. The network provided highly granular and detailed information about how the Ridgecrest earthquake series shook the Los Angeles area and how different buildings responded to the quakes. "For our next batch of stations, we want to focus on the area around West Los Angeles," says Kohler, "to capture what the effects would be on those high-rises."



In the Community

A Better Match

From left: Federico Echenique, the Allen and Lenabelle Davis Professor of Economics; Laura Doval, assistant professor of economics; and Adam Wierman, professor of computing and mathematical sciences.

As the father of two school-age children, Adam Wierman knew that Pasadena Unified School District's open-enrollment process was not optimal. "I couldn't help but notice that it wasn't particularly well designed," says Wierman, a Caltech professor of computing and mathematical sciences. "There was a huge opportunity, I thought, to improve."

PUSD's open-enrollment system allows parents to participate in an annual lottery for the chance to get their children into non-neighborhood schools. The problem, Wierman says, is that the process was both inefficient and prone to gaming by anxious parents. Eager to come up with a better algorithm to support the district and its parents, Wierman collaborated with Caltech social scientists Federico Echenique, the Allen and Lenabelle Davis Professor of Economics; and Laura Doval, assistant professor of economics. Both had experience with similar problems in the area of school choice assignment.

With the team's new and improved algorithm, which rolled out in early 2019, families not only were more likely to get their top match but also were more likely to keep their children in their school district rather than enroll them in private or charter schools.

PUSD's previous open-enrollment system involved two rounds of applications and offers, in between which families found out whether they had been admitted to private schools as well. The existence of so many non-public-school options in Pasadena provided an additional wrinkle that made the problem interesting to the Caltech researchers.

Some parents would also attempt to manipulate the system: instead of listing schools in order of their actual preference, they would estimate which schools had a larger number of open slots and then rank those first.

To tackle the problem, the Caltech group came up with a new algorithm that incorporated several changes including an increase in the number of schools families can list from five to unlimited. "When there's a limitation, you tend not to list schools that have very few slots available," explains Wierman. "Once you go to unlimited, there's no reason not to just list every school in the order that you prefer them."

Another significant change was aimed at families who might leave the district. Historically, families participated in one round in which they were asked to rank the schools and were given an initial assignment. If they were unhappy with that assignment, they could enter a second round during which they could resubmit their preferences. The catch was that they had to give up their original assignment.

In the new system, families rank the schools just once; if they are not fully satisfied with their initial assignment, they can move on to the second round but are guaranteed that they will not lose their original seat until and unless they are given a seat in a school they ranked higher.

Data from PUSD show that these changes to the algorithm had a significant impact, even in its first year. The number of families matched to their top choice went up by 10 percent overall, with even greater improvement at particular grade levels: 97 percent of high school families and 80 percent of middle school families were matched to their first choice. PUSD is continuing with the changes for its upcoming open-enrollment season.

This new program could be helpful to other school districts, says Doval, since the issues it addresses are "by no means exclusive to Pasadena."

—Judy Hill

The Case of the *Surfing Bees*

by Robert Perkins

When stuck in water, bees create a wave and hydrofoil atop it, according to a recent study.

Walking on Caltech's campus, research engineer Chris Roh (MS '13, PhD '17) happened to notice a bee stuck in the water of Millikan Pond. Although it was a common-enough sight, it led Roh and his then-adviser Mory Gharib (PhD '83) to a discovery about the potentially unique way that bees navigate the interface between water and air.

Roh spied the bee during California's yearslong drought, when the pond's fountain was turned off and the water was still. The incident occurred around noon, so the overhead sun cast the shadows of the bee, and, more importantly, the waves churned by the flailing bee's efforts, directly onto the bottom of the pool.

As the bee struggled to make its way to the edge of the pond, Roh noticed that the shadows on the pool's bottom showed the amplitude of the waves generated by the bee's wings as well as the interference pattern created as the waves from each individual wing crashed into one another. "I was very excited to see this behavior, and so I brought a honeybee back to the lab to take a look at it more closely," Roh says.

Roh worked with Gharib, Caltech's Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering, to recreate the conditions of Millikan Pond. He placed water in a pan, allowed it to become perfectly still, and then put bees, one at a time, into the water. As each bee flapped about in the water, filtered light was aimed directly down onto it, which created shadows on the bottom of the pan. Roh and Gharib studied 33 bees individually for a few minutes at a time, then carefully scooped them out to let them recover from their swimming efforts.

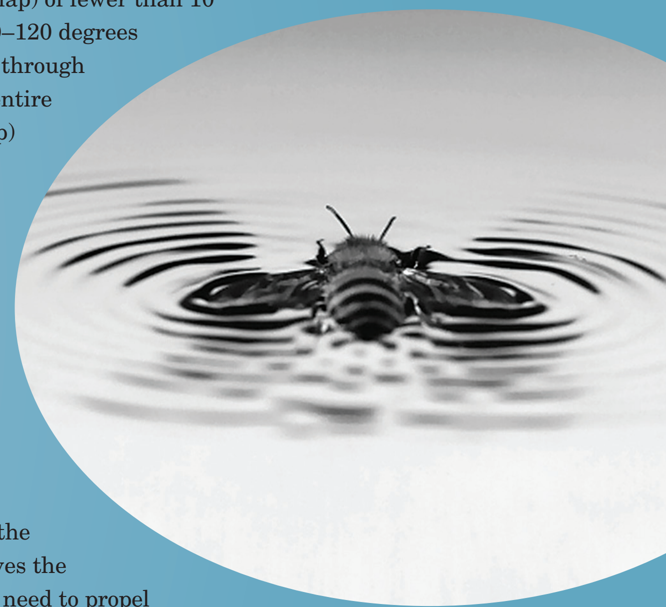
When a bee lands on water, the water sticks to its wings, which rob it of the ability to fly. However, that stickiness allows the bee to drag water and create waves that propel it forward. In the lab, Roh and Gharib noted that the generated wave pattern is symmetrical from left to right. A strong, large-amplitude wave with an interference pattern is generated in the water at the rear of the bee while the surface in front of the bee lacks the large wave and interference. This asymmetry propels the bees forward with the slightest of forces, about 20 millionths of a newton. (For reference, a medium-sized apple held in your hand exerts about 1 newton of force on your palm due to gravity.)

"The motion of the bee's wings creates a wave that its body is able to ride forward," Gharib says. "It hydrofoils, or surfs, toward safety."

> "The motion of the bee's wings creates a wave that its body is able to ride forward."

Slow-motion video revealed the source of the potentially life-saving asymmetry: rather than just flap up and down in the water, the bee's wings pronate, or curve downward, when pushing down the water and supinate (curve upward) when pulling back up out of the water. The pulling motion provides thrust, while the pushing motion is a recovery stroke.

In addition, the wingbeats in water are slower, with a stroke amplitude (the measure of how far the bees' wings travel when they flap) of fewer than 10 degrees, as opposed to 90–120 degrees when the bees are flying through the air. Throughout the entire process, the dorsal (or top) side of the wing remains dry while the underside clings to the water. The water that sticks to the underside of the wing gives the bees the extra force they need to propel themselves forward. "Water is three orders of magnitude heavier than air, which is why it traps bees. But that weight is what also makes it useful for propulsion," Roh says.



The bees do not seem to be able to generate enough force to free themselves directly from the water, but their wing motion can propel them to the edge of a pool or pond, where they can pull themselves onto dry land and fly off. The motion has never been documented in other insects and may represent a unique adaptation by bees, Roh says.

Roh and Gharib, who work in Caltech's Center for Autonomous Systems and Technologies (CAST), have already started to apply their research to their robotics research, developing a small robot that uses a similar motion to navigate the surface of water. Though labor-intensive, the motion could one day be used to generate robots that can both fly and swim.

Watch a video of surfing bees at **magazine.caltech.edu/post/bees-surf**

TALES OF SPITZER

Earlier this year, Spitzer Space Telescope was officially retired after 16 years in orbit, leaving behind a trove of memories for hundreds of people involved in its trailblazing mission.

In January 2020, NASA's Spitzer Space Telescope mission ended, bringing to a close a pivotal chapter in astronomy. Designed to last up to five years, Spitzer spent more than 16 years probing the cosmos with its infrared vision. The mission's observations led to many discoveries, including soccer-ball-shaped molecules in space called buckyballs; the largest ring around Saturn; and infant galaxies at the dawn of time.

Some of the biggest surprises from Spitzer involved its studies of planets around other stars, or exoplanets. Though not designed to study exoplanets, Spitzer turned out to be a trailblazer in this field. Perhaps its most notable detection was of a family of seven rocky planets around the star system TRAPPIST-1.

The Spitzer mission was led by JPL, and its science operations took place at IPAC. Spitzer data will continue to be archived at IRSA (NASA/IPAC Infrared Science Archive) and studied by astronomers around the world. Here, in excerpts from blogs that can be found on Spitzer's website, various members of its staff recall their favorite memories.

Matthew Ashby is an astrophysicist at the Center for Astrophysics in Cambridge, Massachusetts. Ashby has been a member of Spitzer's Infrared Array Camera instrument team since 1998.

"At one point during the troubleshooting, I was invited in to Lockheed's clean room to view the spacecraft up close, partially unwrapped and disassembled to expose the nozzles that needed work. It was about the size of a comfy living room chair.

I had two thoughts. The first was: 'Look at that! We're going to send THIS THING millions of miles out into space!' (Because there was no real doubt the nozzles would get fixed.) The second was: 'Step back, Matt. You could sneeze on, or even worse, bump into that. You'll knock it over and be remembered forever as THAT guy.' …

You can imagine the anxiety we all felt later when it came time to launch Spitzer. Would it reach orbit? Would it work once it got there? (Selfish corollary: Would I have a job next week?) I carried quite a bit of excitement mingled with worry when my family and I went to the jetty on the Banana River across from Cape Canaveral on launch night. From there, we joined many other Spitzer people (outnumbered by the nighttime anglers) to enjoy the clear view of the brightly lit, blue-and-white Delta II heavy rocket sitting on its pad while the launch sequence counted down to zero.

the size of a comfy living room chair

If you've never seen a spacecraft launch, well, I recommend it. I'll never forget my panic trying to wake up my 2-year-old son in time to watch Spitzer lift off. But that was unnecessary: it was LOUD! It shook my whole body. And I'll never forget the sight a few moments later when the booster rockets separated downrange over the Atlantic. The moment the boosters spun away and blinked out one by one in the darkness is when I finally let myself start to relax and believe everything was going to work okay.

Whitney Clavin is a senior content strategist in Caltech's Office of Strategic Communications. Clavin worked at JPL for 13 years as a science writer and media specialist, and covered the Spitzer mission.

the rumble
of a rocket in my bones

"Only a month or so after I started the job, in the summer of 2003, Spitzer launched into space aboard a rocket that blasted off from NASA's Kennedy Space Center. One of my first assignments was to attend the Spitzer launch and help with press. In reality, I'm not sure I was much of a help, being so new to Spitzer and NASA launches. But in that swampy place of alligators and space shuttles, I was bit by the Spitzer bug and was thrilled to learn more.

Another JPL media rep, Gay Hill, was sent out to the launch with me. We were both new to NASA launches and wound up lost a few times on the grounds of Kennedy; at one point, we found ourselves deep into the Cape Canaveral air force station, and security had to escort us out. The trip was probably one of the most memorable of my life, and the launch itself, which took place at night, amounted to the first time I felt the rumble of a rocket in my bones.

Mike Werner is project scientist for the Spitzer Space Telescope and chief astronomy and physics scientist at JPL. He is co-author of *More Things in the Heavens: How Infrared Astronomy Is Expanding Our View of the Universe*, a new book about Spitzer's legacy.

the afterglow
of a gamma-ray burst

"I have a soft spot in my heart for a fairly obscure Spitzer result—our detection of the afterglow of a gamma ray burst. The story begins on the morning of Thursday, March 20, 2008 when Spitzer Science Center Director Tom Soifer (BS '68) and I were having our regular weekly tag-up with program scientist Doug Hudgins at NASA Headquarters. … On this occasion, he surprised us by asking if we had heard about the naked eye gamma ray burst.

This was too good a chance to pass up, so right after the call I contacted Shri Kulkarni at Caltech, an experienced and enthusiastic observer of transient phenomena. Before the end of the day we had generated a Director's Discretionary proposal asking the Spitzer team to interrupt its already scheduled observing sequence to squeeze in an observation at the position of the gamma-ray burst. The urgency was dictated by the fact that the afterglow of gamma rays bursts was known to decay within a few days, at least at visible wavelengths. After seeking external advice, Soifer approved the request, and Spitzer was pointed at the burst position in less than two days after making the request. … We imaged the field with the thumbnail-sized 15um peakup array of the infrared spectrograph (IRS), readily detecting a source at the position of the afterglow. …

This is where the fun begins. Because we could only be certain of having seen the burst if something varied with time, we had scheduled a second observation eight days after the first. In between the two observations, it was observed that the data coming back from the IRS were badly garbled. … Jeff van Cleve of the IRS team and Jim Ingalls at the SSC somehow figured out that if the corrupted data were shifted by just the right amount the images could be reconstructed. When they reconstructed the second epoch of the burst source in this fashion, the afterglow could no longer be seen. The Spitzer data were thus important in constraining the time history of the afterglow.

So this is one of my favorite Spitzer stories. All of us who worked on the project have a treasure trove of these; they form part of the fabric of our lives.

Anna Sajina is an associate professor of astronomy and astrophysics at Tufts University, Sajina was part of one of the very first groups of visiting graduate students at the Spitzer Science Center in 2003.

"In analyzing the Spitzer mid-IR spectra, some of our key results involved finding dust-obscured, accreting supermassive black holes and finding that this kind of activity is much more common than previously thought. One of my favorite memories is a project I led where we detected the presence of water ice in galaxies nearly 10 billion years in the past. This water is likely part of the icy mantles of interstellar dust grains. Combined with the ubiquity of complex hydrocarbons, again seen in the mid-IR spectra, this finding makes it clear the raw ingredients for the development of life are already commonly found throughout the universe, and only a few billion years after the Big Bang!

Read more Spitzer blog posts at www.spitzer.caltech.edu/explore/blog

Aomawa L. Shields is an assistant professor of physics and astronomy at UC Irvine. Shields is also an actor.

It was the exoplanets
that kept stopping my heart

"I had almost forgotten that I loved the stars and the universe. I had left an astrophysics PhD program to study acting because I didn't think I belonged, and I loved to tell stories. I ran away from the stars and then tried to become one, getting a master's in fine arts and then working odd jobs to pay the rent. …

Then I looked back up at the sky, and I didn't want to look anywhere else again. I emailed a research adviser from my undergraduate days. She told me jobs were often posted on this website for the Infrared Processing and Analysis Center, or IPAC, at Caltech. So, that day, I went to that website. And there it was: an ad for a helpdesk operator supporting NASA's Spitzer Space Telescope. …

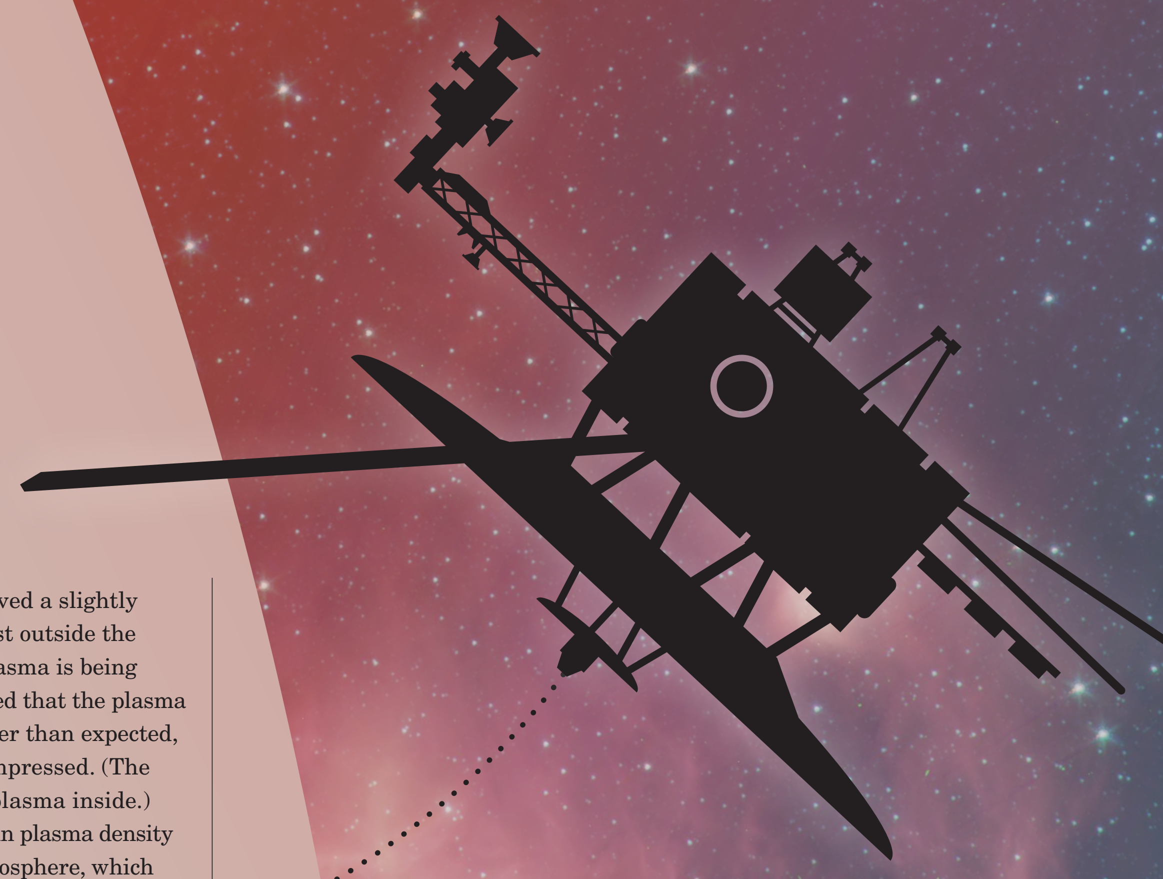
I never mentioned I was an actor in the interview. I didn't want to be labeled as a flake. … Once my supervisor on the science user support team was confident I was dependable, going to auditions during my lunch break wasn't a big deal. But I ended up wanting to stick around and go to astronomy talks. Since I'd left the field, the discovery of planets orbiting stars other than the sun, called exoplanets, had exploded. Scientists came to IPAC to talk about all sorts of astronomical phenomena, but it was the exoplanets that kept stopping my heart. …

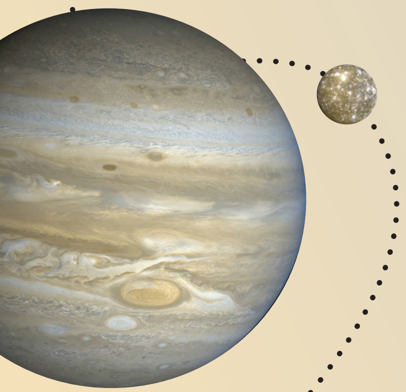
Later, I got to schedule observations on the spacecraft, which was like fitting jigsaw puzzle pieces together. How efficiently could I schedule my week this time? How little could I make the spacecraft have to slew between targets? … My supervisor was so patient, so kind, and so meticulous, and I learned how to be that way, too. I tried to bring those qualities with me back to graduate school when I studied astronomy the second time around. The meticulous part was especially useful in research, but the kindness has also never failed me.

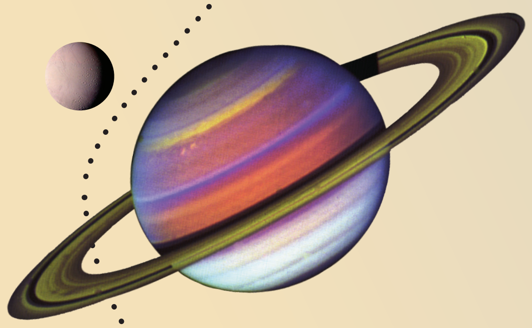
I'm a professor of astronomy now. I am also an actor and speaker. It all works together. … I can't help thinking that everything I have, including things I never knew I wanted, I have because I got to work for such a fantastic mission. Thank you. Even as it ends, I won't ever forget. C

INTO THE DEEP:

VOYAGER 2 *Sails through* Interstellar Space







In November of 2018, NASA's Voyager 2 became only the second spacecraft in history to leave the heliosphere, the protective bubble of particles and magnetic fields created by our sun. At a distance of 11 billion miles from Earth, well beyond the orbit of Pluto, Voyager 2 had entered interstellar space, or the region between stars. Now, scientists are able to describe what they have observed during and since Voyager 2's historic crossing, which helps to paint a picture of this cosmic shoreline, where the environment created by our sun ends and the vast ocean of interstellar space begins.

Both the heliosphere and interstellar space are filled with plasma, a gas that has had some of its atoms stripped of their electrons. The plasma inside the heliosphere is hot and sparse, while the plasma in interstellar space is colder and denser. The space between stars also contains cosmic rays, or particles accelerated by exploding stars. Voyager 1 discovered that the heliosphere protects Earth and the other planets from more than 70 percent of that radiation.

Scientists have confirmed that Voyager 2 is not yet in undisturbed interstellar space: Like its twin, Voyager 1, Voyager 2 appears to be in a perturbed transitional region just beyond the heliosphere. "The Voyager probes are showing us how our sun interacts with the stuff that fills most of the space between stars in the Milky Way galaxy," said Ed Stone, project scientist for Voyager and David Morrisroe Professor of Physics at Caltech.

The two Voyager spacecraft have now confirmed that the plasma in local interstellar space is significantly denser than the plasma inside the heliosphere. Voyager 2 has now also measured the temperature of the plasma in nearby interstellar space and confirmed it is colder than the plasma inside the heliosphere.

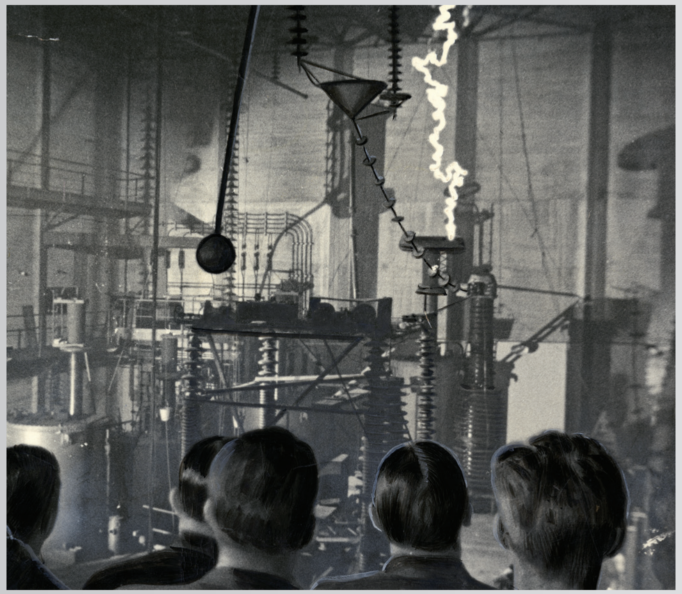
Back in 2012, Voyager 1 observed a slightly higher-than-expected plasma density just outside the heliosphere, which indicated that the plasma is being somewhat compressed. Voyager 2 observed that the plasma outside the heliosphere is slightly warmer than expected, which could also indicate it is being compressed. (The plasma outside is still colder than the plasma inside.) Voyager 2 also observed a slight increase in plasma density just before the spacecraft exited the heliosphere, which indicates that the plasma is compressed around the inside edge of the bubble. But scientists do not yet fully understand what is causing the compression on either side.

Scientists also learned that the protective bubble is not impenetrable. One of Voyager's particle instruments showed that a trickle of particles from inside the heliosphere is slipping through the boundary and into interstellar space. Voyager 1 exited close to the very "front" of the heliosphere, relative to the bubble's movement through space. Voyager 2, on the other hand, is located closer to the flank of the heliosphere, and this region appears to be more porous than the region where Voyager 1 is located.

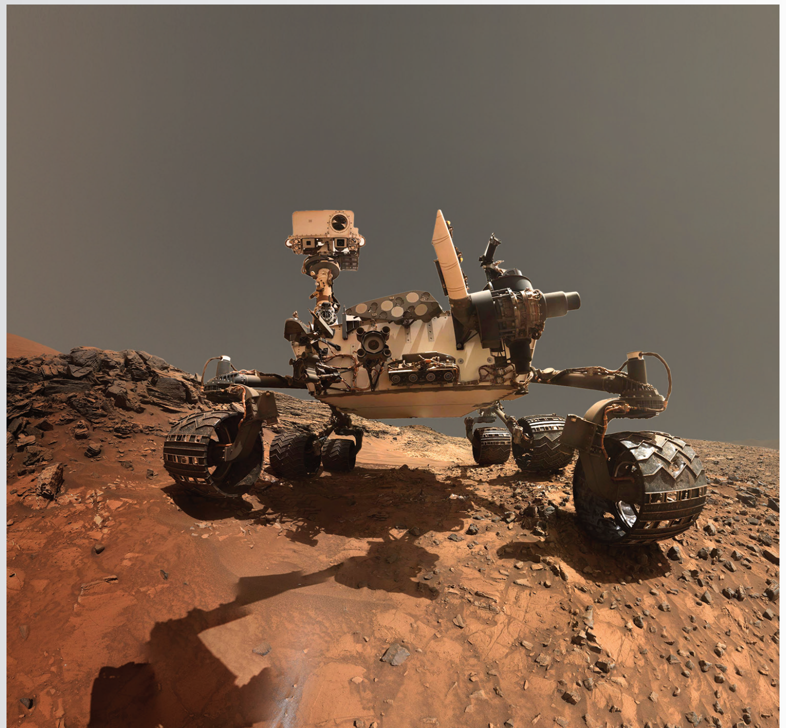
The Voyager probes launched in 1977, and both flew by Jupiter and Saturn. Voyager 2 changed course at Saturn in order to fly by Uranus and Neptune, the only close flybys of those planets in history. The Voyager probes completed their Grand Tour of the planets and began their interstellar mission to reach the heliopause in 1989. Voyager 1, the faster of the two probes, is currently more than 13.6 billion miles from the sun, while Voyager 2 is 11.3 billion miles from the sun. It takes light about 16.5 hours to travel from Voyager 2 to Earth. By comparison, light traveling from the sun takes about eight minutes to reach Earth. C

Learn more about the Voyager program at **voyager.jpl.nasa.gov**

Then



Now



Becoming Caltech

In 1920, when the Throop College of Technology became the California Institute of Technology, more than just its name changed.

On February 10, 1920, the Board of Trustees of what was then the Throop College of Technology (pronounced Troop) changed the name to the California Institute of Technology. Just over two months later, on April 13, the California secretary of state certified that the name-change petition had been officially filed in his office, completing the legal process.

If it had simply been a name change, there might be little reason to mark that occasion today. After all, Caltech's origins trace back to its founding in 1891, and it had changed its name twice previously, from Throop University to Throop Polytechnic Institute and then Throop College of Technology.

But the 1920 name change was a signal of something much more significant: a fundamental change in focus. Caltech not only amended its name but its student body as well, adding graduate students. This represented a move from teaching knowledge to creating knowledge, which transformed this regional manual-arts school into what would become an internationally renowned scientific-research institution. The name change was the first step in an evolution that has guided the Institute ever since.

Then (from top): The "Dugout" fireplace in the Student Center, 1924; chemistry lab in Gates, 1921; demonstration in High Volts, c. 1930. **Now (from top):** Students outside the Red Door Marketplace; in the lab of chemical engineering professor Mikhail Shapiro; the Mars Science Laboratory Mission's Curiosity rover.

A Q&A with Caltech Archivist Peter Collopy

A new exhibit put together by the Caltech Archives, Becoming Caltech: Building a Research Community, 1910–1930, *showcases the decades before and after the Institute's transition from Throop College to the California Institute of Technology.*

What is the scope of *Becoming Caltech?*

In the exhibit, we focus on the transformation of the institution in two periods. The first started in the late aughts, around 1908, when there was a really deep rebuilding of the Institute from one that had tried to be many things to many people in Pasadena to one that was very specifically and narrowly an engineering school. The second period begins when that engineering school, which lasted in that form for about a decade, was successful enough that its leadership decided it could expand to be a scientific institute as well.

One section of the exhibit features the architecture of the campus during this period. This was when many of the original buildings were constructed: from what was originally Pasadena Hall (which then became Throop Hall, the central building on campus until the 1970s) to the Athenaeum, which was dedicated in 1930. Many of the core scientific or laboratory buildings were also added to campus during this period: Gates for chemistry, Bridge for physics, Kerckhoff for biology. As each of these disciplines was established in the late teens and early ’20s, an architectural history developed with them.

Through the exhibit, the Caltech Archives also captures the history of science during this period, which is largely the story of the establishment of chemistry, physics, geology, and biology, and their scientific leaders. Robert Millikan, the most prominent American physicist of his time, and Thomas Hunt Morgan, maybe in the top two or three most prominent American biologists of his time, came to Caltech and built research apparatus around themselves.

Was there anything that surprised you about the earliest days of the Institute?

How central World War I was to the Institute is really striking to me. There was interest from people like George Ellery Hale in making Throop a more professional, scientific, research-oriented institution throughout the teens, but what brought the resources together and what brought the people together who could really make that happen was the level of collaboration among scientists demanded by a war. It’s not a new observation among historians of science that war leads to new collaborations, the development of new disciplines. It leads scientists to refocus their efforts on different problems than they had been focused on in peacetime, but the extent to which that provided the opportunity for the founders of Caltech to rebuild the Institute has been really remarkable.

Becoming Caltech *will remain on display in Beckman Institute 131 through December 23, 2020. Learn more at* ***library.caltech.edu/becoming-caltech.***

Insights into Caltech History

Speeches and correspondence that span more than 80 years recently gathered from the Institute’s Archives reveal how significant figures in Caltech history perceived the Institute’s place in the world.

George Ellery Hale (1868–1938)

Already a member of Throop Polytechnic Institute’s governing board, astronomer Hale convinced the trustees to dramatically change the school and its mission. In a 1908 letter to James A. B. Scherer, who would soon become Throop’s president, Hale laid out a vision for what would become the modern Caltech.

“It certainly seems feasible to educate men broadly and, at the same time, make them into good engineers. In my opinion, the man who [does so] will make a contribution of the highest importance to educational methods. I believe the principal technical schools of the country will be forced to do this thing before many years have passed, and the institution that sets the pace will benefit greatly.”

Thomas Hunt Morgan (1866–1945)

Morgan, a renowned biologist who would receieve the Nobel Prize in Physiology or Medicine in 1933, included a budget mindful of all the components needed to establish Caltech as a leader in the biological sciences in a 1927 letter to Hale.

“The proposed budget of $80,000 should give us a good start. … Nevertheless, I shall hope to persuade the Trustees to let us put aside enough of it to pay the car fares for the men and their families who go to Woods Hole (or elsewhere) for work during the summers. Here we have a unique situation, where all the biological world comes together. Such contacts should be of prime importance if our group is to go forwards and keep in the first rank.”

Martin Luther King Jr. (1929–1968)

In February 1958, the Rev. Martin Luther King Jr. visited Caltech as part of the Caltech Y’s Leaders of America program. After his three-day visit, King sent a letter of thanks to the Caltech Y for its sponsorship.

“As I said riding to the airport the other night, I was quite pleased in knowing that students in scientific research were so interested in social problems. This, it seems to me, is very promising and it is certainly all important as we think of the fact that our scientific and technological progress has so far outdistanced our moral and spiritual progress.”

Lee Alvin DuBridge (1901–1994)

Launched on February 17, 1965, NASA’s Ranger 8, which was designed by JPL, took more than 7,000 images of the moon before it was retired on February 20. The first secretary of the U.S. Department of Health, Education and Welfare, Oveta Culp Hobby, sent then-Caltech president DuBridge a telegram that read, “Hooray, the moon is now an old friend.” DuBridge responded to the congratulatory telegram in a letter.

“All of us here are very pleased with this new Ranger success, and we are becoming old friends with the moon. It has occurred to us that we really won’t be sure that the moon isn’t made of green cheese until we can reach out and pick up a handful of lunar firma. But this day is not far off.”

Harold Brown (1927-2019)

Brown, Caltech’s president from 1969 to 1977, implemented equal-opportunity programs and opened Caltech to female undergraduates. Brown reveals his thoughts on co-education at the Institute in a March 1990 interview.

“There had been a decision, in principle, to admit women as undergraduates. The trustees had approved that but had made it conditional upon the building of new student houses for women, which would take at least two years. I concluded that it was not a good idea to wait that long, and I pressed rather hard for an arrangement that would set aside corridors for women in the existing student houses. A good many of the trustees were very reluctant to do that, strange as it may seem in 1990—but that was 1969. Essentially, they did it because I made bringing in women in 1970 an issue of confidence in me.”

Brown said he pushed for their swift inclusion “very hard. In retrospect, I think it was the right thing to do.”

“It had always seemed to me that it was up to Caltech, for its own good as well as the good of society, to encourage those who reached the point of college admissions to go to as good a place as they could. And Caltech was such a place. Moreover, there is a certain positive effect—not enough, but some—in having women

Then

The “Old Dorm,” with a view toward the San Gabriel Mountains.

Now

The Hameetman Center, Caltech’s new community center, which was dedicated in February 2019.

who go to Caltech become role models who could reach down and help offset some of the biases that work the other way.”

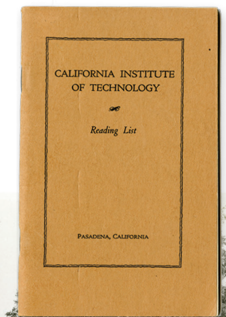
Frances Arnold (b. 1956)

Arnold, awarded the 2018 Nobel Prize in Chemistry, addressed the campus community after the prize announcement and spoke in part about the role Caltech played.

“We’re celebrating a small and very special institution that made it possible for me to do the work that led to the Nobel Prize. ... Only here could I convince students from very different disciplines—engineers, chemists, biochemists, molecular biologists, computational scientists—to throw their hat into this kooky ring and this completely unexplored field, and really contribute their creativity to this idea that you could breed proteins like you breed cats and dogs. And only here would I have been challenged to solve ever harder problems.”

Then + Now

Below far left: English Professor Clinton Judy’s Reading List, c. 1927. **Below left:** Commencement in front of what is now Parsons-Gates Hall of Administration, 1923. **Below right:** Each year, before commencement, the graduates gather in front of Parsons-Gates for a group photo. **Facing page, left:** Engineering professor Arthur Klein in the 10-foot wind tunnel. **Facing page, right:** Students conducting research in the Center for Autonomous Systems and Technologies. **Facing page, below:** From the Caltech Flags Collection.



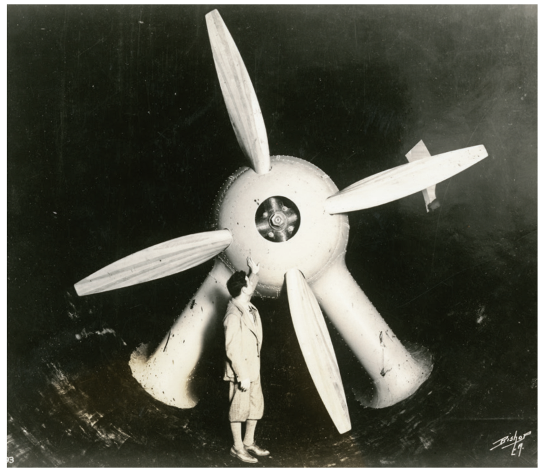
Caltech’s President and Provost on Caltech’s Evolution

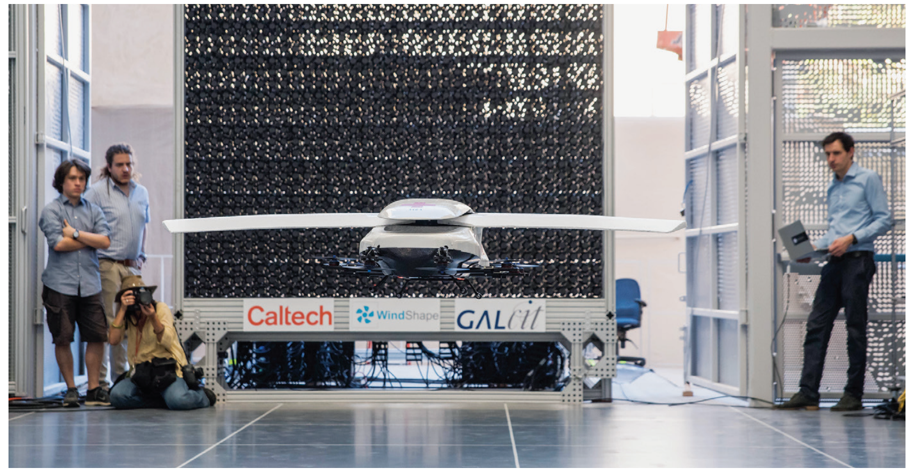
President Thomas F. Rosenbaum and Provost David A. Tirrell recently sat down for a conversation about the Institute’s first century of research and discovery as Caltech. They discussed how the 1920 name change reflected a decision to focus the Institute’s resources on science and engineering, how that decision has shaped Caltech’s success over the last century, and how it is being woven into their vision for the future.

David A. Tirrell: I think Caltech has always both addressed fundamental questions that are driven by curiosity about the nature of the physical world and taken account of the pressing questions of the day. This was certainly true with respect to our participation in the development of the aerospace industry and the Jet Propulsion Laboratory [JPL], and, more recently, in setting up the Resnick Sustainability Institute [RSI].

I think the RSI provides a striking example of that outlook. To understand the climate is an enormous intellectual challenge, but, at the same time, doing so is essential if we are to address an important societal issue. I think that Caltech’s ability to balance those two kinds of considerations and, in particular, to maintain a focus on the fundamentals while most external influences would push the Institute in the other direction, is important to its overall success.

Thomas F. Rosenbaum: One of the striking aspects of the modern founders of Caltech involved the risks they took at the beginning. They had the courage of their convictions. They saw that there were opportunities in science and





technology in Southern California at that time, and they completely switched the orientation of the Institute, focusing its mission and shrinking its size drastically, even to the point where it might not have continued to exist.

We retain the strong interactions between individuals, the lack of bureaucracy, the fact that faculty have a sense of what their colleagues are doing, that divisions are broad, that institutes connect between divisions. This all depends on not growing too big. It means you can’t do everything. That’s the cost. But it does permit us to do things in a different, supple, flexible way that other institutions simply can’t. I think it’s really important to maintain this advantage.

Tirrell: Maintaining our small size seems to be a commitment broadly shared by the Caltech community. At the same time, there are some things that we’ve done on a very large scale: large telescopes, LIGO. We balance small size against extraordinary investments in certain areas, and that’s a tension that I think has served Caltech well, one that demands constant thought about where we want to be small and where we need to scale up in order to do something important.

Rosenbaum: Yes. We’re trying to understand, given the close connections between the disciplines at Caltech, how we can make a contribution in the way that only Caltech can. And, in order to do that, you have to hire people who are fearless and who want to grapple with these gray areas, and you have to provide resources that let them take risks. You have to cast your net broadly.

Talent is distributed among people from every country, every ethnicity, among men, among women. If Caltech is going to compete, it needs to be a destination for the most creative, original minds across the world, but it also needs to be an environment where people then bring those different perspectives together to create knowledge. I consider diversity central to our sustainable existence as a leading research university.

Tirrell: This is an area where we need to constantly reexamine our practices. I believe a frank analysis would suggest that we have to continue to look for more effective ways to approach the challenge.

To start with, we need to be sure that we’re talking with the communities that are not yet fully represented at Caltech. We need broad conversations with people who can tell us about their first-person experiences and guide us to more effective practices.

Rosenbaum: I absolutely agree. In addition, we have to address some of the related issues that we face, including the free movement of people and ideas. Forty-five percent of our faculty were born outside the United States; almost 50 percent of our graduate students are international. The Institute has benefited enormously from people coming from around the world to join us. That historical advantage is becoming more difficult to sustain.

There is also the question of creating an environment where people can exchange ideas on all subjects. I think that it’s extraordinarily important to continue to create an environment where you get a vibrant clash of ideas. The other challenge we have is to make sure that we can continue to provide seed funds that allow people to follow their dreams, to have great ideas and then try them out. Trying risky ideas is something that I think we do well, but it takes substantial resources.

Tirrell: Yes. Caltech is an extraordinary place because of the unusually talented people who work and study here. Our colleagues want to be part of this community primarily because they want to work with each other. Our most important challenge is to make sure that we continue to attract extraordinary people: staff, students, and faculty. [C]

The above is an edited excerpt from a longer conversation. To read more, visit **magazine.caltech.edu/post/caltech-evolution.**

These people are ... on a mission to build a sustainable world.

chemists, biologists, geologists, ecologists, engineers ...

One day in 1903, a bout of smog darkened the skies of Los Angeles so much that many people thought a solar eclipse had occurred. For several decades to follow, smog outbreaks regularly closed schools and forced residents to don gas masks.

By mid-century, Caltech chemist Arie Haagen-Smit had discovered that ozone was the chief cause of this haze and the automobile industry a primary culprit that produced these noxious molecules. He went on to pioneer policy changes for motor vehicle pollution standards and now, while there are more cars and people in L.A. than ever, dark smog days are a thing of the past.

Water

Graduate student Andre Vyatskikh (MS '17) builds tiny light-activated devices that could be used to purify drinking water using sunlight.

Caltech researchers have long been central to sustainability research, and they are now on the cusp of new opportunity: in September 2019, philanthropists and entrepreneurs Stewart and Lynda Resnick pledged $750 million dollars to the Resnick Sustainability Institute (RSI) at Caltech to fund innovative research and education. In existence for a decade, the RSI is reenergized by this pledge.

"Addressing the challenges of climate change and the stewardship of our precious natural resources is a responsibility we all share. This historic pledge affords the Caltech community a unique opportunity to respond via bold research and educational initiatives that can have transformational societal impact," says RSI director and Bren Professor of Chemistry Jonas Peters. "As a small but remarkably impactful institution with a demonstrated capacity to solve really tough problems, we will now have resources, tools, and some of the world's brightest minds on a mission to deliver real-world solutions to society's vexing challenges in energy, climate, water, and the broader environment."

This support also has established four core research initiatives, each led by a faculty researcher: Water Resources (Mark Simons, John W. and Herberta M. Miles Professor of Geophysics and JPL Chief Scientist), Climate Science (Paul Wennberg, the R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering), Sunlight to Everything (Harry Atwater, Howard Hughes Professor of Applied Physics and Materials Science), and Ecology and Biosphere Engineering (Dianne K. Newman, Gordon M. Binder/Amgen Professor of Biology and Geobiology).

As plans take shape for these new initiatives, the RSI continues to shed light on some fundamental questions. What does it mean to create a sustainable society? Where can we improve, and where are we doing well? What questions is Caltech in particular best positioned to answer?

THE CHALLENGE:

Availability of Fresh Water

Ensuring sustainable supplies of fresh water to meet human and environmental needs, which are stressed by changes in climate, land use, and population, requires a dynamic understanding of both natural and human systems, and how they interact. Acquiring this understanding is the overarching goal of the RSI's Water Resources initiative led by Mark Simons.

POWERED BY PEOPLE

The RSI has supported 96 graduate students and postdoctoral scholars. These junior scientists, collectively known as the Resnick Fellows, are central to innovative research projects and creative solutions to a wide range of sustainability challenges. Already, Resnick Fellows and alumni have started a number of sustainability-focused companies.

The landmark 2019 pledge provides for an additional focus on undergraduate education. Funds from the gift will support the renovation of undergraduate chemistry laboratories and help restructure core undergraduate courses that will train generations of scientists in sustainability science.

To that end, the RSI has formed a campuswide education committee led by Professor of Chemistry Theodor Agapie (PhD '07) and Jess Adkins, Smits Family Professor of Geochemistry and Global Environmental Science. The committee will examine how best to enrich and create a focus on sustainability within all of Caltech's educational programs.

The Resnick Sustainability Resource Center, funded by the pledge, will include laboratories focused on ecology and biosphere engineering, and translational science and engineering, as well as a solar science and catalysis center, a high-performance computing center, a water and environment lab, and a remote-sensing center. The RSI center also will feature lecture and interaction spaces as well as new state-of-the-art undergraduate teaching labs. Every first-year undergraduate student will rotate through these labs in conjunction with redesigned core educational courses that incorporate sustainability science and engineering.

"We will aim to develop new tools to accurately measure surface and underground water resources, and how these resources change over time," says Simons. "With these data we will develop a new scientific understanding of water flow as impacted by site-specific geography. This framework will inform decision-support tools and expand our knowledge of built and natural water systems. The design and engineering of new and innovative water treatment technologies is also a central element of our vision."

To that end, the RSI recently sponsored projects that have helped to create models for the interconnected surface water network, which will enable better water management in the face of climate change.

Simons also notes the importance of remote sensing as a tool for studies of water resources. Recently, using an unprecedented number of satellite radar images, Caltech geophysicists tracked how the ground in Southern California rises and falls as groundwater is pumped in and out of subsurface aquifers. The results of this research may provide water management districts with means to assess the precise shape and size of aquifers, and the impact of the region's water use on those aquifers.

Next Steps:

The group's research priorities, says Simons, are to:

- Investigate the potential of tools developed by seismologists to be used to monitor underground water
- Monitor the budget of subsurface water in aquifers with remote sensing
- Enhance understanding of groundwater interactions with surface waters to best replenish underground reservoirs and optimize their use
- Develop an integrated model of the land surface and near-surface that accounts for the role of plants, geography, climate, and hydrologic processes
- Improve treatment options for both salt and wastewater to increase fresh water supply
- Build smart nanostructured materials that can efficiently extract salt from water

THE CHALLENGE:

Climate Change

Greenhouse gas concentrations are increasing as a result of emissions from fossil fuel extraction and use as well as those produced in nearly all aspects of society: from agriculture and air conditioning to Ziploc bags and zoning, nearly everything impacts the climate. It is hard to determine what the future holds for the levels of carbon dioxide and other greenhouse gases.

Climate

Graduate students Siraput Jongaramrungruang (MS '18) (left) and Liyin He (MS '18) (right) use satellite imaging and machine learning models to predict crop yield and measure greenhouse gas emissions, respectively.

The goal of the Climate Science initiative is to answer questions about the impact of elevated temperature and carbon dioxide on the biosphere; why methane concentrations rapidly increase; and how we should respond to these changes.

"Fundamentally, we want to know what the fate of Earth is and how we can improve our predictions of that fate. Developing pathways to alter that fate is perhaps the biggest challenge we face," says Paul Wennberg. "We aim both to reduce the uncertainty around prediction and to engineer solutions to mitigate climate change."

One of the major climate science tools is remote sensing: observing and making measurements of Earth from space and on the ground. The last several decades, says Wennberg, have been revolutionary in terms of being able to observe the earth, both in situ and through remote sensing. Now, scientists can observe global changes in atmospheric composition, in the land surface, and in our oceans and polar regions. They also can monitor emissions of carbon dioxide from burned fossil fuels and leaks of methane from the natural gas infrastructure.

Next Steps:

The initiative's next priorities, says Wennberg, are to:

- Quantify the factors that drive climate change, including emissions of methane from agriculture and natural gas production, land-use changes in tropical regions, the rapidly changing arctic, and carbon dioxide emissions from growing megacities
- Develop new methods and models to improve climate change forecasts
- Develop methods to mitigate greenhouse gas emissions through the reduction of methane losses from the energy infrastructure and agriculture, and removal and burial of carbon dioxide
- Create resiliency in built and natural systems so that they can adapt to rising temperatures, floods, drought, and sea level changes

THE CHALLENGE:

Sustainable Energy

The RSI's focus on sustainable energy is based on the recognition that while coal, oil, and natural gas make up 81 percent of the United States' energy consumption, these resources are finite, and the use of fossil fuels injects massive amounts of carbon dioxide into the atmosphere, which contributes to climate change. As Harry Atwater notes, this means that the development of renewable energy from naturally replenished sources will be vital for a more sustainable future.

Perhaps the most renewable resource of all, says Atwater, is sunlight: more energy from the sun falls on the earth in one hour than is used by every person in the world over the course of a year. Photovoltaic solar energy, where photons are harnessed from the sun and converted into usable energy, offers a promising alternative to fossil fuels. While the price of oil has remained relatively steady over the decades, photovoltaic solar energy technology has become less and less expensive. "Sunlight could power everything we make and do in our world," says Atwater.

The Sunlight to Everything initiative aims to develop technological capabilities to advance zero-carbon renewable resources and reimagine industrial and manufacturing processes in an environmentally sustainable way.

Though solar power is abundant, its supply still fluctuates; when clouds block the sun, for example, no power can be created. Thus, batteries that can store excess solar-derived electricity are crucial if solar energy is to replace fossil fuels. Caltech researchers have recently

Sunlight

Graduate students Madeline Meier (left) and Jackie Dowling (right) co-taught a course on sustainability in fall 2019, where students conceived and implemented practical solutions to make the Caltech campus more sustainable.

Biosphere Ecology

Postdoctoral scholar Kurt Dahlstrom studies the intimate relationship between bacteria and fungi in soils to demonstrate how fungi protect plants from harmful toxins. In a warming world, this work could be used to make crops more sustainable.

developed a new method to develop rechargeable batteries based on fluoride, which can last up to eight times longer than today's standard lithium-ion batteries.

Researchers at the Institute also have developed complex mathematical frameworks to map the energy grid across the nation, frameworks that will help determine when and where energy may be used most efficiently and where blackouts may occur.

Next Steps:

Atwater says the group will focus on research that will:

- Turn solar and wind energy into baseload electricity as well as fuel sources
- Use solar power to produce cheap and energy-efficient fertilizers and fuels
- Make dramatic leaps forward in battery technology and efficient electrical grids
- Utilize machine learning to find new catalysts for chemicals, energy, and materials
- Develop commercially viable solar power that can be beamed from space to Earth
- Harness microbial biomass degradation to generate biofuels

THE CHALLENGE:

A Harmonious Biosphere

Many of Earth's organisms, from microbes to plants to humans, profoundly affect important global processes, including the flux of greenhouse gases into and out of the atmosphere. Throughout Earth's history, no group of organisms has been more important in this respect than microbes; their metabolic activities have shaped the atmosphere, lithosphere, and hydrosphere over billions of years. However, in the past century, human activities have changed the earth's systems significantly.

The goal of the Ecology and Biosphere Engineering (EBE) initiative, led by Dianne Newman, is to understand how complex ecological relationships are affected by human activities and to identify means to promote more sustainable ecosystems. Specifically, the initiative will support research to advance knowledge of the distribution, abundance, and global impacts of diverse lifeforms on Earth; the physical, chemical, and biological interactions that define them; and how the control of particular organisms or communities may lead to desirable outcomes.

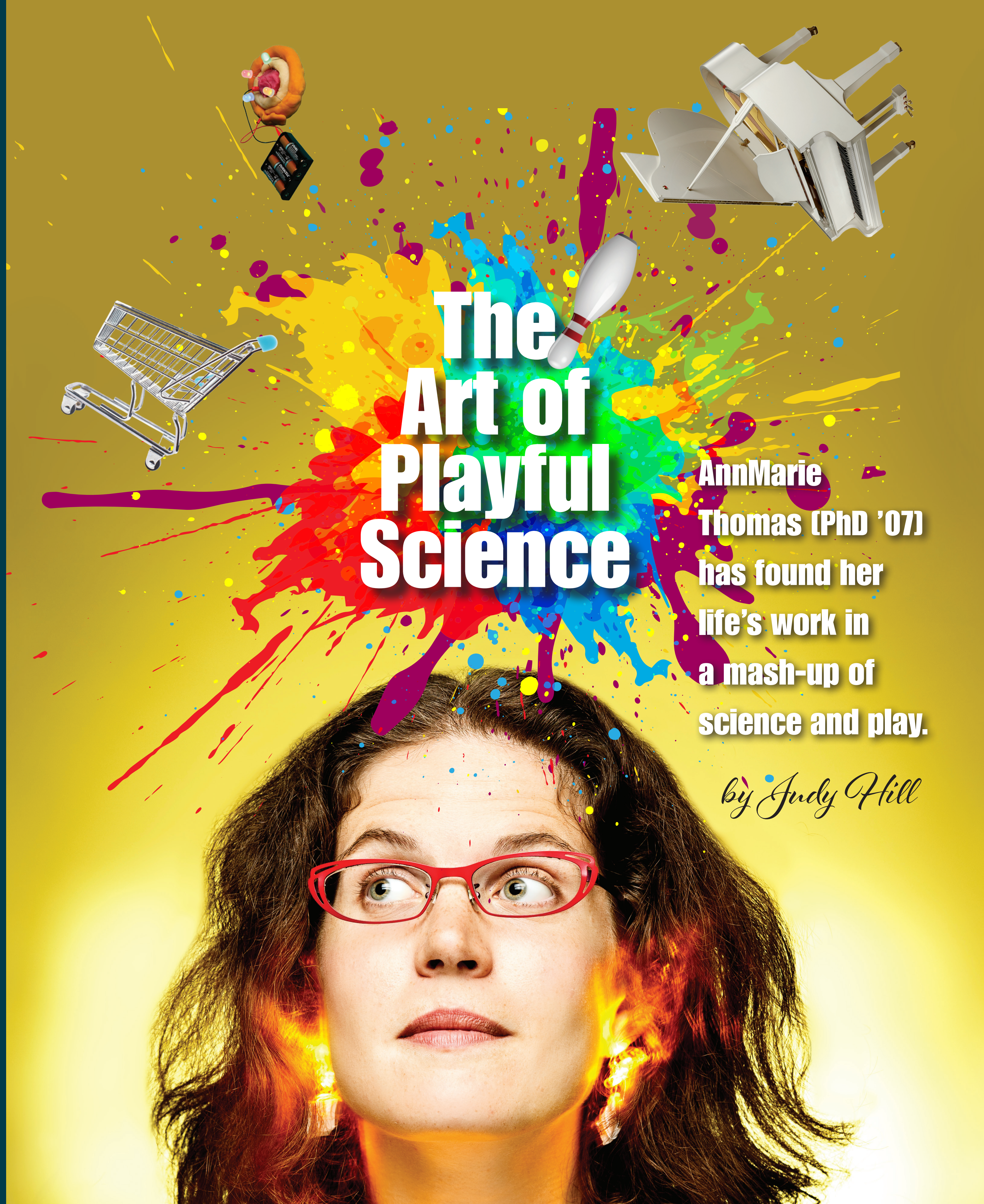
"A focus on ecology and biosphere engineering will be a new direction for Caltech," says Newman. "Though we have many interested scientists and engineers on campus, ecology is an area we have not traditionally studied."

Newman notes that Caltech's interdisciplinary Center for Environmental Microbial Interactions (CEMI) provides an example of the type of focus and collaboration that will characterize the EBE initiative. Members of CEMI, which has brought together more than 30 faculty from nearly every division since its inception in 2012, work on diverse problems that range from the control of methane by microbial communities in deep ocean sediments to the development of new tools for ultrasound imaging that harness microbial gas vesicles.

Next Steps:

Areas for initial investment, says Newman, could include research that will:

- Develop more accurate ways to monitor and/or control certain species in ecosystems
- Develop real-time sensors to monitor ecosystem changes over diverse spatial and temporal scales
- Characterize soil microbial communities that associate with particular crops or forests in order to explore ways to bolster plant resilience in the face of increased drought or floods, to maximize nutrient retention and recycling, and to protect plants from pathogens whose ranges are expanding due to climate change
- Find ways to better model the terrestrial biosphere's contribution to the global carbon cycle to minimize negative consequences associated with fertilizer production, transport, and runoff.
- Engineer novel capabilities in photosynthetic organisms to make them more efficient at energy capture
- Devise new ways to make greener plastics [C]



AnnMarie Thomas partners with preschoolers and college students to design a project for the Works Museum, an interactive children's museum in Bloomington, Minnesota, that focuses on technology and engineering.

At 10 a.m. on a recent December morning in Beckman Auditorium, nearly a thousand L.A. County school children chuckle, whoop, and occasionally applaud as they take in the controlled mayhem playing out on the video screen in front of them. A minute and a half into a chain-reaction sequence worthy of Rube Goldberg, a soccer ball falls off the end of a track, hitting a plank, which causes a suspended piano to crash to the ground, which trips a lever that sends a shopping cart down a ramp, spewing its contents, which (eventually) unleashes a hanging sledgehammer that smashes a TV, which ultimately causes a row of cannons to splatter four white-overall-clad musicians with brightly colored paint.

The music video the middle schoolers are watching is "This Too Shall Pass" by the American rock band OK Go, and the four band members are onstage at Caltech to talk about how they created this and other videos throughout their 20-year career, including one filmed on a plane in microgravity and one shot in 4.2 seconds and played back in slow motion over four minutes (fully synced to the music). Bursting salt canisters, flying paint, exploding guitars, and erupting water balloons abound, but so do lessons in mathematics, physics, fluid dynamics, and parabolas.

The students' questions range from "Did you feel like throwing up when you were in zero gravity?" to "How did you figure out the spreadsheet for the slow-motion video?" Gently guiding the conversation is AnnMarie Thomas (PhD '07), a mechanical engineering professor at the University of St. Thomas in St. Paul, Minnesota, who also heads up OK Go Sandbox, a free website for educators that uses OK Go's music videos as starting points for teaching children STEAM (science, technology, engineering, art, and math) concepts.

Thomas met OK Go lead singer Damian Kulash at TED2017 in Vancouver, British Columbia, when Kulash spoke about how the band comes up with ideas for its music videos. Thomas, who for years had included OK Go's videos in her lesson plans, bumped into Kulash as they were both grabbing a cup of coffee after the talk. She told Kulash how much she enjoyed his presentation, and three weeks later they gave a joint talk at UCLA and had started to put together the OK Go Sandbox venture. In less than three years, they have produced almost 20 educational videos and a host of additional material for teachers.

If that sounds fast, for Thomas it is normal operating procedure. "When I like a project, I move fast," says Thomas. "And I have an amazing student research team."

On the faculty of the University of St. Thomas since 2006, Thomas co-founded and co-directs the university's Center for Engineering Education. She also is a professor of entrepreneurship in St. Thomas's business school.

Through her research group, which is called the Playful Learning Lab, Thomas and her team create hands-on experiences for pre-K–12 students and educators. Thomas also is the inventor of Squishy Circuits (a method for using homemade conductive and insulating doughs to sculpt electrical circuits) and the author of several books including *Making Makers: Kids, Tools, and the Future of Innovation.*

In her spare time, Thomas, who also has a certificate in sustainable design, is an avid aerialist, a juggler, and, during summers in her native New Jersey, a surfer. She and her husband, Chris Thomas (PhD '04), a research chemist, have two daughters, Grace (9) and Sage (12), and whenever the family members' downtimes coincide, they play board games together in their St. Paul home or spend an afternoon in a local puzzle or escape room.

Working with OK Go seemed like a natural fit to the playful and energetic Thomas. "The band knew that teachers used their videos," she says, "and that made them super happy, but they also knew they were musicians, not educators." Thomas and her lab provided the missing expertise, surveying teachers and zeroing in on topics and themes to explore through educator guides. It was that work, in collaboration with OK Go, that resulted in OK Go Sandbox.

"Damian is one of the most creative people I have ever met," says Thomas. "Quite a polymath." Their work style is to chat frequently, run ideas back and forth, and then get together with the band and a film crew, usually in L.A., to shoot segments for OK Go Sandbox.

For "This Too Shall Pass," the Rube-Goldberg-inspired music video, the team put together a behind-the-scenes video. "We wanted to encourage kids to make their own chain-reaction machines," says Thomas. "And I wanted to look more closely at simple machines. You can use this whole video as a simple-machine scavenger hunt, so we have that in the teacher resources."

When the team films educational videos, they always have at least one teacher on set, and every resource guide developed by OK Go Sandbox is play-tested by teachers and then tweaked in response to their feedback. "People think we do the stuff for the kids. And it's true," says Thomas. "I love kids, but really my heart is in how we can give educators ways to enjoy what they're doing, to be engaging and engaged with the material."

Thomas is equally focused on giving her undergraduate students once-in-a-lifetime experiences. The Playful Learning Lab is completely staffed with undergraduate students, approximately 30 in all, and they are a diverse group. "About a third are computer science or engineering students," says Thomas, "and the other two-thirds are

Previous page: AnnMarie Thomas, wears a pair of homemade LED earrings. In the upper left, just above the headline, is a Squishy Circuit, one of Thomas's inventions.

students from a mix of communications, journalism, education, business, finance, marketing, and music."

Krista Schumacher, a junior majoring in elementary education at the University of St. Thomas and a lead education researcher for the Playful Learning Lab, says, "AnnMarie has taught me a multitude of things, but the most important is the ability to apply each person's unique strengths in our work." For Schumacher, that has translated into designing exhibits at the Minnesota Children's Museum and working on a mathematics-

Members of the rock band OK Go experiment with zero gravity in their music video "Upside Down & Inside Out."

educator guide to accompany OK Go's slow-motion "The One Moment" music video.

Collin Goldbach, a senior in mechanical engineering and lead engineering researcher for the lab, has worked on projects as diverse as embedding sensors and microcontrollers to accentuate the performance of trapeze artists and building life-size pop-up books for exhibits at local children's museums. "While we all have some capacity to bring change, the effect when we work together is greater than the sum of its parts," says Goldbach, who then adds that he learned that lesson from Thomas.

As a St. Thomas undergraduate, Rachel Gehlhar worked with Thomas on a project with Chicago's Michelin three-star restaurant Alinea to measure the organic volatiles of black and white truffles. She says Thomas gave me "opportunities as an undergraduate to lead a graduate-level research project and connected me with people I couldn't have dreamed of meeting on my own." Gehlhar is now a graduate student at Caltech in the lab of another St. Thomas alum, Aaron Ames, Bren Professor of Mechanical and Civil Engineering and Control and Dynamical Systems.

Play, in the Playful Learning Lab, is defined by Thomas as "joy, whimsy, surprise, and new people." The lab rules are: "Be kind, play well with others, and clean up your messes." By having her students take responsibility for marketing, budgets, travel, and lab operations, as well as for the research and design work, Thomas hopes to help them develop competency in many areas.

She says she is less concerned with her students' grades than with the meaningful work they are accomplishing. When she was a student herself, Thomas says, she excelled at doing projects in classes because she was able to organize and bring together the right mix of people. "If the class didn't have a major project component, though, whether it was a physics class or a math class, I struggled and did not get an A and probably did not even get a B."

As a child, Thomas had widely varying interests ("I was a little odd," she admits) and in high school was convinced she would be a painter or an actress or a musician. Her bachelor's degree from MIT was in ocean engineering, but she earned a minor in music composition. And while at Caltech, though her PhD was in mechanical engineering, she also took classes at ArtCenter College of Design, even becoming a faculty member there in her third year of graduate school, teaching bioinspired design and robotics as well as collaborating on installation artwork with exhibitions director Stephen Nowlin.

Though Thomas was hardly a typical Caltech graduate student, she says the experience worked for her largely because she found an understanding adviser in mechanical engineering professor Joel Burdick, who "let me do a lot of things." Burdick, who calls Thomas "a tornado with glasses," says he knew early on that she was interested in teaching and public outreach, and encouraged her teaching at ArtCenter as well as her leadership role with the Caltech Robotics Outreach Program. He is not surprised that his hardworking and productive graduate student, whose thesis involved robotic jet propulsion, has continued to lead and innovate. "What does surprise me," he says, "is her ability to juggle so many different things."

As Thomas tells it, she began to find her true calling after the move to Minnesota, when she invented the conductive, insulating Squishy Circuits as a way for her daughter to play with circuitry. When that took off, she began to realize she had found her sweet spot. At around the same time, she taught a class on the physics of circus arts, where she had students learn circus skills and then wear sensors while they performed, and later analyze the data they recorded. "And once you're that professor, then other weird things start happening," says Thomas.

Thomas glows with pride as she talks about Code + Chords, the software project students in her lab have created, and the awards and published papers that have resulted from this open-source coding library that creates real-time visual displays based on vocal inputs. She lights up still more when she describes the science workshops her students have conducted at the Metro Deaf School in St. Paul and how the students there are now learning to code using the music software from the earlier project.

Add to that a newly established five-year residency at the Minnesota Children's Museum, where Thomas and her team spend one day a week studying how families interact in the museum and designing new exhibits and experiences, plus a partnership with Jeff Bezos's space company Blue Origin that will send children's art designs into space, and it is not hard to see why a colleague recently said to Thomas, "I'd be happy with just one of your projects." "So would I," replied Thomas wryly, though she also believes that as stand-alones they would have less impact.

"All the projects I do are related," she says. "Learning is about curiosity and pulling together unusual things. How do you take things that seem unrelated, be they music and coding, physics and circuses, rock stars and preschoolers, or chemistry and chefs, and smash them together in new ways? That's our happy spot: we take all these different things and try to see them in new ways."

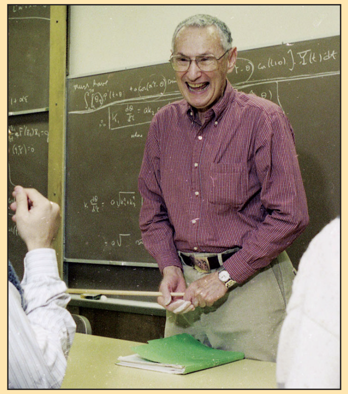
As much as her work focuses on play, Thomas takes collaboration seriously. Too often, she says, people say they collaborate when they are simply calling on someone who has the right piece of software or knows the right math equation. "That's not collaboration," she says, "that's consulting." She will only agree to a project when she has had a "playdate" with the people involved, and they have started to dream up ideas together.

Naturally, given Thomas's personality, those early get-to-know-you sessions often end up being playful. When her team was considering working on a music-visualization software project with an a cappella group, she insisted on meeting every member of the group first. "I got to the coffee shop before them and wired up the coffee spoons to a circuit board so they could play music with their spoons," she says. "With everything I do, it's about how you bring play to a situation, whether it's a course or a topic or a project." Or a meeting with an a cappella group about software.

Learn more about OK Go Sandbox and watch OK Go videos at okgosandbox.org

In Memoriam

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



Donald S. Cohen

1934-2020

Donald S. Cohen, Charles Lee Powell Professor of Applied Mathematics, Emeritus, passed away on January 9. Cohen was one of the first faculty members recruited for Caltech's newly formed applied mathematics program in 1965, earning tenure in 1971. Colleagues and former students remember Cohen's outgoing personality, quick wit, and engaging lectures. Cohen's research on nonlinear differential equations, pattern formation, stability, and bifurcations had a significant impact on mathematical biology and chemical engineering.

Shirley Marneus

1935-2020

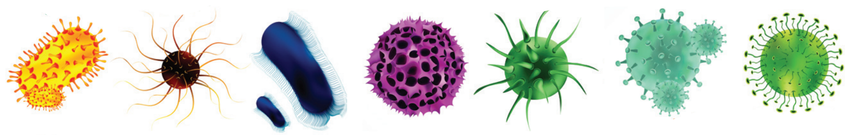
Shirley Marneus, who founded Theater Arts at the California Institute of Technology (TACIT) and directed stage productions at Caltech for more than 20 years, died on January 13. Before coming to Caltech, Marneus worked for the Pasadena Playhouse and NBC's *Jack Benny Show.* Marneus created TACIT in the mid-1980s to provide students a formal theater program with a didactic purpose as well as an entertainment purpose.

Endnotes

What will Caltech accomplish in the next 100 years?

The multidisciplinary, collaborative science conducted by people like Nobel laureate/chemical engineer Frances Arnold and microbiologist Dianne Newman will also push boundaries in medical fields. Their research will result in better treatments for debilitating diseases like autoimmune disorders, cystic fibrosis, and other chronic illnesses.

Rebecca Witkosky (PhD '19)
LOS ANGELES, CA



Substantially improve biomedical engineering devices, including nanomachines to fight diseases and physical disabilities.

John Haworth (BS '61)
RESEDA, CA

Remain "Caltech."

Saif Hussain (BS '78)
WOODLAND HILLS, CA

With the recent $750 million Resnick donation, if Caltech can soon find major breakthroughs to avert global climate disaster, that may be the most significant accomplishment.

Dave Hermeyer (BS '70)
SAN FRANCISCO, CA

We'll find Planet 9 ... or not!

David Shaffer (PhD '74)
FLAGSTAFF, AZ

Show how to scale up quantum computers using a modular approach. Caltech will also contribute an answer to the foundational question in physics: "What is the meaning of quantum mechanics?"

James Davis (BS '62)
SANTA BARBARA, CA

For more Endnotes responses, go to **magazine.caltech.edu/post/endnotes-accomplish**

Caltech will lead the creation of the information industry after CMOS, setting the standards for technology and architecture for 2030 to 2070.

Phil Neches (BS '73, MS '77, PhD '83)
SUMMIT, NJ

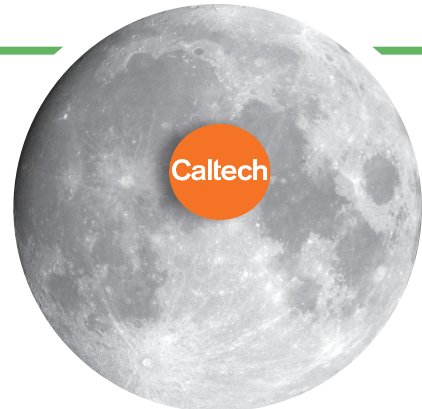
Develop cellular and nanotechnology to modify embryos to repair birth defects in utero.

CJ Beegle (BS '82)
TRONDHEIM, NORWAY

Achieve sustained gender parity and greater diversity among faculty and the student body.

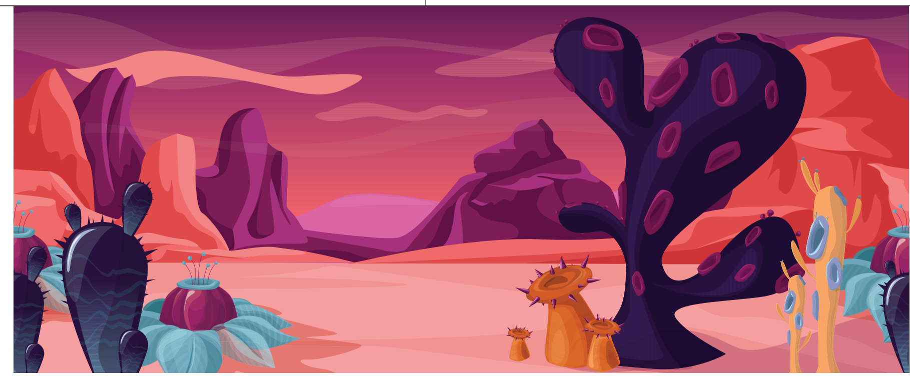
Diverse communities are successful communities! Let's not forget the social progress aspect of sustaining excellence in innovation and technological advancement!

Stephanie Reyes (BS '16)
CHICAGO, IL



Open a campus on the moon.

Woodrow Wilson (PhD '70)
SAN MARCOS, CA



Discover life outside the solar system.

James Wolfenbarger (PhD '90)
RIALTO, CA

Discover renewable energy sources to help curtail global warming and develop electronic devices that will run on the power sources available in the surrounding nature. Caltech will also enable breakthroughs to develop cures for AIDS and neurodegenerative diseases.

Ardsher Ahmed (MS '86)
SAN JOSE, CA

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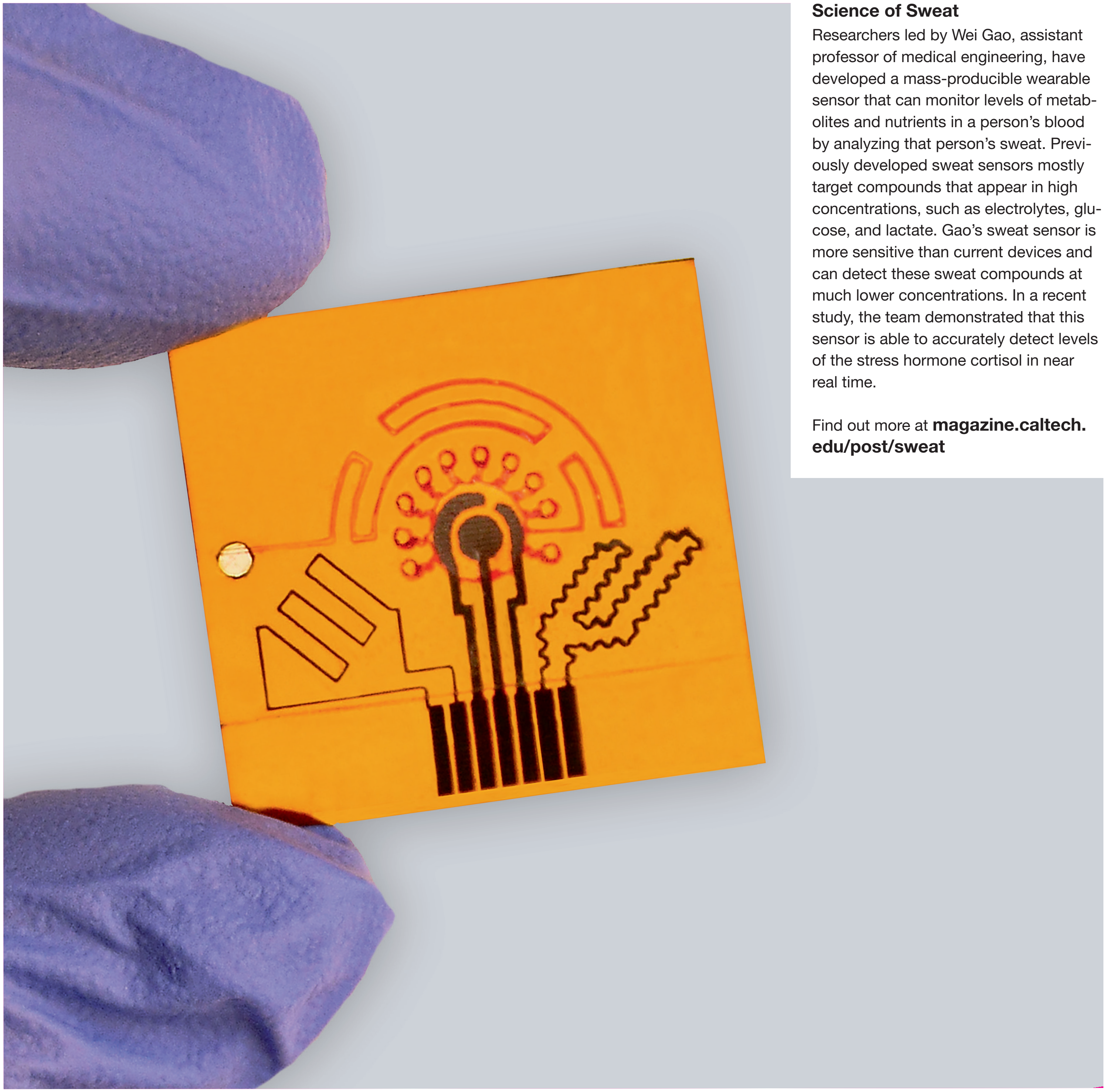

Science of Sweat

Researchers led by Wei Gao, assistant professor of medical engineering, have developed a mass-producible wearable sensor that can monitor levels of metabolites and nutrients in a person's blood by analyzing that person's sweat. Previously developed sweat sensors mostly target compounds that appear in high concentrations, such as electrolytes, glucose, and lactate. Gao's sweat sensor is more sensitive than current devices and can detect these sweat compounds at much lower concentrations. In a recent study, the team demonstrated that this sensor is able to accurately detect levels of the stress hormone cortisol in near real time.

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