Caltech
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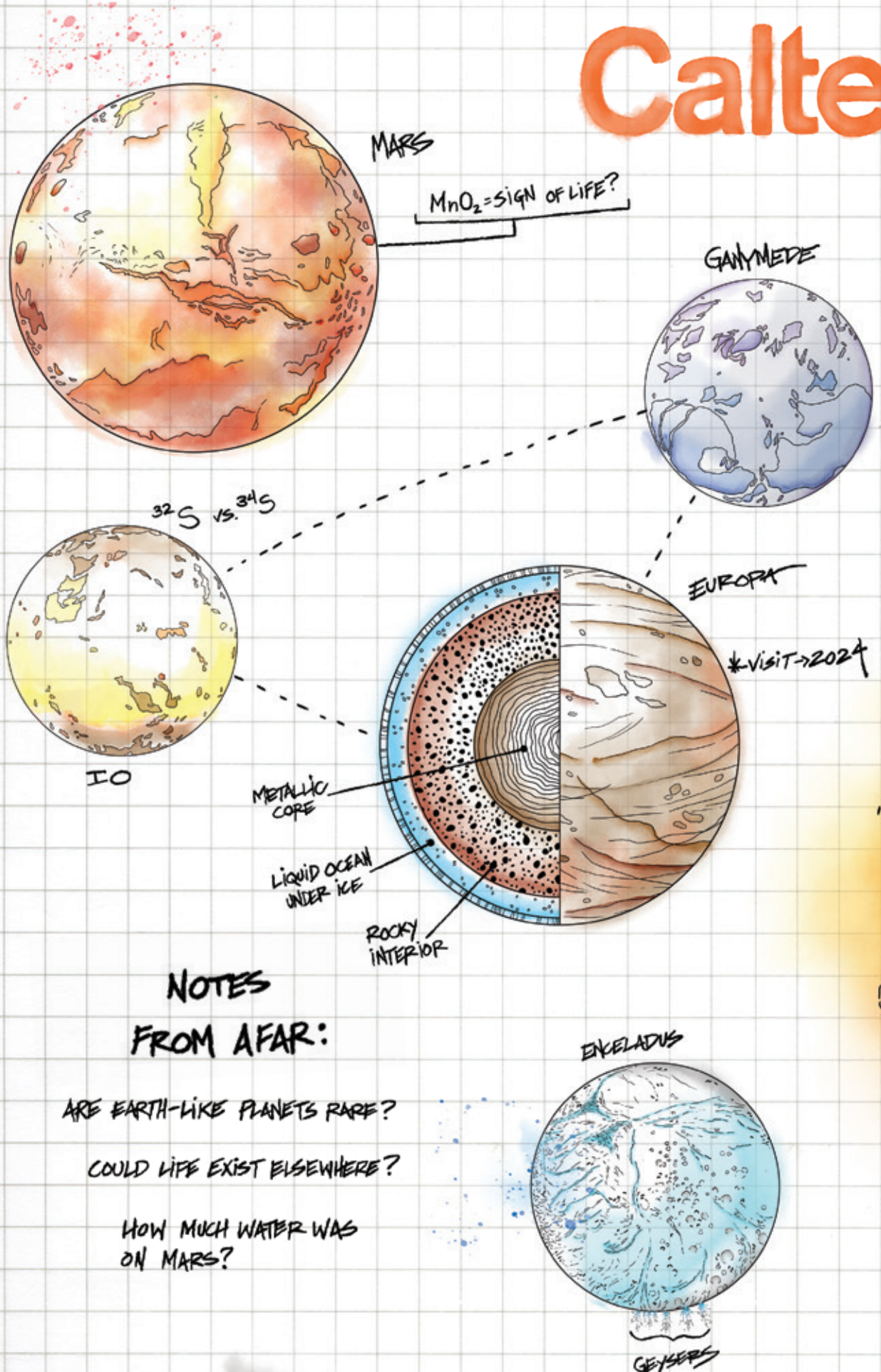

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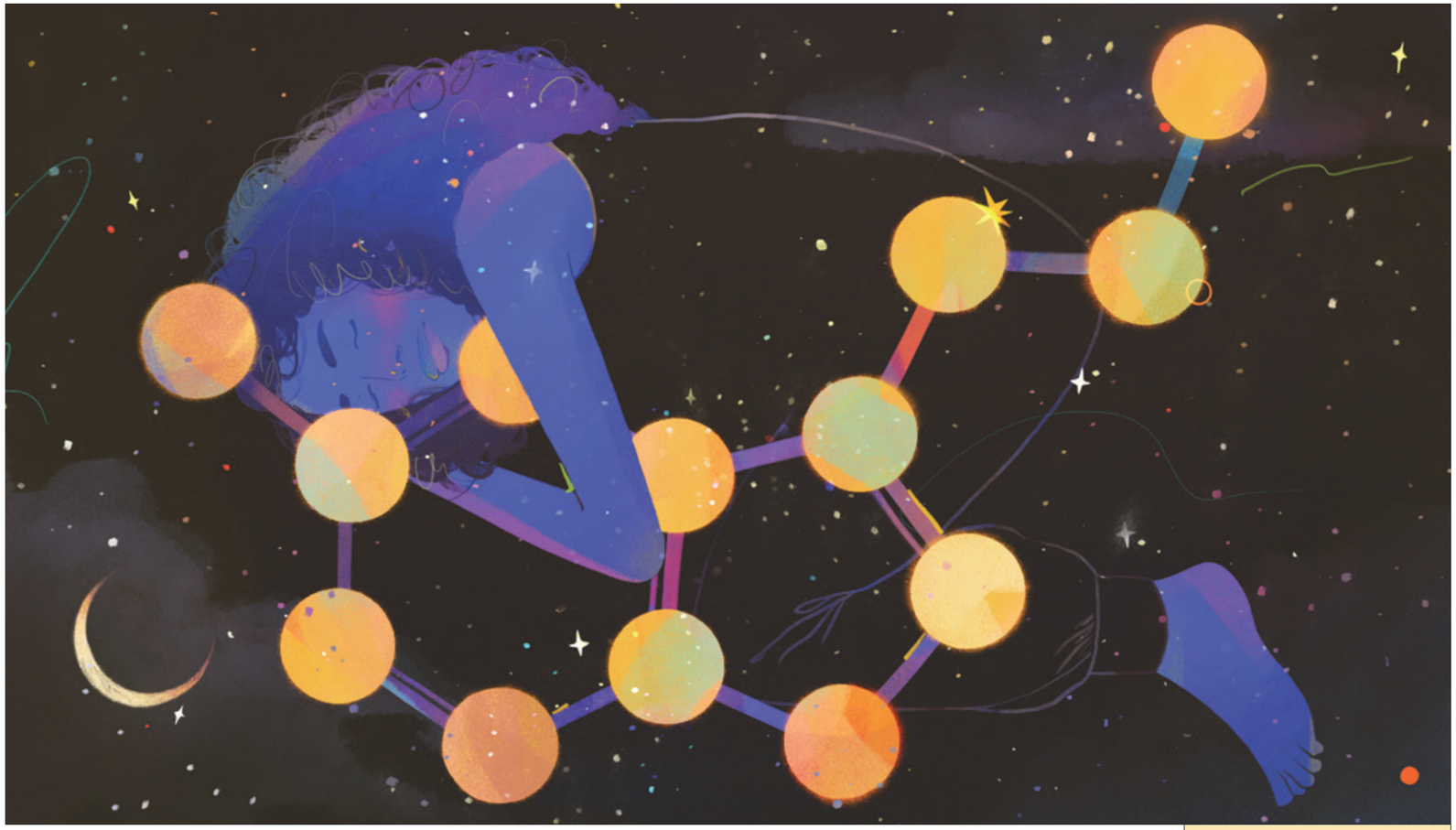

Left: This illustration by Kristen Uroda depicts the serotonin molecule, whose role in sleep is explored in the most recent issue of The Caltech Effect. See article on page 36.

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Letters

What if human beings simply possess insufficient intelligence to understand the fundamental nature of the universe?

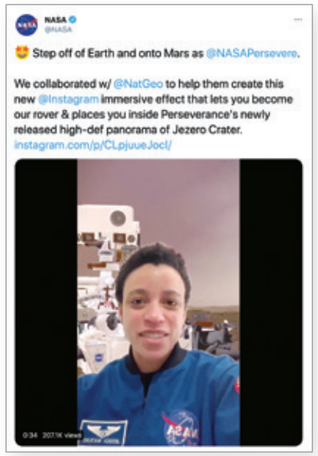
Ponder this question. Pass it on. Discuss it with others. Consider implications and additional questions generated by this question. The deeper you explore, the more fun you will have!

Bill Miller (BS '67)

About 30 years ago, I was one of about six students in the Cal State Los Angeles Geology program. A classmate of mine, Altair Maine, who went on to pursue graduate work at Caltech, mentioned to me that the Geology Club and the geology (open) seminar meetings at Caltech were available to anyone. Amazing! I began attending in earnest while still attending Cal State, but after being hired full time it became too difficult. Some years later, I got interested in dancing. Caltech had an amazing array of high caliber dance clubs, performances, and venues. Unbelievable!

Dana Cole

Caltech



In a NASA tweet posted after the JPL-built *Perseverance* rover touched down on Mars on February 18, NASA astronaut and former Caltech postdoc Jessica Watkins explains one way Earth dwellers can experience the rover's Martian adventure. For more on the mission, go to page 12.

from the

Caltech Associates

Celebrating 95 Years

Founded March 9, 1926, the Caltech Associates is a vibrant membership organization devoted to lifelong learning and supporting the groundbreaking research and education at Caltech. Through unique programming and travel opportunities, the 2,000-member Associates community learns together about the big ideas and world-changing discoveries that their membership helps support.

Join us

Bethany Ehlmann

on the **Lunar Trailblazer mission**

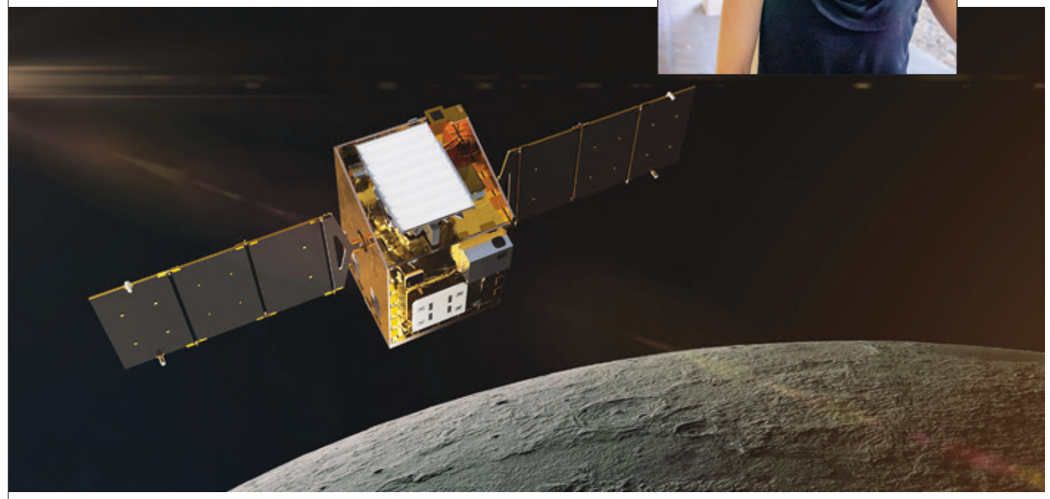
April 27, 2021
5 p.m. PT (on Zoom)

All are invited to attend this family friendly Associates event to hear about the detection of water on the Moon's sunlit surface, one of the most surprising discoveries of the last decade. **Bethany Ehlmann,** professor of planetary science, will discuss the Caltech-led Lunar Trailblazer mission (of which she is co-principal investigator) to map water on the Moon and help determine its value to future human explorers. To register, please visit **associates.caltech.edu/0427**.

For more information about becoming a member of the Caltech Associates community, please contact Catherine Reeves, executive director, at **caltechassociates@caltech.edu**.

"Joining the Caltech Associates is like opening a window to the world. This is a challenging time, and it's important that people get to know more about science."

— Betty Huang
Caltech Associates Board President, pictured above with Shang-Li (SL) Huang (PhD '76)



Borderlands No. 2: They almost got me (Pajarita Wilderness), 2019. Hand-processed watercolor on amate paper

SoCaltech

- Frances Arnold, White House advisor
- Where the biggest instruments were built
- A warm farewell to Ernie
- Meet Caltech's accessibility specialist

Earth Tones

Six years ago, on a trip to Oaxaca, Los Angeles-based artist Sandy Rodriguez walked into a tiny bookstore and picked up a jar of powdered cochineal, the intensely red dye derived from insects. Her painting life has not been the same since.

"It was that carmine red, the most stunning red you've ever seen," says Rodriguez, whose work focuses on the intersections of history, social memory, contemporary politics, and cultural production. "I came back to my studio and made oil paint from it. That was the moment when I understood that this particular historic material could support the content of the work in a powerful way."

Following that artistic epiphany, Rodriguez began taking weeklong field-study trips off-grid in the California deserts to learn about native plants and continued to explore centuries-old methods and materials of painting in the Americas, with a focus on the minerals, plants, insects, and organic materials that go into making paint.

This winter, Rodriguez joined Caltech as artist-in-residence in the Division of the Humanities and Social Sciences' Caltech-Huntington Program in Visual Culture. Established in 2018 with a grant from the Andrew W. Mellon Foundation, the visual culture program is administered jointly by Caltech and The Huntington Library, Art Museum, and Botanical Gardens.

Rodriguez's current painting series, *Codex Rodriguez-Mondragón,* is inspired by manuscripts of the Mexican colonial era and takes the form of large-scale map paintings on amate, a traditional Mexican paper handmade from the bark of fig, jonote, and mulberry trees. Painted with hand-processed pigments, the works capture the timeless physical features of the landscapes, including the animals and plants, as well as contemporary political moments such as the police killings in

continued on page 6

Earth Tones

continued from page 5

Los Angeles, immigration detention facilities, and the building of child-separation centers that have impacted Latino communities on both sides of the border.

Each week during her Caltech teaching residency, which ran from January through March, Rodriguez introduced her students, via Zoom, to a new pigment or colorant. "We conducted our experiments and learned about meaning, use over time and across cultures," she says. "After discussing our readings, we processed the color together into paint. Picture a live cooking show, but we were processing colors."

Before the term began, Rodriguez mailed each of her students a "historic color box" filled with insects, mushrooms, and bark; gum arabic to bind the powder into paint; mussel shells for paint containers; and a variety of natural raw pigments native to Southern California. Although the limits of remote learning meant the students could not share the experience of processing colors in actual proximity, they were able to experience things individually, says Rodriguez, and then compare notes. For instance, she says, "when you crush the cochineal, it's really interesting to see how different people respond to the fragrance. One of my students said it smelled faintly like M&Ms."

Rodriguez (pictured below in her studio), says she found the opportunity to reconnect with lost knowledge and build community through shared experiences rewarding. "It is inspiring," she says, "to get to work with this dynamic group of students and see how they respond to learning about materials that were instrumental to the artistic practice of the Americas."

See more of Rodriguez's work at **www.studiosandyrodriguez.com**

Frances H. Arnold
White House Advisor

"Like the rest of this extraordinary team, I am here today because of love. A love of science, yes, but also a deeper love, of our planet and of our people, without whom science has no purpose or meaning. … In a moment of torrential divisions, science offers us a common shelter of facts and truth within which we can begin to come together and, in time, to heal. Science … is not about cold solving of problems, it's a warm and beautiful exploration of the unknown, an expression of human curiosity that propels us forward and allows us to fulfill our most important responsibility. The moment we fail to nurture it, we resign ourselves to living in the past and lose the chance to guide the future. … When we put science back to work for the benefit of all people, revitalizing our economy, fueling our climate response, broadening our perspective as we rebuild around greater equity and opportunity, we are making a society worth passing on to our children and our grandchildren. It is an act of love, and I am honored by the opportunity to help nurture this effort."

–Frances Arnold, *2018 Nobel laureate and Caltech's Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry, accepting the nomination (at right) by then-President-elect Joe Biden to serve as co-chair of the President's Council of Advisors on Science and Technology*

Adiós, Ernie, and *Thank You*

Ernie Mercado was a fixture on Caltech's campus for more than three decades as the proprietor of Ernie's Al Fresco, a food truck beloved by students, staff, and faculty alike. Mercado announced his retirement last October. Students and alums, upon hearing the news, organized an online collection effort to honor his retirement and thank him for his service. Here are some of the tributes that were posted.

Ernie's tacos dorados played more of a role in my decision to go to Caltech than I'd like to admit. … Good luck, Ernie! It's the end of an era.

Sam Johnson (PhD '16), Computational Scientist at Pacific Northwest National Laboratory

Ernie of Caltech food truck fame is retiring. … End of an era!! I spent > $6,000 at Ernie's during grad school, and he got an acknowledgment in my thesis.

Ian Tonks (PhD '11), Associate Professor of Chemistry, University of Minnesota

Just look at that smile. Anyone who went through Caltech knows the impact this man had on our community. Wishing you a happy and fulfilling retirement, primo. Legend!

Moh El-Naggar (PhD '06), Robert D. Beyer Early Career Chair in Natural Sciences, USC

Ernie has been a member of the Caltech family for so long. No matter how tough grad school got, he always was there and always greeted you with a smile and a laugh. Ernie's food truck may no longer be in operation, but Ernie will not be forgotten!

Jeffery Byers (PhD '07), Associate Professor of Chemistry, Boston College

Ernie has contributed to more science than any professor on campus! How lucky we've been to have Ernie's food and joy in our lives.

Celeste Labedz (MS '19), Caltech Geophysics PhD Student

Ernie's quick smile, as much as his hearty plates of food, have been an important support for generations of Caltech students and staff. There have probably been hundreds of scientific breakthroughs dreamed up over a round of his burritos; I know one of my papers was.

Jackson Cahn (PhD '16), Postdoctoral Researcher at ETH Zurich

It's too bad that next time [I visit] Caltech, I won't be able to get my Ernie's fix. Truly an end of an era. This guy was more popular than Nobel laureates, beloved by all, always up for a joke, and affordable! Enjoy retirement!

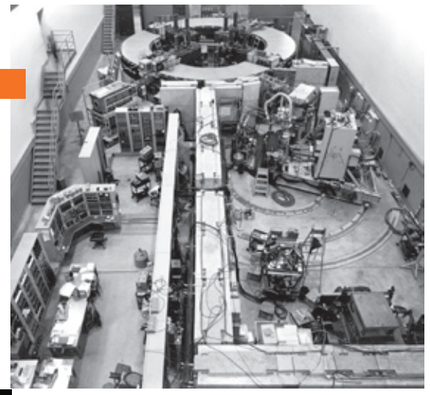
Roland Hatzenpichler, Assistant Professor, Chemistry & Biochemistry, Montana State University

Read more about Ernie at **magazine.caltech.edu/post/ernie**

Where Big Ideas Take Shape

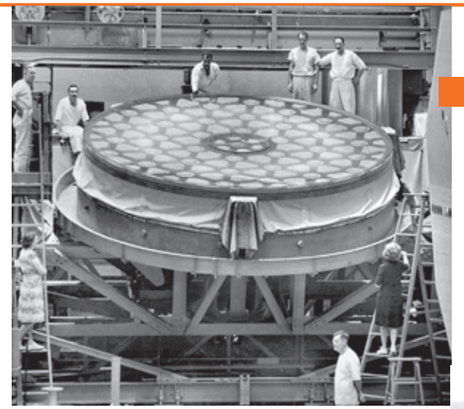
Situated inconspicuously on the south side of campus is a cavernous building that has witnessed some of the most influential developments in the history of astronomy and physics. Called the **Synchrotron Building**, the 48-foot-tall structure, originally dubbed the Optical Shop, was constructed in the 1930s as a place to polish and grind the giant 200-inch mirror of Palomar Observatory's Hale Telescope. In 1949, the building was renamed the Synchrotron Building when construction began on Caltech's synchrotron, a particle-smashing experiment that sped electrons up to nearly the speed of light. Shown here are a handful of the many projects to have been developed in the Synchrotron Building over the years.

Over the decades, the Synchrotron Building has been a hothouse in developing novel instruments to measure the cosmic microwave background, the glowing relic radiation from the Big Bang. Pictured above is the latest instrument, the **BICEP** (Background Imaging of Cosmic Extragalactic Polarization) Array, which, like its predecessors, will carry out observations at the South Pole in search of primordial gravitational waves from the Big Bang.

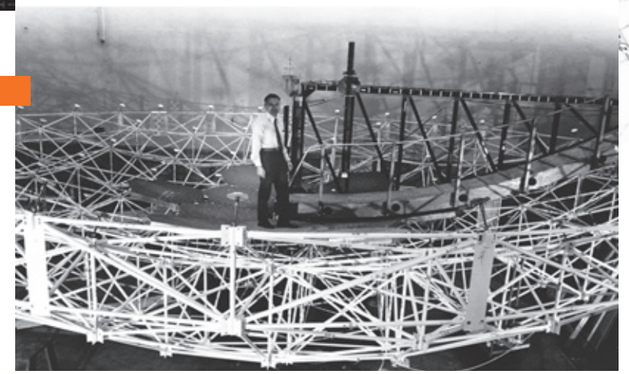


At the time of its operation in the 1950s and '60s, Caltech's **synchrotron** was the most powerful atom smasher ever built, operating at energy levels of 1 billion electron-volts. Today's largest atom smasher, the Large Hadron Collider (at CERN), reaches energy levels up to 14 trillion electron-volts.

This giant thermos bottle–like vessel currently being built in the Synchrotron Building will be incorporated into the **nEDM experiment**, which will make precise measurements of the neutron's electric dipole moment. The experiment, planned to begin at Oak Ridge National Laboratory in Tennessee in about five years, will seek to answer the question: What happened to all the antimatter in our universe?



To prevent **Palomar's 200-inch mirror** from being scratched while it was being ground and polished, workers constantly swept and mopped the floor, and even washed the walls of the room. Upon entering the space, workers were required to remove their shoes and clothes, and don rubber-soled shoes and uniforms. A magnetic sweeper was also kept in constant operation on the floor.



Eight **10-meter radio dishes**, designed by the late Caltech physics professor **Robert Leighton** (BS '41, MS '44, PhD '47), were constructed in the building at the end of the 1970s. Six of these would go on to be used for studies of the cosmos at Caltech's Owens Valley Radio Observatory (OVRO); another dish became Caltech's Submillimeter Observatory in Hawaii; and the final dish went to the Raman Research Institute in India.

The 4,500-pound **MOSFIRE** instrument now at W. M. Keck Observatory in Hawaii was assembled in the Synchrotron Building over a period of seven years. The near-infrared spectrometer is an astronomy workhorse and has been observing the cosmos since its installation in 2012.

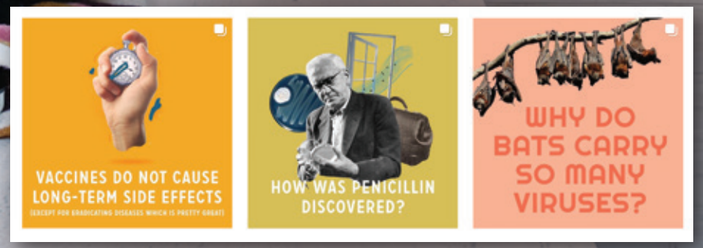
LIGO research took place in the Synchrotron Building in the 1990s and early 2000s. To accommodate the westward extension of a necessary beam tube, a tunnel was dug under the bridge between the Guggenheim and Firestone buildings. Today, one may notice a gentle bump in the pavement directly under the bridge; this is where the tunnel was built.

Jessica Griffiths (third-year graduate student)

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

Jessica Griffiths is a bioengineering graduate student in the lab of Sarkis Mazmanian, Caltech's Luis B. and Nelly Soux Professor of Microbiology. With her sister, Kate, an art director in Portland, Oregon, she started an Instagram account, ***Science Translators****, that aims to present scientific topics—from prion diseases to penicillin to vaccines—in an engaging and understandable way.*

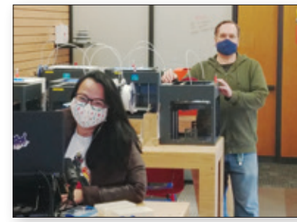
"My sister, Kate, has degrees in both advertising and theater, and works as an art director at an advertising firm. She's very, very creative. As a bioengineering grad student, I have a different skill set. I was feeling a bit frustrated at the science material that's out there. There's a lot for kids—simple and basic things—but for adults it's often just filled with jargon. I felt like there was an area in the middle to make something visually appealing and interesting that also would be understandable. We've really enjoyed starting this Instagram account, and we've gotten some good feedback, like, 'I just spent all weekend trying to understand this concept and reading articles. And just going through this post, you've already put it all together, and now I understand it, so thank you.' It's not rocket science. Anybody with the scientific knowledge would be able to communicate this way if they had practice. Talking each post through with my sister and getting feedback about stuff she doesn't understand, I've learned what the most important parts of explaining are. Distilling it down is a lot of the process because we have limited space on Instagram. But also, less is just sometimes more. Obviously, the thing on people's minds right now is SARS-CoV-2, COVID-19, and the vaccine. We also have some more posts like the one we did on Alexander Fleming and his discovery of penicillin in the pipeline. When you tell those stories, about the individuals and what they thought about their research and how they stumbled along the way, it's so much more relatable and exciting to people than just describing science as a series of chemical or biological interactions."



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

The Campus COVID Response One Year Later

It has been a year since the COVID-19 pandemic changed every facet of campus operations. Following are examples of how the community has continued to adapt and connect during this time.



Caltech Together is a campuswide initiative and website designed to help community members support one another during the pandemic. Members of the community can find information on testing, vaccine planning and distribution, current case activity, campus policies and preventative measures, remote teaching and learning tools, and mental health resources at **together.caltech.edu.**

A special social media series, #CaltechTogether, shines a spotlight on the many ways members of the community have been supporting each another during the pandemic.

"The fact that a brief conversation between staff members could turn into a small but meaningful project like this that helped out the COVID response team is pretty heartwarming."

— Paula Gaetos

Gaetos manages Caltech Library's Techlab. Recently, she and system administrator Ian Roberts designed and 3D-printed specimen tube collection racks as part of the campus COVID-19 surveillance testing program.

Virtual Rotation gave first-year students a way to experience rotation from home with events tailored to the virtual setting. For soon-to-be grads, the Senior Series includes online wine tasting and an evening of Pixar films.

New webinar series:

Conversations on COVID-19, hosted by the Caltech Science Exchange, features Caltech scientists talking about issues related to the coronavirus, such as the effectiveness of masks and vaccine development. Read more at: **scienceexchange.caltech.edu/connect/conversations-covid-19**

What Matters To Me and Why, an online interview series for students, explores the paths, choices, challenges, and joys encountered as part of the personal and professional journeys of a variety of speakers from the Caltech community. Read more at: **ore.caltech.edu/events/WMTMW**

Conversations with Caltech Faculty bridges the virtual gap between faculty and students with casual conversations that mimic the candid discussions that would normally happen naturally during office hours or in the hallways.

In Memoriam

While the pandemic has caused a sense of collective loss, for some in the Caltech community, the toll has been more tragic and personal.

José Mendez, a member of Caltech's custodial services group, died on January 4. José—along with his wife, Gloria Mendez—had been a Caltech employee since 2008. He is remembered as a caring, honorable person who enjoyed spending his spare time in the garden and with his family and dogs.

Ramon Ramirez, a Caltech roofer and valued member of the facilities group for the last 15 years, died on December 14, 2020. Ramon is remembered by close colleagues and friends as a caring individual whose goodwill and humor touched all who interacted with him.

Research across campus is contributing to a more thorough understanding of SARS-CoV-2 and informing societal response to the pandemic through studies on how the virus disables cells, how models can help track its spread, and how people perceive risk during the pandemic. Some of this work has a direct impact on the on-campus response. For example, researchers are currently partnering with Facilities to implement a new trace gas technique for assessing ventilation in campus buildings. Read more at **together.caltech.edu.**

Testing is offered free of charge to community members experiencing symptoms. Caltech's surveillance testing program, run in partnership with Swabseq, provides regular screening of all individuals reporting to campus or accessing campus facilities. Campus is currently operating at 25 percent capacity.

Life on Mars?

Perseverance Starts its Search

Perseverance, the largest, most advanced rover NASA has sent to another world, started its exploration of Mars on February 18, after a 203-day journey traversing 293 million miles. With the announcement of "Tango Delta. Touchdown confirmed," the skeleton crew on site at JPL, which Caltech manages for NASA, broke out into applause as the rover landed on the planet's boulder-strewn surface.

The 2,263-pound, car-sized rover is investigating the rocks and sediment of the ancient lakebed and river delta of Mars' Jezero crater. A fundamental part of its mission is astrobiology, including the search for signs of ancient microbial life. To that end, the Mars Sample Return campaign will allow scientists on Earth to study samples collected by *Perseverance* to search for definitive signs of past life.

"The idea of bringing a sample back from Mars goes back decades," says Ken Farley, Caltech's W. M. Keck Foundation Professor of Geochemistry and the mission's project scientist. "We are in a position now where if everything goes according to plan, samples will be coming back to Earth in 2031."

Jezero crater sits on the western edge of Isidis Planitia, a giant impact basin just north of the Martian equator. Scientists have determined that 3.5 billion years ago the crater had its own river delta and was filled with water. "Life as we know it could have lived in that lake," Farley says, "and the mud of a delta is really good at preserving the biosignatures of life."

Equipped with seven primary science instruments, the most cameras ever sent to Mars, and a complex sample caching system (the first of its kind sent into space), *Perseverance* is now beginning to scour the Jezero region for fossilized remains of ancient microscopic Martian life, taking samples along the way.

A pair of zoomable science cameras on the rover's remote sensing mast, Mastcam-Z, of which Caltech's Bethany Ehlmann, professor of planetary science, is a co-principal investigator, will create high-resolution, color 3D panoramas of the Martian landscape. Also located on the mast, the SuperCam, which Professor of Geobiology Woody Fischer has helped develop, will use a pulsed laser to study the chemistry of rocks and sediment.

"There is this real opportunity for us to discover something amazing from Mars," says Fischer, "but also to discover something on Mars that we take for granted on Earth. Maybe there are abiotic ways to generate some of the materials and textures that we assume to be produced by life on Earth."

Meet some of the people involved and watch day-of-landing reactions at magazine.caltech.edu/post/perseverance

Five Questions for:

Accessibility Services Specialist

Marc Lazar

Marc Lazar recently joined Caltech in the newly created position of accessibility services specialist within Caltech Accessibility Services for Students (CASS). In this role, Lazar is the primary support person for students with disabilities, both undergraduate and graduate, with the goal of ensuring equitable access to the full experience of being a part of the Caltech community. Lazar has worked with individuals with disabilities in a variety of settings, including colleges, high schools, the community, and the workplace, and has particularly deep experience and expertise working with the autism community.

1. Why is it important to have someone in your role at Caltech?

Accessibility is a crucial issue in schools, including on college campuses. I think it's really important to have somebody whose role is dedicated to focusing on accessibility, not just the physical accessibility of buildings but also giving students the access to fully participate in everything that the college experience has to offer. It's a big equity issue for me.

2. What are some misconceptions about disability?

I think for a lot of people, when you talk about disabilities, the first thing that comes to mind is somebody in a wheelchair or somebody who's visually impaired or deaf. It's only more recently that people have begun to realize that invisible disabilities such as psychological and developmental and other less visible health disabilities actually impact a greater number of individuals.

3. What are some of the issues you want to address early on?

I think number one is really outreach, just increasing the visibility of CASS and accessibility throughout the Caltech community, and helping students feel more comfortable reaching out for help before they're in a crisis situation.

Being at an elite institution like Caltech can be an obstacle for students seeking help. At the same time, there is a growing disability community that is finding support and strength in one another. And that's starting to emerge throughout academia. I think it would be wonderful to tap into that and connect students and the whole Caltech community with the larger disability rights and support community.

4. What about the special challenges of adjusting to learning online?

Students who have executive functioning challenges, which can often be found with attention deficit disorders and autism, more of them have been struggling in this environment. I think that has to do with having a little bit less structure, having to really manage your time in an online environment. A lot of students with executive functioning challenges rely on routines and sometimes external reminders to really do their best. Being able to sustain attention for long periods of time staring at a screen is hard for everyone, but I think when you have challenges related to focus and attention, that can be especially difficult.

5. In terms of physical accessibility on campus, what are some challenges that you see?

I know that there are some older buildings on campus, so some things need to be retrofitted. My impression is that it's not feasible to tackle everything at once. It's more about addressing issues as the need arises. I'm interested in exploring how we can make it easier for students to reach out to us when an accessibility issue comes up for them so that we can address it as quickly as possible. And, hopefully, going forward, they can be more included in the planning phases for new facilities so things are fully accessible from the get-go.

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

In the Community

Millikan and Other Eugenicists' Names to be Removed from Campus Buildings, Assets, and Honors

In January, Caltech president Thomas F. Rosenbaum, acting on the authorization of the Institute's Board of Trustees, set in motion the process to remove the name of Caltech's founding president, Robert A. Millikan, from campus buildings, assets, and honors. Rosenbaum and the Board also approved the removal of the names of Harry Chandler, Ezra S. Gosney, William B. Munro, Henry M. Robinson, and Albert B. Ruddock.

The decision was made in response to the named individuals' participation in the eugenics movement through affiliation with the Human Betterment Foundation (HBF), a California-based organization that promoted eugenic sterilization in the early 20th century. During the summer of 2020, two petitions that called for Caltech to remove the names of Institute leaders who had been associated with eugenics from all campus assets and honors—one by the Black Scientists of Engineers of Caltech and the second by a Caltech alumnus—garnered more than 1,000 signatures each.

"Renaming buildings is a symbolic act, but one that has real consequences in creating a diverse and inclusive environment," Rosenbaum said in announcing the decision. "It is an act that helps define who we are and who we strive to be."

The Committee on Naming and Recognition (CNR), which was charged with considering current and future naming and recommending specific actions, released its final report in December 2020. By recommending the removal of these names, the committee stated, it was not proposing that Caltech break its ties with Millikan or other problematic figures in its history, but rather advising the Institute to delve even more deeply into its history through initiatives designed to inform and educate its community and the public.

In an interview with the *Los Angeles Times,* Nicolás Wey Gómez, a Caltech history professor and a member of the CNR, said the committee was unequivocal in its condemnation of eugenics. "It is dehumanizing, it is wrong," he said. "Central to moving forward as an institution, we on the committee felt a deep sense of obligation to renounce any part of our past that is inconsistent with the Caltech of today."

Below are answers to some frequently asked questions around the renaming decision.

How did Caltech reach this decision?

The committee considered Caltech's existing naming policy, spoke with two members of the Caltech community about the submitted petitions, met with experts on the history of eugenics and the Human Betterment Foundation, consulted extensive documentation on these topics and on the individuals of concern, and surveyed similar efforts by peer institutions. The committee also solicited feedback from members of the Caltech community via an online form, which garnered 1,517 comments from staff, faculty, undergraduate and graduate students, postdoctoral scholars, trustees, parents, and alumni.

How quickly will the names be removed?

The Institute is working expeditiously, and in accordance with all legal gift agreements and contractual obligations with the named individuals or their descendants, to implement the committee's recommendations.

How will the community be informed moving forward?

Updates and new developments will be shared with the community through the website and the Ion Caltech newsletter. Questions and comments about the decision may be directed to **naming@caltech.edu.**

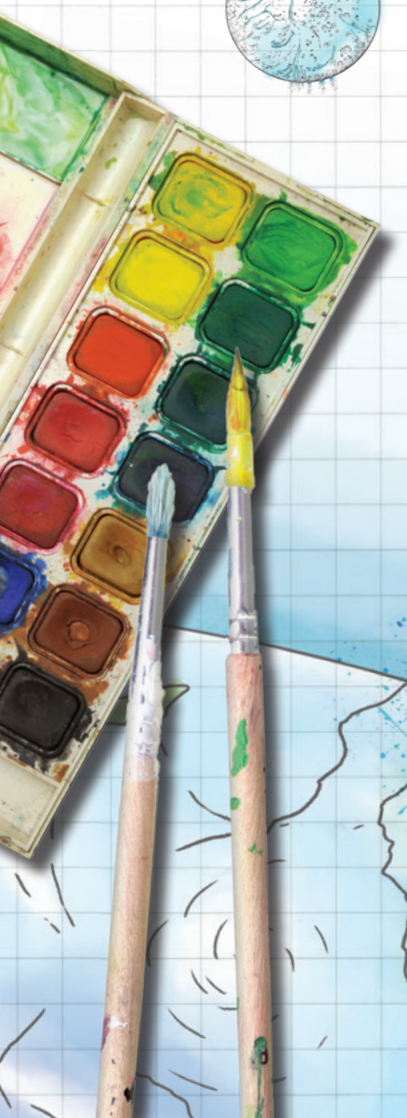
Answers to more frequently asked questions, the committee's full report, and other resources can be found on Caltech's newly launched Diversity, Equity, and Inclusion website at ***inclusive.caltech.edu.***

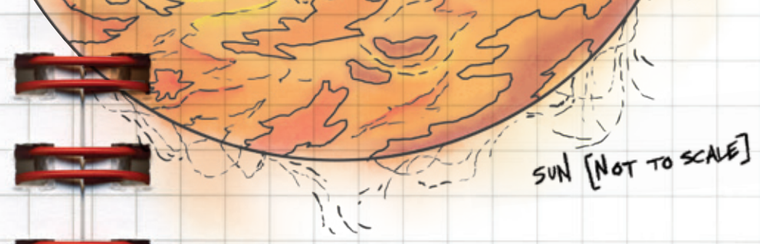
WORLDS TOGETHER

THE CALTECH CENTER FOR COMPARATIVE PLANETARY EVOLUTION (3CPE) UNITES ASTRONOMERS, GEOLOGISTS, PLANETARY SCIENTISTS AND OTHERS IN ONE SHARED MISSION TO UNDERSTAND WHAT DIFFERENT PLANETS CAN TELL US ABOUT THE EVOLUTION OF THE COSMOS AND THE RISE OF LIFE.

BY ANDREW MOSEMAN

ILLUSTRATIONS BY LANCE HAYASHIDA





Woody Fischer loves a problem with a bewitching name. Consider, for example, the "faint young sun paradox."

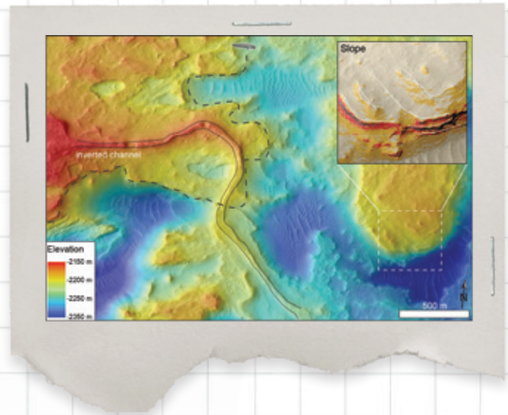
Fischer, a Caltech professor of geobiology, explains the problem this way: based on the well-understood physics of similar stars, the sun should have been 30 percent dimmer a few billion years ago. If our star were so dim, Fischer says, Earth would have been a ball of ice. Yet geologic evidence shows plenty of liquid water on the surface at that time, and we know life found a way.

In the 1970s, astronomers including Carl Sagan proposed a solution: Earth back then had more atmospheric greenhouse gases than researchers expected there would have been, which would have trapped enough sunlight to warm the planet. Their answer seemed to be satisfactory, until a new problem arose from the surface of another world. Data from the rovers and orbiters sent to Mars over the past several decades revealed that the Red Planet was warm and wet during the same period. But Mars is even farther from the sun than Earth is, and it would not have possessed enough atmosphere for Sagan's solution. Something else must have been going on, Fischer says.

"That's just an example of what you stand to learn when you get data from another planet and it shakes you out of your understanding," he says. "This thing I thought I understood that we all accepted, wrote up in the textbooks ... maybe this thing's not settled at all."

The new Caltech Center for Comparative Planetary Evolution (3CPE) is dedicated to such a premise: that comparing planets and moons to one another can lead to new insights and raise new questions. These scientists work to unite core topics for Caltech and the Jet Propulsion Laboratory (which Caltech manages for NASA), such as geochemistry, astronomy, and planetary science as part of an interdisciplinary effort that seeds collaborative research projects among these disciplines. Mike Brown, the Richard and Barbara Rosenberg Professor of Planetary Astronomy, holder of the Terence D. Barr Leadership Chair for 3CPE, and head of the new center, says the joint effort will deepen the understanding of our solar system, aid the hunt for new Earth-like worlds, and further the quest to understand the origin of life on this planet and the search for it elsewhere.

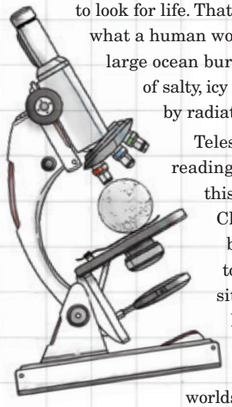
WOODY FISCHER



ANCIENT DELTA AND MINERAL DATA SUGGEST MARS WAS WARM & WET — BUT WHAT DOES THAT MEAN FOR EARLY EARTH AND THE RISE OF LIFE?

"We're all really asking the same questions about how planets and planetary systems evolve," Brown says. "But, typically, we tend to ask these questions from within our own areas of expertise while perhaps missing some of the bigger picture and accumulated knowledge around us. There are real reasons for geochemists to talk to astronomers and vice versa. If you want to try to understand how an atmosphere of a planet evolves, for example, you need those conversations to happen."

A MOON IN A LAB



Jupiter's moon Europa is one of the most promising places to look for life. That does not mean its environment is what a human would call hospitable. The moon has a large ocean buried beneath a cracked surface made of salty, icy material that is constantly bombarded by radiation.

Telescopes have taken spectroscopy readings to understand the makeup of this strange world, and the Europa Clipper NASA mission, led by JPL, will launch in 2024 to fly by the moon, study it, and scout sites for a potential future Europa lander. "This is a big push over the next decade or so," Brown says. "NASA is going to these ocean worlds, these icy locations, and this is kind of the beginning of that exploration."

CAN'T WAIT!

Still, so much about this promising moon remains a mystery. For instance, Brown says, "What is it that you would see that would tell you something has been alive?" Geochemists have dedicated decades to deepening their understanding of how organic materials degrade and are preserved on Earth, but no place like Europa exists on this planet. That is why Brown and Caltech collaborators including Alex Sessions, professor of geobiology, and Victoria J. Orphan, the James Irvine Professor of Environmental Science and Geobiology, have begun to recreate the surface of Europa.

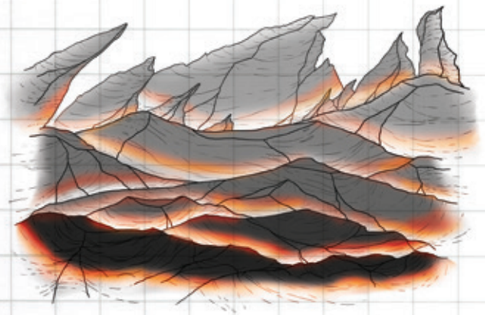
To simulate the moon's chemical interactions, the team repurposed a cesium-137 irradiator previously used for cancer research to bombard rock samples embedded in ice with gamma rays. A second instrument, nicknamed Sputnik, employs a vacuum chamber that can mimic the temperatures and atmosphere present on Europa to measure how water ice and other basic molecules react to such conditions. The project could determine what materials should be present on Europa's surface and, by extension, which materials would be an interesting aberration, and perhaps a sign of life, if found.

Jupiter's moons tell a story not only of ice but of fire. The most volcanically active body in the solar system, Jupiter's moon Io, is a pockmarked hellscape of lava lakes and liquid rock. Formerly volcanic places, such as Mercury and Earth's moon, wear their history on their surfaces, as their craters and lava plains testify to long-ago impacts and ancient eruptions that solidified as they cooled. Not so Io, where lava paves over the past.

Katherine de Kleer, Caltech assistant professor of planetary science and astronomy, seeks to rediscover Io's hidden history. Celestial mechanics can explain the reason why the moon is so volcanic. Io is locked in an orbital resonance with Europa and with Jupiter's moon Ganymede, and the various gravitational pulls create tidal heating within Io. But researchers do not know how long the moon has been volcanically active.

MIKE BROWN

KATHERINE DE KLEER (ON EARTH)



SURFACE OF IO?

One of the few ways to elucidate the billion-year history of Io, says de Kleer, is by focusing on sulfur, as her lab is now doing. The element abounds on Io: sulfur dioxide frost coats the surface, while sulfur-dioxide and sulfur-monoxide gases are found in the atmosphere. Some of these gases will escape into space while the rest freeze onto the surface and are recycled into the moon's interior. Sulfur exists in nature primarily as sulfur-32, which contains 16 protons and 16 neutrons, but Io also contains a smaller amount of the isotope sulfur-34, which carries two additional neutrons. Each time the sulfur cycles from the atmosphere back to the moon's interior, the two kinds of sulfur are lost at different rates and the ratio between the two isotopes changes. At Io's current resurfacing rate, its entire mantle would have been recycled about 50 times during its history; de Kleer's lab is trying to use Io's sulfur isotopes to prove it.

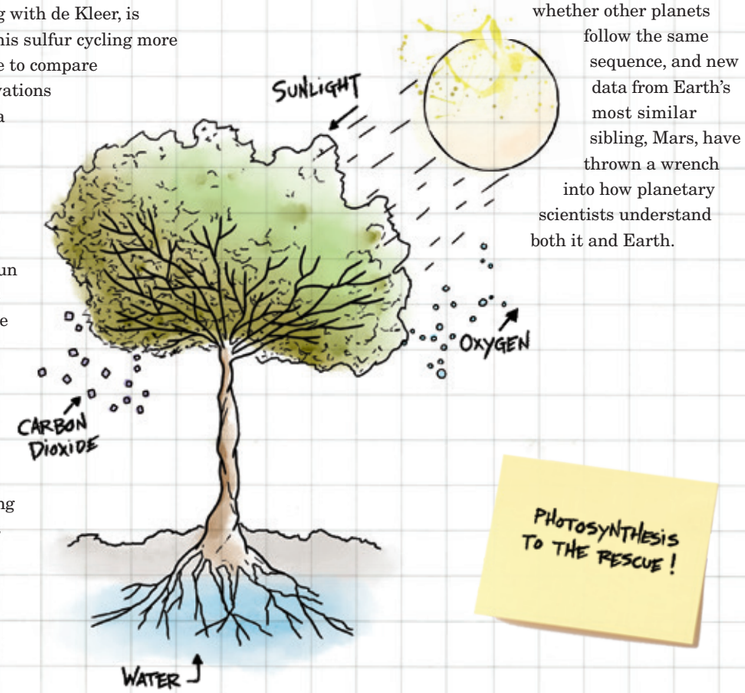
Ery Hughes, a postdoc working with de Kleer, is building a model to understand this sulfur cycling more completely. She and de Kleer hope to compare those predictions with real observations of sulfur isotopes from the Atacama Large Millimeter/submillimeter Array, or ALMA. (The ALMA isotope data for this study were supposed to arrive in March 2020 but have been delayed because of the COVID-19 pandemic.) "If we run that for the history of Io," Hughes says, "would we be able to recreate the isotope ratio we see today?" If so, that would indicate Io has been about as active as it is now throughout its history; if not, then the moon could have become volcanic more recently.

The scientists aren't just learning about Io for Io's sake, however. "It gives us an opportunity to better understand this process that is driving geological activity on moons all over the solar system as well as on exoplanets," de Kleer says. (An exoplanet is a planet that orbits a star outside our solar system.) Active geology also hints at the possibility of life existing on Saturn's moon Enceladus, which is another prime candidate for scientists in the search for life because of its geysers and warm subsurface ocean. Scientists have already modeled potential tidal heating in the TRAPPIST-1 system, composed of seven terrestrial planets discovered in 2017 and lying around 40 light-years from the sun.

TWO WORLDS ARE BETTER THAN ONE

It may be that Earth is a lonely outlier, perhaps the only world in the Milky Way that abounds with liquid water and life. Or it could be ordinary, just one of countless worlds that orbit in the habitable "Goldilocks" zones around their stars and contain the right stuff for life. Or the truth could lie somewhere in the middle. Science cannot begin to unravel this puzzle just by studying conditions on Earth, Fischer says. Researchers must learn more about other planets, be they neighbors within our solar system or distant newfound exoplanets.

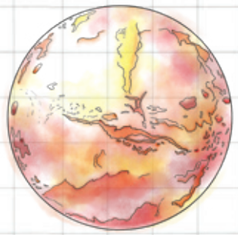
Earth history tells Fischer a tidy story: The planet becomes warm and wet. Life arises, creating a biosphere without much atmospheric oxygen. The arrival of photosynthesis pumps up the oxygen supply, allowing for multicellular complexity and, eventually, intelligent life. However, what Earth history cannot tell scientists is whether other planets follow the same sequence, and new data from Earth's most similar sibling, Mars, have thrown a wrench into how planetary scientists understand both it and Earth.



"One of the biggest breakthroughs in planetary science in the last 20 or 30 years is the recognition that Mars has a geologic record," Fischer says. "Just that discovery means that you're not stuck with what Mars looks like today, but you can ask questions about what it looked like in the past and how it came to be."

One example involves the manganese oxides the Mars *Curiosity* rover found near Gale crater in 2016. "Mars wasn't supposed to have these materials," Fischer says. That is because the manganese oxides on Earth postdate the rise of photosynthesis and the oxygenated atmosphere. One possible explanation for this difference is that Mars once had life; another less-explosive hypothesis is that there are ways for planets to make manganese oxides other than the biologically driven process found on Earth. Either way, Fischer says, surprises from the Red Planet not only change the perception of Mars but also raise new questions about how well we know our home world.

"Being able to take a discovery like that and flip it back on Earth is amazing," he says.



Other 3CPE researchers are refining techniques that could aid in the search for conditions friendly to life, including on Mars. Ilya Bobrovskiy, Texaco Postdoctoral Scholar Research Associate in Geobiology, focuses on life from the Precambrian eon, the vast period that predates the arrival of hard-shelled creatures 541 million years ago and makes up the bulk of Earth's history. Bobrovskiy takes samples from rock layers that have not been substantially changed since that time and studies the ratios of certain carbon isotopes (carbon-13 and carbon-12) to illuminate what happened in an environment that allowed more complex multicellular life to appear on the scene.

"In terms of comparative planetary evolution, the question I'm asking is, What does it take for a planet to create complex life?" Bobrovskiy says. That question will become increasingly important as scientists look for biosignatures around the solar system and beyond.

BEYOND THE SOLAR SYSTEM

Over the past quarter century, the catalog of known exoplanets has grown from a handful to several thousand. That explosion was driven largely by the Kepler space telescope, which operated from 2009 to 2018, finding planets by detecting a telltale dip in a star's brightness as a planet passed in front of it. But a telescope like Kepler is limited because of its restricted observing time and point of view. Consider this: if the Kepler telescope had studied our solar system from the other side of the galaxy, it could have possibly found only Venus and Earth and missed the other six planets, either because they are too small or because their orbits take too long for Kepler to have seen them during its mission.

This startling fact reveals just how much remains to be discovered, says Heather Knutson, Caltech professor of planetary science and 3CPE faculty member. Even so, she says, the barrage of newfound worlds has already told scientists something important about the universe. "The number one thing we learn from exoplanets is that when we make predictions based on our solar system, those predictions often turn out to be incorrect, or at least not representative of planetary systems as a whole. Exoplanets keep surprising us in all the ways that they are different from the planets in our solar system."

Our solar system contains four small rocky planets, four outer gas giants, and nothing in between. Not so with other star systems. When astronomers found their first big hauls of smaller planets, the most common type they turned up was one falling between gas giant Neptune and small rocky Earth in size, as Knutson described in a recent paper. "You have to ask, Why are these planets so incredibly common around other stars," she says, "and, given that, why don't we have one in this solar system?"

Knutson focuses on understanding the atmospheres of faraway worlds, which requires extrapolating from Earth, using what scientists have learned from weather patterns and climate models to predict conditions on an alien world with a different atmospheric makeup. Sometimes planets surprise her and do not fit the pattern, which she says is the best part.

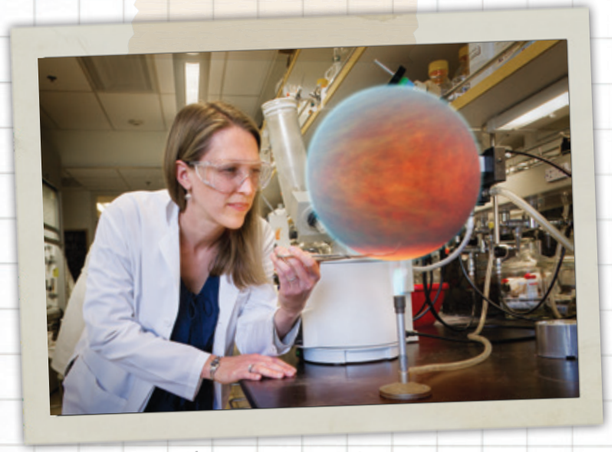
"Then there's a neat chance to go back and improve those models to incorporate new physics and new chemistry that we had never thought about before," she notes. "Some of those improvements actually may help us to better understand the planets in this solar system."

The next generation of telescopes will further that understanding. Knutson is one of many researchers who are now vying for observing time on the James Webb Space Telescope, scheduled to begin operation in 2021 as the most powerful space telescope ever launched. Yet even the James Webb may not be able to tell researchers much about the atmospheres of small, terrestrial exoplanets, Knutson says. "It's a big leap over what we have now, but you need another equivalently big leap in sensitivity to do terrestrial planets well."

That work is underway at Caltech. Inside the Cahill Center for Astronomy and Astrophysics, Professor of Astronomy Andrew Howard is building a next-generation spectrometer called the Keck Planet Finder, an instrument that will upgrade the Caltech-operated W. M. Keck Observatory in Hawaii. "It's going to be the most capable instrument for measuring the masses of planets anywhere in the world," Mike Brown says. Meanwhile, Dimitri Mawet, professor of astronomy and JPL research scientist, is focusing on the instrumentation and techniques that would be needed to directly image small exoplanets: a tall order, because it means separating their light from the overpowering light of their stars.

The 3CPE initiative depends upon and also promotes such breakthroughs in instrumentation. But above all, it is meant to inspire new and unlikely collaborations. Jennifer Jackson, the William E. Leonhard Professor of Mineral Physics, researches how minerals behave under extreme pressures within the earth; she has partnered with Victoria Orphan to investigate whether life can survive in hostile environments such as the interior of Mars. Konstantin Batygin (MS '10, PhD '12) and Phil Hopkins, astrophysicists from different sides of the field who say they would not have collaborated if not for their 3CPE project, are working together to predict the formation of moons around giant planets.

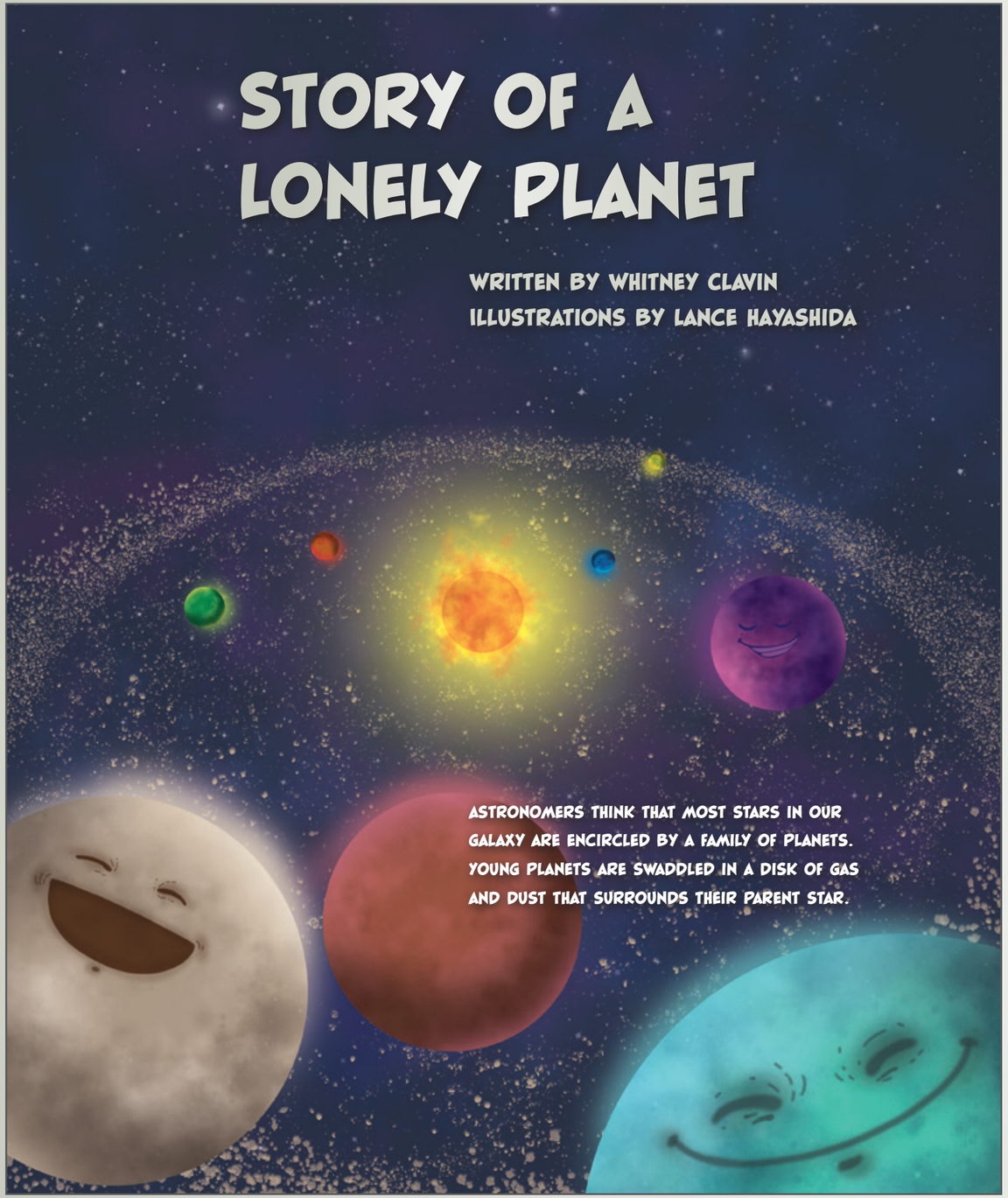
ANDREW HOWARD GAZING INTO THE FAR REACHES OF THE UNIVERSE

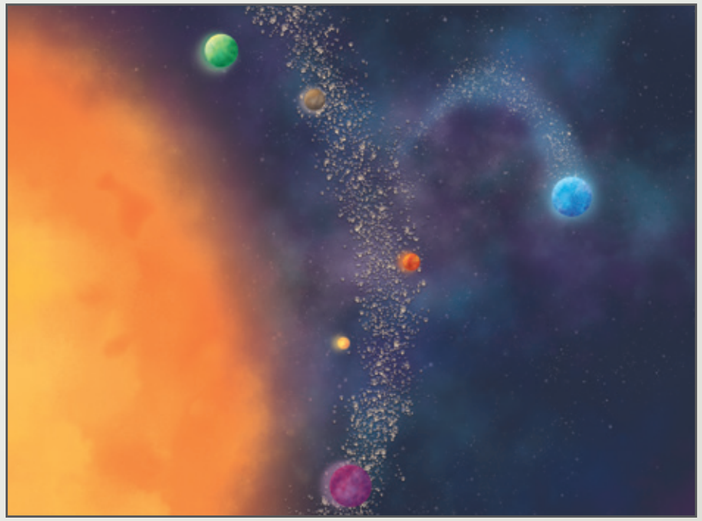


HEATHER KNUTSON COOKS UP A PLANET

These collaborations are not happenstance. They are part of a concerted effort within 3CPE to unite scientists from across campus and across disciplines to find new ways to illuminate our world and others. "Our rule," Brown says, "is that it can't be a collaboration that exists. You have to find someone out there that you have not collaborated with, and you have to come up with a big idea. All of these projects are getting at this whole idea of how a planet evolves chemically, physically, and biologically. And getting all these people together and learning each other's common language is the way forward."

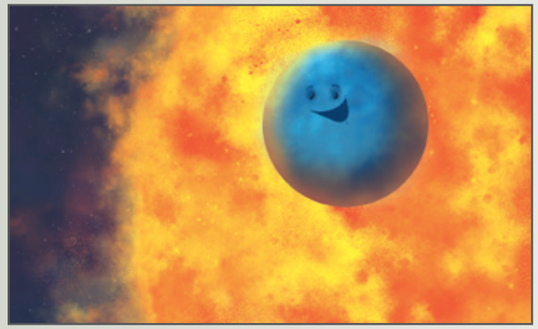
Donors whose support helped to launch the 3CPE initiative include Jose (BS '79) and Katie Helu; Leigh Engen (BS '99); L.E. Simmons; Caltech senior trustee Charlie Trimble (BS '63, MS '64); and the Melza M. and Frank Theodore Barr Foundation.





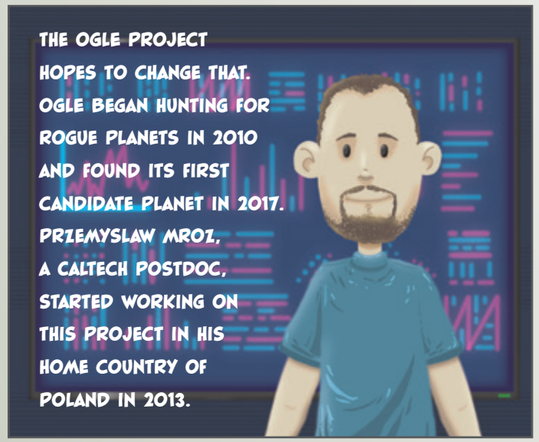
AND IT IS THOUGHT THAT SOMETIMES THE COLLISIONS IN YOUNG SOLAR SYSTEMS EJECT PLANETS INTO SPACE.

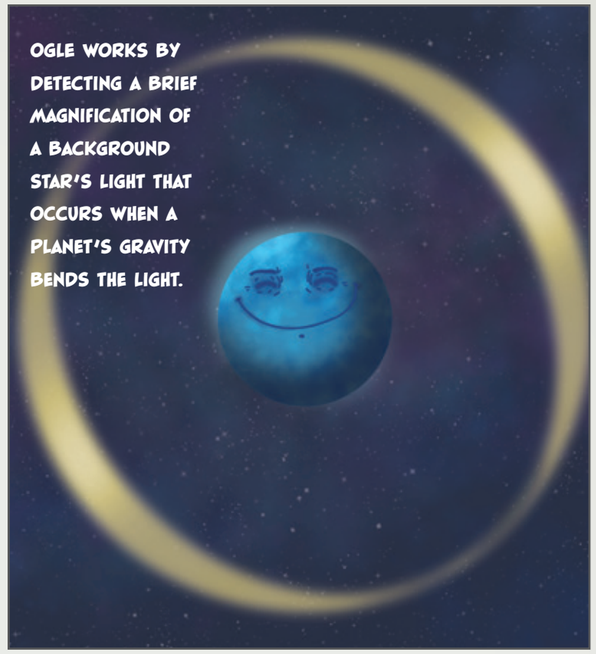
ASTRONOMERS ESTIMATE THERE ARE BILLIONS OF THESE LONELY PLANETS IN OUR GALAXY. THEY ARE SOMETIMES CALLED FREE-FLOATING OR ROGUE PLANETS.



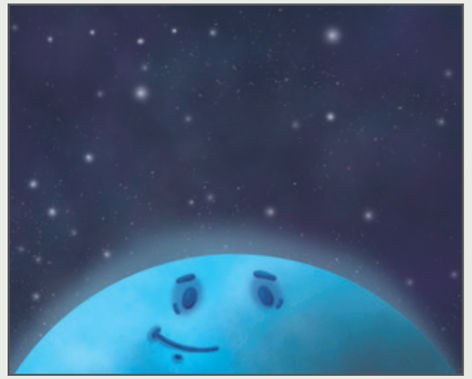
TYPICALLY, PLANETS WITH STARS ARE DETECTED INDIRECTLY THROUGH EFFECTS ON THEIR STARS: THEY CAUSE STARS TO WOBBLE OR BLINK.

BUT ROGUE PLANETS DO NOT HAVE STARS TO INFLUENCE, SO THEY ARE HARDER TO FIND.

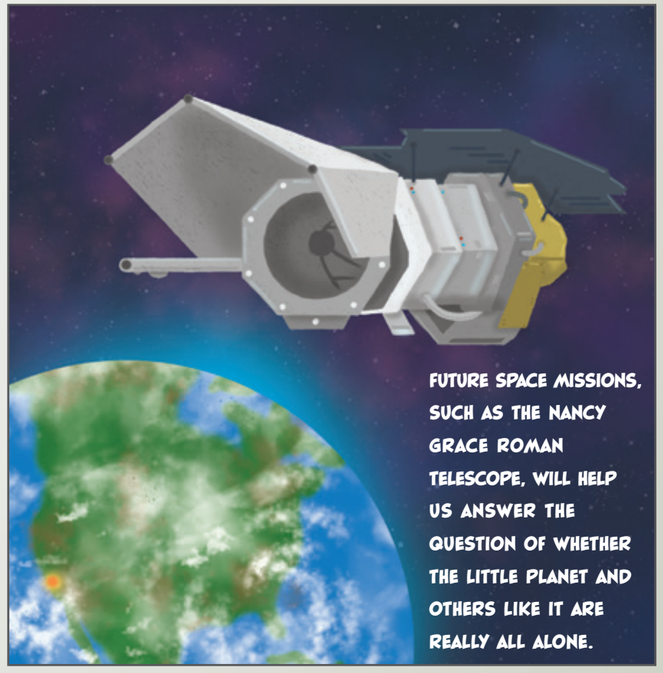




SO FAR, THE PROJECT HAS FOUND EVIDENCE FOR 12 ROGUE PLANETS.



AS FOR MROZ AND HIS TEAM'S NEWFOUND LITTLE PLANET, THEY THINK IT IS ALL ALONE BUT HAVE NOT BEEN ABLE TO RULE OUT THE POSSIBILITY THAT IT HAS A PARENT STAR THAT IS JUST REALLY FAR AWAY FROM IT.

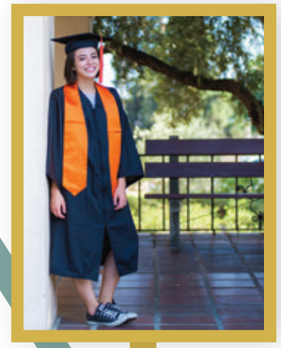


FUTURE SPACE MISSIONS, SUCH AS THE NANCY GRACE ROMAN TELESCOPE, WILL HELP US ANSWER THE QUESTION OF WHETHER THE LITTLE PLANET AND OTHERS LIKE IT ARE REALLY ALL ALONE.

Crossing paths

The two most recent Nobel Prize-winning Caltech alumni talk with a fellow alum about their work, their campus experiences, and life after Caltech.

by Lori Dajose (BS ’15)



Left: **Andrea Ghez** (PhD ’92) in 1987, her first year of graduate school at Caltech. Upper left: **Charles Rice** (PhD ’81), in a photo from the mid–’80s. Above: **Lori Dajose** (BS ’15) at her Caltech commencement.

When you discover someone who has shared with you the Caltech student experience, there is a kind of instant camaraderie. Whether you studied biology in 1980 or planetary science in 2010, you likely can bond over sleepless nights working on hard questions, sunny campus days, and, perhaps most importantly, bright and inspiring collaborators and mentors. In this way, no matter what our life trajectories have looked like, all Caltech alumni have crossed paths.

Though the number of Caltech alumni is small compared to many universities, 24 scientists within our ranks have been recipients of a total of 25 Nobel Prizes; as a whole, 44 Caltech faculty, alumni, and postdocs have won a total of 45 Nobels. Two of those 24 alumni Nobelists joined this distinguished list in 2020: virologist Charles Rice (PhD ’81) and astronomer Andrea Ghez (PhD ’92).

Rice, who is the Maurice R. and Corinne P. Greenberg Professor in Virology at Rockefeller University, studies pathogenic viruses and innate antiviral immune mechanisms; he received the Nobel Prize in Physiology or Medicine for his contributions to discovering the Hepatitis C virus. Ghez, who is currently distinguished professor of physics and astronomy and head of the Galactic Center Group at UCLA, studies observational astrophysics and received the Nobel Prize in Physics for her role in the discovery that there is a supermassive black hole at the center of our galaxy.

When *Caltech* magazine suggested I reach out to both of Caltech’s most recent Nobelists for a conversation, I was excited for the opportunity to talk to them alum-to-alum, to discover our shared experiences, and to learn from the paths traveled before me.

I’m honored to share their stories here.

CHARLES RICE (PhD '81)

2020 Nobel Prize in Physiology or Medicine: "For the discovery of the Hepatitis C virus."

Q In a year so dominated by talk of viruses, what was it like for you as a virologist to be chosen for the Nobel Prize?

A I think 2020 will be remembered as the year of the virus. Virologists have always had to try and explain to people what the hell a virus is, and we don't have to do that as much anymore. I don't know how much the emergence of SARS-CoV-2 and COVID-19 disease might have influenced the deliberations of the Nobel Committee, but it's a mind-boggling coincidence.

Q You work on hepatitis C. Can you explain the virus and the disease?

A Hepatitis C is a blood-borne pathogen that infects hundreds of millions of people, but many people don't know they've been infected because acute infection symptoms can be relatively benign. Unfortunately, that means that even with the treatments that we have today, there are many people out there who have had the virus percolating in their bodies for decades, and some have developed severe associated liver disease.

It's been called a stealth virus, a silent killer. But there are also people who have been infected with hepatitis C for 50 years, and their livers are fine. Hepatitis C and SARS-CoV-2 are similar in that they can produce very different outcomes in different people.

Q Can you talk about your contributions to hepatitis C research?

A By the mid-century it was known that liver inflammation, or hepatitis, was caused mainly by two viral agents that later turned out to be hepatitis A virus and B virus. The discovery of hepatitis B virus was the subject of a Nobel Prize in 1976. But my co-recipient Harvey Alter showed that there was another distinct form of chronic hepatitis that was caused by neither of these, which he creatively called the non-A, non-B agent. My co-recipient Michael Houghton isolated the genetic sequence of the unknown virus and found that it was a novel RNA virus in the family *Flaviviridae* and named it hepatitis C virus (HCV).

So a virus associated with hepatitis C had been found, but we needed to know if it was solely responsible for causing the disease. At the time, I was at Washington University in St. Louis, and we noticed that in the isolated sequence, a piece of the genome was missing, a piece that is very important for replication. We genetically engineered our lab sample to have that piece and thus be more similar to the virus that was actually circulating in the population. Because our first clones in the lab had variations, we fixed these by constructing a consensus sequence. This lab-made RNA was then shown to launch HCV infection and cause the disease in chimpanzees. This defined the genetic sequence of a functional viral genome and provided a foundation for using modern molecular biology to study the virus and develop new systems for drug discovery. Although this was a very important milestone, there were still many challenges ahead leading to the development of today's drugs, which can cure just about everyone in a few months with a daily pill.

Q What got you interested broadly in science? And why virology and this particular class of viruses?

A I went to college [at UC Davis] thinking that I would be a vet, but I got interested in biology, chemistry, and genetics, and just took a lot of courses.

Between my junior and senior years at Davis, I had a really fantastic summer at the Woods Hole Marine Biological Laboratory. It was intense, basically 24/7 lectures, laboratory research, a transformative research experience. But I still wasn't 100 percent sure that I wanted to do research, so I took a year off between finishing my studies at UC Davis and arriving at Caltech as a graduate student, and became a traveling vagabond for the better part of a year in Central and South America.

When I eventually arrived at Caltech, I had planned to study developmental biology using sea urchins, but I found that I had been placed in the laboratory of Jim Strauss [Ethel Wilson Bowles and Robert Bowles Professor of Biology, Emeritus (PhD '67)], not in Eric Davidson's lab. This was a molecular virology lab studying an enveloped RNA virus called Sindbis virus, an obscure but attractive model virus for studying an RNA animal virus.

That's how I ended up getting exposed to virology. I don't know if the placement in the Strauss lab was random or who orchestrated that. I think if I ended up in an immunology lab, I probably would've ended up being an immunologist.

Q How did your time at Caltech shape or influence your career? And do you have a favorite memory from your time here?

A When I arrived at Caltech, I thought I was going to go to Caltech and do my PhD and move on. That turned out to be totally wrong. I loved the environment and ended up staying at Caltech for about 10 years.

Part of the reason for that was the wonderful atmosphere among graduate students in the biology division. Everybody was so passionate about doing research. People were basically in lab seven days a week around the clock.

But we didn't work all the time. There were softball games and lots of picnics. As I recall, there was also some beer drinking associated with some of those.

I ended up finishing my PhD formally in 1981, but I was having so much fun, I thought I would just stay and keep doing what I was excited about. We had started working on other viruses, including yellow fever, which was the prototype member of what was later a new family of viruses, the *Flaviviridae,* which is the family where the hepatitis C virus landed.

Q Running a lab is obviously a lot of work. And now that you have won a Nobel Prize, there must be even more demands on your time. Do you get tired? What keeps you going?

A I still have a lab of 30 people working on all kinds of different topics. We have studies going on with SARS-CoV-2 virology and COVID-19 disease. I also agreed to be on the New York governor's clinical taskforce, charged with evaluating and summarizing COVID-19 vaccine safety and efficacy for New Yorkers.

It is a bit overwhelming at times, but I'm fortunate. I have some incredibly talented people in the lab who share a lot of the responsibility.

Q In a normal year, what do you like to do when you're not working in lab?

A Growing up in California, I love the outdoors. My spouse and I enjoy taking a break and getting a remote mountain fix. We grab our dogs and drive from Manhattan to a very remote cabin in the Wind River Range in Wyoming. It's one of the most beautiful spots on the planet. There's no internet or telephone, and it's 15 miles away from the nearest paved road.

Q What was it like to get that phone call from the Nobel Prize committee?

A I was by myself in our apartment in Manhattan. It was pitch black, and I thought, "What the hell is going on here? Who's calling me at 4:30 in the morning?"

Then there was this voice with a Swedish accent on the phone. It still didn't really dawn on me at all. I didn't think that there was even a remotest possibility of me winning a Nobel Prize.

It was a pretty strange, surreal experience. And I have to say it still is. It's not something where you can hang up the phone and go back to bed.

ANDREA GHEZ (PhD '92)

2020 Nobel Prize in Physics: "For the discovery of a supermassive compact object at the centre of our galaxy."

Q What led up to the discovery of this supermassive compact object?

A Stellar mass black holes had been theorized for a long time, and now we have strong observational evidence for them from LIGO [the Laser Interferometer Gravitational-wave Observatory]. Roughly 50 years ago, people suggested that all galaxies have supermassive black holes, those that are a million to a billion times the mass of the sun, located at their core.

We set out to prove this. The center of our galaxy was the best place to look because it's the closest center of a galaxy that we'll ever have to study.

The center of the galaxy is obscured by a lot of dust, so you need to go to infrared wavelengths. Having worked at Palomar Observatory during my PhD at Caltech, I knew that the Keck Observatory that was just about to come online in 1993 would be a powerful telescope to observe with.

With large telescopes, the blurring effects of the earth's atmosphere obscure the fine detail. We had to be able to compensate for that, so at first we used a very simple technique called speckle imaging. That allowed us to prove that there were stars in the center of the galaxy and then to track their motions. Then, about 10 years into this work, it became possible to use adaptive optics, which was a much more powerful technique.

We went from measuring just velocities on the plane of the sky to accelerations and then full orbits. From this, we could show that there was 4 million times the mass of the sun contained inside a region that corresponds to the scale of our solar system.

Q What were some of the challenges you encountered?

A We were turned down [on our first request to use Keck to measure these phenomena]. To me, it was just so damn obvious that this was going to work. Then it ended up working out so much better than we could possibly imagine. It had so many phases of excitement: excitement because the first image worked, excitement because we just discovered stars, excitement because the next year we could show that they were moving.

At that point, people started suggesting that there were all sorts of ways that these things could be moving fast without a black hole. So, every step of the project, there was questioning and skepticism. In a sense, that's how science works. You're not supposed to just accept, so it drives you on to the next stage of the project.

As the technology has gotten better and better, more and more results have actually come out. We were able to not only answer the question we set out to address, but we've also uncovered a host of other questions to answer or to think about.

Q What got you interested in science initially and why astronomy, in particular?

A Growing up, I had no idea what I wanted to do, but the moon landing happened when I was 4. In hindsight, that's the thing I like to point back to in terms of the first time I was really inspired to think about the universe, and it really took hold with me. Although, at that time, I also wanted to be a ballerina.

I think it became quite clear that I had an aptitude for math and science. I really enjoyed it, and it was a language that came naturally to me. I just thought of it as a giant puzzle. To me, math and science is that world of just figuring out how to put the pieces together in a logical way. So by the time I went to MIT [as an undergraduate], I felt like I had "found my people."

Q I was excited to interview you today because when I was in high school and applying to college, I wanted to study astrophysics. Looking up women astronomers in Southern California, I came across your name and noticed that you went to Caltech. It feels really cool to finally meet you.

A I love hearing that because one of the things that I really believe is that the best way you can encourage young women into science is by being successful yourself and making that success visible. In other words, really engaging with the public. I remember being an undergrad, at some points I'd look around and think, "Well, there are not a lot of women in this field. Am I on the wrong playground?"

In 1995, I was contacted by a couple [Judith Love Cohen and David Arthur Katz] that writes this series of books: *You Can Be a Woman Engineer,* and so on. They reached out to me and asked if I would be interested in participating in their project, so we worked on *You Can Be a Woman Astronomer*. I was delighted to do so because I've always been interested in encouraging young women into the sciences. I think it's great to engage kids at that age.

Q How did your time at Caltech shape your career?

A Tremendously Caltech is such an amazing place in terms of the resources and the facilities. Certainly, in astrophysics, having access to all those telescopes is just remarkable. Then in the community of people there is just deep intelligence and incredible dedication to science. I'm really grateful for the opportunity I had as a student to work with a truly remarkable scientist, my PhD adviser, Gerry Neugebauer (PhD '60), who was a huge influence.

One piece of advice I remember from Gerry was to have deep respect for the data, paying attention to what the data are telling you without being biased by what you may or may not want to see come out of it.

There are so many pressures today associated with getting the resources that it's really important as a scientist to respect the process, to be patient, and just get it right. I think I learned that discipline at Caltech.

Q Being a principal investigator and now a Nobel laureate must be a lot of work. What keeps you going?

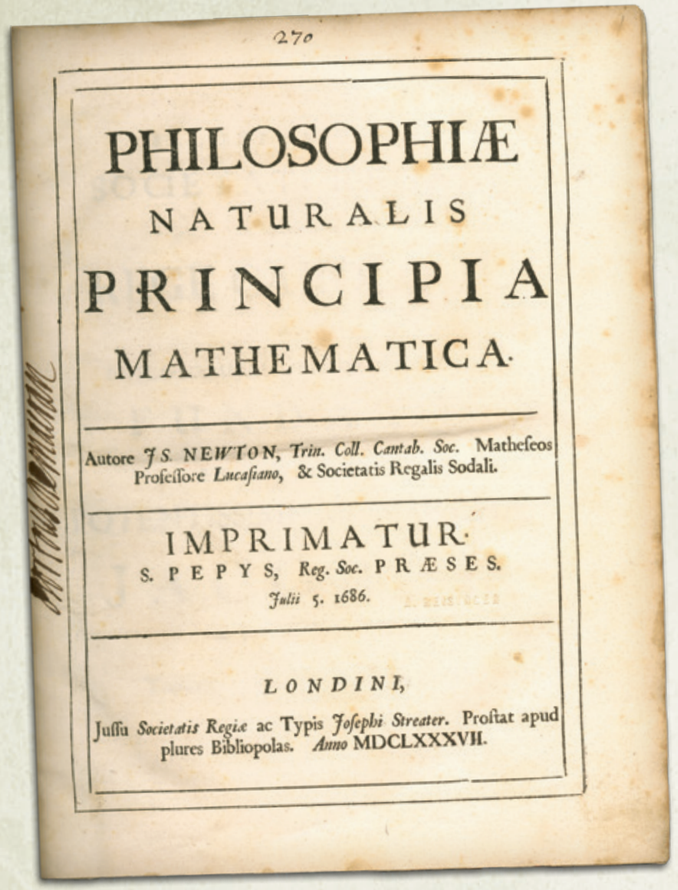
I think it's a true privilege to be able to do this kind of work, to be in a field where you get to set the questions that you're interested in asking.

And then there's teaching, which is so immediate. I'm very grateful to be able to do these two things because I think they complement each other well. Being able to bring forefront research into the classroom is exciting to the students. Then being able to bring students into the research is also really exciting for me because students ask you those basic questions, and they remind you to think deeply about "Why is it that we do it this way?" and "How do we know what we know?"

Q What was it like getting that 2:45 a.m. phone call?

A I think anyone's first reaction to the home phone ringing in the middle of the night is "Is everybody OK?" But then, very quickly, you realize this is a very different kind of phone call. It's breathtaking, kind of unbelievable, and I was just over the moon for days. One of the most delightful things, actually, about getting it during COVID times is it brings such joy to have good news to share.

A GLOBAL TREASURE HUNT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PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

Autore *Js. NEWTON, Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Jussu *Societatis Regiæ* ac Typis *Josephi Streater.* Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

The Caltech Archives' copy of *Principia* is seen above; at right, is another copy located at The Huntington Library, in which Newton's own handwriting can be seen in the margins.

How a term paper on Newton's **Principia** *led to a decade-long search for first-edition copies around the world.*

by Whitney Clavin

In a story of lost and stolen books and scrupulous detective work across continents, two Caltech-affiliated historians recently made headlines with their discovery of hundreds of previously uncounted copies of Isaac Newton's groundbreaking science book *Philosophiae Naturalis Principia Mathematica,* known as the *Principia*.

"We felt like Sherlock Holmes," says Mordechai (Moti) Feingold, Caltech's Kate Van Nuys Page Professor of the History of Science and the Humanities, who, along with his former student Andrej Svorenčík (MS '08), spent more than a decade tracing copies of the book around the world. Feingold and Svorenčík, who is now at the University of Mannheim in Germany, are co-authors of a paper about the survey published in the journal *Annals of Science.*

"We felt like Sherlock Holmes."

The new census more than doubles the number of known copies of the famous first edition, published in 1687. The last census of this kind, published in 1953, had identified 189 copies, while the new Caltech survey finds 386 copies. Up to 200 additional copies, according to Feingold and Svorenčík, likely still exist undocumented in public and private collections.

From Slovakia to South Africa

The project was born out of a paper Svorenčík wrote for a course in the history of science taught by Feingold. Originally from Slovakia, Svorenčík had written a term paper about the distribution of the *Principia* in Central Europe. "I was interested in whether there were copies of the book that could be traced to my home region. The census done in the 1950s did not list any copies from Slovakia, the Czech Republic, Poland, or Hungary. This is understandable, as the census was done after the Iron Curtain descended, which made tracing copies very difficult."

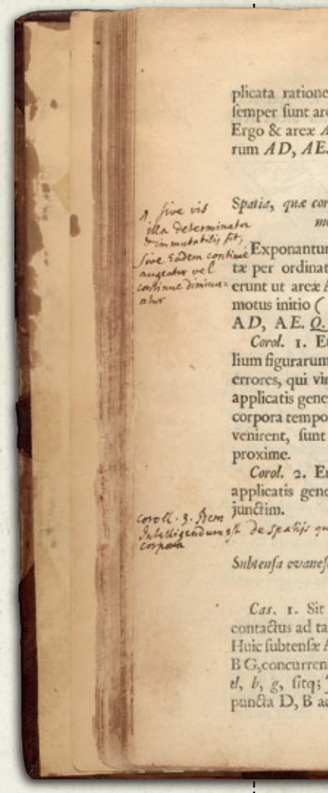
To Svorenčík's surprise, he found many more copies than Feingold had expected. The summer after the class, Feingold suggested to Svorenčík that they turn his project into the first-ever complete, systematic search for copies of the first edition of the *Principia*. Their ensuing detective work across the globe turned up about 200 previously unidentified copies in 27 countries, including 35 copies in Central Europe, and others in such far-flung locales as the Vatican, South Africa, Norway, Ireland, and Japan.

Feingold and Svorenčík even came across lost or stolen copies of the masterpiece; for example, one copy found with a bookseller in Italy was discovered to have been stolen from a library in Germany half a century earlier.

"We contacted the German library to let them know, but they were too slow to make a decision to buy back the copy or apprehend it somehow, so it ended up back on the market," says Feingold.

A masterpiece, with a mystique

The primary person behind the book's publication was Edmond Halley, a well-known English scientist who made several discoveries about our solar system, including the periodicity of what later became known as Halley's Comet. Feingold explains that, before the *Principia* was written, Halley had asked Newton for some calculations regarding elliptical orbits of bodies in our solar system. When Halley saw the calculations, "he got so excited, he rushed back to Cambridge and basically forced Newton to write the *Principia*," says Feingold. In fact, Halley funded the publication of the book's first edition.



In the *Principia*, Newton introduced the laws of motion and universal gravitation, "unifying the terrestrial and celestial worlds under a single law," says Svorenčík.

Soon after its publication, the book was recognized as a work of genius. "Because Halley had already prepared the public for what was to come," says Feingold, "there was a widespread recognition that the *Principia* was a masterpiece." Later, a "mystique" about Newton started to develop, according to Feingold, exemplified in a story about two students walking in Cambridge and spotting Newton on the street. "'There goes a man,' one of them said, 'who wrote a book that neither he nor anybody else understands,'" says Feingold.

"By the 18th century, Newtonian ideas transcended science itself," says Feingold. "People in other fields were hoping to find a similar single law to unify their own

respective fields. The influence of Newton, just like that of Charles Darwin and Albert Einstein, exerted considerable influence on many other aspects of life, and that is what made him such a canonical figure during the 18th century and beyond."

Copies of the first edition of the *Principia* sell today for between $300,000 and $3,000,000 via auction houses like Christie's and Sotheby's as well as on the black market. Feingold and Svorenčík estimate that some 600, and possibly as many as 750, copies of the book's first edition were printed in 1687.

In the margins

By analyzing ownership marks and notes scribbled in the margins of some of the books, in addition to related letters and other documents, the researchers found evidence that the *Principia*, once thought to be reserved for only a select group of expert mathematicians, was more widely read and comprehended than previously thought.

"One of the realizations we've had," says Feingold, "is that the transmission of the book and its ideas was far quicker and more open than we assumed, and this will have implications on the future work that we and others will be doing on this subject."

"When you look through the copies themselves, you might find small notes or annotations that give you clues about how it was used," says Svorenčík, who has personally inspected about 10 percent of the copies documented in this new census. When traveling to conferences in different countries, he would make time to visit local libraries. "You look at the condition of the ownership marks, the binding, deterioration, printing differences, etc."

Even without inspecting the books up close, the historians could trace who owned them through library records and other letters and documents, and learn how copies were shared.

"It's harder to show how much people engaged with a book than simply owned it, but we can look at the notes in the margins and how the book was shared," says Feingold. "You can assume that for each copy, there are multiple readers. It's not like today, where you might buy a book and are the only one to read it. And then we can look for an exchange of ideas between the people sharing copies. You start to put together the pieces and solve the puzzle."

Svorenčík and Feingold hope that their census, which they call preliminary, will yield information about other existing copies tucked away with private owners, book dealers, and libraries. Continuing this line of research into the future, the historians plan to further refine our understanding of how the *Principia* shaped 18th-century science.

A copy that came up for auction at Sotheby's in **London** was discovered to have been stolen from a library at **Edinburgh University**. Feingold contacted the university, which put a stop to the sale. After several months, the university and the auction house reached an agreement, and the book came up for sale again and is now owned by a private collector in **Greenwich, Connecticut**.

The researchers found a copy owned by an **English nobleman,** Wriothesley Russell, 2nd Duke of Bedford. Feingold and Svorenčík discovered that the nobleman's tutor was Nicolas Fatio de Duillier, a good mathematician and friend of Newton. It seems the tutor taught the nobleman from Newton's book.

Feingold knows of one book that appears to have been destroyed. A **French mathematician,** Abraham de Moivre, as the story goes, came to **England** in 1687. He saw a copy in the house of his employer and got so excited about it that he bought himself a copy. But since he traveled so much for his work, he cut out the pages and carried one page of the book with him each time he went to give a lesson.

A copy from **Uppsala** was stolen in the late 1960s, then appeared at auction in **Vienna** in the early 1980s. Subsequently, it was bought at a Christie's auction in 2004 by a **Swedish-American collector** who returned it to Uppsala, where it was reunited with its original owner in 2009.

A copy offered for sale by an **Italian bookseller** was discovered to have been stolen from a **German library** half a century earlier, probably during WWII. The researchers let the library know, but they were too slow to buy back the copy or apprehend it, and it has disappeared again.

Feingold and Svorenčík are still looking for a copy in **China.** "I have a colleague in China, and I've written to him and he said, 'Yes, there is a copy in **Beijing,**'" says Feingold. "He sent someone to the library, and the answer came back, 'We can't find it.'"

A copy in **Prague** belonged to Anton Ernst Burckhard von Birckenstein, a tutor to Leopold I, Holy Roman Emperor and the author of several geometry books. An elder courtier in Prague, the mathematician Ferdinand Ernst Karl, Graf von Herberstein, also owned a copy that was found in **Graz, Austria.** A third copy, owned by Herberstein's associate, Johan A. Graf von Schaffgotsch, who was also a mathematician, is currently preserved at the **University of Arizona.** The three mathematicians moved in the same circles and likely knew each other.

The Arizona copy ultimately got into the hands of Herbert McLean Evans, a famous collector in the states who, during his lifetime, owned five different copies. Every time he ran out of money, he had to sell his library. This copy got to the **University of Arizona** in the 1970s.

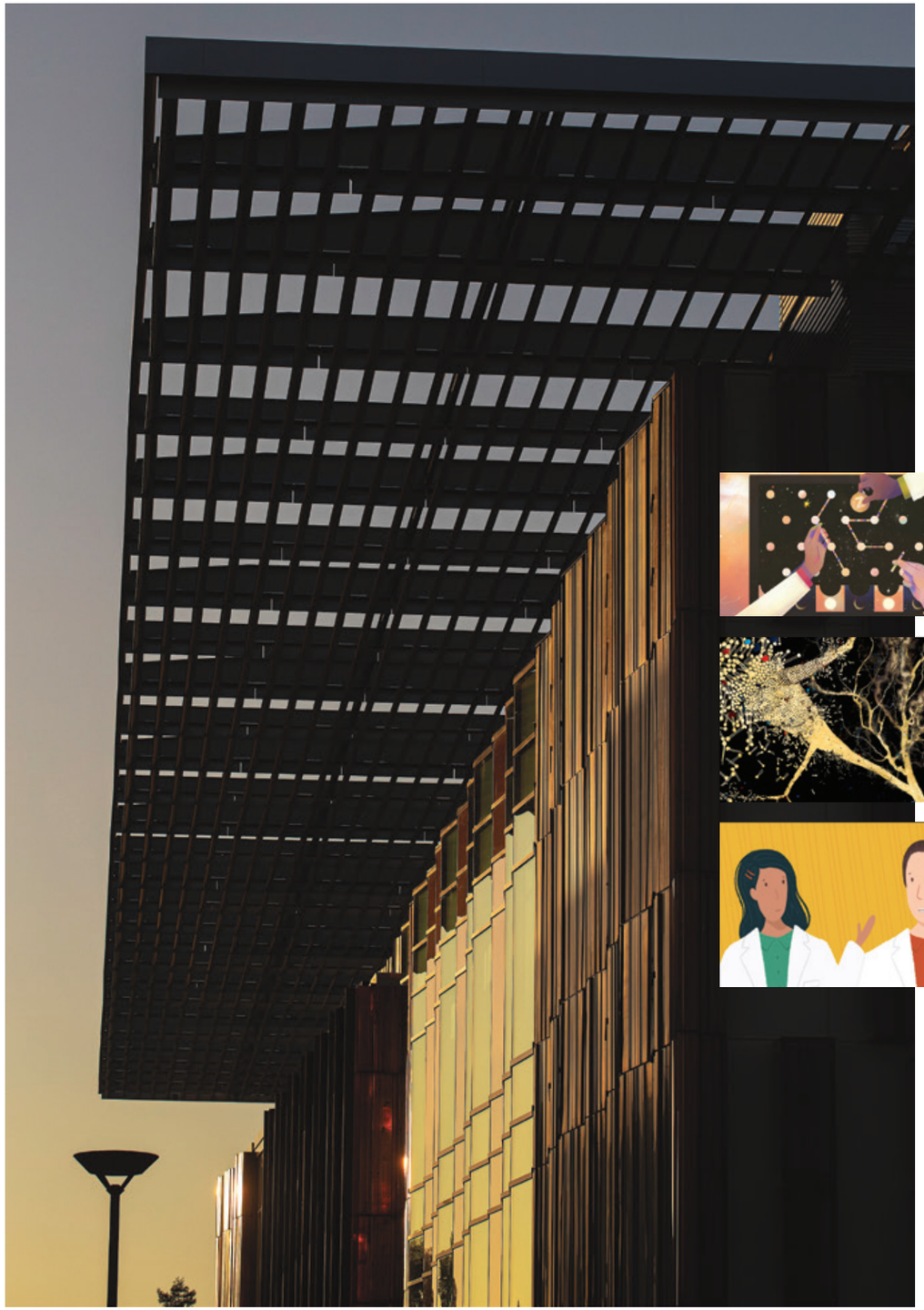
Where in the World?

Locations of newly found copies of the Principia

Number of copies
- 1-9
- 10-19
- 20-29
- 30-39
- 40-49
- 50-59
- 60-69
- 70-79
- 80-89

How to be a book detective

"Much of the information that we have is available on the title page or somewhere else in the book. When you have a name, sometimes it's a famous name, but sometimes it's an obscure figure. In those cases, we have to go and investigate who that person is. If a book was auctioned in the last several decades, the auction houses will try to ascertain the provenance of that book. But often, many earlier copies don't really have provenances, and one of the great difficulties that we have is to try to match books that we find in catalogs to present known copies. So it's a kind of detective work that is on several levels, and often lines of transmissions are not continuous but broken, and we have to try to fill in what happened in the interval between one owner to the next. It's kind of a continuous labor, a never-ending story." —Moti Fiengold



Neural Networking

With the opening of the Tianqiao and Chrissy Chen Neuroscience Research Building, Caltech scientists have a vital new hub for interdisciplinary brain research.

The 150,000-square-foot building, made possible by a $115 million gift from Tianqiao and Chrissy Chen, houses research and teaching laboratories, a neurotechnology lab, and a 150-seat lecture hall. As headquarters for the Chen Institute for Neuroscience at Caltech, which reaches across Caltech's six academic divisions, the new building promises to become an "idea factory" where advances in fundamental science will transform into knowledge that can help humanity.

The most recent issue of the ***Caltech Effect*** focuses on the new building and its importance to neuroscience research at Caltech. The following is a glimpse into the research, people, and stories shared.

Sleep with the Zebrafishes

Over the last several years, Biology Professor David Prober and his team at Caltech have used zebrafish to make breakthough discoveries in the three known ways that sleep is regulated: homeostatic regulation, which is based on internal cues for sleep need; circadian regulation, which responds to external cues tied to an animal's 24-hour circadian rhythm; and masking, the direct effects of light and dark on sleep and wakefulness.

In 2019, for example, his lab showed that serotonin produced by regions in the brain collectively known as the raphe nuclei is required for zebrafish to achieve normal amounts of sleep. Since the neurons in the raphe nuclei are most active when animals are awake, the researchers theorized that their release of serotonin during wakefulness leads to a buildup of pressure to sleep. By performing sleep deprivation experiments, they demonstrated that serotonin is essential for homeostatic regulation of sleep.

Prober's team will soon be able to take their zebrafish sleep studies to the next level when they move into a spacious new lab in the Chen Building that houses a microscope capable of monitoring all of the neurons in a fish's brain almost simultaneously.

"If you want to save people, if you want to reduce their suffering, you need to understand the secret of the brain."

— Chrissy Chen

"...[T]he science that we're creating, it isn't just for us. It doesn't stop there. It continues on, and it will impact millions and millions of people."

— Sabera Talukder
Chen Graduate Fellow

"There is this ability to dream together. You can talk to your colleagues about some crazy idea, and they will say, 'Oh yeah, that's an interesting idea. Let me put my spin on it.'"

— Long Cai
Professor of Biology and Biological Engineering

Tell us about the contributions of someone who is part of the Chen Institute whose work you find inspiring.

"I find [Assistant Professor of Biology and Biological Engineering] Joe Parker's work really inspiring. He's going in this completely new direction, trying to understand how the brain evolves and symbiosis evolves. I don't know what it's going to reveal, but I feel like it's such an exciting new direction. Not just studying the brain as this static organ but this thing that's changing over these evolutionary timescales and really understanding what are the precise changes in the circuits that enable these incredible symbiotic relationships. So I think that's so pioneering, and I'm really excited to see what comes with that."

— **Doris Tsao** (BS '96), Professor of Biology and T&C Chen Center for Systems Neuroscience Leadership Chair and Director

How to Build a Better Fly Feeder

Research Professor Daniel Wagenaar is a neuroscientist and a problem solver. He also runs the Kevin Xu Neurotechnology Lab, where he helps his fellow scientists find novel solutions to a wide array of research equipment challenges. His move to a larger space in the Chen Building means he can say yes to more projects than ever.

"One of my favorite ever projects was a fly food mover for Betty Hong's [BS '02] lab. Betty and I invented this chamber where the flies would just sit in their usual cylinder, but a dish underneath could be moved back and forth at a very slow pace allowing us to surreptitiously change food sources to control what food was available at what time.

"With our new space in the Chen Building, many of the labs we work with will be much closer. It's surprising how much difference that makes, for people to just be able to walk along the hallway or take an elevator down. It really helps accessibility. And ultimately that's what this whole thing is about."

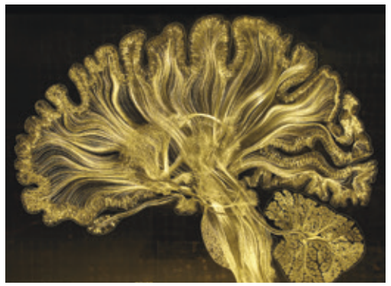
— **Daniel Wagenaar,** Director of the Kevin Xu Neurotechnology Laboratory

"We will find things that we could never imagine."

— **Viviana Gradinaru** (BS '05)
Professor of Neuroscience and Biological Engineering

Many Pathways into the Brain

The Chen Institute for Neuroscience at Caltech has been supporting graduate student research since it was inaugurated in 2016. Among them are: **Annie Erickson**, Chen Graduate Fellow, who aims to understand and map the pathways in the fruit fly brain when in flight; **Jonathan D. Kenny**, who studies the neural circuit dynamics of general anesthesia; **Guruprasad Raghavan**, who is growing neurons on a dish to fabricate "cortical computers" with graduate student **Varun Wadia**; **Sanghyun Yi**, a Chen Graduate Fellow, who studies how the human brain solves problems to improve machine learning algorithms; and **Jennifer Sun**, who is training machine learning models to recognize mouse behavior, allowing researchers to process larger volumes of data.



A Universe of Complexity

In the lobby of the Chen Neuroscience Research Building sits a triptych depicting the human brain. It is the work of Greg Dunn, who earned a doctorate in neuroscience before embarking on his artistic career. The large centerpiece, titled *Self Reflected*, is a National Science Foundation-funded project created by Dunn, his applied physicist collaborator Brian Edwards, and a team of scientists over a two-year period. It is an animated and extraordinarily detailed representation of human brain activity, designed to mirror the functioning of the viewer's own mind.

"I hope this artwork serves as a daily reminder of the audaciousness of our attempts to tackle some of the most difficult and compelling scientific questions of our time," says Dunn.

Read the most recent issue of *Caltech Effect* at **breakthrough.caltech.edu/magazine/the-caltech-effect-february-2021**

In Memoriam

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

Bill May 1942–2020

William "Bill" H. May, chairman of the board of directors of the Arnold and Mabel Beckman Foundation and former member of the advisory committee for Caltech's Division of Chemistry and Chemical Engineering, died on October 10. He was 77. May was senior vice president, general counsel, and secretary for Beckman Instruments, the company founded by Arnold O. Beckman (PhD '28). After his retirement, May served as chair of the board of directors of the Arnold and Mabel Beckman Foundation.

Bill Iwan (BS '57, MS '58, PhD '61) 1935–2020

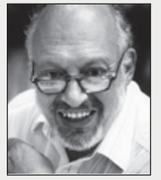
Wilfred D. (Bill) Iwan, professor of civil engineering, emeritus, passed away on October 29. He was 85 years old. He joined the Caltech faculty in 1964 and remained at the Institute for the rest of his career. Iwan's research focused on fundamental areas of mechanics, including work to understand and characterize strong earthquake ground motion and the analysis and monitoring of the response of structural systems subjected to extreme events.

Vince McKoy 1938–2020

Basil Vincent "Vince" McKoy, emeritus professor of theoretical chemistry, died on November 2. He was 82. Work he conducted in the 1960s led McKoy to focus on quantum scattering theory, a field of study that seeks to understand how waves and particles scatter after a collision. For the rest of his career, he continued to study collisions between particles, later focusing on how electrons affect large biomolecules like DNA when they collide with them.

Kim C. Border (BS '74) 1952–2020

Kim C. Border, a longtime professor of economics at Caltech, died on November 19. He was 68 years old. Border specialized in decision theory and sought to better understand how and when people behave rationally when presented with risks. He applied insights from mathematical areas to design incentives to solve resource allocation problems; for example, his research helped in the design of auctions, such as those for greenhouse gas permits or online advertising.



Jean-Paul Revel 1930–2020

Jean-Paul Revel, the Albert Billings Ruddock Professor of Biology, Emeritus, died on December 4 at the age of 89. Revel served as dean of students at Caltech from 1996 to 2005. In his research in cell biology, Revel studied cell-to-cell communication, electron microscopy, and scanning probe microscopy. He was the first to identify and characterize gap junctions, a means whereby cells can communicate to exchange small molecules and ions.

Ward Whaling 1923–2020

Ward Whaling, professor of physics, emeritus, at Caltech, died on December 15. He was 97 years old. Whaling was an experimental nuclear physicist who taught for many years at Caltech and served as the secretary of the faculty for 16 years. Late in his scientific career, Whaling used spectrometers, including the one at Kitt Peak National Observatory in Arizona, to measure precise energy levels of atoms

Clarence Allen (MS '51, PhD '54) 1925–2021

Clarence Allen, professor of geology and geophysics, emeritus, and a prominent seismologist, died from COVID-19 on January 21. He was 96 years old. During his career, he was best known for his contributions to the evaluation of seismicity and fault movements in regions where earthquakes are common.

In addition to those individuals listed here, Caltech mourns the passing of staff members **Jose Mendez** and **Ramon Ramirez**. **Read more about them on page 11**.

Endnotes

We have been living with the impact and challenges of the coronavirus pandemic for a year now. How have you changed and what have you learned?

I have learned that I am OK with not interacting in person with anyone outside my family, and my wife and I really are hermits.

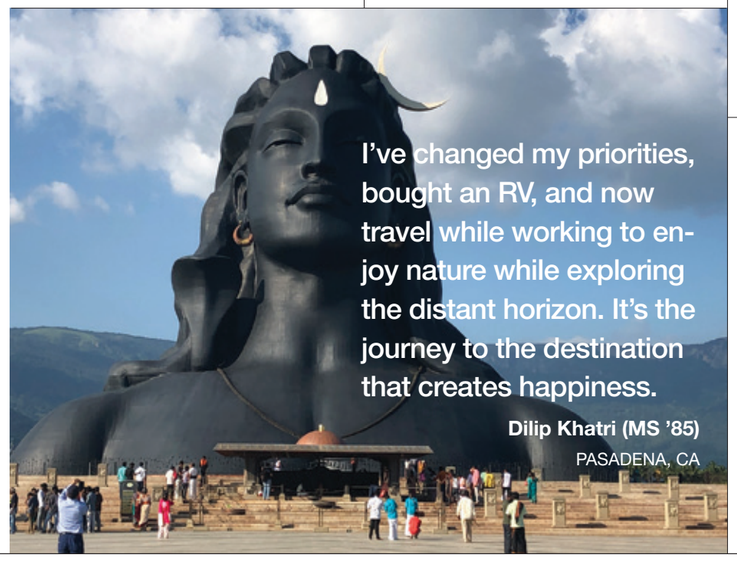
Martin Goldberg (BS ’78)
MATAWAN, NJ

No planes
+ no trains
+ many fewer trips by automobile =
lots more time for work and leisure.

Philip Neches (BS ’72, MS ’77, PhD ’83)
SUMMIT, NJ

Professors have become the DJs!

Roger NG (BS ’85)
HONG KONG SAR, CHINA



Being an introvert has its advantages. My mind has kept me company. The extra time is precious, and making time is (hopefully) now a habit. Time for my family, time to get back to favorite activities, and time to just breathe.

Karen Kiselewski (BS ’82)
DELRAY BEACH, FL

More self-reliant for entertainment & intellectual stimulation. Closer communication with my wife. Better connected to more culture and intellectual events via Zoom than previous in-person interactions, although maybe not as much fun!

Jeffery Richardson (BS ’70)
LIVERMORE, CA

I’ve learned that even a life with unscheduled weekends leaves you with too little time to get things done prior to the Monday work week restart!

Tara Gomez-Hampton (PhD ’11)
PASADENA, CA

Probably 50 years ago I read *The Plague* by Albert Camus. It has remained with me as being prescient and honest. Dr. Fauci seems like the reincarnation of Dr. Rieux in Camus’s great novel.

David Rennels (MS ’65)
LA CAÑADA-FLINTRIDGE, CA

As an advocate for social change and a city councilperson, I have learned that Zoom can save us a massive amount of “vehicle miles traveled”! I have also learned that I am not so much a person who can just live in my own head as I thought; I was fine for three to four months, but over the last six months have felt increasingly starved of contact with my extended human “posse”!

Dennis Pocekay (BS ’70)
PETALUMA, CA

I’ve learned to love all kinds of webinars. I’ve been learning about the 1918 pandemic, virus proofreading, and face masks. Too many DIY projects.

Douglas Ikemi (MS ’80)
INGLEWOOD, CA

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Jonas Peters
Bren Professor of Chemistry and Director of the Resnick Sustainability Institute

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Dianne K. Newman
Gordon M. Binder/Amgen Professor of Biology and Geobiology

These Zoom webinars are free and open to the public. Advance registration is required.

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Why can't we predict earthquakes?

"There are 50 earthquakes in California today. You don't want me to predict every one of them. You want a prediction of which of the 20, 30, 40,000 earthquakes we will record this year is going to be the one large enough to actually do some damage. So we don't want prediction of just the time of an earthquake. We want prediction of the magnitude of the earthquake, but the magnitude … is determined by the length of the fault that moves in the event. And it doesn't move over the whole fault at once. It starts at a point and moves down the fault until it hits something that makes it stop. And that determines how big the earthquake is going to be. So it may be … that the earth doesn't have the information about how big an earthquake will be before it begins."

—Seismologist and science communicator Lucy Jones, a visiting associate in geophysics at Caltech, answered this question and others on the Caltech Science Exchange. Find out more at **scienceexchange.caltech.edu.**