e&s

Engineering & Science

POINTS OF ORIGIN

Caltech

VOLUME LXXVIII, NUMBER 1, SPRING 2015

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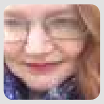
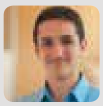
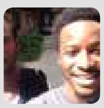


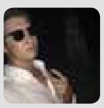
@notanastronomer It has been term for two hours. I am already behind on my work. Ah, @Caltech.



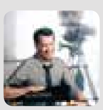
@abnormalxy Watched #Interstellar twice, love the #physics! So lucky I took Ph136 w @kipthorne just before he retired from @Caltech! Outstanding class!



@binnix_ @Caltech please stop with the free food at every event. You're not helping me get to my fitness goals.

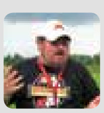


@Aaron_Reecer Good luck to all the @Caltech students attempting a Tommy's run tonight. Godspeed, brave souls.



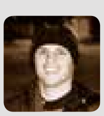
@seanmcarroll Quarks have boring names (up/down/charm/strange/top/bottom). My suggested replacements: cinnamon, nutmeg, allspice, clove, ginger & wasabi.

@astroholbrook Saw #bighero6. There is a thanks to my alma mater @Caltech in the credits. A good nerd movie. Wait for the last last last scene.



@bacteriality 2 people, 2 dogs, 2 babies, 1 car crammed full of stuff on our way to @Caltech #sabbaticalroadtrip

@arielconn Thank you @Caltech for such a wonderful collection! Einstein Papers Project at Caltech http://bit.ly/1tQvU4d



@DHagan7 Looks like it's time to transfer to @Caltech #bostoniswaytoocold

@Miquai My @Caltech team was in 1st place going into the last q but lost to those smartypants from @NASAJPL. We'll get you next time! #TriviaTuesday

Tweets may have been edited for spelling and grammar.

Caltech
Engineering & Science

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Its and Starts

It starts here.

I'm the kind of editor who dislikes the article that leads with a nonspecific, vaguely mysterious "it." *It is broad and bright and blue. It covers us like a canopy. It is the sky.* To me, that's a fill-in-the-blank, one-size-fits-all lead, and we can do better, usually.

But I'm going to give myself a break this one time. Because, in this issue of *E&S*, we are telling our origin stories, looking at some of the things—the ideas, the inventions, the too-many-to-name *it*s—that got their start at or can trace their roots to Caltech.

Like JPL, which started here on campus with the birth of the so-called Suicide Squad. (See page 30.)

Or X-ray crystallography, which took shape—as a field and a technique—in the labs of Caltech's own Arthur Amos Noyes, Roscoe Dickinson, and Linus Pauling. (See page 24.)

In this issue, we also look back to Caltech's own origins, telling the story of how Pasadena Hall became Throop Hall, which became the Throop Memorial Garden—and how, today, we can still find traces (literally) of those early days right here on campus. (See page 20.)

This photo from the Caltech Archives shows Throop Hall and the famed Engelman Oak. The year in which this image was captured is unknown, but it seems to date back to the Institute's early days.

When we sat down some six or eight months ago—because that is how long it takes to produce an issue of this magazine—and talked about which origin stories we wanted to tell, our editorial staff quickly became overwhelmed. After all, Caltech is a place where ideas and techniques and technologies are seeded and take root. And so we realized that almost any topic we considered—almost every story we have ever told in this magazine—is an origin story of sorts.

Rather than arm wrestle over our personal favorite ideas, we've decided instead to take this issue's theme and turn it into a regular one-page feature at the end of the Random Walk section of the magazine. You'll see our brand-new "Origin Stories" page beginning in our Summer 2015 issue.*

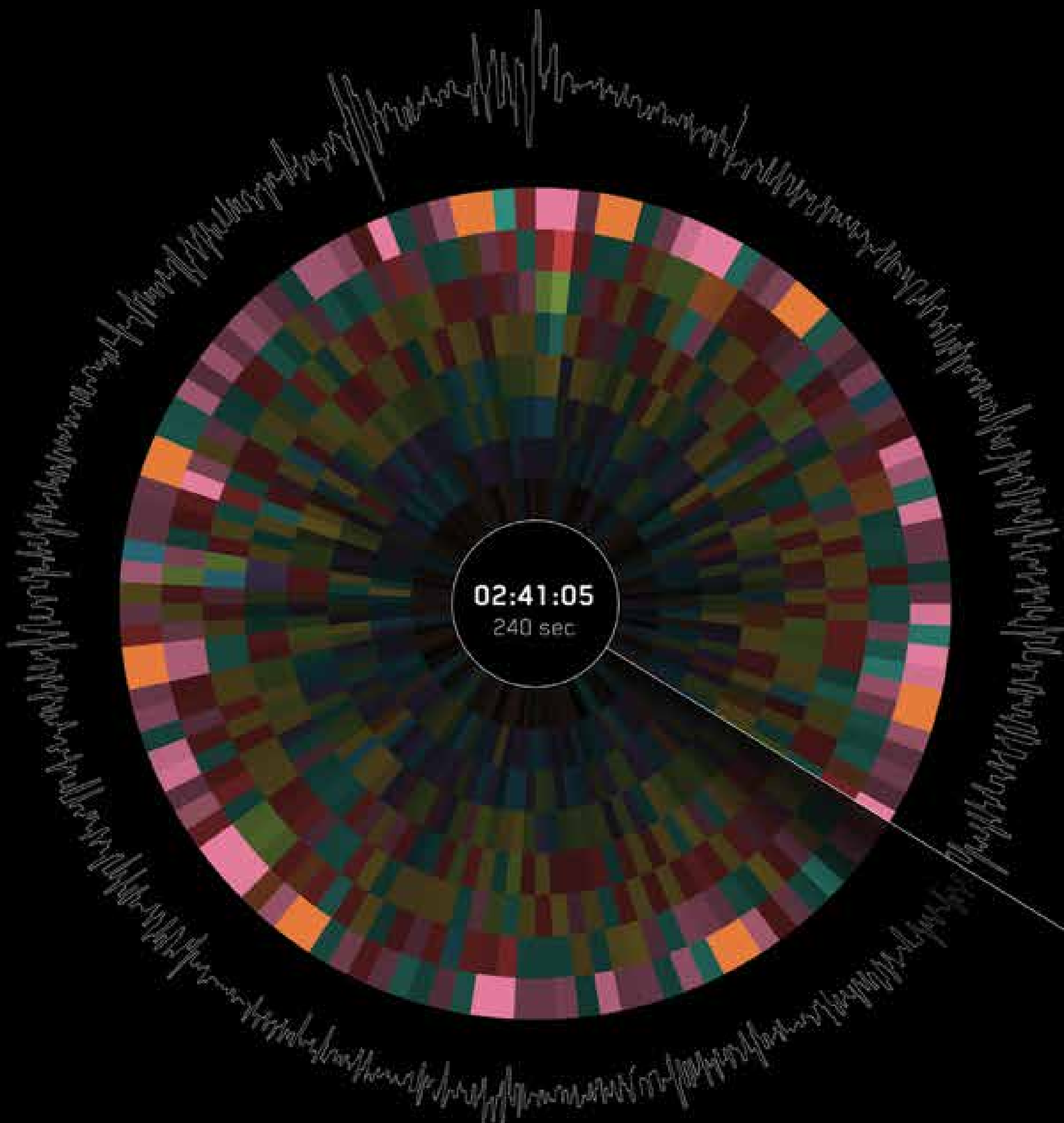
Burgeoning ideas. Audacious science and technology. It really *does* start here.

Lori Oliwenstein

—Lori Oliwenstein, Editor-in-Chief

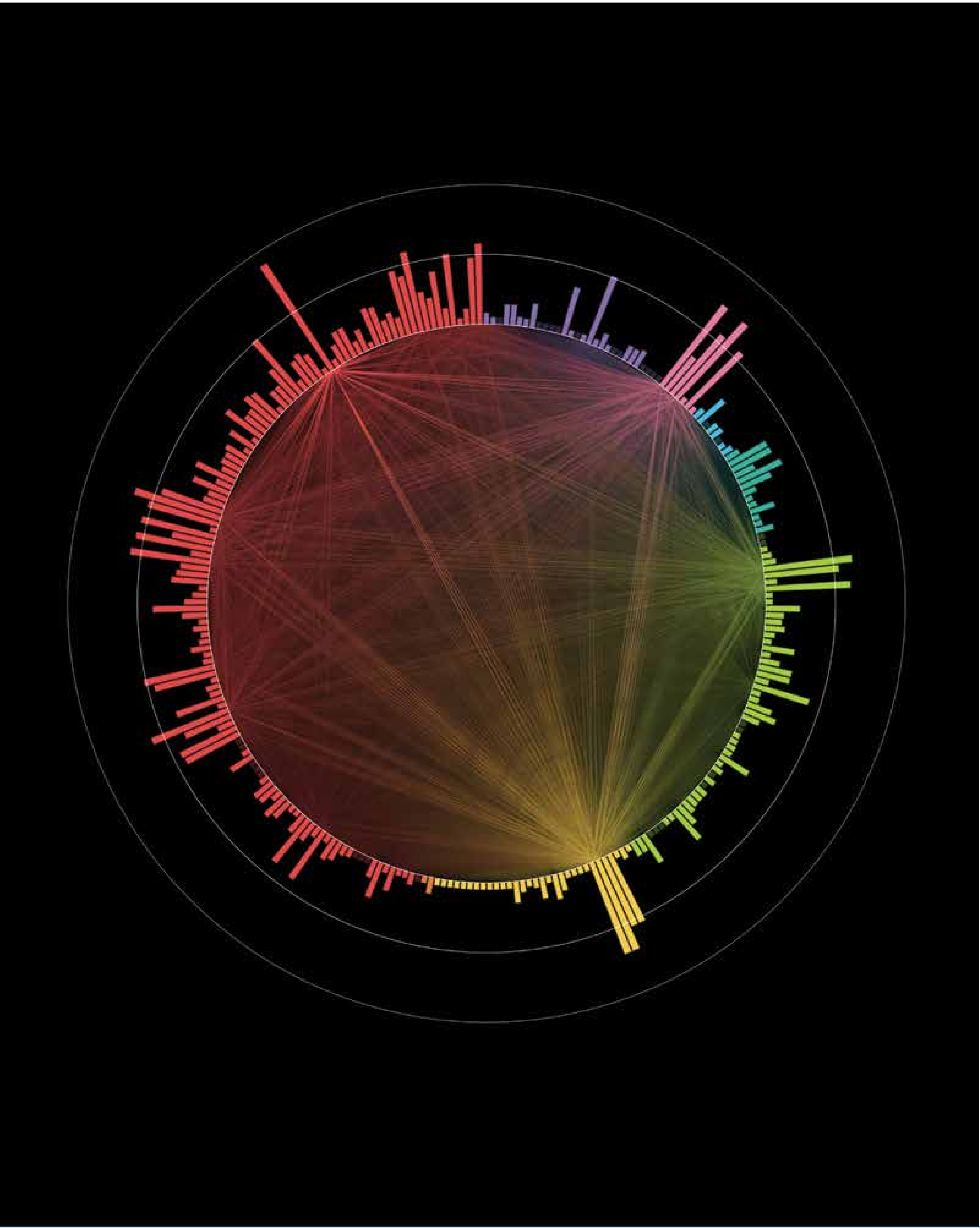
**Have an idea for a Caltech origin story you'd like us to cover? Drop me a note at* lorio@caltech.edu *and we'll look into it.*

Random Walk



DIALING IN TO NOISE

In their search for gravitational waves—stretches in space-time produced by dramatically violent events in the distant universe—researchers at the Laser Interferometer Gravitational-Wave Observatory (LIGO) have created some of the most sensitive detectors in the world. Unfortunately, these detectors also pick up on lots of other disturbances—for example, strong winds or the sounds of a passing truck. Students from the Data Visualization Summer Internship program—operated by faculty members from Caltech, JPL, and Art Center College of Design—were tasked with determining if a blip on the detector is a gravitational wave or instead just a signal from ordinary bumps and shakes. To do this, they developed these colorful visualizations to represent how signals are related to known events. The dial on the left marks the time at which each event was recorded; on the right, the height of the bars indicates the strength of each event while the lines connecting the bars indicate how strongly these events are correlated to one another. Coupled with the existing analytical methods used by LIGO, this new way of looking at things will help researchers identify and eliminate terrestrial noise sources, directly improving the astrophysical reach of the LIGO detectors—and making those elusive gravitational waves just that much easier to detect.



Letters From Einstein

In the fall of 1923, Albert Einstein was living in Berlin, but after outbursts of anti-Semitic violence in the city and rumored threats to his life, he suddenly fled for the Netherlands, enduring what he called a "cheerful banishment" in the university town of Leyden. Although these experiences contributed to Einstein's social and political engagement at that time, he was also simultaneously engaged in establishing the Hebrew University in Jerusalem and at work on significant scientific challenges—such as attempting to find a unified theory of gravitation and electromagnetism.

This important period in Einstein's life is documented in the latest volume put out by the Einstein Papers Project at Caltech. *The Collected Papers of Albert Einstein, Volume 14: The Berlin Years: Writings & Correspondence, April 1923–May 1925*, published in February, includes some one hundred writings by Einstein and more than one thousand letters by and to him over those two years. The volume provides a wealth of detailed material on his experimental and theoretical work, including the Bose-Einstein statistics, and many insights into the Nobel Prize winner's academic and personal life during this politically tumultuous time.

In addition to its release of the new print collection, the Einstein Papers Project partnered with Princeton University Press to launch *The Digital Einstein Papers* in December 2014. This makes available online for free the previous 13 volumes of the *Collected Papers*—meaning that you now need nothing more than an Internet connection to easily access and experience the project's vast scholarship on Einstein. —*JSC*

On September 1, 2014, Professor of English Cindy Weinstein became a vice provost at Caltech. Her research has focused primarily on 19th-century American literature, and she is interested in interpreting books with reference to the culture in which they were written. She has published two books: one on how novelists imagined their writing as a kind of labor, and another on the place of family in 19th-century fiction. Weinstein's forthcoming book, *When Is Now? Time in American Literature*, analyzes novels ranging from the 18th to the 21st centuries in relation to their representations of time.

Here are a few more things you might find interesting about Weinstein:

- Her dogs are named Wendell and Scout; Scout is named after the protagonist in *To Kill a Mockingbird*.
- Weinstein's family, including her son and daughter, once drove across the country for a sabbatical year on the East Coast. One of her favorite memories from that trip is stopping in Topeka, Kansas. During a lightning storm there, her son, then five years old, remarked, "Mom, Zeus is hurling his lightning bolts." "This greatly amused my husband, a classicist," she says.
- Her love of words comes from her parents. She played Scrabble with her mother, starting at a very young age. "She was extremely competitive, and I had to get better fast," says Weinstein. She also spent many hours doing *New York Times* Sunday crossword puzzles with her father in her childhood home in in Verona, New Jersey.

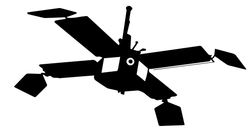
A Meeting of the Energy-Minded

The Caltech Energy Forum, hosted by Caltech Facilities, celebrated its fourth annual event on October 30, 2014, bringing together 150 industry leaders from a wide variety of specialties including education, entertainment, health care, architecture, engineering, construction, real estate, and energy-service providers. The diverse group gathered in the Athenaeum for a daylong conference, themed "Making Big Data Work," to learn how Caltech manages its own building data and to learn key success strategies from the five-year history of Caltech's green revolving fund, the Caltech Energy Conservation Investment Program (CECIP). Caltech has invested $15 million in CECIP to date and has achieved an overall 26 percent return on investment from the program. Speakers included Caltech's Jim Cowell, associate vice president for facilities; Matthew Berbee, director of maintenance management and energy services; and John Onderdonk, director for sustainability programs. Keynote presenters were Energy Efficiency Funding Group's founder and president, Mark Jewell, who spoke on the how to effectively sell energy efficiency to an organization's various stakeholders; and Microsoft's director of worldwide energy and building technology, Darrell Smith, who spoke on how Microsoft quietly lay the groundwork for the city of the future, utilizing energy-efficient facilities and automated diagnostics.

Insider Info

JPL has launched more than

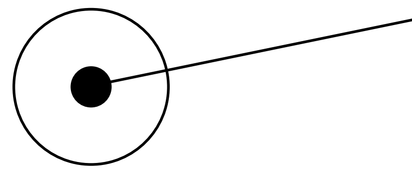
70



missions toward space, despite starting out with a very different type of goal. To learn more about the Lab's inception, see page 30.

There are

18



"points of origin" represented in this issue's abstract cover, which was illustrated by our magazine's designer, Keith Knueven.

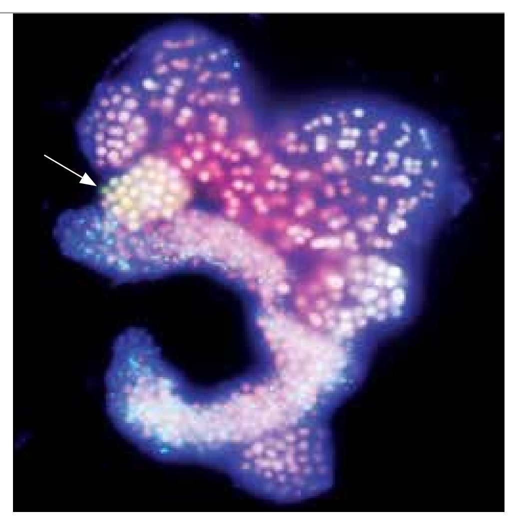
7

individual pieces from Caltech's very first building, Throop Hall, are scattered around campus. Go to page 20 to find out where they are.

On the Grounds

The green and yellow stained cells in this image correspond to bacteria that were actively making new proteins in a sample taken from a well-known campus feature. The sample was treated using a visualization technique, called BONCAT (for bioorthogonal noncanonical amino-acid tagging), which was developed in the lab of chemical engineer David Tirrell. BONCAT relies on synthetic amino acids to fluorescently tag newly formed proteins in cells. Here, geobiologist Victoria Orphan and her colleagues applied BONCAT to environmental samples including this one, which was likely taken near a hidden koi fish or turtle. Using a fluorescence microscope, the technique can reveal which bacteria in a sample are active. Where was this sample collected?

Answer: The sample came from Caltech's lily pond, just south of Baxter Hall.



A Nobel Honor

Caltech added another win to its Nobel scorecard in 2014, bringing to 33 the tally of Caltech alumni and faculty laureates, who have won a total of 34 Nobel Prizes.

Eric Betzig (BS '83), a group leader at the Howard Hughes Medical Institute's Janelia Farm Research Campus in Ashburn, Virginia, was awarded the 2014 Nobel Prize in Chemistry along with Stefan W. Hell of the Max Planck Institute for Biophysical Chemistry and William E. Moerner of Stanford University. He is the second Caltech alum in two years to be awarded the prize; Martin Karplus (PhD '54) received the Chemistry Prize in 2013.

The three were honored "for the development of super-resolved fluorescence microscopy," a method that allows for the creation of "super-images" with a resolution on the order of nanometers, or billionths of a meter. In essence, the work turns microscopy into "nanoscopy."

The technique developed by the trio overcomes the so-called Abbe diffraction limit, which describes a physical restriction on the sizes of the structures that can be resolved using optical microscopy. Essentially, the limit shows that nothing smaller than one-half the wavelength of light, or about 0.2 microns, can be discerned by optical scopes. The result of the Abbe limit is that only the larger structures within cells—organelles like mitochondria, for example—can be resolved and studied with regular microscopes; individual proteins or even viruses cannot. The restriction is akin to being able to observe the buildings that make up a city but not the city's inhabitants and their activities.

Betzig, who was a physics major from Ruddock House during his time at Caltech, built on earlier work by Hell and Moerner to find that it was possible to work around the Abbe limit to create very-high-resolution images of a sample, such as a developing embryo, by using fluorescent proteins that glow when illuminated with a weak pulse of light. Each time the sample is illuminated, a different, sparsely distributed subpopulation of fluorescent proteins will light up and, because the glowing molecules are spaced farther apart than the Abbe diffraction limit, a standard microscope would be able to capture them.

Still, each of the images produced in this way has relatively low resolution—that is, the images are blurry. Betzig realized, however, that by superimposing many such images, he would be able to obtain a sharp super-image, in which nanoscale structures are clearly visible. The new technique was first described in a 2006 paper published in the journal *Science*. —*KS*

DID **YOU KNOW?**

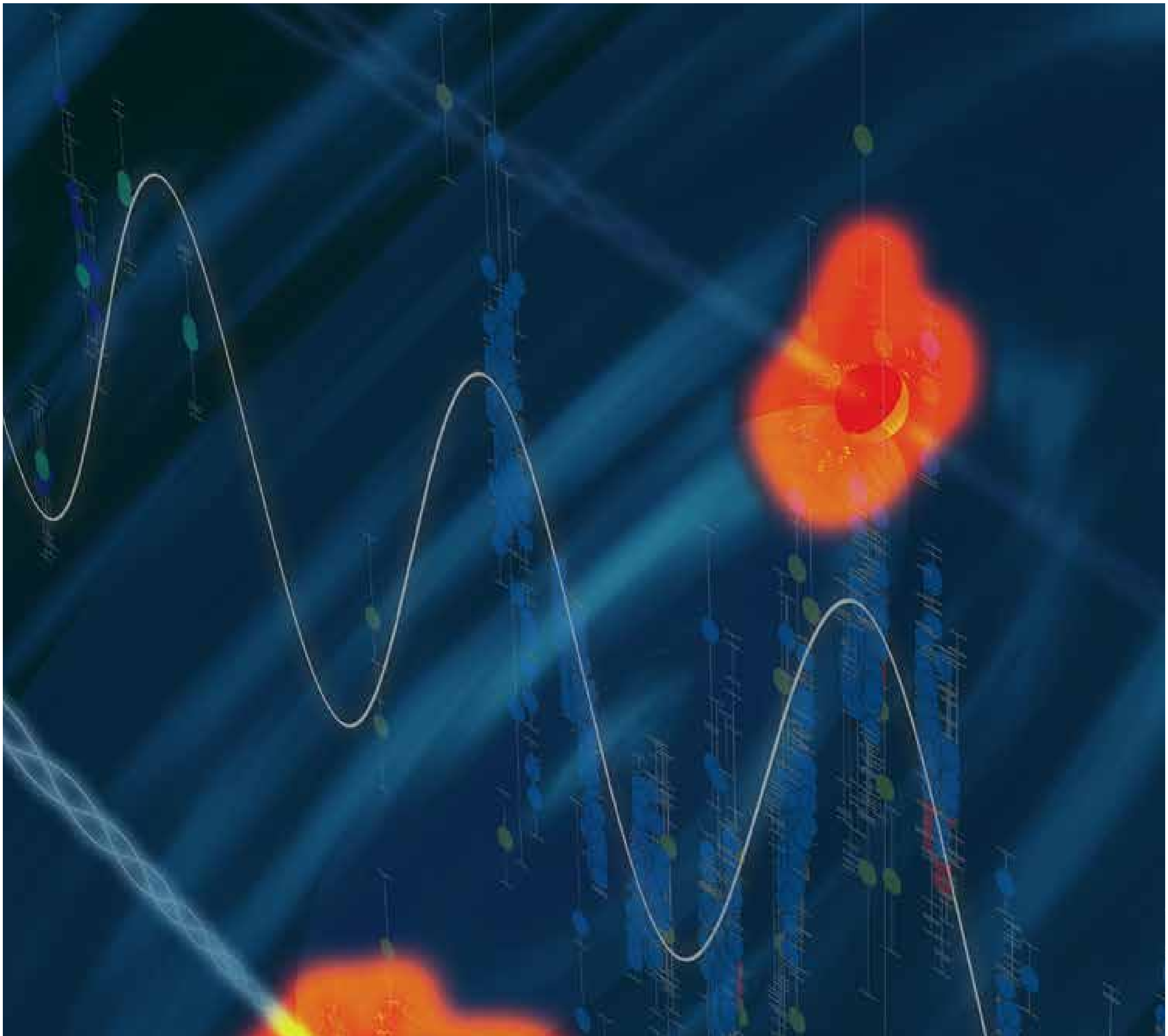
The Caltech Karate Club is the oldest university karate club in the United States. Tsutomu Ohshima founded the club in 1957 and—until his retirement in 1994, the same year in which he received the Caltech ASCIT Teaching Award—trained its members in a traditional form of karate called Shotokan. In 2014, the club celebrated its 58th year of hosting an annual karate exhibition and tournament.

> "The pulsar appears to be eating the equivalent of a black hole diet. This result will help us understand how black holes gorge and grow so quickly, which is an important event in the formation of galaxies and structures in the universe."

—Fiona Harrison, Caltech's Benjamin M. Rosen Professor of Physics, commenting, in a NASA press release, on the discovery of a dead star that pulsates, beaming the energy of 10 million suns. Harrison is principal investigator for NuSTAR, the telescope that found the stellar remnant.

One More Look Back at Inauguration

The Caltech community welcomed the Institute's ninth president, Thomas F. Rosenbaum, at a number of campus events in late October 2014. At top left, participants in a "Science and the University-Government Partnership" panel talk about the future of academic science and its evolving relationship with government, industry, and private philanthropy. At top right, University of Chicago President Emeritus Don Michael Randel presents his keynote speech at the inauguration convocation. After the ceremony, Caltech hosted a public reception on the Olive Walk, featuring live music and fare from local food trucks. In the bottom two photographs, President Rosenbaum is seen with party attendees (right), and with his wife, materials scientist Katherine Faber (left). For more on the day, visit inauguration.caltech.edu.



available now on **CALTECH.EDU**

HEARTS OF DARKNESS

A Caltech research team has observed a repeating light signal from a distant quasar that is likely the result of two supermassive black holes in the final stages of a merger. Learn more at **caltech.edu/news**.

Watch

C is for cookie … and carrots. Did you know your ability to exercise self-control may depend upon how quickly your brain factors healthfulness into a decision? Find out more at **youtube.com/caltech**.

Read

Learn about our people, our impact, our vision, and our community. Flip through the 2014–15 version of the Caltech Overview at **caltech.edu/content/viewbook**.

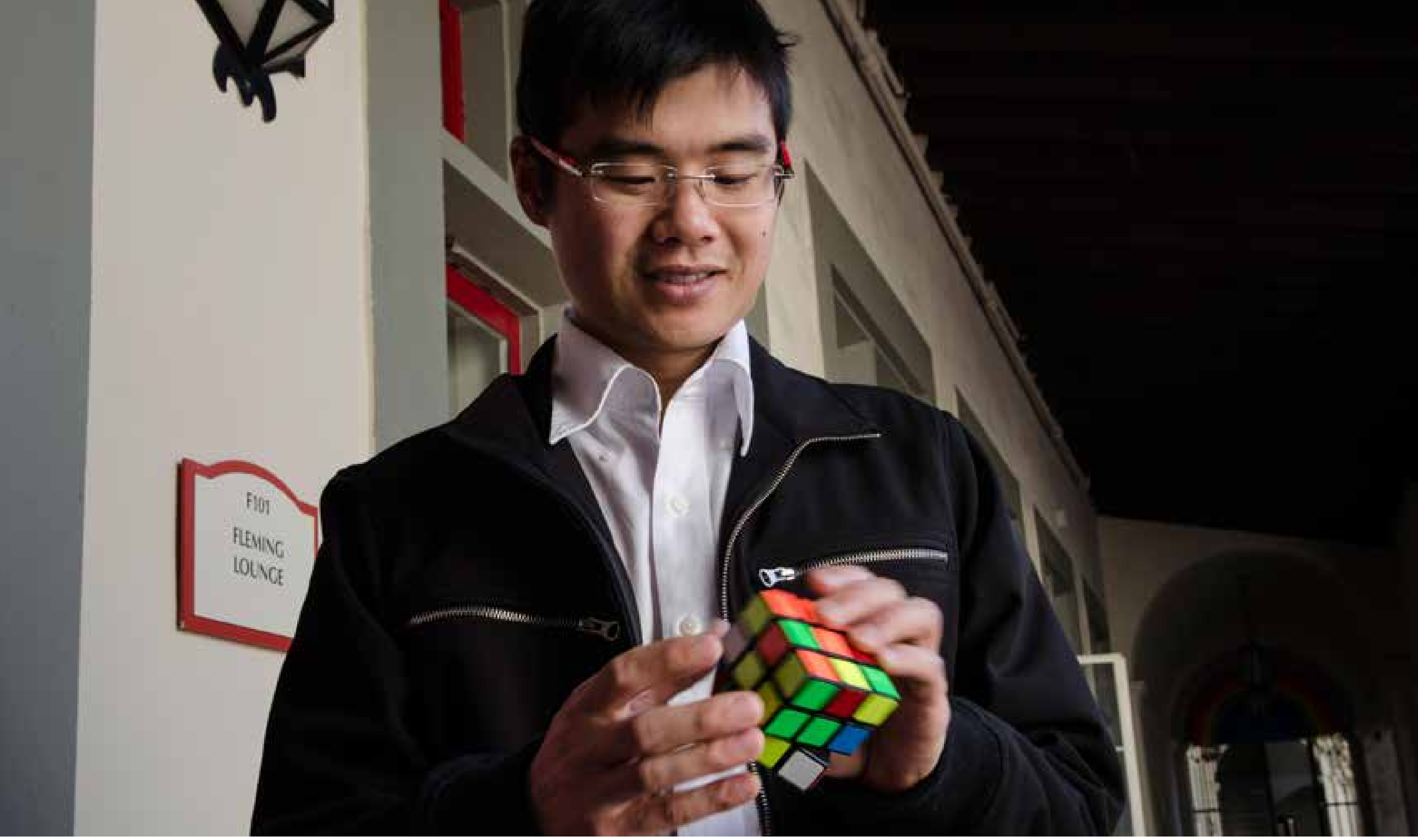
Engage

Experience the beauty and splendor of Argentina with an evening of tango and chamber music in *Te Amo, Argentina* on Saturday, April 25, 2015, at 8 p.m. Find out more at **caltech.edu/calendar/public-events**.

THE STARTING LINE

The college years often skew the path we expect to follow, creating new routes to unexpected places, relationships, careers, and passions. They are, in oh-so-many ways, the beginning of our lives as adults. They provide the origins of our own personal stories.

That is why, in this issue's Endnotes (see page 36), we asked Caltech's alumni what it was that started for them here during those transformative years. We received so many fascinating and surprising answers that we couldn't possibly fit them all on one page; in addition, some were stories that needed more room to be fully told. And so, here, we've given that room to just a few of those stories.



A CUBE COMPETITION

The summer between my freshman and sophomore years, my brother learned to solve a Rubik's Cube. After a two-hour teaching session, I too could solve the Rubik's Cube—in 10 minutes and with a sheet of notes. I became quite dedicated during my sophomore year, to the detriment of my Ph 12a final exam, and practiced more hours than I should have to bring those 10 minutes down to 30 seconds.

Soon, my housemates in Fleming had joined me in my new hobby—Mithun Diwakar (BS '06) and Mark Polinkovsky (BS '06) were particularly involved—and the Rubik's Cube craze spread to other communities at Caltech. I played violin in the Caltech orchestra, and fellow musicians Leyan Lo (BS '07) and Shelley Chang (BS '07) quickly became hooked on the cube as well. We had all become "speed cubers"—poor souls addicted to the art of solving the Rubik's Cube faster. With the help of Mithun and Mark, I used Caltech's friendly room reservation system to book Winnett Lounge for Pasadena's first local Rubik's Cube competition, held on January 24, 2004. Our winter competition led to a spring competition. Through that event, I connected with Ron van Bruchem, a cuber in the Netherlands, and the World Cube Association was born. By standardizing the regulations and process, we made it possible for people from all over the world to compare times.

I eventually went on to host the United States national championship in 2004. The team at Caltech, which started with my friends, has organized every national championship in the United States as well as the World Rubik's Cube Championship 2013.

Today, the World Cube Association includes competitors from all six continents; tens of thousands of these cubers travel to WCA events every year. I graduated from Caltech in 2006 and was fortunate enough to have the foresight to find my successor by tricking Daniel Lo (BS '09) into leading the Caltech club. He eventually passed the torch on to Ambie Valdés (BS '10) and Michael Young (BS '14).

The impact of the Rubik's Cube on my life has been incredible. As I wrote the previous paragraph, I realized that what started for me at Caltech has also led to my gaining a sister-in-law. My brother, who taught me how to solve the Rubik's Cube, is now engaged to Ambie, whom he met through me. They plan to marry next year.

It all started for me at Caltech. Caltech had a wonderful community of people who were willing to not only put up with my addiction but to also nurture it. At Caltech, my impulses and my ideas became many things. They became an international organization, they became lifelong friendships, and they became my family.

—Tyson Mao, BS '06

A PASSION FOR STATS

Unusual for Caltech, what started for me was a career in sports, one that now has me in the front office of the Sacramento Kings. In the last years of high school, the annual *Bill James Baseball Abstract* was my link between sports and numbers. Those books had me thinking when I entered Tech about how to scientifically break down sports using statistics. In my freshman year, math professor Gary Lorden showed me how James calculated the chances that the Detroit Tigers would have a 36-4 record after 40 games given their previous performance. Conversations with my freshman adviser, Peter Haff, about the physics and statistics of basketball encouraged me to apply what I was learning at Tech to sports.

And so, as finals wound down in my freshman year, I decided to systematically chart the NBA Finals that were occurring at the same time. The system I developed would ultimately form the basis for much of the basketball analytics that are now used across the NBA and for college basketball.

In my sophomore year, Caltech hired longtime Mt. San Antonio College coach Gene Victor to coach the basketball team—and I found another person to talk basketball with. Entering my junior year, I showed Coach Victor some of the work I had done, and he encouraged me to work with and join his coaching staff—maybe because I wasn't a great player.

My friends at Tech weren't all sports fans, but they appreciated the science behind what I was doing. Being able to talk basketball to scientists and science to basketball people helped build the language of sports analytics.

For graduate school, I turned down MIT, Stanford, and Harvard to go to the University of North Carolina, which had both a great basketball team and a great environmental engineering program. Coach Victor put me in touch with Bill Bertka, assistant coach of the Los Angeles Lakers, so that I could work as an advance scout in North Carolina. Four years later, I had a PhD in engineering and a lot of basketball experience.

At the time—1994—there was no market for what would eventually be called "basketball analytics." There *was* a market for environmental consulting, so that's what paid the bills. Then, in 2002, Michael Lewis sat down to write *Moneyball*, the story of how the Oakland A's used analytics to win in baseball. At the same time, I took time off from consulting to write *Basketball on Paper*, a book on how to use analytics to win in basketball. The coincidental timing encouraged me to quit my job and take a chance at getting into the NBA.

That was 2004. Since then, I've been to the NBA Conference Finals, worked with Hall of Famers like Magic Johnson and Chris Mullin, helped build the sports analytics industry, and made sure to stay in touch with the friends and coach from Caltech who helped get me here.

—Dean Oliver, BS '90

A PLACE TO GATHER

When I visit Caltech and see the Red Door Café, I am proud to remember helping to get it started. Costas Synolakis (BS '78, MS '79, PhD '86) suggested the idea of creating a grad-student coffeehouse in the first place. The late L. Bruce Kahl, MD, then the head of Counseling Services, agreed that grad students needed a place to meet. Astrid Howard (MS '83) came up with the great name. Morgan Gopnik (MS '82) did more of the work than anyone else, including painting the door red. As for me, my role was to get the project off the ground: once we had a committee together, I got the permission and the money to get the coffeehouse started. I also remember buying the first, home-level espresso machine—and then its replacement restaurant-grade model.

It all started on the second floor of Winnett, which had a few student offices, the Caltech Y, and two meeting rooms. We somehow negotiated to get an office next to a meeting room, and a split door was put in between the two, along with a service counter. I still remember vividly when Astrid suggested that we paint the door red. That was not too well received, but then she added if we did that we could call it the Red Door Café. Everyone liked that, and the name was set.

In the beginning, you could get coffee, tea, and hot chocolate, as well as homemade desserts. We had some paid staffing, but most counter duty was handled by volunteers.

The Red Door was a place that grad students hung out at; it was sometimes visited by undergrads but not very much by faculty. Before it got started, grad students only tended to know the other students in their department. This was one small way that grad students could meet outside of their direct professional activities, and I think it was helpful in making Caltech a more human place for us.

—Brian Toby, PhD '87

A DANCE TO REMEMBER

I met my future wife on a blind date to a Ricketts House barn dance in my sophomore year, arranged by classmate Bill Graham (BS '59). We became engaged in the middle of our senior year (she was a student at Pomona), and we married the evening I received my BS in physics from Caltech: June 12, 1959. I also was commissioned into the Air Force Reserve at the graduation ceremony. Quite a day! My wife and I recently celebrated our 55th wedding anniversary when we made a trip to Pasadena for my 55th class reunion

—Phil Harriman, BS '59

A MUSICAL JOURNEY

While Caltech certainly enhanced my scientific curiosity, it was my interests in music and musical theater that found their origins at Caltech. Never having done any musical activities in high school, I was plunged into the annual Caltech musical my sophomore year (*Guys and Dolls*), getting one of the leads, Nathan Detroit—a surprise given my utter lack of acting experience. But with the help of our exceptional director, Shirley Marneus, and the wonderful support of all the other cast and crew, I had an absolutely and indescribably marvelous time. I then went on to be in the musicals for my following two years at Caltech, as well as joining the Glee Club.

I can honestly say that those experiences in the musicals had as much of an impact on me as my classes. I learned how to focus on the moment, learn from those around me, communicate my thoughts, and assimilate information coming in from multiple places at the same time, as well as how to give of myself emotionally to others. Learning how to effectively communicate my thoughts and feelings in a larger setting has been indispensable to me in my current lectures to students as a professor of cell biology. When I think of the things that helped me to develop at Caltech, I think of my peers, my classes, my professors . . . and the musicals.

—Stan Cohn, BS '79

A COLLABORATIVE START-UP

In 2014, fellow alumna Vanessa Burns (BS '11) and I cofounded LumosTech, a start-up based on technology that hacks the body's master circadian regulator to treat jet lag and other circadian-rhythm disorders.

My experience as a TA at Caltech was part of the inspiration for founding LumosTech. I noticed that the hormonally late-shifted circadian rhythms of my students—people in their teens and early twenties—combined with the night-owl undergraduate culture at Caltech, made early class times suboptimal for learning. As a result, I held my recitation section in the evening and found that my students were much more animated and engaged than at the morning lecture. While college culture is relatively forgiving to late chronotypes, or night owls, the modern workplace is rarely so accommodating, and many people find it difficult to go to bed early enough to get a full seven to eight hours of sleep before they need to wake up for their morning commute to work.

Using millisecond pulses of light, the smart sleep mask we are developing can shift your circadian rhythm while you sleep, using the same neural pathways as natural light in a way that is optimized to your sleep schedule through a companion smartphone app.

Collaborating with another Techer has been awesome, and I credit much of our success so far to the close and productive working relationship we have. Our experiences at Caltech significantly shaped our ability to develop and manage an early-stage tech start-up. We built our own prototypes, analyzed the scientific literature, and developed a business plan that we could pitch to investors. Without the skills and perseverance we learned as Caltech students, we would not have been able to overcome the many obstacles facing a start-up.

—Kristin Rule Gleitsman, PhD '10

THEY CAME FROM OUTER SPACE

by Katie Neith

Down in the basement of Arms Laboratory, in a room covered in acoustic paneling, staff scientist Chi Ma has spent the past eight years looking for clues that will help uncover the secrets of the early solar system. But Ma is neither an astronomer nor a physicist, rather he is a nanomineralogist—a term he has coined for the kind of scientist who peers into the smallest of nooks and the most minute of crannies in rock and mineral samples from meteorites, looking for clues to the evolution of the interstellar gas and dust cloud left over from the sun's formation.

While more than 4,900 minerals have been identified on Earth, at present only about 60 such substances have been identified that are believed to have first existed in the cloud, called the solar nebula, from which the planets of our solar system were formed.

"As our solar system started to develop about 4.6 billion years ago, high-temperature minerals arose when condensation processes turned some gasses into solids," explains Ma. "These refractory minerals—meaning they are the first solar solids and formed at high temperatures—along with presolar grains mark the very beginning of mineral evolution at the very beginning of our solar system and also mark my proudest contribution to science."

That's because, out of the 50 or so refractory minerals identified to date, Ma has found and characterized 20 using an electron microscope and analytical tools in the Division of Geological and Planetary Sciences Analytical Facility, where he has worked since 1998.

But Ma wasn't always a meteorite guy. The child of a mineralogist and a petrologist, Ma grew up tagging along on field trips and wondering how the things he saw around him right here on Earth came to be.

"For as long as I can remember, I wanted to know the basics of what makes something, down to its atoms," he says. And so, for many years, he studied increasingly smaller bits of terrestrial minerals, finding inclusions—embedded chunks of other materials—at the micro- and nanoscale that gave new insights into minerals that had been thought to be well known. For example, in 1997, then-postdoc Ma and Caltech mineralogist George Rossman examined samples of rose quartz and discovered the tiny borosilicate fiber inclusions that give the stone its pink hue, upending previous theories that suggested the color comes from manganese or titanium.

Additional experiments revealed similar insights about other minerals, like obsidian and rainbow hematite, finding crystals, films, and other inclusions at a very small scale that explain why some minerals look the way they do. (See "The Secret Lives of Minerals," *E&S* 2007, no. 1.)

"By taking the analysis of minerals down to nanoscales, we find all sorts of new things, like inclusions, thin coatings, and tiny pores, all of which tell us something about what was happening when it was formed or when the sample was altered," Ma says. "Sometimes those tiny features help us answer big questions. Because of these clues, we are solving some questions that already had textbook answers . . . and finding that those answers were not correct."

In the mid-2000s, Ma was studying benitoite—a bright blue crystal that is the state gemstone of California—when he found and characterized a new mineral for the first time, a natural occurrence of $BaTiO_3$ he named barioperovskite. $BaTiO_3$ had already been synthesized by materials scientists, and it was reported in one paper to exist in the Allende meteorite, a giant space rock that fell in Mexico in 1969 and is often described as the world's best-studied meteorite. (This is in part because the Allende meteorite fell at a time when U.S. labs were preparing to analyze lunar rock samples about to be returned from the moon by the Apollo program. So researchers used Allende samples to test their state-of-the-art, newly developed instruments.)

But when Ma started to look at samples from Allende, he saw nothing of the kind. "That was in early 2007," he says. "And I still haven't found it!"

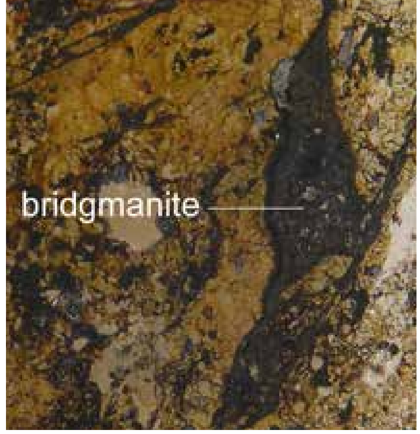
Still, that exposure to the study of meteorites—and to the enduring hunt for barioperovskite—hooked Ma, and it has been his focus ever since. "I call my research curiosity-based science," Ma says. "I let my inquisitiveness lead the way in what I study next."

His nanomineralogy approach has paid off: he's identified 15 new minerals with his colleagues in the Allende meteorite alone. "Allende is where scientists first found those refractory inclusions, the first solids to form from the gasses in the solar nebula," says Ma. "The meteorite is very primitive—our current understanding about early solar evolution is heavily based on intense studies of this rock. It's that important."

Today, Ma looks far beyond the Allende meteorite, using a suite of fine-tuned instruments to peer into the deepest recesses of various far-flung minerals. In the GPS Analytical Facility, where he serves as director, he has both a high-resolution analytical scanning electron microscope (SEM) and an electron probe microanalyzer (EPMA). The SEM can be found in a room with acoustic panels that are meant to dampen sound vibrations, since merely talking in the lab can cause tiny tremors that would impact the images created by the machine.

An SEM, which is typically used for geological, biological, and materials science purposes, produces images by scanning a focused beam of electrons

THESE REFRACTORY MINERALS . . . MARK THE VERY BEGINNING OF MINERAL EVOLUTION AT THE VERY BEGINNING OF OUR SOLAR SYSTEM.



over a sample and detecting signals that reveal information about the sample's topography and composition. The microscope is perfect for Ma's purposes, he explains, because it can image samples down to nanoscales and analyze the composition and structure of any areas in which he thinks he may have spotted something new.

Once he comes across an interesting mineral using the SEM, Ma uses the EPMA to further measure its composition. This helps him identify whether or not it is, in fact, a new mineral.

For some new minerals, where the SEM alone cannot unlock the crystal structure, the last step requires a trip beyond Caltech's boundaries to a synchrotron facility—there are only eight such facilities in the United States—where he joins his colleague Oliver Tschauner (a former visiting associate at Caltech who is now at the University of Nevada, Las Vegas) to use the synchrotron's high-flux X-ray to determine the crystalline structure of particular minerals through X-ray diffraction. (For more on X-ray diffraction and crystallography, see *X-ray Vision*, p. 24.)

Once Ma or one of his colleagues has determined the composition and structure of a new mineral, the International Mineralogical Association (IMA) Commission on New Minerals, Nomenclature and Classification has to officially approve the minerals, as well as their suggested names, for inclusion on the commission's list.

Naming, Ma says, is the easy part. When Ma first identified a new mineral in the Allende meteorite in 2007, he appropriately named it allendeite. A more recent Ma find, panguite, is a new variation of titanium oxide named after Pan Gu, the giant from ancient Chinese mythology who established the world by separating yin from yang to create the earth and the sky. Panguite is one of the oldest refractory minerals formed in the solar system, but Ma thinks it is more than just a curiosity; he thinks it could be useful for materials science. His colleague, John Beckett, a senior research scientist in geochemistry, has been able to synthesize it in the lab.

"To our surprise, panguite has a complex chemical composition in a relatively simple structure, and we'd like to see if it could be something that engineers could use," Ma says. "People look at the periodic table to dream up combinations when they want to make new engineering materials, but now we know this new material already exists in nature. It's pretty exciting."

Not every mineral that Ma names is a reference to mythology or the meteorite in which they were found: some of his appellations simply call out the mineral's structure and composition, so that—as Ma explains—when people hear it, they can get a good idea what it looks like or is made of. Take hexamolybdenum, for example—it is hexagonal in its crystal symmetry and rich in molybdenum, a chemical element.

Other mineral monikers have a more personal meaning behind them, one example being bridgmanite. It was made an official mineral in the summer of 2014 and was named by Tschauner and Ma in honor of Percy Bridgman, who won the 1946 Nobel Prize in Physics for his fundamental contributions to high-pressure physics. Scientists have long believed that something like bridgmanite makes up about 38 percent of our planet's volume and sits from 400 to 1,600 miles below Earth's surface in a thick layer called the lower mantle. But even though scientists have been able to create synthetic examples of this mantle mineral since the 1970s—and study its supposed compositions—no naturally occurring samples had ever been confirmed in a rock on Earth's surface.

Ma, along with Tschauner, had a hunch they might be able to find a naturally occurring specimen of the elusive bridgmanite in a meteorite. In particular, they had their eyes on the Tenham meteorite, a space rock that fell in Australia in 1879. It was a good candidate, because at 4.5 billion years of age, apparently the recipient of high-impact shocks, the meteorite had undoubtedly survived high-energy collisions with asteroids in space; this meant that parts of it were believed to have experienced the high-pressure, high-temperature conditions seen in Earth's mantle.

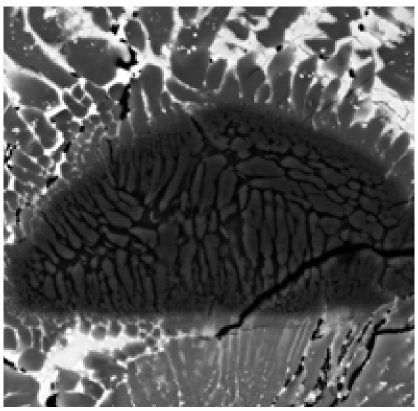
When Ma and Tschauner used their trio of machines to deeply probe a sample, lo and behold, they uncovered bits and pieces of bridgmanite, the discovery of which Ma says is their biggest accomplishment to date.

"The finding not only provides new information about shock conditions and impact processes on small

Bridgmanite, above left, is shown in a shock melt vein in the Tenham meteorite. Ahrensite, above right with a bluish green color, is seen in the Tissint meteorite. On page 19, the top photo is a back-scatter electron image showing tissintite—the dark material in the center region—in a shock melt pocket. The bottom photo shows a piece of the Allende meteorite in the GPS Mineral and Meteorite Collection room, also featured on page 16 with Ma and other meteorites from the collection.

bodies in the solar system, but the tiny amount of bridgmanite found in a meteorite could also help investigations of the deep Earth," says Ma.

In addition to naming bridgmanite after Bridgman, Ma and his colleagues dubbed another new high-pressure, shock-induced mineral found in a meteorite ahrensite, after the late Caltech geophysicist Thomas J. Ahrens. They wanted to honor Ahrens's pioneering and fundamental contributions to high-pressure mineral physics. Two additional minerals in Allende have been named to honor Caltech cosmochemists for their contributions to meteorite research: burnettite for Donald Burnett, professor of nuclear geochemistry, emeritus; and paqueite, for associate research scientist Julie Paque.



Ahrensite also marks something of a new branch of study for Ma: the examination of martian meteorites. Two years ago, Yang Liu, a colleague from JPL, brought Ma a sample from a meteorite called Tissint, which fell near a Moroccan town of the same name in 2011. Scientists determined the meteorite to be martian based on its chemical compositions. During a nanomineralogy investigation of this martian rock, Ma and his colleagues uncovered two new minerals from the sample: ahrensite and a mineral Ma is calling tissintite, which is brand new to science and has neither been observed before in nature nor made in a lab. The two discoveries were reported at the Eighth International Conference on Mars held at Caltech in July 2014.

Both are high-pressure minerals most likely formed by a shock process during the impact event on Mars that excavated the Tissint meteorite and ejected it from the Red Planet. The investigation by Ma and his colleagues of ahrensite—which had been previously described—provided the full set of chemical and structural information needed to officially establish it as a new mineral.

Ahrensite and tissintite are among the first IMA-approved new minerals from Mars. Since tissintite is brand new to researchers, the next step is to try to determine the conditions under which it formed, says Ma.

It is this kind of work—and these kinds of discoveries—that keeps Ma constantly engaged in the study of the minerals both on Earth and beyond.

"We already have a story about the solar system's evolution, but adding these new details gives a clearer picture," he says. "They are pieces of the big-picture puzzle. Some people call the rare new minerals we find bizarre, but I just think they all are beautiful." e&s

Chi Ma is a member of the professional staff and the director of the GPS Analytical Facility, which is supported, in part, by National Science Foundation grants.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Memories of Throop

by Katie Neith

Long before ducks made their nests among turtles and squirrels in what is now known as Throop Memorial Garden, the very first building on the Caltech campus called that space home. Where there are now ponds stood the pillars of what was called Pasadena Hall, built in the early 20th century. The building held up by those pillars was renamed Throop Hall in 1920—the same year the Throop College of Technology became the California Institute of Technology—to honor the school's founder, Amos G. Throop.

When the building opened in 1910—jam-packed with classrooms, laboratories, and administrative offices—it was said to be earthquake proof. The 6.6 San Fernando temblor of 1971 seemed to disprove that notion, leaving behind deep cracks in the facade of the great hall. Engineers, lacking the original construction plans and thus unable to know if the building was likely to be savable, recommended demolition. When a wrecking ball started to smash away at the concrete exterior, however, it revealed large amounts of steel rebar. The building, it turned out, likely could have stood for many more years.

But that was not to be. In 1973 Throop Hall came down, and it was soon replaced by the lush gardens seen on the site today. However, physical reminders of this historic heart of the campus still remain . . . if you know where to look.

CALDER ARCHES

One of the defining features of Throop Hall was the archway above its main entrance, a Beaux Arts–inspired sculpture by Alexander Stirling Calder, father of the artist of the same name who is known for creating large-scale artistic mobiles. Inspired by themes in the inaugural address by Caltech's first president, James Scherer, the elder Calder created allegorical figures to represent Scherer's vision of the Institute. According to the book *Caltech's Architectural Heritage*, by Romy Wyllie, the archway was considered to be one of the most important sculptural projects in Los Angeles at the time.

For over 60 years, the figures on the arches—representing Nature, Art, Energy, Science, Imagination, and Law—watched over the campus and served as the backdrop for celebrations and class photographs.

Despite the '71 quake and the decision to tear down Throop Hall, the sculptures were saved; at the last moment, they were carefully cut from the building. For 13 years they sat in a Pasadena city yard, the victims of government plans to place them at city hall that never came to fruition. Then, in the mid '80s, Caltech pulled the forlorn figures out of the dirt and weeds, and gave them a place of honor on the second-story bridge spanning the (at the time) newly renovated Church and Crellin buildings, which together composed the Arnold and Mabel Beckman Laboratory of Chemical Synthesis.

It is on that expanse that most of the carefully restored archway can be found today. Although the arches are nearly identical to how they appeared on Throop Hall, the bridge corrects a curious mistake made in the original sculpture: two of the bottom plaques had been placed incorrectly, with the mask of Art appearing under the column showing Science, while the hammer and anvil hung below the depiction of Art. They now appear in their originally intended positions.

In addition, two of the pilasters, or columns—along with their plaques—were sacrificed, unable to be crammed onto the bridge. They can be found in the courtyard between the buildings and behind the Beckman bridge, where they seem to be guarding the not-so-secret passageway between Crellin and the Kerckhoff Laboratories. Standing among a collection of trees, one represents "the emblem of the Law," while the other—decorated with sunflowers—is meant to represent Nature. Their concrete plaques flank the northern entrance of the passageway and depict life, death, and eternity (on the plaque that hung below the sunflower column on the original building) and a hand on an open book (on the plaque embodying of the concept of Law).

THROOP CLOCK

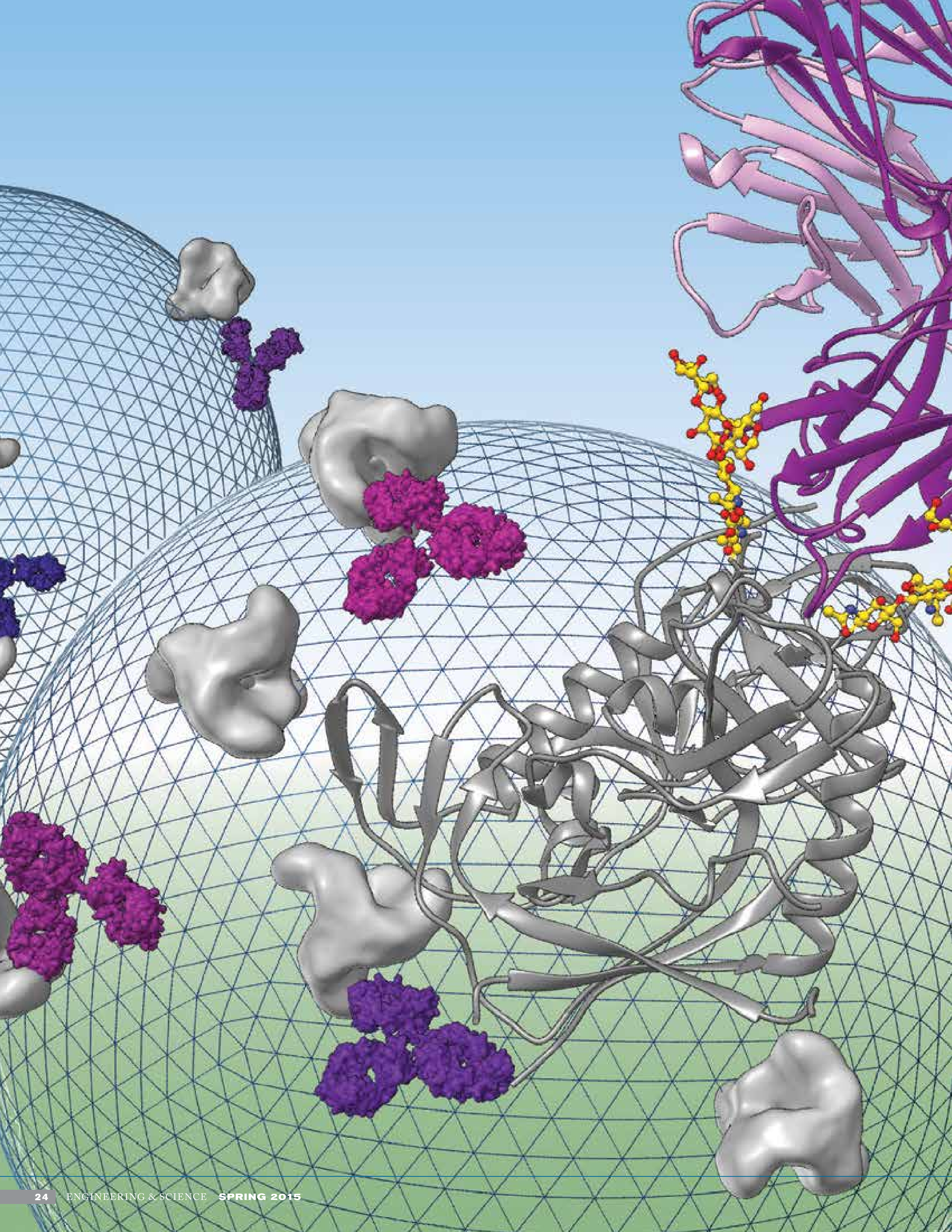
In the early 1940s—long before Throop Hall's demise—a clock was added to its facade, high above Calder's arch. It endured years of pranks, including a 1965 prank in which students turned its face into a Mickey Mouse watch, with the Disney character's arms keeping time. It was also saved from Throop Hall's fate and, a few years after the hall's demise, was renovated by undergrads from Ricketts House and remounted on the northeast corner of the Kellogg Radiation Laboratory. It can still be found there today, quietly ticking away in the shade provided by the trees in Throop Memorial Garden.

APOLLO STATUE

When Throop Hall first opened, one of its inaugural visitors was Apollo Belvedere—or, rather, an exact copy of the classical sculpture of that name, whose original can be seen at the Vatican Museum. Apollo stood on a staircase in the entryway, guarding the hall for 30 years, a gift to one of the hall's architects, Elmer Gray, who decided to display sculpture in his newest achievement. When the staircase was remodeled in the 1940s, Apollo was moved to a balcony that connected Throop to Kellogg Lab. The balcony was a victim of the Throop demolition, but Apollo escaped, spending some time in the Dabney gardens, among other places, and eventually making his way to the Braun Athletic Center, where he still resides today, perhaps to serve as inspiration for those toiling away on stationary bicycles or heading out to the track. He is a Greek god, after all. e&s

To learn more about Throop Hall and its peripatetic pilasters and statues, check out:

- Caltech's Architectural Heritage: From Spanish Tile to Modern Stone *by Romy Wyllie (Balcony Press, 2000)*
- Raised Arches, or, You *Can* Go Home Again, E&S *(May 1986)*
- Caltech's Throop Hall *by Judith R. Goodstein and Alice Stone (California Institute of Technology, 1981)*



X-ray Vision

Caltech has played a central role in developing a powerful technique for revealing the molecular machinery of life and creating new types of medicine.

by Marcus Woo

In a speech given in 1959, Caltech legend Richard Feynman—the embodiment of the brash, know-it-all physicist—described his idea for tackling some of the biggest mysteries in biology. To understand how biological molecules like DNA and proteins work, he suggested, "You just *look at the thing.*"

The idea sounds obvious. After all, to understand how, say, an engine works, it helps to know what the thing looks like. To know how the molecular machinery of the cell works, it makes sense to look at the molecules in question. Feynman had been referring to the possibility of developing better electron microscopes to directly see these molecules. But even now, the best electron microscopes have their limitations.

So to infer the structure of molecules, chemists and biologists have been using a technique called X-ray crystallography, which allows them to visualize what those molecules look like, albeit indirectly. The tool is powerful, and for the last 100 years, researchers have used it to probe everything from small and simple compounds to increasingly large and complex proteins. Crystallography gave birth to the fields of structural chemistry and biology, both of which can claim much of their origins at Caltech, thanks to the pioneering work of two-time Nobel laureate Linus Pauling (PhD '25).

Today, Caltech researchers are continuing that legacy, using X-ray crystallography to determine the structures of molecules that are more complicated than even Pauling thought would be possible to analyze. In doing so, the researchers are not only uncovering the molecular processes central to life, they are also developing treatments for HIV and laying the foundation for future drugs.

There are many ways to study a molecule, but if you don't know its exact structure, your tools can only hint at what it looks like and how it works. It's as if you're blindfolded, says biochemist André Hoelz. X-ray crystallography, however, unveils the whole picture. "Someone takes off your blindfold, and you say, yeah it all makes sense," he says.

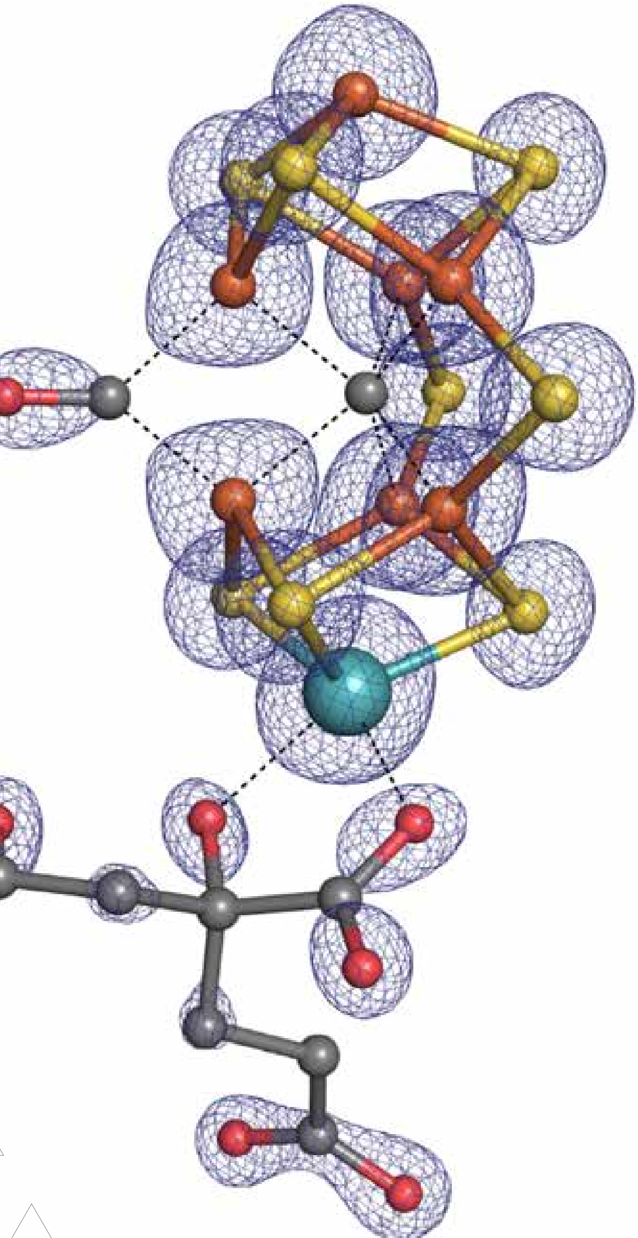
Unlike X-ray techniques whose images reveal a broken bone, X-ray crystallography doesn't produce an actual picture of molecules. It's an indirect method that involves shooting X-rays at a molecule and measuring how those rays scatter, data that can be used to establish the molecule's structure. It's the closest you can get to a photograph.

Molecules are tiny and often treated abstractly, relegated to the diagrams and ball-and-stick models you remember from chemistry class. But with X-ray crystallography, molecules become physical, tangible structures. Biochemist Bil Clemons compares the experience to that of a mountaineer seeing Mount Everest for the first time. "Until you've really engaged in it, you haven't really discovered it," Clemons says. To see is, in the most visceral sense, to discover.

The Birth of a Field

X-ray crystallography was discovered in 1912, when German physicist Max von Laue realized that the atoms of a crystal—or, more precisely, the electrons in those atoms—can deflect the trajectory of an incoming X-ray. When you blast a crystal with X-rays, the crystal diffracts

This schematic representation shows antibodies (magenta and purple Y-shaped objects) binding to spikes (gray solid objects) on the surface of HIV virions (gray mesh). High-resolution structural information from X-ray crystallography experiments is depicted by the structures of an antibody (magenta and light pink ribbons) binding to an HIV spike protein (gray ribbons) while also interacting with HIV carbohydrates (yellow, red, and blue ball-and-stick models).



Above, a figure from Doug Rees's research shows the active site of catalysis for nitrogenase, the enzyme responsible for biological nitrogen fixation. The mesh surface depicts the electron density map determined by X-ray crystallography, interpreted in terms of the molecular structure, which is shown as balls and sticks. Iron atoms are represented by rust-colored spheres, sulfur by yellow, carbon by dark gray, oxygen by red, and molybdenum by cyan. At right, André Hoelz inspects his laboratories' chromatography columns in a 4 degrees Celsius cold room. These columns are employed for the purification of nuclear pore complex proteins, called nucleoporins, which are then combined in a test tube to generate larger assemblies; those assemblies are then crystallized for X-ray crystallography.

the incoming beam. Von Laue didn't fully understand the resulting pattern of the diffracted X-rays, but researchers soon realized that the pattern was a fingerprint that reveals the unique structure of the crystal. He was awarded the Nobel Prize just two years later.

Arthur Amos Noyes, who in 1919 resigned from MIT to join full time the faculty of the school soon to be renamed Caltech, recognized the potential of this discovery. He established an X-ray crystallography lab where research was conducted that led to the first PhD awarded at Caltech, to Roscoe Gilkey Dickinson in 1920. Three years later, when Pauling arrived to work on his PhD with Dickinson, Caltech was already the best place outside of Europe to do crystallography. Following a brief stint abroad after earning his degree, Pauling returned to Pasadena, and his efforts to understand chemical structures and bonds would make Caltech the center of what's now known as structural chemistry.

The following decades were the golden age of the field, says chemist Doug Rees, whose own PhD adviser at Harvard, Nobel laureate William Lipscomb (PhD '46), was a student of Pauling's. "Almost anyone who became anyone in small-molecule crystallography and structural chemistry was here in Pasadena or studied with someone who had been here," Rees says.

Pauling moved from simple molecules toward the more complex ones involved in biology, using the same technique to help establish the field of structural biology. By the 1930s, thanks to the Nobel Prize–winning work of chemist James Sumner, biologists learned that proteins could be turned into crystals—which meant that crystallography wasn't just for simple compounds, but also for complex, biological molecules.

With the help of X-ray crystallography, Pauling uncovered the nature of the peptide bond, which holds together amino acids, the building blocks of proteins. In 1951, he and colleagues figured out the structures of alpha helix and the beta sheet, the two major structural components of proteins.

The discovery of the alpha helix blazed the trail for understanding more complex molecules and the structure of DNA, Rees says. In fact, Pauling was racing to solve DNA but was beaten in 1953 by James Watson, Frances Crick, and Rosalind Franklin and her X-ray diffraction measurements. Pauling had proposed a triple helix, instead of the correct double-helix structure.

Using X-ray crystallography, the Pasadena and Cambridge groups pioneered the structural approach, which, Rees says, is based on the thesis that, to understand how a molecule works, you have to know what it looks like. "That world view permeates everything that we do," he notes.

In 1939, Pauling had written that, given how long it took at the time to solve the structures of just a couple of amino acids, it might never be possible to determine the structure of an entire protein. Pauling was brilliant, Rees notes, but about this he was wrong. "Now, with time and technical advances, we're able to approach problems that were inconceivable in Pauling's time," he says.

Crystallography Today

In the past, the calculations needed to interpret X-ray diffraction patterns and solve molecular structures were the most time-consuming part of crystallography. Now, X-ray technology is constantly improving, with better detectors and with beams that can be controlled with greater and greater precision, allowing researchers to analyze bigger and more complex structures. Computers now take less than a second to do the math that once took weeks by hand. These advances have made crystallography nearly limitless in its potential, Hoelz says. Researchers can study as complex a system as they wish. "We pick a project and we make it happen," he says.

To aid in their experiments, Caltech researchers have access to the Molecular Observatory, which includes an automated X-ray beam line at the Stanford Synchrotron

Radiation Laboratory. The campus also has its own in-house macromolecular X-ray crystallography facility. The Macromolecular Crystallization Laboratory in the Beckman Institute provides automated and robotic facilities (yes, there are actual robots) to help researchers prepare their samples efficiently.

Such automated methods allow researchers to do experiments with much less sample material than before, and thus to solve more challenging problems. According to Clemons, in the roughly 15 years since he started doing crystallography the amount of sample protein needed has dropped by about 20-fold. Still, preparing and crystallizing samples is laborious, and is the hardest part of crystallography today.

In general, there are no rules that tell you how to crystallize proteins. Researchers must resort to trial and error, and even when they do find the right methods, the crystallization process often takes weeks to months.

The basics of crystallization, however, are simple enough. You can make your own crystals at home by dissolving sugar (a sample) in hot water (a solution). As the water cools, the sugar molecules come out of solution and arrange themselves in a regular pattern, forming a crystal. The same general process applies to crystallizing more complicated samples like proteins. But because such molecules are so big and complicated, it's hard to fit them together in an organized crystal structure. Stacking boxes is easy. But what if you had to stack chandeliers?

Gatekeepers

Hoelz, for example, is tackling one of the most elaborate structures of them all, a top-shaped behemoth called the nuclear pore complex. This structure acts as the gatekeeper of a cell's nucleus, which contains the organism's DNA—the genetic blueprint for all the proteins that enable the cell to function.

Whenever the cell needs a protein to complete a task, a signaling molecule is sent to the nucleus, where the genetic instructions for building that protein are read and sent back out in the form of a molecule called messenger RNA. The protein is then synthesized outside the nucleus in the cytoplasm. The nuclear pore complex ensures that the signals get into the nucleus and the messenger RNA gets out. Many other kinds of molecules go in and out of the nucleus, including up to 40 percent of all proteins, Hoelz says. The nuclear pore complex is the portal through which they all must pass.

Finally understanding the structure of the nuclear pore complex could lead to a new class of cancer or antiviral medicine, Hoelz says. Some viruses, like HIV, hijack this structure to invade the nucleus, integrating themselves with the host's genome. If researchers can figure out how the nuclear pore complex works, then they might be able to design drugs to block such intruders.

The nuclear pore complex is enormous, containing roughly 10 million atoms. For comparison, the alpha helix that Pauling modeled contains fewer than two dozen atoms. "This is a totally different scale from what people have done in the past," Hoelz says.

In fact, it's so big and complicated that you can't use X-ray crystallography on the whole thing. The center of the complex can move, so if you try to do crystallography on the entire structure, the results are blurry, like when you try to take a picture of a squirming toddler.

So the researchers have to break it down into more than 1,000 components and solve the structure of each, one by one. Electron microscopy then provides a rough picture of the complex's overall shape, which helps them piece together the puzzle.

Some declared the nuclear pore complex too big to solve, Hoelz says. "People said, 'You're crazy. It'll take you forever to get any structures and any insight.'" But over the last 10 years, he and his colleagues have made tremendous progress, and he says they may be able to figure it all out in another 10 years.

Border Control

Meanwhile, Rees has already spent over three decades studying the structure of enzymes that help bacteria convert nitrogen—an important nutrient, but inert and useless in its gaseous form—into chemicals such as ammonia, which can be used by living organisms.

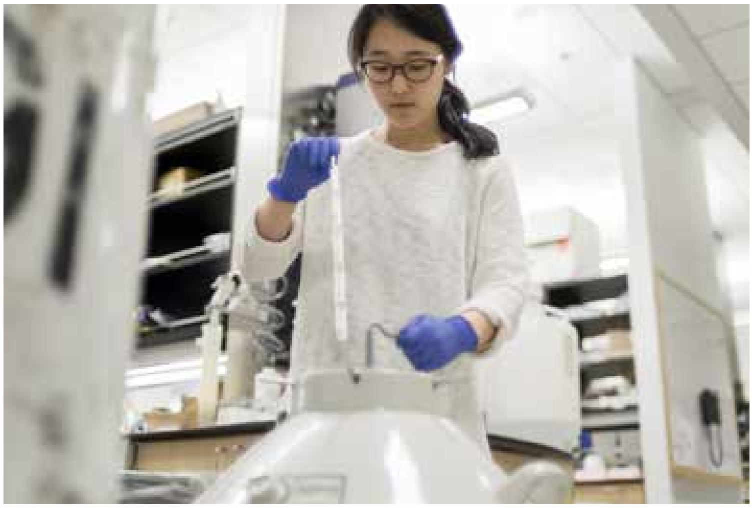
In addition, Rees focuses on molecules called membrane proteins. Sitting inside the cell membrane, which separates the cell from the outside world, these proteins act as border control, determining what can enter or exit. We have several thousand types in our body; about 30 percent of the genome encodes for these proteins.

And they're particularly challenging to study, says Clemons, whose research also focuses on membrane proteins, in particular those that control the comings and goings of other proteins. The layers inside the cell membrane are hydrophobic, meaning that, like oil, they don't adhere to water. Because membrane proteins are embedded inside these layers, they assume especially complicated structures that enable them to interact with the watery world outside the membrane as well as the oily interior.

Rees looks at membrane proteins called transporters, which control the passage of smaller molecules such as the amino acids, sugars, and other nutrients that come from food. He and his colleagues are trying to understand how transporters efficiently use energy to pump those molecules into the cell. They're also studying how the transporters themselves are regulated. As border-control agents, they have to know when, for instance, to turn away a particular nutrient if the cell already has enough.

Because membrane proteins play such a major role in the cell, many drugs are designed to alter their behavior, Clemons says. Studying them can thus lead to new and better drugs.

Transporters are particularly involved with drug resistance, Rees explains. One feature of cancer cells is that they often produce transporters specialized to pump out anticancer drugs that have entered the cell. By better understanding how these pumps work, researchers may be able to devise ways to inhibit these transporters and allow the anticancer drugs to attack the tumor.



At far left, Bil Clemons prepares a robot for setting up crystallization trials of proteins. At left, Hyun Gi Yun, a graduate student in the Clemons lab, retrieves frozen protein crystals from a liquid nitrogen storage vessel.

Fighting HIV

While much of structural biology is basic research that may eventually lead to new treatments for diseases, biologist Pamela Bjorkman is using X-ray crystallography to tackle HIV head-on by examining the structures of antibodies.

Antibodies are proteins that roam the body, hunting for foreign intruders. When an antibody finds such a pathogen, it latches on, preventing the invader from harming cells. A typical mammal can produce more than 10 thousand trillion antibodies to attack all kinds of enemies. But when it comes to HIV, the body has trouble mounting a defense. Although antibodies have two arms with which to grab onto the molecular spikes protruding from the outside shell of a virus, HIV has very few such spikes, making the distance between them hard to bridge. Plus, it mutates, moving the spikes around and changing their shapes, thwarting antibodies that try to attack it.

Still, some HIV patients can develop effective antibodies. Using a variety of tools including X-ray crystallography, Bjorkman is identifying what makes those rare antibodies successful. But because those antibodies are specific to unique strains of the HIV virus, they aren't able to defend against HIV in other patients. The idea, then, is that by learning how those antibodies work, researchers can engineer new ones able to defeat HIV. For example, Bjorkman and her team recently engineered antibody-based molecules that could grab one spike with both arms, an approach that shows strong promise.

Some antibodies are being tested in human clinical trials, but it's still too early to know how well they work, Bjorkman says. Lately, however, researchers have developed better ways to isolate unique antibodies. Before 2009, there were only four such antibodies known. Now there's about a hundred, giving researchers like Bjorkman much more to work with. "There's just been an explosion," she says.

A Frontline Tool

For an entire century, X-ray crystallography has continuously propelled science forward, particularly in chemistry and biology. As many as 29 Nobel Prizes arguably involve discoveries related to X-ray crystallography, according to the International Union of Crystallography. Crystallography has even made its way to Mars. In 2012, the Curiosity rover used X-rays to analyze minerals in the martian soil, finding that it's similar to the volcanic grains found in Hawaii.

Right now, crystallography provides great snapshots of molecular structure. But such pictures are only equivalent to still photographs. "My dream in the end is that we have a movie," Hoelz says. Researchers like him hope to eventually be able to take sequential measurements of biological molecules in action. Then they can play the sequence and watch the molecular motions of life unfold before their very eyes.

X-ray crystallography is still but one technique. Researchers rely on many others, as well as ingenuity and good old-fashioned hard work. But as a single bread-and-butter tool, nothing beats crystallography, Rees says. "For 100 years, crystallography has been the frontline tool for solving structures," he says. "I think that will always be the case." e&s

Pamela Bjorkman is the Max Delbruck Professor of Biology and an investigator with the Howard Hughes Medical Institute. Her research is funded by the National Institutes of Health (NIH) and the Bill and Melinda Gates Foundation.

Bil Clemons is a professor of biochemistry. His work is supported by the NIH National Institute of General Medical Sciences.

André Hoelz is an assistant professor of biochemistry. His work is funded by the NIH, the Sidney Kimmel Foundation for Cancer Research, the Leukemia and Lymphoma Society, The V Foundation for Cancer Research, and the Edward Mallinckrodt, Jr Foundation.

Doug Rees is the Roscoe Gilkey Dickinson Professor of Chemistry and an investigator with the Howard Hughes Medical Institute. His work is funded by the NIH and the Howard Hughes Medical Institute.

LAUNCH POINTS

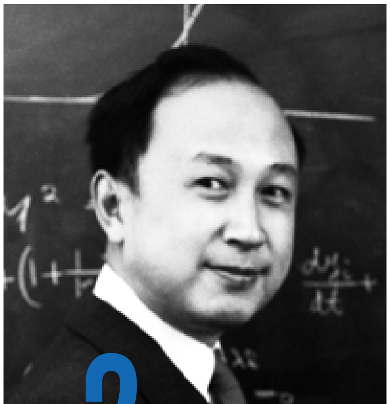
From a ragtag group of rocketeers shooting off their latest creations in Pasadena's Arroyo Seco, to a world leader in space exploration capable of sending a spacecraft into interstellar space and landing a car-sized robotic rover on Mars, the Jet Propulsion Laboratory has come a long way in 78 years. The path it has followed has not been straightforward—the Lab's history is full of twists and turns. Here, we look at several bites of that history, which just might contain a nugget or two you didn't know.

THE SUICIDE SQUAD

JPL traces its roots to a small band of young experimenters who started testing their handmade rocket engines in Pasadena's Arroyo Seco on Halloween day in 1936. The crew initially came together at Caltech, with the core group consisting of Frank Malina (MS ME '35, MS AE '36, PhD AE '40), a graduate student who worked for Theodore von Kármán, then director of GALCIT (at that time the Guggenheim Aeronautical Laboratory at Caltech); and two local, self-taught rocket enthusiasts, Jack Parsons and Edward Forman.

According to JPL's historian, Erik Conway, after the rocketeers completed a number of successful tests in the Arroyo, von Kármán was encouraged enough to give them space for a test facility at Caltech. When the group set off a couple of explosions there, including a detonation that launched a piece of a gauge straight into one of GALCIT's walls, Conway says, people on campus started referring to them as the Suicide Squad. Soon enough the squad was asked to do their work elsewhere and landed back in the Arroyo, where they leased some land from the city of Pasadena.

The crew went on to secure funding from the National Academy of Sciences to develop what would be known as Jet-Assisted Take-Off (JATO) rockets, which gave airplanes extra oomph while taking off from short runways. That work eventually led, in 1944, to the formation of the Jet Propulsion Laboratory.



2 THE FATHER OF THE CHINESE SPACE PROGRAM

The Suicide Squad's efforts spawned several important innovations, not the least of which was the development by Parsons of the first castable solid propellants, which made rocket motors more stable and storable. Conway says that later JPLers improved upon the original design, paving the way for the solid rocket motors that were used, for example, to help launch the space shuttles.

A lesser-known aspect of JPL's origin story is the journey of Tsien Hsue-shen (PhD '39), or Qian Xuesen as currently transliterated. Originally from China, Tsien was one of a handful of students to join the Suicide Squad in its early years and was one of the authors of the proposal submitted to the U.S. Army in 1943 that first used the name Jet Propulsion Laboratory. He went on to advise the Army on ballistic-missile guidance during World War II and later debriefed Nazi rocket scientists as a temporary lieutenant colonel. During the McCarthy era, Tsien was accused of having Communist leanings and had his security clearance revoked. When he tried to return to China, the U.S. government held him under virtual house arrest, but he was eventually able to go home. In China, he applied his vast knowledge of aerodynamics and rocket propulsion, and through his work became known as the father of the Chinese missile and space programs.

4 FROM ROCKETS TO PLANETS

In 1958, shortly after Explorer 1's success, William Pickering, the Lab's director at the time, and members of his senior staff decided that JPL's future lay in interplanetary exploration. While it was clear that there would be competition from private companies in rocketry and Earth satellites, the planets were a wide-open field. "It made sense for them to go into business where there was no business," says Conway.

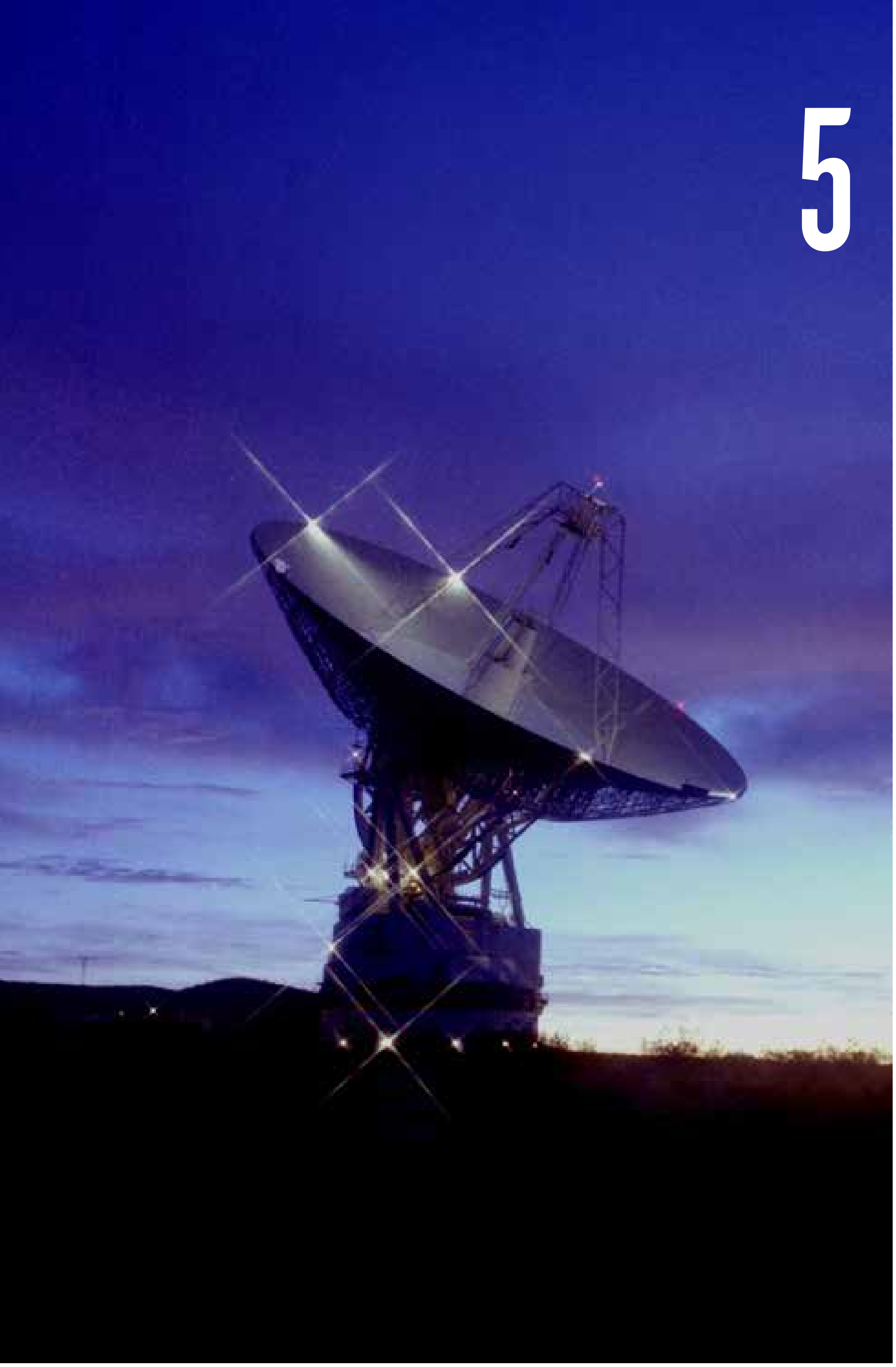
The new focus was also ideal in light of the fact that Pickering and Caltech's president at the time, Lee DuBridge, sought to shift the Lab's work away from military research toward science. President Dwight Eisenhower made JPL part of NASA, and the Army officially transferred JPL to the new space agency in December 1958.

3 THE RAPID BIRTH OF EXPLORER 1

Shortly after the Soviet Union shocked the world by launching Sputnik, the first artificial satellite, into low Earth orbit on October 4, 1957, JPL was commissioned to develop America's response. The Lab stepped up to the challenge and delivered Explorer 1 in a shockingly short 84 days. The accelerated delivery was enabled not only by an around-the-clock effort but also by work that JPL and the Army Ballistic Missile Agency (ABMA) had already conducted beginning in 1955 as part of a confidential reentry test vehicle program.

The project was aimed at proving that a heat shield could protect warheads from burning up upon reentry into Earth's atmosphere. JPL built the upper stages of the new vehicle for the program, as well as a tracking system, and ABMA provided the rocket booster. In all, the program built nine sets of hardware, but after three tests—the last, on August 8, 1957, being completely successful—everyone was satisfied that the technology worked, and the unused equipment was placed in storage.

When JPL got the go-ahead to begin working on an orbiting satellite, they were able to pull out that technology and hit the ground running.



5

MISSION: COMMUNICATION

When engineers at JPL first started considering how to bring data back from planetary spacecraft in 1958, the first thing they did was ask Caltech astronomer John Bolton for a survey of the state of the art in radio telescope technology. They knew that in order to track spacecraft, they were going to be seeking relatively faint signals from space—just the type of thing radio astronomers were doing. Bolton had just written a paper on the topic that had not yet been published and was able to immediately provide the engineers with the information they needed to start piecing together a network that could help them track and keep in touch with spacecraft as Earth continued to rotate.

Today, JPL operates what is known as the Deep Space Network (DSN), with locations near Madrid, Spain; near Canberra, Australia; and at Goldstone, California. With multiple antennas at each location, the DSN supports all interplanetary spacecraft missions and some Earth-orbiting missions, providing a crucial link between Earth and our robotic emissaries in space.

6

THE CENTER OF THE UNIVERSE

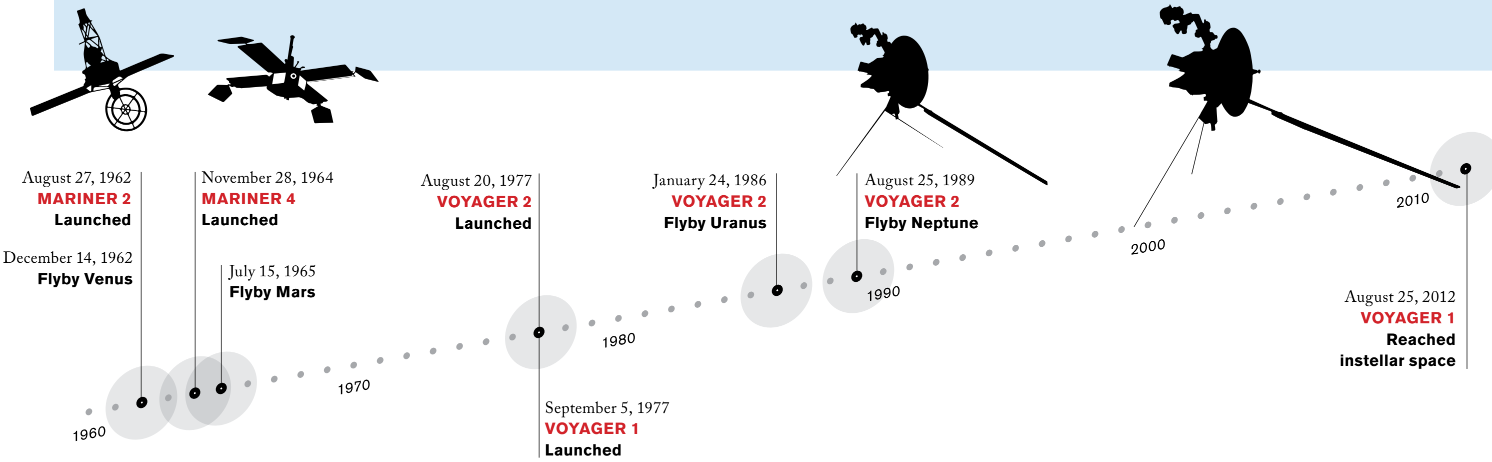
JPL's Space Flight Operations Facility, also known as the SFOF—pronounced "essfof"—or as Building 230, is the central hub for the DSN. The facility is a designated National Historic Landmark and is on the National Register of Historic Places. A plaque in the middle of the room dubs the location, half-jokingly, "The Center of the Universe."

7

THE LUCKY PEANUTS

On July 28, 1964, launch day for the Ranger 7 lunar impactor, tensions were running high in JPL's mission operations room. The previous six spacecraft in the Ranger series had failed, and Dick Wallace, a mission trajectory engineer for the mission, thought handing out peanuts might dissipate some anxiety.

Ranger 7 succeeded beautifully, and now the lucky peanuts show up in mission control not only during launches but leading up to just about any risky maneuver. You might have noticed copious amounts of peanuts being handed out and consumed during the hair-raising landing of the Mars Science Laboratory in August 2012.



8 GOT THERE FIRST

Since its serendipitous yet second-place showing in the satellite space race set JPL on its current course of planetary missions, the Lab has seen a lot of firsts. The missions above, designed, built, and managed by JPL, propelled inaugural visits to Venus, Mars, Neptune, Uranus, and interstellar space.

9 THE FIRST CLOSE-UP OF MARS

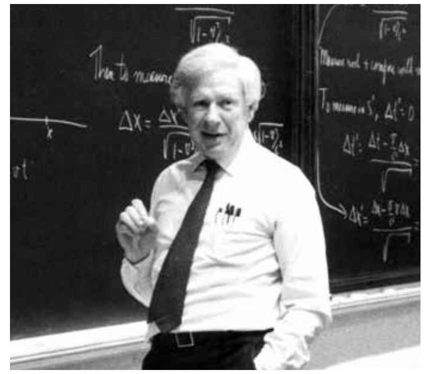
In July 1965, JPL and the world were anxiously awaiting the first close-up image of the Red Planet, which would be delivered by Mariner 4. The spacecraft flew by Mars on July 15 and started transmitting the pictures it took the next day at a frustratingly slow rate of eight and a third bits per second. Once the data had been received, the image still had to be processed. Getting impatient, members of the Mariner team started stapling to the wall strips of data related to one of the transmitted images, and coloring them by hand based on the brightness values of the pixels. That paint-by-number creation hangs today in Building 186 and is known as the “first image of Mars.”

10 THE ULTIMATE JPL WALKABOUT

As JPL has grown and has continued to expand its role in space exploration, the number of buildings on its 177-acre site has increased in tandem. All of the facilities are assigned a number according to the order in which they were built. Buildings 1 through 10 no longer exist, so Building 11, constructed in 1943, is the oldest on JPL’s campus. Building 349, the Arroyo Parking Structure, is the newest.

In 2012, JPL graphic designer Luke Johnson decided to go on a tour of the buildings in numerical order. The walk that he thought he might complete in an afternoon ended up taking him on a 52.2-mile hike over four days. After his walkabout, he collaborated with a team of designers to create a map that is handed out to all new JPL hires. It includes highlights about what can be found in various buildings on campus. For example, the atomic clock housed in Building 298 is one of the world’s most stable clocks. e&s

Marvin L. Goldberger 1922–2014



Marvin L. "Murph" Goldberger, Caltech president and professor of theoretical physics, emeritus, passed away on November 26, 2014. He was 92.

A Chicago native, Goldberger received his BS from the Carnegie Institute of Technology (now Carnegie Mellon University) in 1943 and, in 1948, his PhD in physics from the University of Chicago, where he later served as a professor of physics. In 1957, he was named Higgins Professor of Mathematical Physics at Princeton where he remained until 1978, when he was named Caltech's fifth president and a professor of theoretical physics.

During his tenure as president, Goldberger helped to spearhead the development of the first 10-meter telescope at the W. M. Keck Observatory in Hawaii—that telescope and its twin are the largest optical telescopes in the world—and he worked to secure the support of the Arnold and Mabel Beckman Foundation to build the Beckman Institute. While Goldberger was in office, Caltech's endowment more than doubled. In addition, the Institute's teaching standards were revised and the curriculum was restructured, and the undergraduate houses were renovated.

The recipient of numerous awards and academic honors, including the Dannie Heineman Prize for Mathematical Physics, the Presidential Award of the New York Academy of Sciences, and the Leonard I. Beerman Peace and Justice Award, Goldberger was a member of the National Academy of Sciences, the American Physical Society, the American Association for the Advancement of Science, the American Academy of Arts and Sciences, the American Philosophical Society; served as cochairman of the National Research Council; and was a member of the Council on Foreign Relations, the Institute on Global Conflict and Cooperation International Advisory Board, and the President's Science Advisory Committee.

Goldberger was predeceased by his wife, Mildred Goldberger, in 2006. He is survived by his sons, Joel and Sam, and three granddaughters, Nicole, Natalie, and Natasha.

To learn more about Goldberger's life and work, visit caltech.edu/news/marvin-l-murph-goldberger-44963.

Gerry Neugebauer 1932–2014

Gerry Neugebauer, Caltech's Robert Andrews Millikan Professor of Physics, Emeritus, and one of the founders of the field of infrared astronomy, passed away on September 26, 2014. He was 82.

Neugebauer earned an AB in physics from Cornell University in 1954 and a PhD in physics from Caltech in 1960. He then served two years in the United States Army, stationed at the Jet Propulsion Laboratory, before returning to Caltech in 1962 as an assistant professor of physics. He was named an associate professor in 1965, professor in 1970, Howard Hughes Professor in 1985, and Millikan Professor in 1996. He retired in 1998.

He served as the director of the Palomar Observatory from 1980 to 1994 and as the chair of the Division of Physics, Mathematics and Astronomy from 1988 to 1993.

In addition to his leadership of the Two-Micron Sky Survey—the first infrared survey of the sky—Neugebauer led the science team for the first orbiting infrared observatory, the Infrared Astronomical Satellite, which conducted the first far-infrared sky survey and detected hundreds of thousands of objects. He and his colleagues also obtained the first infrared view of the galactic center, and he was the codiscoverer of the Becklin-Neugebauer Object, a massive but compact and intensely bright newly forming star in the Orion Nebula, previously undetected at other wavelengths of light.

Neugebauer also played a key role in the design and construction of the W. M. Keck Observatory in Hawaii.

He was a member of the National Academy of Sciences, the American Philosophical Society, and the American Academy of Arts and Sciences, and was a fellow of the Royal Astronomical Society.

He is survived by his wife, Marcia Neugebauer, a geophysicist at JPL; daughters Carol Kaplan and Lee Neugebauer; and two granddaughters.

To learn more about Gerry Neugebauer's life and work, visit caltech.edu/content/remembering-gerry-neugebauer.

Ray D. Owen 1915–2014

Immunology pioneer Ray D. Owen, professor of biology, emeritus, at Caltech, passed away on September 21, 2014. He was 98.

Owen's major scientific contribution was his discovery, in 1945, of immunological tolerance in twin cattle. Using blood typing, he recognized that one of a set of fraternal twin cattle had no immune response to the foreign antigens (substances that provoke an immune response) introduced from their twins. The finding paved the way for the experimental induction of tolerance through immune suppression and for early tissue grafting—which initiated the era of organ transplantation. His later work included studies on human antibodies, the evolution of immune systems, and the genetic analysis of the major histocompatibility complex of the mouse.

In 1937, he received a BS from Carroll College in Waukesha, Wisconsin, and in 1941, earned a PhD in genetics from the University of Wisconsin. Owen became an associate professor at Caltech in 1947, was promoted to full professor in 1953, and became professor emeritus in 1983. He served as chairman of the Division of Biology from 1961 to 1968 and as vice president for student affairs and dean of students from 1975 to 1980.

He chaired the ad hoc "Committee on the Freshman Year" that spearheaded the effort to admit female undergraduates to Caltech; in 1970, the first female students enrolled.

At Caltech, Owen was honored for teaching excellence by the Associated Students of the California Institute of Technology. He received the Thomas Hunt Morgan Medal from the Genetics Society of America in 1993, and was a member of the National Academy of Sciences, the American Academy of Arts and Sciences, and the American Philosophical Society, among others. As a scientist-member of the three-person President's Cancer Panel, he served as an advisor to Presidents Nixon and Ford.

Owen was predeceased by his wife, June, in 2013, and by a son, Griffith Hugh. He is survived by his son David.

To learn more about Ray Owen's life and work, visit caltech.edu/content/remembering-ray-d-owen-1915-2014.

Thomas A. Tombrello 1936–2014

Thomas A. Tombrello, Caltech's Robert H. Goddard Professor of Physics, passed away on September 23, 2014. He was 78.

Tombrello was an expert in the application of theoretical and experimental physics to problems in materials science, surface physics, and planetary science. His research studies included understanding the damage processes caused by megavolt ions in solids, characterizing the sputtering of materials by low-energy ions as well as growing and studying novel light-emitting materials.

A native of Texas, he received his bachelor of arts degree in physics in 1958, his master's degree in physics in 1960, and his doctoral degree in physics in 1961, all from Rice University. He was a research fellow at Caltech from 1961–1963, then an assistant professor at Yale University from 1963–1964 before returning to Caltech, again as a research fellow. He was named assistant professor of physics in 1965; associate professor in 1967; professor in 1971; William R. Kenan, Jr. Professor of Physics in 1997; and Robert H. Goddard Professor of Physics in 2012.

He served as the chair of the Division of Physics, Mathematics and Astronomy from 1998 to 2008.

Tombrello was a fellow of the American Physical Society and the recipient of an honorary doctor of philosophy from Uppsala University. At Caltech, he was noted for his commitment to student education, receiving awards for teaching excellence from the Associated Students of the California Institute of Technology for 1982–1983 and 1986–1987, and, in 1994, the inaugural Richard P. Feynman Prize for Excellence in Teaching, given annually to a teacher who exhibits "unusual ability, creativity, and innovation in teaching."

Tombrello is survived by his second wife, Stephanie; his first wife, Ann, and their children, Christopher Tombrello, Susan Tombrello, and Karen Burgess; and seven grandchildren. He was predeceased by his stepdaughter, Kerstin.

To learn more about Tom Tombrello's life and work, visit caltech.edu/content/remembering-tom-tombrello.

WHAT STARTED FOR YOU AT CALTECH?

We asked alumni to share what originated for them at Caltech. Here is what a few of them had to say.

My four years of **football provided insight about team effort,** which was very useful in my career as a program manager at the former Hughes Aircraft Company!

I met my wife through the Caltech all-student musical *The Castle*. Forty-three years, four children, and three grandchildren later, it is beginning to look like a **long-term relationship**.

MY REALIZATION that computers and computer science would transform society.

The recognition that, while **I am smarter than the average bear**, there are a lot of bears that are smarter than I.

Everything.

In retrospect, **my fascination with the campus layout** and design was probably an indicator that I'd be working as an urban planner now.

My passion to try to **understand the universe**.

The desire to develop a **new theory of physics** that is physically understandable.

I simply started to understand that **there were others like me**, that I could have a community.

I had always loved symphonic music, but the chamber music concerts at Dabney Lounge and the lending record library introduced me to what became and has remained **my favorite genre**.

The idea that a well-designed anything—material, experiment, device—should not be just efficient, or adequate, or functional, but **DEEPLY ELEGANT**, and that it is possible to recognize that quality.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