Summer 2021

Caltech magazine

The transformative power of failure

Celebrating Caltech's
Newest Alumni
Pullout poster inside

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Left: One way to remove carbon dioxide from the atmosphere is through direct-capture stations that draw in air with fans and isolate the CO_2 in order to make synthetic fuel or to carbonate soda. Read about other sustainable solutions to environmental challenges on page 32.

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Summer 2021 Volume LXXXIV, Number 2

Caltech magazine

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

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Letters

Accessible? Not to Everyone

On page 21 of the Fall 2020 issue ("Universal Truths"), your interview subject posits that the night sky is accessible to everyone if they just go outside and look up. While this is a nice sentiment, and we all wish it were true, it is not. Aside from the light pollution and air pollution that obscure the view (in smoggy California, even, as the alternate alma mater goes), the author or subject fail to remember that people with physical mobility issues may not be able to look "up" or even go outside without help. And there are those who cannot see anything visually. As someone who has studied journalism myself, I know the power of a good story. Unfortunately, in this case, the words are exclusionary. Even more unfortunate was the placement of this article directly after a great piece on diversity, which included disability when many don't. We must all endeavor to do better.

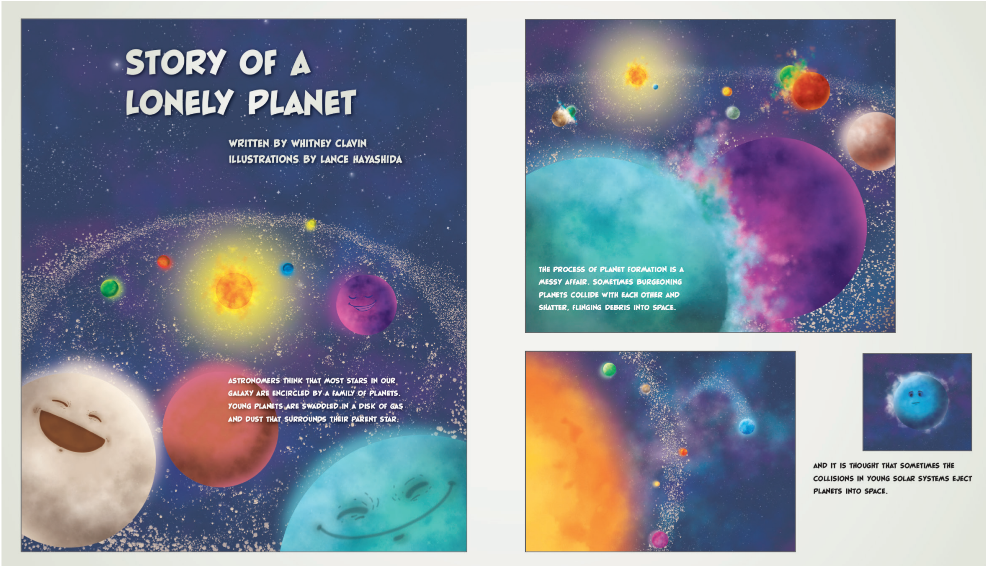
Katie Stofer (BS '98)

Renaming

The article about renaming in *Caltech* magazine ends with a quotation from the recommendations of the Committee on Naming and Recognition (CNR): "It sets a course for Caltech that both remembers where we came from as an institution and lays the groundwork for times to come."

It's difficult to remember where Caltech came from if history is erased in the name of wokeism. Keep the names, but put up prominent disclaimers. For example, on Ruddock House, "He embraced eugenics, popular in his time, but we reject it now."

Van Snyder



Spring Bouquets

I just wanted to comment: kudos to whoever designed the latest issue. Love it!

Renat Bekbolatov (BS ’04)

This magazine is the best piece of content Caltech puts out. It is immeasurably better than Caltech’s old content efforts and is way better than other modern newsletters, whether from nonprofits or for-profits. I am incredibly impressed by the design, content, imagery, and everything in between. Keep up the great work!

Zach Rivkin (BS ’14)

Love for the Lonely Planet

Congratulations on a great job with the Spring 2021 *Caltech* magazine. The design, graphics, and articles are some of the best I can recall. Special congrats on the Clavin and Hayashida “Story of a Lonely Planet.” Please have more of these pictographic stories! I can share them easily with my 11-year-old granddaughter—science in-depth for the younger generation!

John C. Waugh (BS ’71)

I wanted to congratulate Whitney Clavin and Lance Hayashida on the wonderful story and the awesome illustration of the “Story of a Lonely Planet.” Clavin’s storytelling method was brilliant. It turned something complex into something understandable and fathomable. Hayashida’s splendid illustrations brought the story to life.

Marisu Jimenez

Here’s an Idea

Would it work to build seabed-anchored hollow walls made of lightweight material like canvas or plastic, filled with water or air, and deploy them at sea on an endangered coast to blunt the impact of tsunamis? Even if some of the sections fail, it could drastically blunt the potential impact.

High-danger zones could deploy pairs of walls to further reduce the danger. Gaps for navigation could be staggered and overlap. Construction could have minimal impact to sea life.

It should cost much less than cement sea walls constructed at the shore and be much more aesthetic and friendly to the environment. With appropriate sensors, it might be possible to rapidly inflate or fill them on tsunami warnings, rather like airbags deployed when a crash is sensed, except that they would need to stay inflated or filled longer.

Dennis Bicker (BS ’77)

Adios, Ernie!

I am an engineer with the LIGO project. I saw your nice picture of Ernie in the recent issue of the magazine (“Adios, Ernie, and Thank You,” Spring 2021). I thought you might like to see a picture of him I took. I am an avid portrait sketcher and painter, and have been meaning to do a series on Ernie. My backlog is deep, and it takes energy to do, so I haven’t done this yet. Anyway, I hope you enjoy.

Rich Abbott

SoCaltech

In All Its Complexity

Natalie Klco is a Sherman Fairchild Postdoctoral Scholar Research Associate in Theoretical Physics who is interested in discovering how quantum computers can help efficiently simulate the subatomic world. She is also a percussionist and marimba performer and, recently, a nature photographer. Klco, who joined Caltech last fall and has been living in Seattle during the pandemic, became interested in music at an early age. Her love of the marimba led her to double major in music and physics at Ohio University, where she was lured by the percussion studio's "array of beautiful marimbas" and the university's support for pursuing both passions. On forced musical hiatus due to repetitive motion injuries, Klco has been focusing predominantly on her physics and a new artistic outlet: photographing the trees, flowers, and other natural wonders on walks around her neighborhood.

"This is a COVID project. It is a way to get my body away from the computer and intentionally notice the nature around me. I'm not a serious nature photographer; I was simply taking my family on walks with me from afar, sharing with them the small details of nature that I find fascinating.

"To me, these different aspects of my life—my music, my science, and now my photography—are all expressions of one underlying interest. They are three complementary ways to explore complexity.

"Science is a great language for describing complex systems. When things occur on time or distance scales significantly different than those of our everyday human experiences, it can be difficult to understand their importance. Through experimental data, analysis, and theoretical synthesis of events occuring in fractions of seconds to billions of years and on scales smaller than the size of a proton to those of colliding black holes, we gain a deeper ability to connect with our world.

continued on page 6

In All Its Complexity

continued from page 5

"Music is a different language for understanding emotional and neurobiological complexity. Through intricate compositions of sound, from solo performances to symphonies, emotional trajectories that have developed over decades can be captured, processed, and holistically reflected upon.

"Photography is becoming, to me, a language for capturing, admiring, and exalting details of the world that I would have normally ignored. As another way to connect with nature's complexity, this meditative process has made me more attentive, more curious, and more thoughtful about my place on the earth.

"Humans tend to reduce complexity, whether it is ecological, sociological, or computational, before truly understanding the importance of that complex structure. In nature, this has culminated with species being on the brink of extinction before humans realize how exquisitely evolution has embedded them into the elaborate networks that characterize healthy ecosystems. In computation, this has involved realizing that the quantum world is an essential part of a computational framework capable of representing the complexity of nature.

"So, the photography has also been a small attempt to encourage, mainly in myself, an appreciation for the complexity and diversity of nature in the hope of finding a way to motivate humans to celebrate it rather than cause its destruction."

See more of Klco's work at nklco.yolasite.com

Read the full interview at
magazine.caltech.edu/post/gonzalez

Four Questions for:

Assistant Director, Center for Inclusion and Diversity

Yazmin Gonzalez

Yazmin Gonzalez, who joined Caltech earlier this year, will focus on advancing the mission of Caltech's Center for Inclusion and Diversity (CCID) through programming that supports advocacy and education, allyship, and advising. She held previous roles at Loyola Marymount University and UCLA, and brings a particular depth of experience in equity programming directed toward women. She is excited, she says, "to get to work primarily with this constituency at Caltech ... and to be able to team up with the community as a whole to address some of their needs."

1. Describe your vision for addressing the needs of women at Caltech.

I think we have an opportunity to put Caltech on the map when it comes to equity programming that is very targeted to women—professional development resources, salary negotiation seminars, and a wide variety of workshops. The infrastructure is already there. The 'women-in' advocacy groups are already established. There is collaboration among undergraduates, graduates, staff, and faculty. There's a lot of momentum that we can harness to really catapult this type of advocacy and visibility.

I'm also going to be working with Latinx communities, recognizing that there are overlaps. Native American, First Nation folks are a constituency that is also chronically underserved across all institutions of higher learning. So that's another area where I'm hoping to focus.

2. What is one short-term priority you are working on?

The first one that comes to mind is relaunching the Women Mentoring Women program. That program went on hiatus because of COVID, but students definitely want it, and we're going to bring it back in the fall. My goal is also to expand it, to use mentorship to create pipelines that connect undergraduates to industry and then graduate students to industry. So, whether students go into academia or industry, they'll have access to the perspectives of women who have gone before them and who can support them on their journey.

3. What have you learned from talking with the students so far?

We really do have some of the most amazing individuals. I'm proud to be part of this community because the students are not only leaders in their research and science, but they bring so much nuance to the ways they are expressing themselves. They're bringing into the conversation not just the work they're doing in the labs but the other things they care about: issues around gender, equity, social justice, racial justice. I'm impressed by how much depth and perspective they bring. And it makes me really hopeful for the future.

4. What other areas of programming are you are excited about?

We've started conversations at the CCID highlighting the crossover between Latinx and Black communities in the United States, and likewise the overlap and collaboration between Black and Asian American Pacific Islander communities. I'm hoping that I can continue to highlight specific points in history where individuals of different identities or different gender expressions and lived experiences have come together and coalesced around an issue.

To really create social change we need to go back to those chapters of history and hopefully learn from them. I think for a lot of us, even here in Los Angeles, we're accustomed to living in little clusters. So, yes, we might be neighbors, but we're not quite interacting, interfacing, and learning from each other to the depth that we can. Being able to broker and initiate those conversations is something that I'm really committed to and excited about.

Nora Griffith (BS ’21)

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

Nora Griffith graduated from Caltech this spring with a BS in biology. She took over as president of the Caltech Muslim Student Association in her senior year (having served as secretary since her first year at Caltech). She was also co-editor of Totem, *Caltech’s literary and visual arts magazine, and captain of the women’s track team. She holds the Caltech track records for the 200-meter and 400-meter hurdles.*

“When I came to Caltech, I knew the campus was only going to have a small number of Muslim students and I would have to make that community for myself. My freshman year, I reached out to then-president of the Caltech Muslim Student Association Hamza Raniwala [BS ’20], who had already established Friday prayers on campus, and we worked together to organize a carpool to the mosque for Ramadan, set up our own room at Caltech where people who are on campus during the day can pray, and host a speaker event open to everyone in the Caltech community. I have to say, though, it was challenging to maintain the community and find new people, and it was a challenge for me to not have the support of many other Muslim students. In my senior year, I realized I wanted future students to feel more supported, so I reached out and did everything I could to make it feel like more of an active community. I found new first years to join, and we utilized our connection with the greater MSA West organization so we could collaborate and pool our resources to have better [virtual] events, such as guest speakers, which also helped us meet more people [online for now]. We recently had a fundraiser, a livestream with three other MSAs, to help the Uyghur Muslims in China who are being detained in ‘re-education camps.’ Just knowing that there are other Muslims on campus here and at other universities doing the same things you are and with a similar worldview is really nice.”

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

Save the Date!

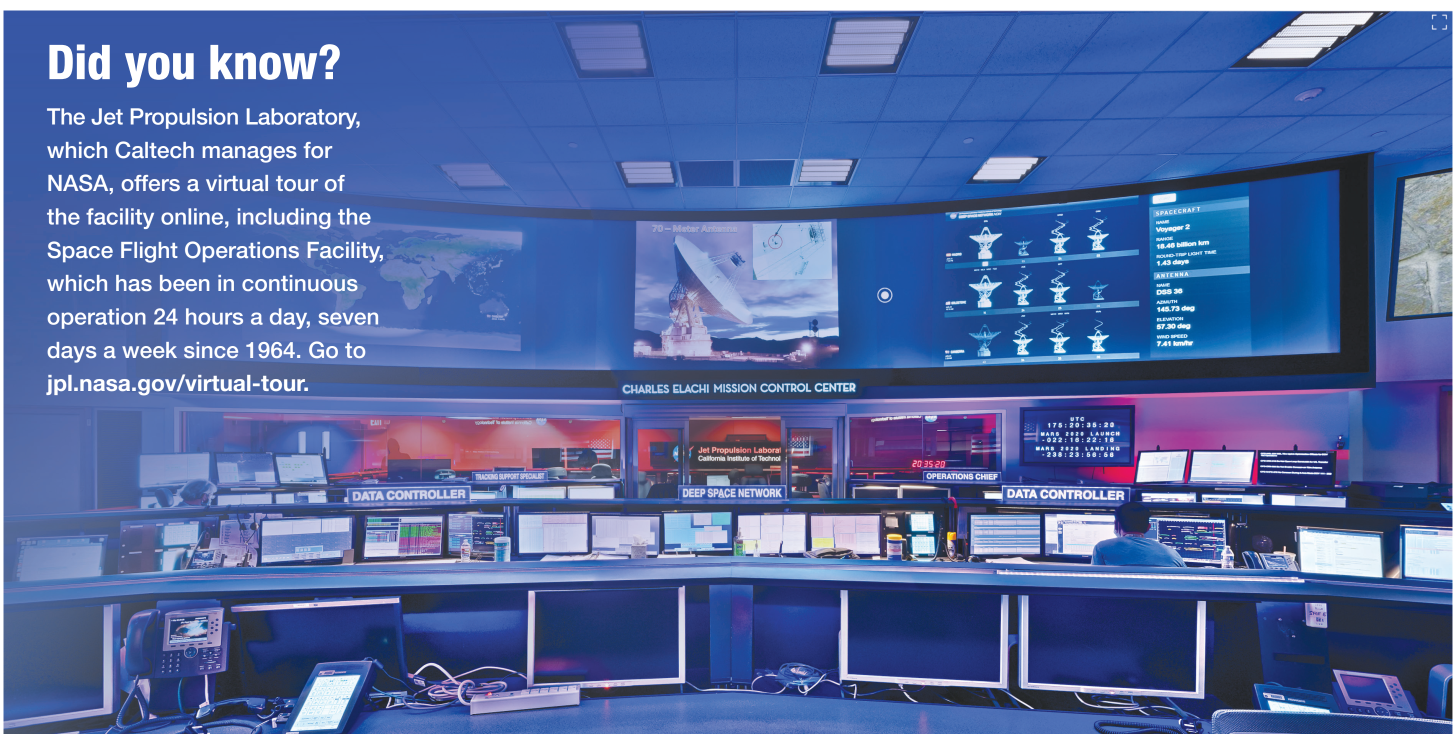
All 2020 and 2021 graduates, along with their families and friends, are invited back to campus on **Saturday, October 16, 2021,** for an in-person celebration that will include a PhD hooding ceremony and other Caltech commencement traditions. Updates will be shared on **commencement.caltech.edu.**

"When I think about my campus life, what impressed me most was about learning capability. Because today, yes, I have some finance background, but now I'm leading such a big organization, such a huge business covering many sectors. It's not about what you learn from a specific major at university. It's about what you learn about learning capability. So, when you come across new things—new business, new opportunities—you can identify the opportunity and hit the pain point of the customers."

— **Daniel Zhang,** *chairman and CEO of Alibaba, in conversation with Caltech president Thomas Rosenbaum at a May 19 Break Through Insight virtual event.*

Did you know?

The Jet Propulsion Laboratory, which Caltech manages for NASA, offers a virtual tour of the facility online, including the Space Flight Operations Facility, which has been in continuous operation 24 hours a day, seven days a week since 1964. Go to **jpl.nasa.gov/virtual-tour.**

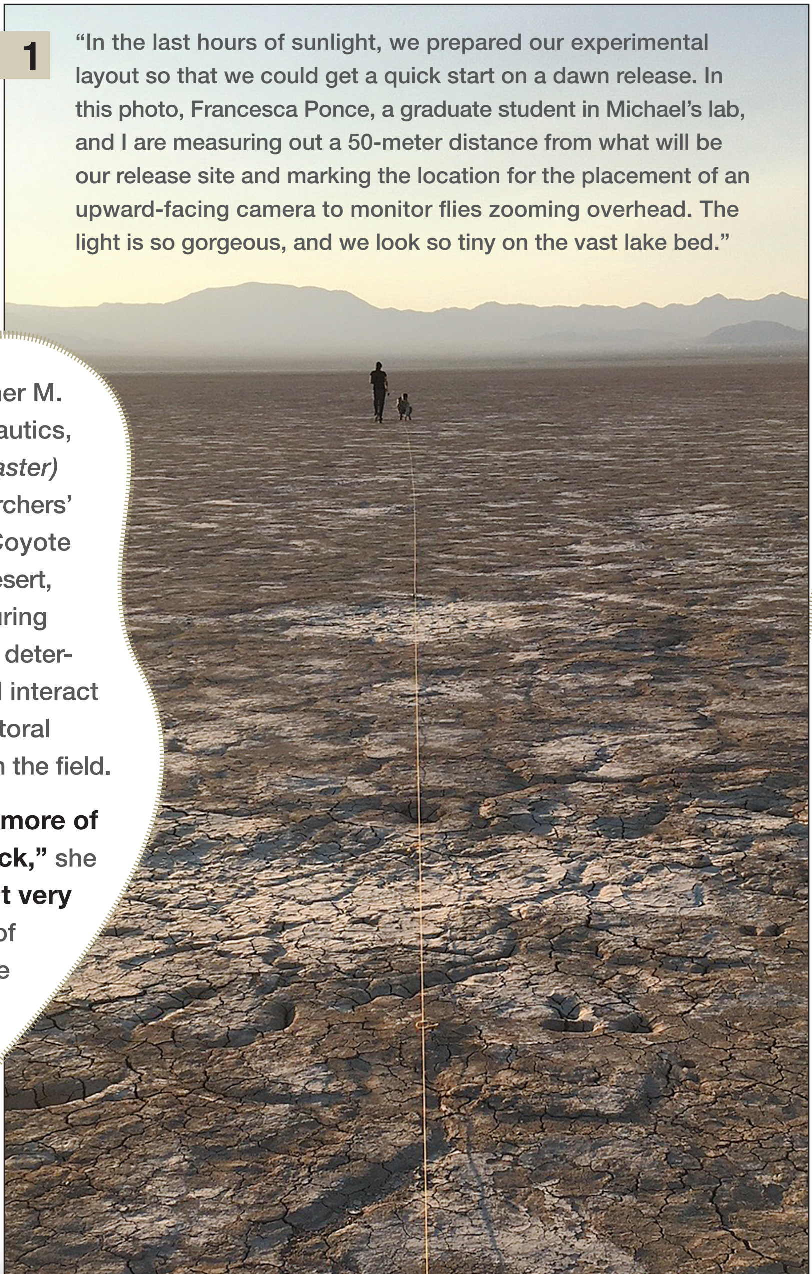


Fruit Fly FIELDWORK

Caltech scientists in the lab of Michael Dickinson, the Esther M. and Abe M. Zarem Professor of Bioengineering and Aeronautics, recently demonstrated that fruit flies *(Drosophila melanogaster)* can travel up to 15 kilometers in a single journey. The researchers' discovery was made through a series of experiments at Coyote Lake, a dry lake bed 140 miles from Caltech in the Mojave Desert, where they released hundreds of thousands of fruit flies, luring them into traps, in different experimental runs that aimed to determine their top speeds and measure how they disperse and interact in the wind. The research team was led by former postdoctoral scholar Kate Leitch, who was new to this type of research in the field.

"I think people in the geology department might have more of a feeling of what it's like to drive around in a dusty truck," she says, **"but as a biologist accustomed to lab work, it felt very special."** She especially appreciated the low-tech nature of the endeavor, which took the research team to the field site around a dozen times over three years. "It was like, **'Is there gas in the truck? Are there flies in the truck? Yes, let's go.'**"

Here, Leitch describes a typical excursion.

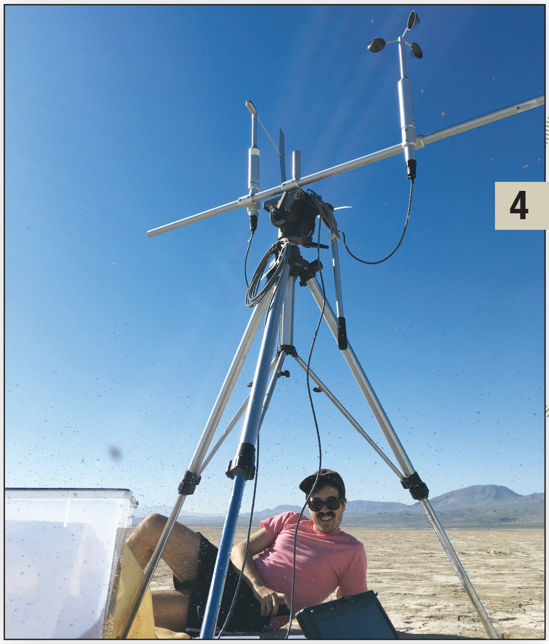


1 "In the last hours of sunlight, we prepared our experimental layout so that we could get a quick start on a dawn release. In this photo, Francesca Ponce, a graduate student in Michael's lab, and I are measuring out a 50-meter distance from what will be our release site and marking the location for the placement of an upward-facing camera to monitor flies zooming overhead. The light is so gorgeous, and we look so tiny on the vast lake bed."

2 "Camping and cooking outside played into this romantic notion I have of fieldwork. We just felt very self-sufficient, and we had all the things we needed to have a cozy good time and get some data. In this photo, we're getting ready for a morning fly release. I'm frying hash browns and eggs for Francesca (wrapped in a sleeping bag) and Román [Corfas], a postdoc in the Dickinson lab. Our tents are in the background, and the Calico Mountains are in the distance."

3

"In this photo, Michael Dickinson and I are rushing to set up the anemometer, a device that measures wind speed, at the release site before the temperatures become too sweltering. The photo shows the vastness of the lake bed. In the background are Michael's Subaru and my 4Runner. There is something beautiful about those vehicles, knowing that they're full of snacks, Sharpie markers, notebooks, and all the gooey mess of fly collection."



4

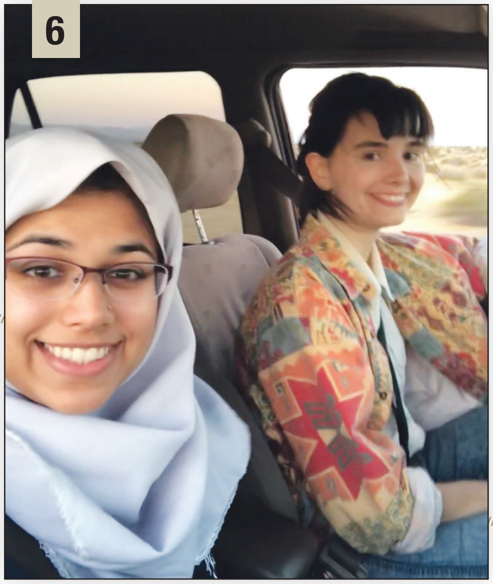
"Here is Román at the release site just seconds after releasing approximately 80,000 flies. We had a ring of traps at a 1-kilometer radius that were evenly spaced around the release site. We baited the traps with an apple ferment to attract the flies. The key innovation of our work was having a simple camera that looked down at the traps so that we basically had a time stamp of when the flies entered."

"This is a photo of me [on the right] and [Ainul] Ainne Huda [former Dickinson lab manager] driving off the lake bed after the windiest experiment we'd ever conducted, which we considered a total failure at the time. Other days, with milder winds, there would be hundreds of flies in a trap, and it just felt like we were rich with data. This photo reminds me how Ainne—with her pragmatism and kindness—always managed to cheer me up."

5

"One of the earliest hurdles was figuring out how to trap the flies. I talked to my mom, who is a seamstress, and decided to try sewing the trap tops myself. I had a sewing machine in the lab for months, and I felt proud that this side of myself could be useful in biological research. Each trap top was a flat surface of polyester mesh, pulled taut, from which 60 mesh funnels projected downward into the bait below."

6



Read more about this research on **page 30.**

amazon on campus

This summer, the new Amazon Web Services Center for Quantum Computing will open on South Holliston Avenue, adjacent to the Pasadena Fire Department station at Del Mar Boulevard.

The center will be led by Oskar Painter (MS ’95, PhD ’01), the John G Braun Professor of Applied Physics and Physics, along with Fernando Brandão, Bren Professor of Theoretical Physics. Painter and Brandão are on leave from Caltech and working full time for Amazon Web Services (AWS) to establish the center, which will bring together researchers from Caltech, other universities, and industry to develop more powerful quantum computing hardware and software, and to identify new applications for quantum technologies.

Painter says that the center will support a more seamless exchange of ideas and technologies from a university research setting to a commercial enterprise. The strong connection between cutting-edge research and development of commercially viable quantum technologies will help to nurture and develop innovative ideas in the area of quantum computing. “Ultimately,” says Painter, “we foresee a cycle in which we will work on quantum technologies that may play a role in new directions of scientific exploration on campus, such as in materials development, quantum chemistry, and precision sensors at the quantum limit.”

The new building will be occupied primarily by scientists, engineers, technicians, and administrative staff from AWS. There will also be several Amazon Scholars, says Painter, who will be faculty from Caltech and other institutions, as well as a small cohort of undergraduate and graduate student interns.

The 21,000-square-foot building presented a design challenge to architects Brooks + Scarpa, of Hawthorne, California, since the ground floor, dedicated to laboratories that call for the most quiet and controlled environment possible, has no windows beyond the main entrance lobby. A windowless box-like building would not have integrated well into the surrounding neighborhood, so the architects broke the structure into smaller components, with generous windows and landscaped terraces on the second floor.

The façade bricks shift from a regular brick pattern into a more complex pattern, rotating and twisting to create subtle shadows, depth, and a refined sense of scale—a look inspired by quantum computing, say the architects. Changing sunlight conditions, they say, will also “make the façade go soft and silver in just a few seconds, a quick-moving phenomenon that bends light and casts shadows.”

Interior work spaces are open and reconfigurable to facilitate a variety of collaborations.

“I do think an important part of talking about science is educating the public about how our level of uncertainty decreases as time passes, as we get more information and more studies are performed. So, being forthright and honest about the level of uncertainty, at the same time as emphasizing that this will change and we will at some point get to the truth … I think that’s the key to it.”

—**Kip Thorne** (BS ’62) *at the February 2021 American Physical Society webinar “Communicating Science to Nonscientists in Post-Election & Post-Pandemic America”*

Origins
Of Ditching and Stacking

The first time seniors ditched their classes en masse and vanished from campus for a day was in 1921, a full century ago. It took another decade, however, before the tradition of Ditch Day really began to take shape, with seniors leaving behind complex, imaginative scavenger hunts, mazes, puzzles, and other challenges, known as “stacks,” carefully planned out to occupy the underclassmen and prevent them from wreaking havoc in the seniors’ rooms, a tradition that over the years has involved such high jinks as relocating the seniors’ possessions while they were gone or “redecorating” their rooms.

At first, “stacking” had quite a literal definition: the seniors would stack all the furniture in the center of the room in a tight configuration to thwart underclassmen’s pranks. This defensive maneuver expanded with time: seniors began filling their rooms from floor to ceiling and wall to wall with neatly nested wooden boxes, crumpled-up newspaper, water balloons, even rebar-fortified cement. The type of effort needed to deconstruct such arrangements caused them to be dubbed “Brute Force” stacks. More intellectual ways of securing seniors’ rooms were soon employed as well. These included the use of sophisticated electronic, optical, chemical, or biological locks and puzzles, and became known as “Finesse” stacks. In the third variety, called “Honor” stacks, seniors left their doors unlocked, but underclassmen were honor bound to solve a thorny problem before entering.

Stacks have continued to evolve over the decades, most recently into complex puzzles that can combine elements of all three types. Today’s stacks typically have themes inspired by books, video games, TV shows, or movies, and underclassmen team up—often clothed in T-shirts bearing the name of their chosen stack—to solve them.

Due to the pandemic, 2021’s Ditch Day, held on May 21, was, like the one in 2020, a virtual event. Themes for the 18 stacks included Indiana Jones, Time Travel, Alice in Wonderland, and Guardians of the Galaxy. Team members were asked to solve online puzzles, create maps, participate in virtual escape rooms and role-playing games, make paper airplanes, and collaborate on art activities. Mini contests within the larger stacks included a breakfast dinner party competition, a Halloween costume contest, and an outdoor scavenger hunt (with selfies as proof of found objects).

“Ditch Day 2021 went very well!” says senior class co-president Allessandra Mondello (BS ’21). “It was so humbling to see the ingenuity and creativity of my classmates, especially in a virtual setting. As seniors, we felt that we owed it to the underclassmen, especially the first years, to give them a taste of what Caltech is really like. I am proud to say that Ditch Day was able to accomplish this and more, bringing many students together in a potentially isolating time.”

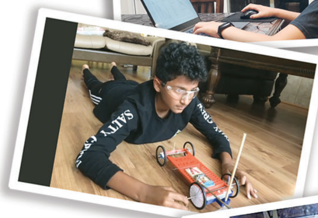
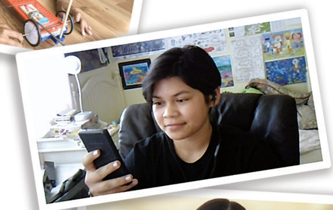
– Judy Hill

Ditch Day scenes from (clockwise from top) 2006, 1985, 1965, and 2019.

In the Community

Caltech Will Host Science Olympiad's 2022 National Tournament




Caltech Science Olympiad Club volunteer **Jolly Patro** (upper left), and **Miriam Sun** (BS '20, bottom) overseeing Science Olympiad competitors in April 2021. **Jaden Tang** works on a Crime Busters event, **Dhruv Panchagatti** sets up his vehicle, and **Joelle Cheeseman** calculates settings for a mousetrap vehicle.

Caltech has been selected to host the 38th annual Science Olympiad National Tournament, an online competition to be held on Saturday, May 14, 2022.

About 2,000 middle and high school students will participate in the event. The 121 teams they represent will have outcompeted thousands of others, advancing from regional and state competitions to this ultimate challenge.

On the tournament day, competitors will test their knowledge, skills, and ingenuity in 23 events focused on topics within physics, biology, Earth science, engineering, and chemistry. Pairs and trios from each team of 15 students will compete in six hour-long blocks of parallel events, from decoding encrypted messages to analyzing chemistry lab scenarios.

Caltech will provide an array of online programs in the days leading up to the tournament for participants to consider career paths, preview student life and academic opportunities at Caltech, and virtually explore Southern California with insider guides. The tournament's livestreamed opening and awards ceremonies will feature Caltech speakers. A STEM Expo will connect students with representatives from science- and engineering-focused companies and universities. And there will be diverse opportunities to talk about cutting-edge research with practicing scientists and engineers, including Caltech students, faculty, and alumni.

"It will be a great opportunity for us to be able to share our research with others and for people in school to get to see that," says Caltech undergraduate Jolly Patro, the co-president and event coordinator of the Caltech Science Olympiad Club.

The club drove the effort for Caltech to host the 2022 national tournament. "Caltech and Science Olympiad students share an inclination to want to try something new, work hard as a team, and present interesting findings," says Felicia Hunt, Caltech's assistant vice president for student affairs and residential experience, who facilitated the Institute's commitment to host the 2022 national tournament. "The students in the Caltech Science Olympiad Club have demonstrated that they run tournaments effectively and with style."

While 2022 will mark Caltech's first hosting of the Olympiad's national tournament, the Caltech Science Olympiad Club has hosted the state tournament since 2016. After COVID-19 safety measures canceled some tournaments in 2020, Caltech volunteers gained expertise in virtual tournaments. The online platform now used nationwide was built and piloted in Southern California. Sixty volunteers from Caltech, working with 120 volunteers from nearby universities, led the development of the first virtual Southern California Regional Tournament in February 2021 and the online Southern California State Tournament in April.

Peter Hung (BS '08, PhD '16), who founded the Caltech Science Olympiad Club in 2004, is one of the 2022 tournament's organizers. He says he became involved in Science Olympiad programming because he wants to give young students access to the life-changing opportunities he had.

Hung first heard about Caltech when his own high school Science Olympiad team reached an impasse while building a Rube Goldberg machine for a challenge. A teammate invited his brother, a Caltech student, to help. Now a two-degree alum employed by The Aerospace Corporation, Hung volunteers as the Southern California Science Olympiad state director and secretary of the organization's national executive board.

"If it weren't for Science Olympiad," says Hung, "I wouldn't have applied to Caltech and my career would be completely different. I wouldn't be a researcher and scientist today."

–Ann Motrunich

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If at first . . .

by Andrew Moseman

The transformative power of *failure*

Behind any scientific success story can be found a researcher who **persevered** through countless failures or **found inspiration** at what appeared to be a dead end. Maybe failure is not only inevitable but necessary.

The Hawaiian skies stayed clear over the Subaru Telescope on that first night in February, despite a gloomy forecast. The second night, too, offered an unobstructed view. And then, on night three, the telescope broke.

"We couldn't open the dome," says Konstantin Batygin (MS '10, PhD '12), Caltech professor of planetary science. "So, we wasted two, three hours just sitting there, watching Netflix and waiting until the telescope was fixed." When Subaru finally got up and running, the fog rolled in.

For Batygin and Mike Brown, the Richard and Barbara Rosenberg Professor of Planetary Astronomy, a third-day glitch is a punch to the gut. The pair uses Subaru to hunt for Planet Nine, the large undiscovered world they have predicted to exist in the far reaches of the solar system based on the gravitational effects it seems to exert on other objects. Theirs is not a search that will culminate in the classic "aha!" moment when an astronomer spots the speck of a new world against the black backdrop of space. Instead, they must scan the sky for three consecutive nights, finding candidate objects on the first night, measuring their velocities on the second night, and measuring acceleration on the third. All three steps are required to know whether a distant object could fit the predicted parameters of Planet Nine. But sometimes, on the third night, the telescope just won't open.

Planet Nine would have a mass 5 to 10 times that of Earth.

Many Ways to Fail

Fieldwork ruined by uncooperative instruments or inclement weather is just one way that failure can strike a scientific endeavor. "There are more ways to fail than just failing to prove something you're out to prove," says Omer Tamuz, professor of economics and mathematics. Sometimes scientists bang their heads against the desk for months and nothing comes of it. Sometimes a mathematician proves a theorem, writes the paper, and only then realizes someone else already proved it 20 years ago. Sometimes a researcher "discovers" something and then sees the world greet the achievement with a shrug of deafening silence. "I've failed in that way also," Tamuz laughs. "Some papers, I think they're great, but I cannot get a decent journal to publish them because nobody else cares about this idea that I think is so magnificent."

Failure lies around every corner of scientific life, notes biochemistry professor Bil Clemons. Papers and grant proposals are rejected. Tenure proves elusive. Promising projects go nowhere, while promising graduate students go elsewhere. All the while, problems bounce around in one's brain for weeks or months with no solution in sight.

"It's not that these problems aren't solvable," Bil Clemons (above) says. "But when you think about the complexities of a cell where you've got hundreds of millions of molecules and all of this information flow back and forth at many different scales, at any given moment to understand what's going on in that cell is beyond our reach right now."

Success in Disguise

In the 1970s, a new rumble emanated from seismology. "It was just at the beginning of the time we were thinking that earthquake prediction might be possible, after having a long time of saying 'No. There's no way,'" says Lucy Jones, visiting associate in geophysics. Caltech researchers had issued an earthquake prediction, and Chinese

Yet there is another way to look at failure.

To Clemons, it is inherent in Caltech's signature brand of high-risk, high-reward science. Pursuing a bold new idea with transformative potential inherently opens one up to the possibility of failing, sometimes in spectacular fashion. Often the path to a breakthrough starts with a failure, he says, but only if we are willing to stare failure right in the face and learn from it.

Batygin goes further, arguing there can be no great success without failure. A performing guitarist when he is not looking for Planet Nine, Batygin compares the practice of science to playing an instrument. "If you're learning something new, you're going to stink at it for the first hundred times you play a passage, and then it's going to be OK. In science, I think it's a similar thing. There's a process of getting the wrong answer time after time, and then something happens and it all snaps into place."

scientists at the Institute of Geology and Geophysics of the State Seismological Bureau in Beijing appeared to have successfully predicted a quake. When China began to normalize relations with the United States, Jones, then a 23-year-old doctoral student who had happened to study Chinese as an undergraduate, traveled to Beijing to see the predictive research firsthand; she was among the first American scientists to work in the country.

The heady days did not last. Caltech's prediction did not pan out, while Jones's trip to China revealed its earthquake prediction to have been more of a lucky guess. "They didn't have a better idea than we did of what made something look like a foreshock," she says. (A foreshock is a smaller quake that precedes a larger one in the same location.) In time, it would become clear that earthquake prediction is not possible, but back then, Jones was convinced an answer could be found in the foreshocks. Surely some unique feature, like their pattern of relieving stress in the earth's crust, would become a telltale sign to separate a harbinger of the Big One from the multitude of small earthquakes that occur every day. She gathered all the data she could find on known foreshocks to look for similarities or connections among them. The signature never showed up.

But something funny happened on the way to a failure: in the process of compiling foreshock data, Jones released what she calls "probably one of the simplest papers I've ever done." It determined that about 6 percent of the time, a smaller earthquake precedes a larger earthquake in more or less the same spot. Now, when a quake occurs, such as the 6.4 that struck near Ridgecrest, California, in July 2019, Jones advises officials that there is about a one in 20 chance of a bigger shock to come. It happened in that Ridgecrest case, when a 7.1 quake occurred the next day. "Every earthquake warning issued in the state of California started in that work, which was just trying to set the baseline to go out and find the real things," Jones says. "And we never found the real things. It turns out the baseline was really interesting."

Lucy Jones is one of the nation's go-to communicators on earthquake science, frequently appearing in the press to explain seismic events.

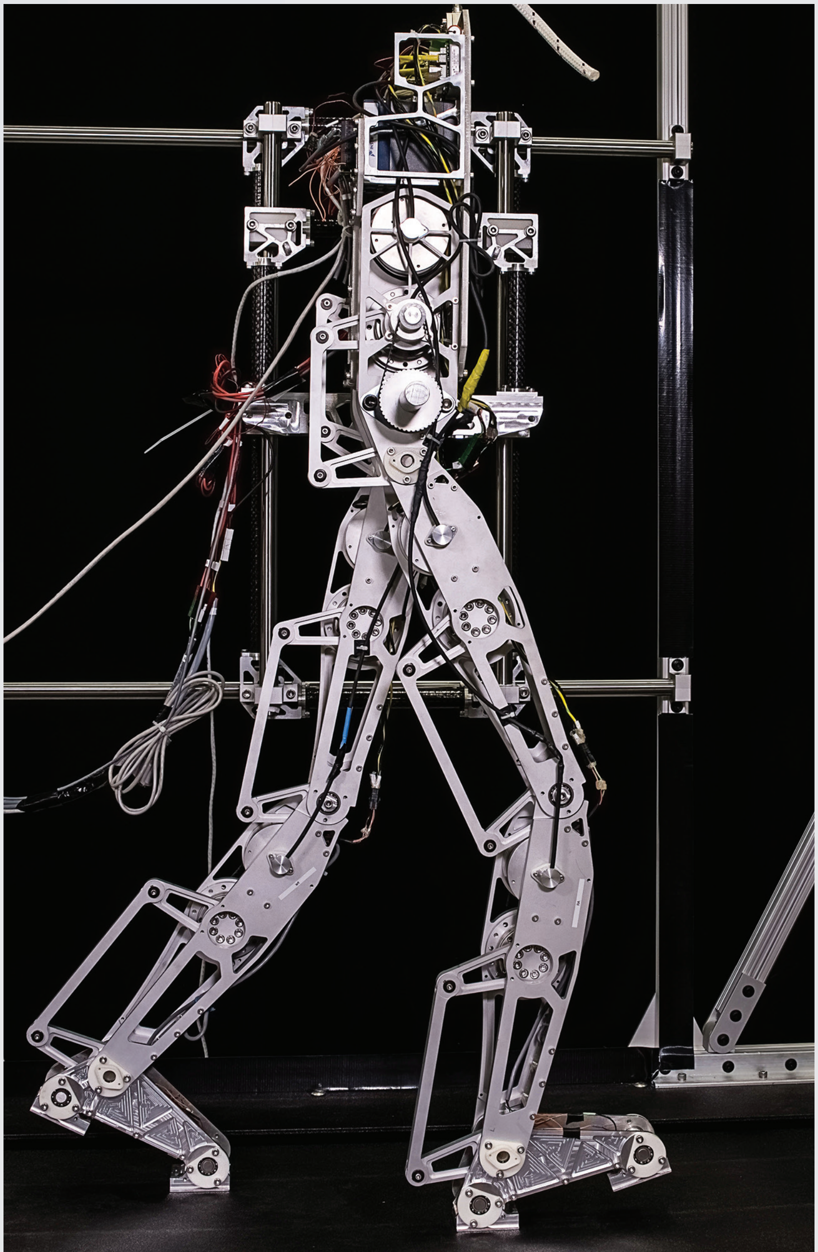
10,000 Wrongs to Make a Right

Sometimes success comes disguised as a failure. But sometimes it simply means persevering through 10,000 failures to find a solution that works.

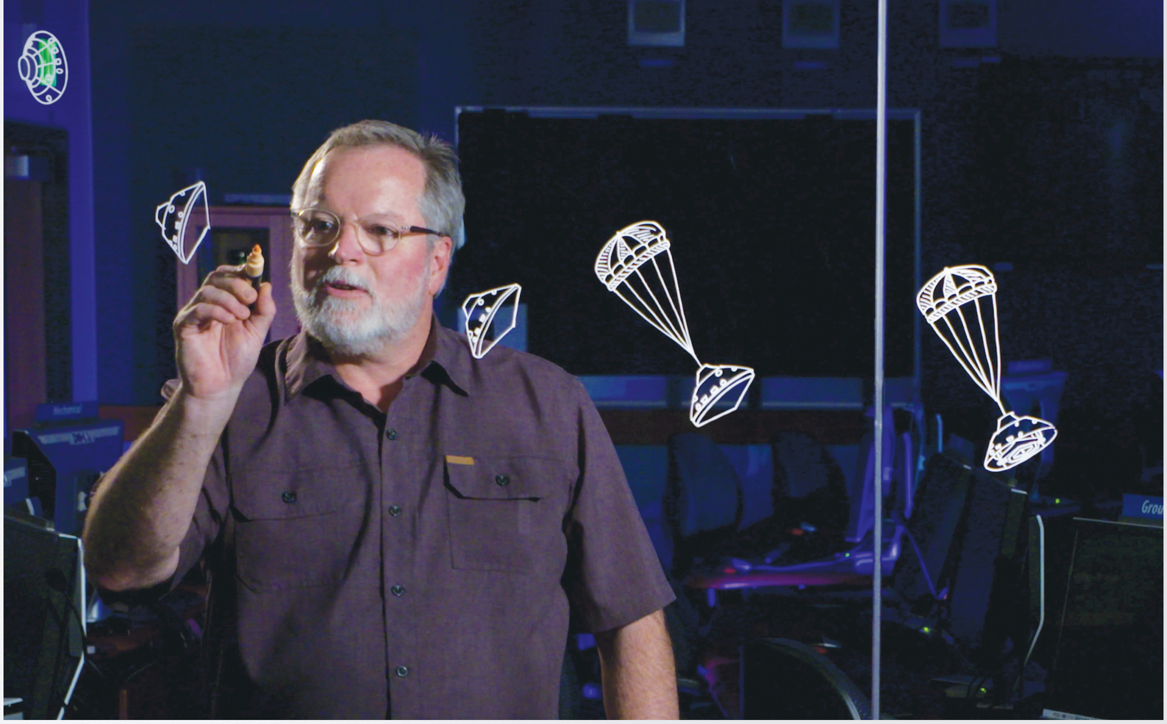
Aaron Ames, Bren Professor of Mechanical and Civil Engineering and Control and Dynamical Systems, builds bipedal robots: those that walk on two legs as humans do. The brain is so good at walking that most humans can do it unconsciously, but walking on two legs is actually a maddeningly complex process that boils down to falling and catching oneself with every step. "You have to land your foot in such a way that you catch yourself from falling in that moment," Ames says, "but also propel yourself forward in the same motion."

To make a working humanlike heel-toe gait, essentially a bipedal robot's manner of walking that is guided by mathematics, Ames begins with around 10,000 candidate gaits. Many of those never make it out of mathematical simulations because it becomes clear the robot would topple. Perhaps a hundred gaits survive long enough to be tested on the hardware, albeit with human scientists holding the unsteady automaton upright. When the Ames Lab finds the best few gaits of the bunch, the iterative process starts again. Each cycle of refinement inches the research toward a two-legged robot that can not only walk tall on a treadmill but smoothly traverse any unexpected terrain it might encounter in the outside world.

"Scientists want to make it sound like it's really fun and rosy and you get to discover things, and it's true,"



Now that Mars 2020's *Perseverance* rover and *Ingenuity* helicopter are safely on the Red Planet, Rob Manning (BS '82; right) is part of a team thinking about a future mission that would bring samples of Mars back to Earth for the first time.



says Julia Greer, the Ruben F. and Donna Mettler Professor of Materials Science, Mechanics, and Medical Engineering. "It's just all in the context of many, many, many failures. Whether it's the failure of the material or the failure of you to perform the right experiment, it's frustrating. It doesn't work the first time, and very often it doesn't work the second or the nth time. That one time when it does, you have to have enough perseverance and wisdom … and the right state of mind."

To Err Is Human

A human brain is a hypothesis machine. To John O'Doherty, professor of psychology, it can act like a scientist: it builds and tests models that make predictions about the world, and when the model fails, or when data prove the prediction wrong, the brain adapts its worldview. "Our brain has all this machinery that enables us to learn from the environment and make good predictions about what's going to happen next," he says. The O'Doherty Lab investigates the neurobiological mechanisms the brain uses to make those predictions, whether they are deeply rooted assumptions that a rustling in the bushes might be from a predator or the kind of sophisticated, goal-oriented decisions that guide an enterprise like science itself. Either way, the ability to learn from failure is a fundamental part of how the brain works.

For scientists like Tamuz, however, it can be hard to be objective and dispassionate about one's lifework. When setting out to prove a mathematical theorem, Tamuz says, he cannot help but root for one outcome over another. Although proving something is false is just as valid a discovery as proving it to be true, it can be so much less satisfying. "That can be very dangerous because you might ignore all sorts of signs that you're wrong. That will make you waste a lot of time."

Indeed, often the instrument that fails is not a telescope, seismometer, or mass spectrometer, but the human brain, says Rob Manning (BS '82), chief engineer at JPL, which Caltech manages for NASA. Part of the reason lies in the limitations of our human "hardware." Consider our visual system, he says. People think of their eyeballs as a pair of super-high-resolution cameras that create this full field of view we see. In fact, a "stunningly small" amount of the information our eyes gather makes it to the visual cortex, Manning says. The brain fills in the blanks.

In the same way, Manning says, a scientist cannot possibly consider all the data in the universe. The brain unavoidably filters information, and, in doing so, sometimes masks important clues that could be used to adjust our hypotheses or worldview. "We tend to be overconfident about what we think we know," he says. Just as your brain builds vision based on small clues that the eyeball sends to the visual cortex, humans do the same thing with our reasoning skills. "The information we get tends to affirm, not negate, the models we simply have in our brains, which is a defense mechanism … and that's a problem."

"Don't Drink Your Own Kool-Aid"

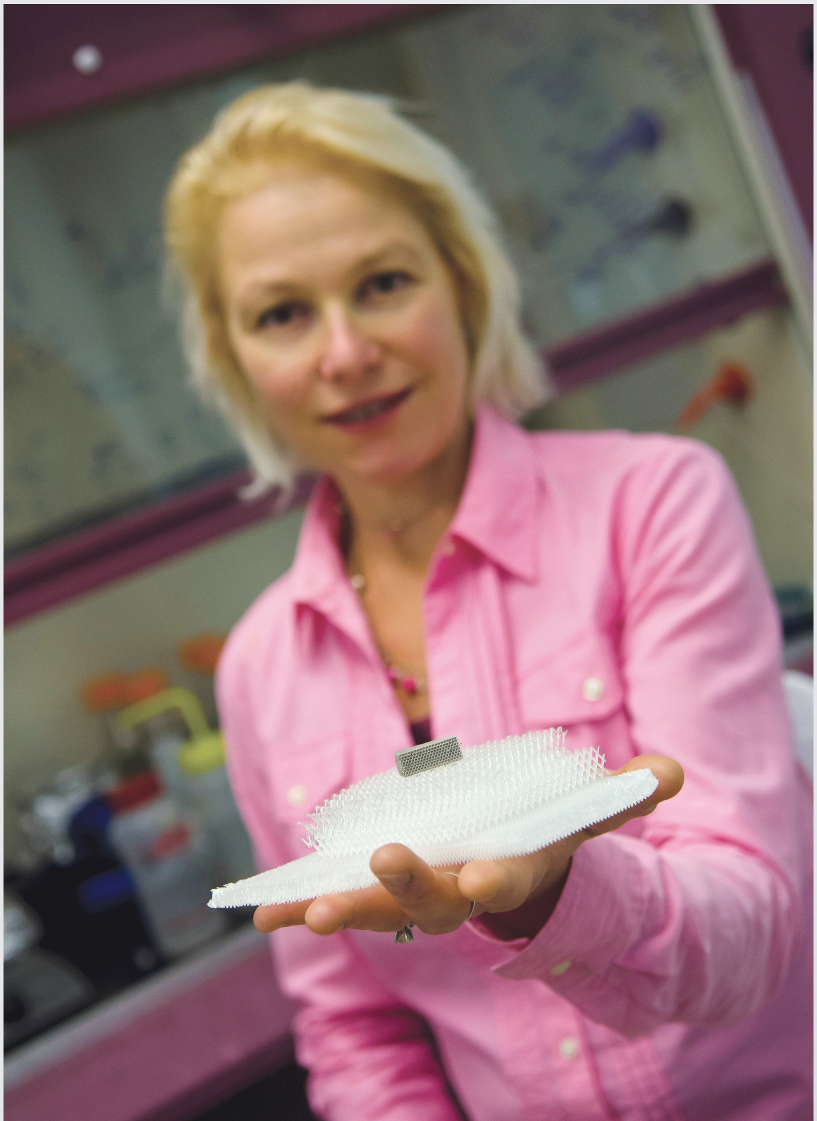
Down at the nanoscale, where things happen on the order of a billionth of a meter, materials are not themselves. Graphite, which in everyday life cracks under pressure (think of a broken pencil tip), deforms and acts like rubber under intense stresses at the nanoscale. Some metals, meanwhile, suddenly become much stronger.

Greer studies these super-small-scale oddities and how to use them to larger-scale materials with new properties. In graduate school, her team built nanoscale pillars of gold and measured their strength while crushing them. They showed that, while soft and malleable in common uses like jewelry, gold acts like steel at the nanoscale. In fact, the smaller the pillars, the stronger they appeared to be. So Greer kept building taller and thinner towers until one showed a truly staggering result. "At that point," she says, "we were so drunk on our success that we boasted, 'Hey, we just made 11-gigapascal-strong gold. That's as strong as diamond. Look at what we did.'"

Outside observers questioned this extraordinary result when Greer presented the data at a conference, but she dug in, having repeated the experiment with the same result. "I was young, and I was ready to fight," she says, so the team published the work. Later, Greer says, she found the true explanation for the outlier: the nanoindenter, the piece of equipment that crushes the gold pillars, was tilted slightly so that it exerted some of its force not on the nanopillar but on the platform it sat upon. Greer had to publish a correction, known as an erratum. "Sometimes you can get so engrossed in your own excitement that it blinds you to the point where you kind of lose sight of what's real and what isn't," she says.

That is especially true in the nascent fields of science Caltech researchers love to explore. Batygin puts it this way: don't drink your own Kool-Aid. The hunt for Planet Nine is a high-stakes pursuit subject to much criticism and skepticism, including numerous studies that claim to disprove its existence. (It is not surprising, he says, if you take the acrimony over Pluto's demotion from planethood—the result of Brown's own findings—as evidence of how much emotion is invested in the structure of the solar system.) So Brown and Batygin try to keep each other honest and seek out the weaknesses in their work long before it appears in someone else's claim that they have debunked the existence of Planet Nine. "We're always trying to find something wrong."

Julia Greer rebounded from her graduate school failure to become a leader in the study of architected materials, where she has shown it is possible to take advantage of the strange properties that emerge at the nanoscale, such as gold becoming super strong. "You can use these nanoscale building blocks to construct larger materials," she says.



"The worst enemy of any scientific or research pursuit is isolating yourself," Julia Greer (left) says. "Most of us really like having colleagues who scrutinize and challenge us because that's kind of like a reality check. Instead of getting defensive about it, you have to treat it as an opportunity to go through research in detail and to make sure that it's right."

High Stakes, High Rewards

Integral membrane proteins (IMPs) are crucial cellular connectors embedded within the cell membrane that separate the inside of the cell from the outside. Many pharmaceutical drugs target specific IMPs because they act as a gateway. Yet the vast majority of IMPs remain uncharacterized because of the laborious trial and error required to do this work. Basically, structural biologists give an IMP's DNA to bacteria and hope the bacteria will grow the protein. Eight times out of 10, that does not happen. Clemons had a better idea: What if computer models could predict what would happen when bacteria receive those DNA segments? Such a process would do away with the time-intensive trial and error of the current method. He just had no idea whether it would work. (A couple of years into the process, he notes he still is not sure.)

Clemons says his experience reflects a common dilemma. Chipping away using a current approach can be inefficient, but it works. It will create data and lead to published papers. Pursuing a new way to understand the problem, on the other hand, could lead to a leap forward or nothing at all. As a researcher in a publish-or-perish world, he says, one must balance projects that are likely to lead to tangible results with those that aim for something more profound.

The history of biology is replete with such risk-takers. Vaccines based on mRNA, like the Moderna and Pfizer COVID-19 vaccines, were born of one person's insight that many other people dismissed. The same is true of the CRISPR gene-editing tool. And as Frances Arnold, the Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry, has noted, some people dismissed her work in directed evolution, which uses nature's mechanisms to drive beneficial mutations and thereby create powerful new enzymes, and which won her the 2018 Nobel Prize in Chemistry.

"Frances Arnold is an example of somebody who was told that their ideas weren't going to work," Clemons says, "and that these were not problems that you could address and that she was doing it the wrong way. She basically said, 'Look I'm going to do the hard work to build the foundation for this.' It's the kind of thing where you have to believe in the principle, be willing to take the risk."

The Human Way

Manning says making space to fail is the modus operandi at JPL, which leads high-profile missions such as Mars 2020, which landed the *Perseverance* rover and, in April 2021, flew the *Ingenuity* helicopter. When something goes wrong on a space mission, it goes wrong explosively, publicly, and permanently. There is no mulligan for a Mars mission that crash-lands on the surface or misses the planet entirely, sending a few billion dollars of taxpayer money careening into the void, which may explain why Manning loves to talk about failure and vehemently objects to its vilification. "We have to create a venue for us to fail locally," he says. "And so we have to create venues that allow us to discover the shortcomings in our design."

Failure, he says, is good, as long as scientists and engineers are willing to acknowledge it rather than sweep it under the rug because it spoils an intended result. (*Ingenuity,* for example, failed to take off on its fourth test flight in April 2021 because of a software glitch, one JPL fixed before its next test.) That is why a major part of JPL culture is the idea of encouraging colleagues to find the holes or weaknesses in a design. With the famously fraught landings of Mars rovers, JPL tests every crucial step countless times under simulated Martian conditions, slightly varying environmental or other factors to make sure the mission can overcome whatever it may encounter. What interests Manning the most from these numerous, varied simulations are the failures, because while 50,000 successes tell you nothing, one failure can be invaluably instructive. "We can go back to test-run 40,361, the one where everything went off the rails, and reproduce it," he says.

One crucial caveat: it is impossible to test everything. Once, while Manning's team sought to study the post-inflation dynamics of parachutes in the skies high over Hawaii, the chutes mysteriously exploded in test after test. After some frustration and head-scratching, the researchers realized that the model they had used to simulate Mars parachutes was flawed. It turns out that a chute inflates much faster in the thin atmosphere of Mars than JPL had realized, and therefore it endures more pressure when the chute snaps open. A computer simulation cannot catch a failure of imagination, Manning says, because the imperfect human brain cannot program what it does not know.

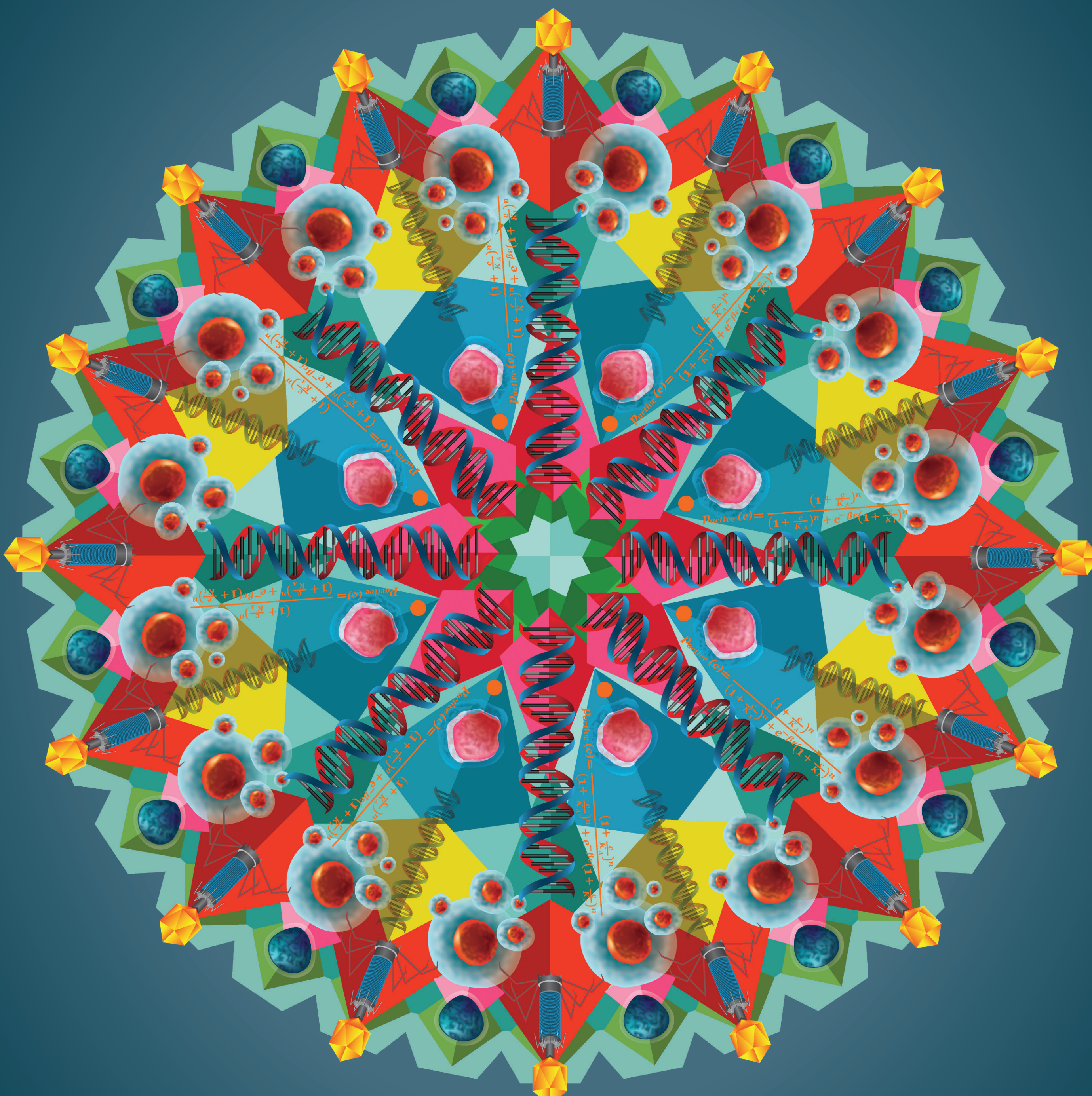
The Mars 2020 mission reached the Red Planet traveling at 12,500 miles per hour and decelerated to a standstill in just seven minutes, thanks in part to its impeccable parachute.

Read more about the parachute's testing at www.jpl.nasa.gov/news/testing-proves-its-worth-with-successful-mars-parachute-deployment

To Manning, the crucial point of such success stories is that they are made out of failure, and yet, he argues, we live in a world that grows increasingly intolerant of failure. Not everybody fails as spectacularly as a doomed Mars mission, but everyone in science has something at stake. Young people in academia feel the pressure to be "failure free" and to present perfect research, he says, never mind that good science is full of wrong turns and false starts.

"Everyone wants to write a paper that just shows nothing but the good things," Manning says. "They don't talk about the real road of how they got there, do they? The real road is they weren't even trying to get that answer."

There must be space in science to fail, Manning says. "People who get their hands dirty, who take risks, fail," Manning says. "I don't want to see the future of STEM being for people who are risk-avoiders because of their fear of failure. The truth of the matter is, we stumble our way in the dark, and there's nothing wrong with that. That is the human way, and that's the way it's always been. We should celebrate it."



Biology through the Eyes of a Physicist

A look at the multifaceted, interdisciplinary world of biophysics

by Whitney Clavin

DNA, the quintessential molecule of all living beings, is composed of two twisted strands that wind around each other in the shape of a helix. The structure was famously discovered in 1953 by Francis Crick and James Watson; prior to that, scientists knew of the existence of DNA but could not crack the mystery of its 3-D structure, nor were they even sure that it was the storehouse of genetic information. One integral piece of the puzzle came in the form of X-ray diffraction images of DNA strands, meticulously captured by Rosalind Franklin and Maurice Wilkins. The images revealed a cross-shaped pattern suggestive of a helix and ultimately helped Watson and Crick solve the mystery as well as propose how DNA's ability to unwind allows for it to be copied and passed on.

The discovery of the double helix exemplifies the multifaceted field of biophysics, in which biology is viewed and better understood through the lens of physics. In this case, the X-ray-based tools of physicists were applied to living matter; in fact, Franklin began her career as a physical chemist, and Wilkins and Crick as physicists.

Recently, Caltech's Division of Physics, Mathematics and Astronomy (PMA), which traditionally includes professors and students who study everything from subatomic particles to exploding stars, hired physics professor Ibrahim Cissé, who is an expert in the imaging of single molecules in living cells. "The questions the physicist will ask, even if they are studying the exact same material as a biologist, are going to be different," says Cissé. "I am a physicist whose subject is living matter."

Cissé and his team use cutting-edge microscopy tools to study the real-time behaviors of individual molecules in cells as a way to understand the fundamental nature of life itself. Having Cissé in the division, says Fiona Harrison, the Kent and Joyce Kresa Leadership Chair of PMA, will help further catalyze the growing interdisciplinary field of biophysics across Caltech.

"Physicists approach problems using fundamental, quantitative principles," says Harrison. "PMA sees the expansion of our efforts in biophysics as an opportunity to apply this approach to issues in biology. This kind of fundamental look at scientific problems is well suited to Caltech, which focuses on basic research."

In the same spirit, chemists and biologists across the Caltech campus use the tools and approaches of biophysics to probe the mysteries of life, including everything from the mechanics of the living cell to the structure of biomolecules. As Cissé explains, there is a lot of overlap among the various fields of science.

"The cell doesn't care if your training is in chemistry, biology, or physics," he says. "It uses all of them. And to understand the cell, we really have to integrate all these different disciplines and bodies of knowledge together."

Condensation in Cells

Cissé specializes in visualizing single molecules inside living cells using a technique called super-resolution imaging, in which the limits of optical light itself, specifically the diffraction limit, are surpassed and cellular structures on the scale of a few nanometers can be resolved.

Cissé and his team have adapted and further developed the tool of super-resolution microscopy to study clusters of molecules that are not static but rapidly assemble and disassemble in living mammalian cells. "We want to push super-resolution microscopy to detect clusters that form in very crowded environments and that are highly dynamic," he says.

One bustling environment of interest is the nucleus of a cell. There, DNA is transcribed into messenger RNA, which ultimately provides the building instructions for the proteins that run the daily business of a cell. In order for the DNA to be transcribed, proteins called RNA polymerases, along with a host of associated proteins, must sit down on, or attach themselves to, the DNA strands and go to work. But how do the proteins gather together?

Using their super-resolution microscopy tools, Cissé and his team were able to see what was actually happening. They learned that the proteins come together in clusters like workers quickly gathering at a construction site. "There is a level of cooperation between the proteins,"

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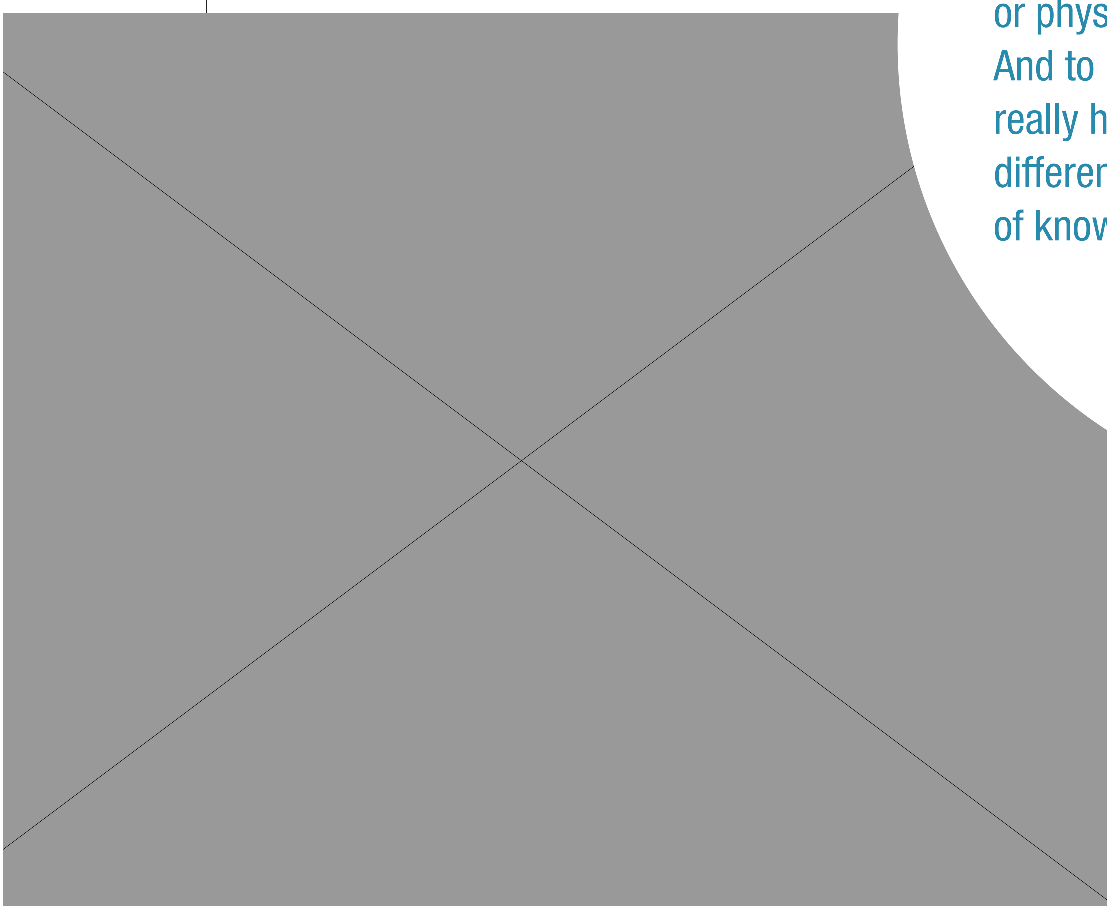
>
> — Ibrahim Cissé



Physics professor **Ibrahim Cissé,** who uses super-resolution microscopy to study protein dynamics, recently joined Caltech's Division of Physics, Mathematics and Astronomy (PMA). His arrival, says Fiona Harrison, Kent and Joyce Kresa Leadership Chair of PMA, will help advance the growing interdisciplinary field of biophysics across the Institute.

“Astrophysicists study the cosmos, condensed matter physicists study nonliving matter, and biological physicists study living matter.”

— Rob Phillips

he says. What triggers this sudden condensation? From a physicist’s point of view, you can quickly condense things with a phase transition, for example when vapor spontaneously condenses into a liquid droplet. “Phase transitions have been thoroughly studied in the realm of physics, and now we are able to study their role in regulating biological processes in the living cell.”

Ultimately, Cissé says, understanding a process as complex as DNA transcription requires an integration of physics with biology and chemistry. “We are studying how the cell works and discovering that living matter exhibits some of the same emergent phenomena, like phase transitions, that we also see in nonliving matter. There may even be a new physical understanding of how nature works that comes out of this line of investigation. Through biology, we are gaining new insights about physics.”

By the Numbers

One distinguishing trait of physicists is the drive to quantify and measure processes in nature. Rob Phillips, Fred and Nancy Morris Professor of Biophysics, Biology, and Physics, exemplifies this with his by-the-numbers approach to the study of biology. For instance, in 2018, he and his longtime collaborators Ron Milo and Yinon Bar-On of the Weizmann Institute of Science made quantitative estimates of the amount of biological matter, or biomass, covering our planet, including everything from bacteria to humans. Their research revealed, among other factoids, that humans and their livestock outweigh all wild animals by a factor of 20.

More recently, the trio, along with Avi Flamholz, a postdoctoral scholar at Caltech, published a similar by-the-numbers report, this time detailing those numbers that describe the COVID-19 virus, such as average concentrations throughout the body, number of genes, infection rate, and more.

“My approach to biophysics involves coming up with principles and theories first. It’s a certain style of inquiry, and it’s about quantifying and measuring things at all scales,” says Phillips, who is also co-author, along with Ron Milo, of the popular book *Cell Biology by the Numbers*. “It is physics unleashed on the nature of living organisms. That runs the gamut from very specific questions about the nature of proteins that interact with DNA all the way up to giant ecosystems.

“Astrophysicists study the cosmos, condensed matter physicists study nonliving matter, and biological physicists study living matter,” he says. “Personally, you will have a hard time convincing me that you and I and other living creatures are not the most interesting matter in the universe.”

Of course, an integral tool for quantifying nature is math. Phillips says that math is front and center in more or less every discussion in his group. “The language we speak in my lab,” he jokes, “is not English but math.” He recalls his graduate school teacher who had a blackboard on his door: “When I would come into his office, he would shut the door and tell me that if I had something to say, I needed to write it down in equations. I’m a devotee of mathematics now. We want to observe and measure.”

Shu-ou Shan, Altair Professor of Chemistry at Caltech, also sees math and quantitative modeling as part of the mindset of a biophysicist. One of Shan’s areas of research focuses on how proteins in cells are sorted to the proper locations as well as folded into the correct 3-D structures. Though her work lies in the field of biochemistry, she says her methods are rooted in both physics and chemistry.

“The biophysical side of our work involves making quantitative measurements, modeling molecular events

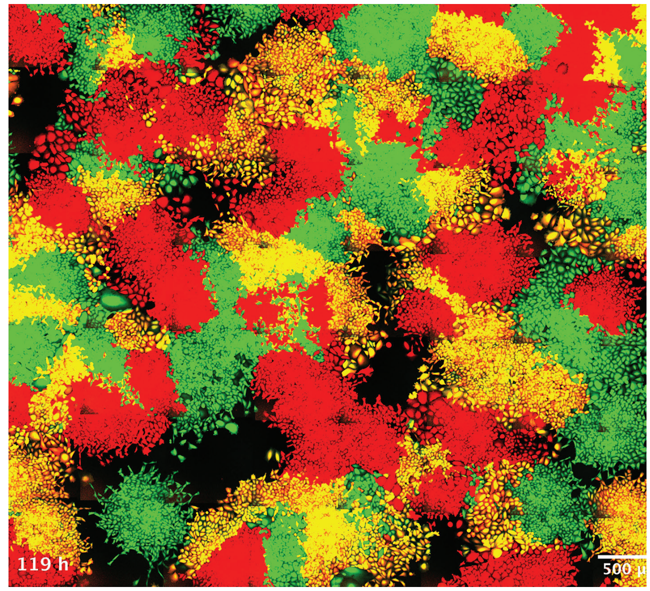
Rob Phillips, Fred and Nancy Morris Professor of Biophysics, Biology, and Physics (seen here pre-pandemic), takes a by-the-numbers approach to biology, exemplified by quantitative reports that describe the COVID-19 virus and Earth’s biomass.

based on first principles, and making predictions," she says. "We also use microscopy and spectroscopy tools that have been developed by physicists." In fact, Shan is leaving this month for a sabbatical at UC San Francisco, where she plans to learn the powerful tool of cryogenic electron microscopy (cryo-EM) for visualizing the structures of biomolecules. "Tools like cryo-EM and NMR [nuclear magnetic resonance] spectroscopy involve math, principles of light scattering, Fourier transforms, and so on. Physics helps us improve these techniques."

Simplicity First

Biophysics is also not the primary field in which Michael Elowitz, professor of biology and bioengineering at Caltech, works. But, he says, his experiences with the principles of physics have given him a taste for a different type of questioning.

"Physicists seek the minimal set of components and assumptions that can explain a phenomenon and then develop models that one can understand as deeply as possible," he says. "Even though, or perhaps because, biological systems are incredibly complex, it is critical to try to identify simplifying underlying principles."

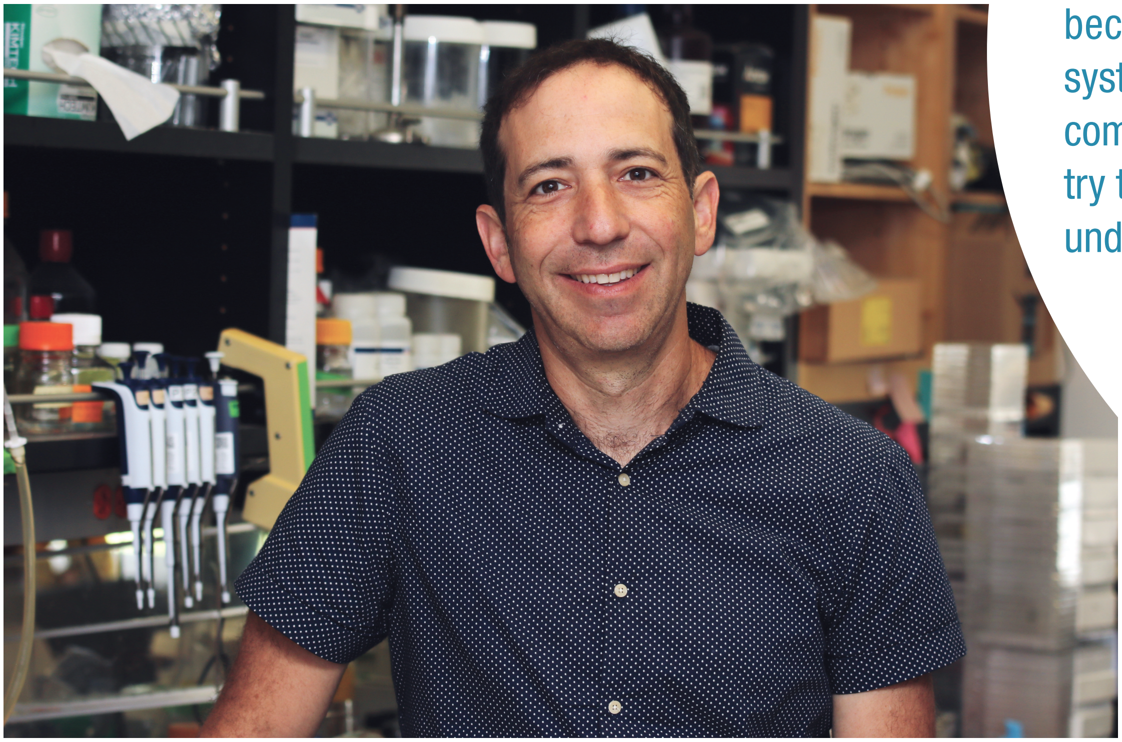


Michael Elowitz, professor of biology and bioengineering at Caltech, seeks to identify the underlying principles behind biological systems. The image above shows a synthetic cellular system created in his lab that maintains cell colonies in distinct cell "fates," indicated by different colors.

Shu-ou Shan, Altair Professor of Chemistry at Caltech, sees quantitative modeling as part of the mindset of a biophysicist. One of her areas of research focuses on how proteins in cells are sorted to the proper locations as well as folded into the correct 3-D structures.

Elowitz and his lab use this approach to create and study synthetic cellular systems. For example, he and his graduate student Ronghui Zhu, along with other collaborators, recently asked what minimal biological-circuit designs could account for the ability of our own cells to take on many different "fates": becoming liver cells, neurons, or other cell types. To find out, they designed a synthetic gene circuit in living cells based on mathematical models and inspired by aspects of natural cell-fate control circuits. The synthetic system establishes multiple stable cell fates and allows researchers to switch a cell from one fate to another. Built "from scratch," as Elowitz says, the system provides insight into critical biological processes and could eventually play a role in the emerging paradigm of engineered-cell therapy, in which researchers design cells, rather than drugs, to target cancer and other disease states.

Elowitz says the approach of building biological systems as a means to understand them takes inspiration from a quote, often cited in the field of synthetic biology, by the late Caltech physicist and Nobel laureate Richard Feynman. The quote, discovered in the upper corner of Feynman's blackboard after his death in 1988, read: "What I cannot create, I do not understand."



"Even though, or perhaps because, biological systems are incredibly complex, it is critical to try to identify simplifying underlying principles."

— Michael Elowitz

A Tradition of Crossing Disciplines

Feynman himself dabbled in biology; in addition to other pursuits, he spent a year in the laboratory of the late Max Delbrück, a Nobel laureate and longtime Caltech professor who helped launch the modern field of molecular biology. While Feynman's interests largely lay in pure physics, Delbrück is a prime example of a physicist turning an eye toward biology.

Delbrück, who was born in Germany in 1906, studied quantum mechanics with some of the great physicists of his time, including Niels Bohr, who reportedly piqued Delbrück's interest in biology. Ultimately, Delbrück and his colleagues Alfred Hershey and Salvador Luria, in the 1940s, would learn the secrets of viral genetics through their studies of bacteriophages, viruses that infect bacteria. According to the press release for their 1969 Nobel Prize in Physiology or Medicine, the scientists "worked out rigorous quantitative methods and this turned bacteriophage research into an exact science."

Today, a strong current of biophysics runs through the Institute, crossing numerous divisions and sparking collaborations among a wide range of scientists. "That's one of the beautiful things about Caltech: we can be in more than one department and have our collaborations be meaningful and real," says Phillips.

"There are no barriers to integrating all of this science," says Cissé. "Once you get a critical mass of people, you can really work together and nucleate new and exciting ideas." [C

Left to right: Jean Jacques Weigle, Ole Maaloe, Elie Wollman, Gunther S. Stent, **Max Delbrück,** and G. Soli. Delbrück, a Nobel laureate and longtime Caltech professor, helped launch the modern field of molecular biology.

FORMIDABLE *Fliers*

In search of food, fruit flies can cover extraordinary distances in a single flight.

By Lori Dajose (BS '15)

In 2005, an ultramarathon runner ran continuously 560 kilometers (350 miles) in 80 hours, without sleeping or stopping. This distance was roughly 324,000 times the runner's body length. Yet this extreme feat pales in comparison to the relative distances that fruit flies can travel in a single flight, according to new research from the laboratory of Michael Dickinson, the Esther M. and Abe M. Zarem Professor of Bioengineering and Aeronautics.

Fruit flies, Dickinson and his group discovered, can fly up to 15 kilometers (about 9 miles) in a single journey—6 million times their body length. To measure how flies disperse and interact with the wind, the team designed "release and recapture" experiments, releasing hundreds of thousands of flies on a dry lakebed in California's Mojave Desert, and luring them back into distant traps containing fermenting juice in order to measure the insects' flying speeds. Led by former postdoctoral scholar Kate Leitch, the group made several trips to Coyote Lake, with hundreds of thousands of the common lab fruit fly, *Drosophila melanogaster,* in tow.

Once onsite, the researchers set up 10 "odor traps" in a circular ring, each trap located along a 1-kilometer radius around the release site. The traps contained a tantalizing cocktail of fermenting apple juice and champagne

To watch a video about this research experiment, go to **magazine.caltech.edu/post/flies** yeast, a combination that produces carbon dioxide and ethanol, which are irresistible to a fruit fly. The traps also each had a camera and were constructed with one-way valves so that the flies could crawl into the trap toward the cocktail but not back out. In addition, the researchers set up a weather station to measure the wind speed and direction at the release site throughout each experiment; this would indicate how the flies' flight was affected by the wind.

Before the release, group members first placed the traps and checked them over time, and found that although *D. melanogaster* are found at date farms within the Mojave, they are extremely rare at Coyote Lake, so the researchers could be confident that the flies they were catching were their own fruit flies.

At experiment time, the group drove the buckets of flies, which had been harvested from a fruit stand in the area and then raised in the lab, to the center of the circle of traps. The buckets contained plenty of sugar so that the insects would be fully energized for their flight; however, they contained no protein, giving the flies a strong drive to search for protein-rich food. The group estimated that the flies would not be able to smell the traps from the center of the ring, forcing them to disperse and search.

At a precise time, a researcher at the center of the circle opened up the buckets simultaneously and quickly released the flies.

"The person who stayed at the center of the ring to open the lids off of all the buckets witnessed quite a spectacle," says Leitch. "It was beautiful. There were so many flies—so many that you were overwhelmed by the whirring drone. A few of them would land on you, often crawling in your mouth, ears, and nose."

The researchers repeated these experiments under various wind conditions.

It took about 16 minutes for the first fruit flies to cover 1 kilometer to reach the traps, corresponding to a speed of approximately 1 meter per second. Previous studies from the lab showed that a fully fed fruit fly has the energy to fly continuously for up to three hours; extrapolating, the researchers concluded that *D. melanogaster* can fly roughly 12 to 15 kilometers in a single flight, even into a gentle breeze, and will go farther if aided by a tailwind. The fruit flies traveling approximately 6 million times their average body length is the equivalent of the average human covering just over 10,000 kilometers in a single journey—roughly the distance from the North Pole to the equator.

"The dispersal capability of these little fruit flies has been vastly underestimated. They can travel as far or farther than most migratory birds in a single flight. These flies are the standard laboratory model organism, but they are almost never studied outside of the laboratory and so we had little idea what their flight capabilities were," Dickinson says.

Read more about Kate Leitch's experiences at Coyote Lake on **page 10.**

Caltech science exchange

Sustainability SOLUTIONS

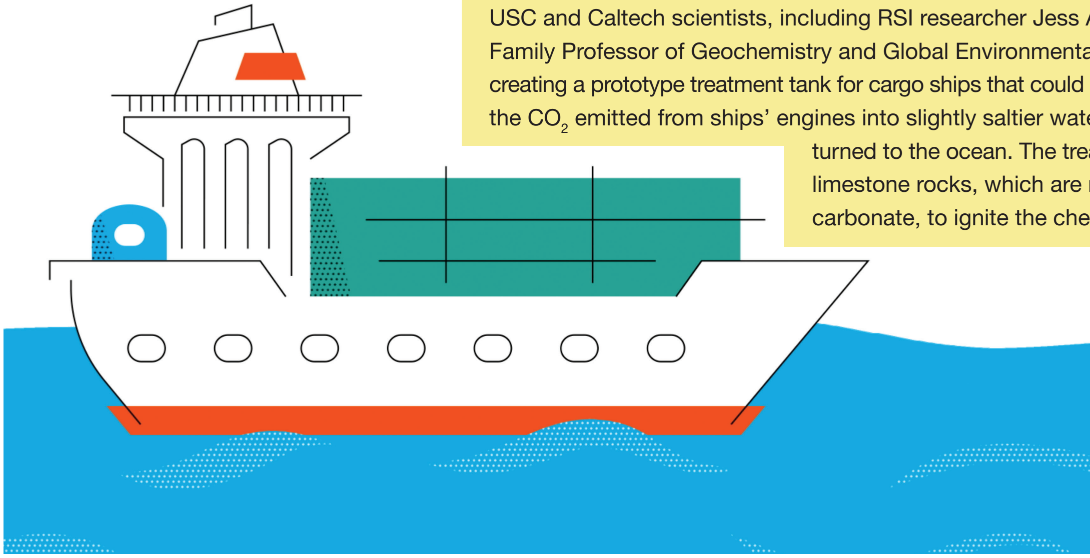
Caltech researchers and engineers on campus and at JPL are pursuing many novel approaches to mitigate the effects of a warming planet. They are using advanced computation to improve the precision of climate models; harnessing solar, wind, and other renewable energy sources; engineering new methods to reduce greenhouse gas emissions; and drawing on data from Earth-monitoring devices to inform more efficient use of resources.

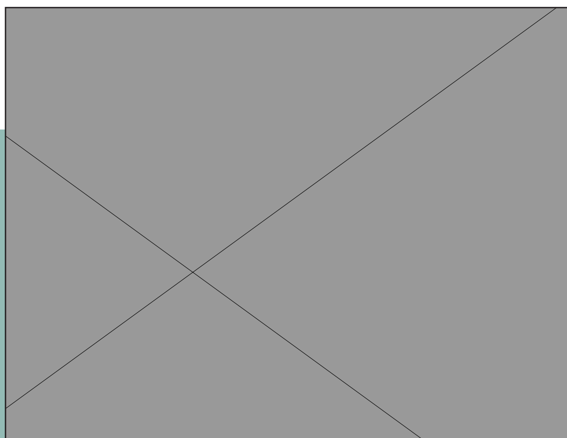
Much of this vital research takes place under the auspices of the Resnick Sustainability Institute, which, in the fall of 2019, received a historic pledge of $750 million from philanthropists and entrepreneurs Stewart and Lynda Resnick. With the new resources and tools afforded by this pledge, Caltech's sustainability researchers have the freedom to explore bold solutions to society's vexing challenges in energy, climate, water, and the broader environment.

Here, as featured in the Caltech Science Exchange **(scienceexchange.caltech.edu)**, a web resource dedicated to explaining scientific issues, RSI-affiliated Caltech researchers share their perspectives on some questions that are central to addressing one of the most significant issues of our times.

How can we remove CO_2?

USC and Caltech scientists, including RSI researcher Jess Adkins, Smits Family Professor of Geochemistry and Global Environmental Science, are creating a prototype treatment tank for cargo ships that could one day transform the CO_2 emitted from ships' engines into slightly saltier water that can be returned to the ocean. The treatment tank uses limestone rocks, which are made of calcium carbonate, to ignite the chemical reaction.





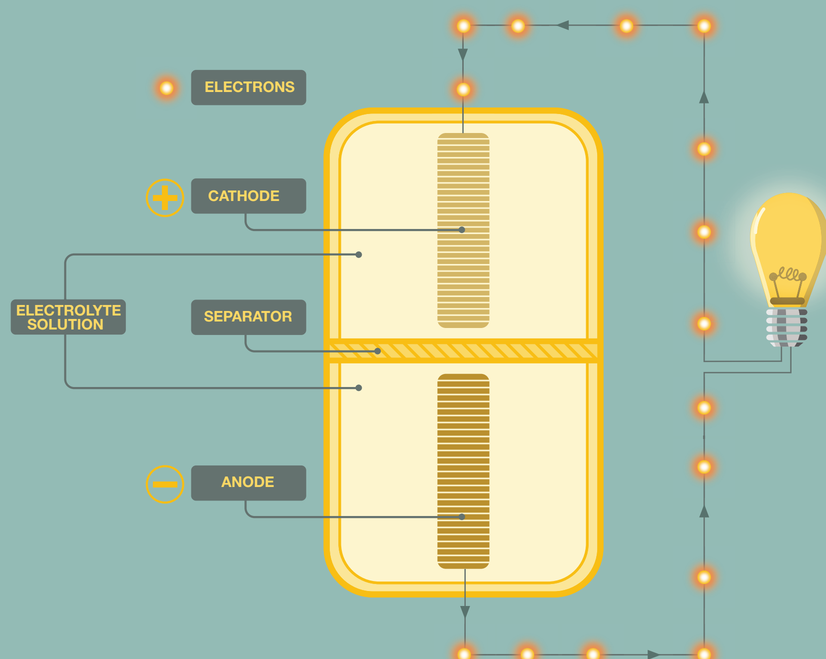
How batteries work

Batteries store chemical energy and convert it to electrical energy, which can be thought of as the flow of electrons from one place to another. Components called electrodes help to create this flow. Electrons move from one electrode, called the anode, to another electrode, called the cathode. The electrodes are separated by an electrolyte, which can be a solution or a solid. How efficiently a battery works depends on which materials are used as electrodes and electrolytes. Lithium-ion batteries, commonly found in portable electronics and electric vehicles, typically use a metal oxide as the cathode and graphite as the anode.

How can we develop sustainable alternatives to lithium-ion batteries?

"To move toward renewable energy, we need battery storage. The lithium-ion batteries we use today are expensive and extracting the raw materials is harmful to the environment. In my research, we make new materials and we try to understand their ability to store electrons. These new materials are usually sourced from resources that are abundant in the earth's crust, like magnesium, iron, and sulfur. … One of the Holy Grails of chemistry in my lab is to target magnesium-sulfur batteries. It's a magnesium anode and a sulfur cathode. Both of those materials are very inexpensive. Magnesium is found all over the world. Sulfur is a by-product of petroleum refining."

—**Kimberly See,** *Assistant Professor of Chemistry*



Where does our water supply come from?

Communities get the water they need from two major sources: surface water and groundwater. Surface water collects on the ground or in streams, rivers, lakes, reservoirs, or oceans. Groundwater collects in aquifers, underground layers of water-saturated rock and sediment. Solutions for protecting access to water rely on precise measurement and monitoring of underground aquifers.

RSI researcher and JPL chief scientist Mark Simons, John W. and Herberta M. Miles Professor of Geophysics, is applying satellite radar technology to track changes in the terrain of Southern California as a result of water flow in and out of aquifers, helping to inform water management districts about the impact of the region's water use on those aquifers.

How can we make chemical manufacturing more sustainable?

"To make a difference in global sustainability via chemical manufacturing, we want to prioritize. Which chemicals offer the best opportunities? That depends on the scale at which they are produced and how much associated CO_2 and other pollutants that production puts in the air. The production of ammonia and ethylene has a significant impact on global CO_2 emissions.

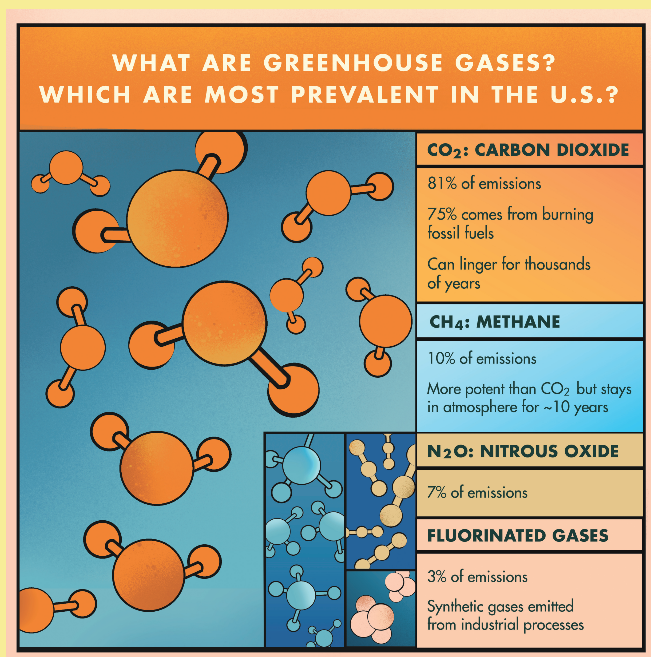
"… In my lab, we think about new ways to make ammonia and ethylene, and other challenges in chemical synthesis that can advance how we make more complicated molecules, such as drug molecules used in medicines. Along with our collaborators, we aim to develop catalysts that can, ultimately, enable carbon-neutral production of ammonia and ethylene using renewably sourced electricity, water, nitrogen gas from the air, or industrial CO_2 waste streams.

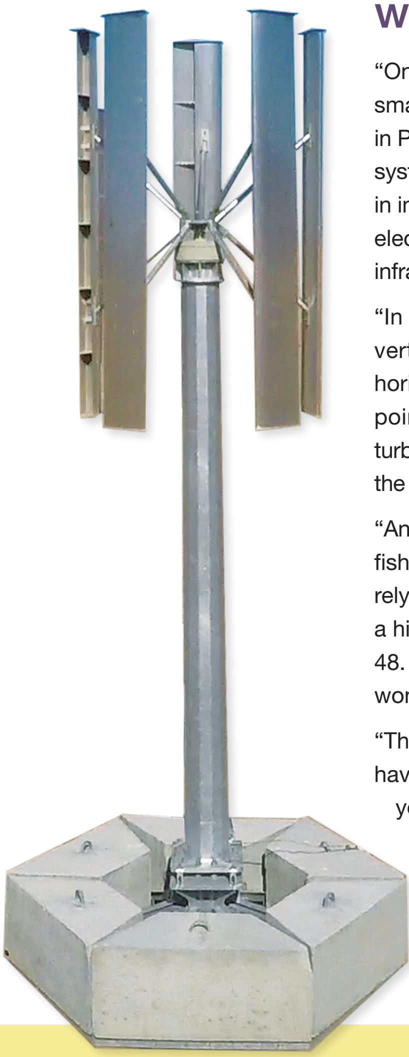
"… My lab is working on a new, different way of producing ammonia, through electrochemical conversion of nitrogen, the main component of air. After years of fundamental research, we now have exciting science that demonstrates how to achieve electrochemical ammonia generation with molecular catalysts. We, along with others in the field, are also excited by the promise of potentially more durable heterogeneous catalysts."

—Jonas Peters

Bren Professor of Chemistry and director of the Resnick Sustainability Institute

What are greenhouse gases and where do they come from?





What is the future of wind energy technology?

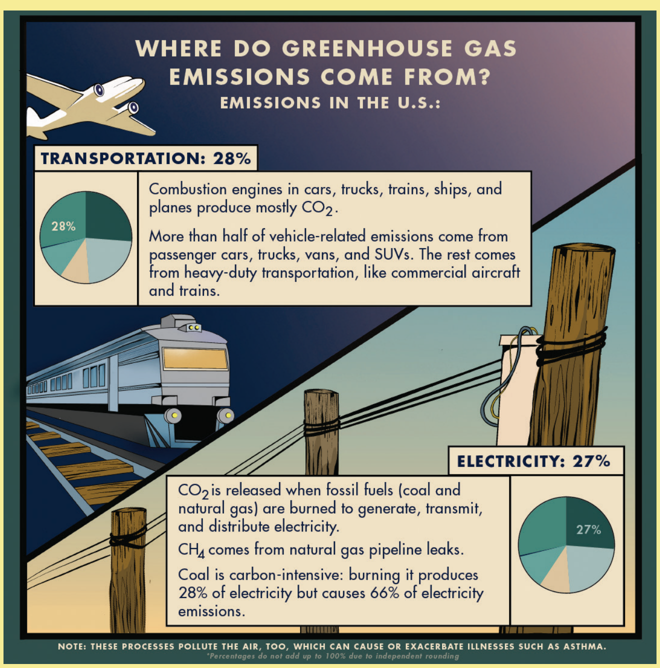
"One of the technologies we're interested in developing are these smaller, distributed wind energy systems that can be equally applied in Pasadena as they can be in rural China. The benefit of these smaller systems is that the local community can take a part in building them, in installing them, maintaining them, and ultimately in consuming the electricity that's generated by them. And they can do it without grid infrastructure.

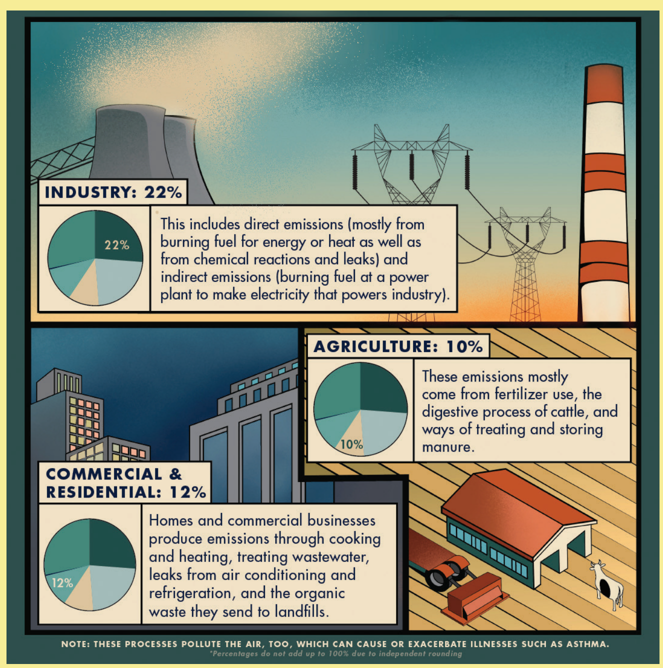
"In our lab, for example, we've developed systems that are called vertical-axis wind turbines. Instead of the blades rotating on a horizontal axis parallel to the ground, they rotate around an axis that points straight up out of the ground. … And those vertical-axis turbines, we've found, can make better use of the wind as a group than the individual horizontal-axis wind turbines that we're more commonly using today.

"An exciting place where we're able to demonstrate the vertical-axis wind turbines is a fishing village in Alaska. It's a community of only about 70 people, and they currently rely on diesel fuel being flown into the village because of its remote location. That is a high cost for them, so they pay much more for their energy than we do in the lower 48. And, of course, the fuel itself is quite polluting. At the same time, the village has a wonderful wind resource.

"The challenge of reliability is really important when you're so remote. These systems have to work. And if you're in a village like this, in the middle of winter, you don't want your power going out. So it's really important that these systems can perform well. And we're almost there."

— John Dabiri (MS '03, PhD '05)
Centennial Professor of Aeronautics and Mechanical Engineering





Learn more about sustainability at **scienceexchange.caltech.edu**

Behind the Vaccine

A Conversation with **Satoshi Ohtake** (BS ’00)

The COVID-19 pandemic and subsequent lockdowns drastically changed work conditions for many people around the globe. For some, that meant working from home instead of the office. For others, like doctors, nurses, frontline workers, and those working in public health, it meant steeling themselves for the intense work ahead. For Satoshi Ohtake (BS '00), Pfizer's senior director of pharmaceutical research and development, the pandemic meant finding a way to develop a vaccine against SARS-CoV-2.

Ohtake, who is also president of the Caltech Alumni Association (CAA) Board of Directors, sat down over Zoom with *Caltech* magazine staff writer Lori Dajose (BS '15) to discuss the history-making process of developing a vaccine against SARS-CoV-2, how his Caltech experience prepared him for such a job, and new changes happening within the CAA.

Lori Dajose [LD]: Pfizer has basically become a household name due to COVID-19. What has it been like to work on a vaccine for the virus that has caused this pandemic?

Satoshi Ohtake [SO]: It's been unreal to say the least. To see your work featured on the news is strange. The biggest challenge was definitely the timeline of developing a vaccine from concept to product under tremendous pressure. Another challenge was to unlearn what we do best, which is to develop a product robustly in a stepwise manner. Instead, we tackled many studies in parallel, which really got us thinking both scientifically and strategically.

On top of that, it was a new technology for us. Although we had been investing in the mRNA [messenger RNA, a type of short-lived genetic material that encodes for a protein] technology prior to the pandemic, this was our first product in which we went all in. We had all hands on deck, and I'm really proud of our accomplishment. All credit to our dedicated team of scientists who worked nonstop to successfully deliver the vaccine.

My responsibility at Pfizer is not only focused on the COVID vaccine. We have 50-plus programs that are just as important when you think about the impact they have on people's lives. While we did everything we could, within our capabilities, to accelerate the development of the COVID vaccine, we didn't take a step back in developing the critical programs in our five therapeutic areas of focus: oncology, vaccines, rare disease, internal medicine, and inflammation and immunology. For example, our next-generation pneumococcal vaccine as well as human growth hormone treatment have been filed for registration, and we're placing a lot of emphasis on developing gene therapies using a different technology platform: adeno-associated viruses.

Now that we've been able to develop the COVID vaccine in such a short period, the question has become, can we accelerate all R&D programs in a similar manner? Management discussions are taking place to assess the ability to prioritize and shift our resources accordingly. How do we balance business needs with our colleagues' needs for their development? That is the challenge.

[My team is responsible for only] a very small fragment of COVID vaccine development. Our experts in the vaccine group conduct preliminary research on the compound to be developed. We have a partner line that figures out a way to scale up the production, and then my team takes it from there. More specifically, we figure out how to stabilize the therapeutic compound and then we develop a robust process to manufacture materials to enable clinical trials and eventually commercial production.

[LD]: People are now talking about ways to prepare for the next pandemic. Given your experience with vaccine and therapeutic development, what are your thoughts on the future of the evolutionary battle between humans and viruses?

[SO]: Pandemics have occurred throughout history. Before COVID, there was the Spanish flu about 100 years ago and the black plague about 650 years ago. We learned a great deal from nature that enabled us to advance our medical technologies. Many biotech companies are pursuing the mRNA approach: some are focusing on monoclonal antibodies, while others are looking at small molecules or adeno-associated viruses. Our toolbox has expanded considerably over the years.

But the minute we come up with a good defense for certain types of infections, nature's pretty smart and figures out a way to get around our strategy. We then work on an alternative approach. It's cyclical. Interest in mRNA and gene-therapy technologies has gone hot and cold many times. It's critical that we continue funding fundamental research in academia, which then gets translated to therapeutics or treatments by industrial partners. I think that's how we continue to progress and try to stay one step ahead of nature. Well, maybe it's more accurate to say not get too far behind nature.

[LD]: What were your research interests at Caltech, and how did they lead to where you are now?

[SO]: Professor Mark Davis [Warren and Katharine Schlinger Professor of Chemical Engineering] was the person who helped me start my career in research. He welcomed me into his research group as an undergraduate researcher my sophomore year. I was browsing through the chemical engineering faculty research web pages (yes, they did exist in the '90s), and I decided to send him a message because I was really curious to learn more about his research. He paired me up with a very talented graduate student, Chris Jones (MS '97, PhD '99), who is now a professor at Georgia Tech, and I learned a lot about catalysis. That was a very different kind of research from what I'm doing now, but I gained a lot of perspective about what it means to be a scientist beyond just doing the scientific coursework.

After Caltech, I went to the University of Wisconsin to study chemical engineering, intending to continue catalysis research. But when I got there, my curiosity led me to change course to research on cryopreservation. We rely on cold temperature storage for many of our therapeutics as well as for tissues and organs for transplant surgery. Nature provides many clues for how best to preserve living organisms. Have you heard about these tiny creatures called tardigrades? Without water, they dry out. Upon rehydration, they come back alive. I'm not sure coming back alive is technically correct since they never ceased to live, but their activity certainly slows down considerably. Trehalose is a [sugar of the] disaccharide [class] found in tardigrades and many desiccation-tolerant organisms. That has spawned a new field of research assessing the role of these sugars and other amino acids in enhancing the stability of biologicals. They have been assessed for their ability to provide protection not only during drying but also during freezing, which is a form of dehydration since water is crystalized.

Satoshi Ohtake at his Caltech Commencement in 2000, with his parents and physicist Stephen Hawking. Ohtake was using a wheelchair because of a broken ankle.

[LD]: Does cryopreservation have anything to do with why the Pfizer vaccine has to be kept at such cold temperatures?

[SO]: In a sense, yes. Most of the biotherapeutic products are sensitive to temperature-induced stress, similar to why food stored in the freezer lasts longer than that left on the counter. As we gain more understanding about the effects of cryopreservation and improve our technology, we can offer the product with enhanced storage stability, sometimes in the form of higher temperature storage, which makes transport and handling easier. An alternative to low temperature storage is drying. We're working on freeze-drying approaches for many of our therapeutics because it enhances the storage stability and ease of transport.

[LD]: You mentioned that your research trajectory shifted a few times. Could you talk about the importance of having that flexibility to switch fields and the freedom to change your mind?

[SO]: Transition is not easy, especially if you've spent so much time and dedication in one field. The unknown can be scary. But in everything that you learn, a lot of the valuable aspects are transferable skills. For example, decision making, the ability to think critically … independent research is just that. When you look at a problem, you derive a hypothesis, propose reasonable assumptions, and set boundary conditions. Does the solution make sense, or do we need to modify any of our assumptions? Or perhaps our hypothesis? Whether you happen to select a topic in, say, catalysis or cryobiology, either way, you approach with the mentality of a researcher. With curiosity.

I've been fortunate to work with many professors and mentors who have made these successful transitions. On the other hand, I've also had many mentors and co-workers who have dedicated their entire careers to one field. In the end, both approaches are valid as long as you're passionate about it. There's really no one correct path.

[LD]: You recently took on the role of president of the Alumni Association Board of Directors. Can you tell us what that role entails?

[SO]: The Caltech Alumni Association is a separate nonprofit organization from the Institute, so we work independently but closely with the Institute and its campus partners. My role is to collaborate with the Alumni Association staff, especially with Ralph Amos, who came on board more than a year ago as our executive director, to enable engagement with our alumni, with the students (our future alumni), and also with the Institute.

[LD]: **What is your vision for your tenure in this position?**

[SO]: One aspect is implementation of digital technology and its many offerings. Due to COVID, many of our alumni are now more digitally savvy. We had a four-fold increase in the number of alumni who joined our first virtual Seminar Day last year, in comparison to the year prior. While I'm not advocating to carry on with only virtual events, I hope we can adopt a hybrid approach. We know the capability that digital tools can offer us, allowing us to connect with our alumni across the globe, but I still find it difficult to replace in-person interactions. Maybe I'm just old school.

Many of our alumni reside outside of Pasadena, so we want to make sure that there are ways in which they can stay connected and engaged with us. We are looking to increase the diversity of the board to better represent the diversity of our alumni community. Over 50 percent of our living alumni graduated post-'90s, and we have observed an increase in the diversity of our graduating class year after year. Correspondingly, our board should shift its composition and mentality.

We look forward to having international alumni serve on the board, and we will benefit from having a wider global perspective. The end result is better programming that caters to the interests of our diverse alumni.

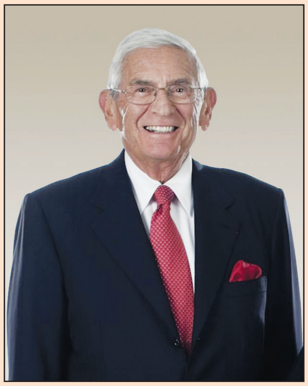
[LD]: **How do you envision the alumni–student relationship?**

[SO]: The level of rigor at Caltech is, bar none, the highest I've ever seen. It trains you well because the standard is so high. And I think it's good that they keep it high. The challenge is adaptation. Student life at Caltech does not necessarily translate well to life in the real world. Not everything can be solved with rationale or logic. And it's going to be difficult to find another place in the world in which you will find yourself surrounded by people just as smart as you, if not smarter. This is an area in which seasoned alumni can help students better prepare to be successful in the next stages of their careers, to share their perspectives about what it's like after graduation. I've enjoyed getting to know many undergraduates and graduate students [who are] considering careers in the pharmaceutical industry. I've also connected with those considering a career transition. For those alumni who have yet to utilize the new CAA website and Alumni Portal, which is like LinkedIn for Techers, please take a moment and connect.

We're evolving as an organization as well. If there are alumni who have any interest, whether it's serving on the board or collaborating with the board on our diverse programs, please reach out. We're more than happy to connect, whether it's on a personal basis or just to look for ways in which we can have an impact on the Caltech community.

In Memoriam

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



Eli Broad 1933–2021

Eli Broad, founder of SunAmerica Inc. and KB Home, former member of the Caltech Board of Trustees, and a Life Member of the Caltech community, passed away on April 30, 2021. He was 87 years old.

An entrepreneur, civic leader, and philanthropist, Broad was an influential advocate for and generous benefactor of life sciences research, public education, and the arts. Throughout his life, he worked to create and foster new businesses, education organizations, scientific research institutions, and museums.

"Eli Broad's distinctive vision and influence shaped the landscape of Los Angeles, cultivating the arts, education, and science, and enriching our society," says Caltech president Thomas F. Rosenbaum. "At Caltech, Eli and Edye catalyzed research in the life sciences, helping our faculty and students illuminate nature and improve the human condition."

Broad's commitment was most evident at Caltech through his leadership on the Board of Trustees and his long-standing investments in the Institute. In partnership with his wife, Edythe, Broad donated more than $40 million to the biological sciences at Caltech through the Eli and Edythe Broad Foundation. Their generosity helped to establish the Broad Center for Biological Sciences, an interdisciplinary campus hub that houses research groups exploring diseases, disorders, and medical treatments and therapies, and provides flexible funding for professors to pursue bold new areas of science.

"His generosity and concern for the city of Los Angeles, for the arts, and for the biomedical sciences was on a scale that was qualitatively different than anyone else," says Caltech president emeritus and distinguished professor of biology David Baltimore. "And while he had no scientific background himself, his belief in and commitment to the people around him enabled him to move forward the kinds of biological science—stem cell science, genomic science—that have made a huge difference the last couple of decades."

Endnotes

2021 graduates, what is your favorite place on campus, and why?

Red Door Café—where my girlfriend and I have met during lunchtime or coffee breaks on an almost daily basis over the past few years. Her lab is in Kármán while my office is in Annenberg, making the Red Door a middle point. This reminds me of a Chinese folk tale—"The Cowherd and the Weaver Girl." In the folk tale, Zhinü (symbolizing the star Vega) and Niulang (symbolizing the star Altair) were only allowed to meet once a year on a bridge formed by a flock of magpies (symbolizing the Milky Way). Every time I see the Milky Way, it reminds me of that short walk from Annenberg to the Red Door Café.

Yu Su (PhD '21)
SHANGHAI, CHINA

I would say my favorite place on campus is the **Page House** courtyard. I have so many memories of having kiddie pool parties and water balloon fights in the summer with my fellow Pageboys!

Isabella Camplisson (BS '21)
SYDNEY, AUSTRALIA

The Morgan Library on the second floor of Kerckhoff. Tarini Singh (BS '21) and I found it while exploring the buildings at night, and it quickly became one of our favorite spots on campus. We would go there to study but also just to sit on the couches and talk about what was going on in our lives. Something about the ambience of the room at night makes it feel like the perfect place to tell secrets and bask in the feeling of being a college student at a renowned university.

Kriti Devasenapathy (BS '21)
PRINCETON, NJ

Tom Mannion's house—where we would have cooking class, de-stress by playing with his dog, Davey, and cook multicourse dinners for Nobel laureates. All great memories because of both the awesome people and the amazing food we made.

Ari Rosner (BS '21)
EDGEWATER, MD

The Scene Shop behind the TACIT house will always be a happy place for me. We used to rehearse for improv in that space. It's full of old props, tools, and so many unexpected items that you feel like you could build or do anything, or travel anywhere you want. At the end of term or over the summer, we'd sometimes go in with snacks and drinks, and make each other laugh for hours.

Heidi Klumpe (PhD '21)
ALTADENA, CA

The new Bechtel Residence. I'll cherish the memory of living in a suite with seven of my closest friends!

Andrew Zhou (BS '21)
MONONA, WI

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A Helicopter Makes History

On April 19, NASA's *Ingenuity* helicopter became the first aircraft in history to make a powered, controlled flight on another planet. The *Ingenuity* team at JPL confirmed that the Mars flight had succeeded after receiving data from the helicopter via the *Perseverance* rover. Altimeter data indicated that *Ingenuity* climbed to an altitude of 10 feet and maintained a stable hover for 30 seconds. It touched back down on Mars after logging 39.1 seconds of flight. *Ingenuity*'s initial flight demonstration was piloted by onboard guidance, navigation, and control systems running algorithms developed by the team at JPL. Before being blasted to the Red Planet, *Ingenuity* was tested in a custom wind tunnel at Caltech. Since April's initial flight, the helicopter has performed additional experimental flights of incrementally farther distances and greater altitudes.

Watch a video on *Ingenuity*'s first flight at **magazine.caltech.edu/post/ingenuity**