Spring 2018

Caltech magazine

Rocky Worlds

ALSO:

LIGO lessons

The flies of Mono Lake

Alumni take on the world of sports

INSIDE

Kip Thorne (BS '62), Caltech's Richard P. Feynman Professor of Theoretical Physics, Emeritus, and Barry Barish, Caltech's Ronald and Maxine Linde Professor of Physics, Emeritus, stroll along the Olive Walk after a reception at the Athenaeum on October 3 to recognize the awarding of the 2017 Nobel Prize in Physics, which they shared with MIT's Rainer Weiss for their successful development of the Laser Interferometer Gravitational-wave Observatory (LIGO). For more on LIGO and what it has revealed to those working on the project, see page 28.

Contents

Features

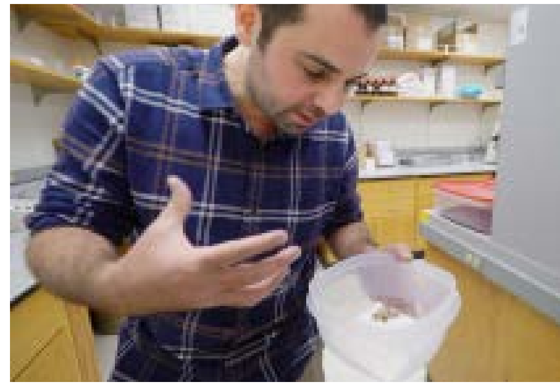
Departments

On the cover: Illustration of the TRAPPIST-1 planetary system, created by Robert Hurt and Tim Pyle.

Left: After graduation, Nasser Al-Rayes (BS '17) signed with the Al Sadd club in Doha, Qatar, fulfilling his dream of playing professional basketball. Read about him and other alumni in sports on page 22.

Online

Joe Parker talks beetles (video)



CTLO: A five-year history

How do they do it? The flies of Mono Lake (video)

Visit **magazine.caltech.edu**

Caltech magazine

EDITOR IN CHIEF
Lori Oliwenstein

SENIOR EDITOR
Judy Hill

DIRECTOR OF BUSINESS OPERATIONS
Doreese Norman

ART DIRECTOR AND DESIGNER
Jenny K. Somerville

ONLINE EDITOR
Jon Nalick

SOCIAL MEDIA COORDINATOR
Sharon Kaplan

CONTRIBUTING WRITERS
Whitney Clavin, Lori Dajose, Judy Hill, Jon Nalick, Robert Perkins, Jennifer Torres Siders, Emily Velasco

PHOTOGRAPHY AND VIDEOGRAPHY
Lance Hayashida, Peter Holderness, Jon Nalick, Jenny K. Somerville

COPY EDITORS
Sharon Kaplan, Carolyn Waldron

PRODUCED BY CALTECH'S OFFICE OF STRATEGIC COMMUNICATIONS
Farnaz Khadem, Chief Strategic Communications Officer

Above: Late-afternoon rays slip between the arches of the East Bridge colonnade.

Read *Caltech* magazine on the go at **magazine.caltech.edu**

Contact *Caltech* magazine at **magazine@caltech.edu**

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

Printed by Lithographix, Inc., Hawthorne, California.

Image Credits: NASA/JPL-Caltech/R. Hurt, T. Pyle (IPAC): cover, 26-27; FIBA: 2-3 (center), 23 (top); Karl Wm. Klein: 4; Ann Cutting: 5; Caltech Facilities: 7 (top, middle); Matthew Lester: 10; Caltech Optical Observatories: 13 (top); ZGF Architects: 13 (bottom); Steven Nass/ Wikimedia Commons: 14; Wikimedia Commons: 14 (background); Floris van Breugel/Caltech: 21; iStock.com/dnaveh: 22 (top); iStock.com/ IvonneW: 22 (bottom); courtesy Collin Murphy: 23 (top right); courtesy Dean Oliver: 24 (left); courtesy Arian Forouhar: 24 (middle); courtesy Ari Kaplan: 24 (right); iStock.com/Murmakova: 25; iStock. com/aelitta: 29 (right); Dan Tabata: 30; iStock.com/ gintas77: 31 (top); original by iStock.com/Mari-naMariya with edits by Dan Tabata: 31 (bottom); courtesy Alasdair McDowall: 34; courtesy of the Caltech Archives: 35 (top two); Lesley Nye: 35 (third from top); Brigitte Lacombe: 35 (bottom); iStock.com/RichVintage: 36 (top); iStock.com/ Popartic: 36 (left).

All other photos: Caltech

Letters

Pun Rationing

A Caltech alum details his experiences as a graduate student and punster.

… There was a core of residents [in David X. Marks House] who wanted to reduce my punning, and used their overwhelming plurality in numbers to impose upon me a numerical limit of three per day. They posted on a bulletin board in the lobby of the dorm a score sheet that listed the dates of the month, with three empty boxes next to each date. When someone heard me make a pun, an "x" was placed in a box for that day. I of course made every effort to meet my quota.

This scoring system was implemented for a couple of weeks before a revision was proposed. Someone—I daresay it was Dick, one of the physicists—declared that the system was flawed because not all puns were equal. The solution was a point system. It was decided that puns would be rated—one point, two points, or three points—with me receiving a 10-point daily limit.

But there was still the question of who would rate these puns, and the problem that not all residents evaluated puns identically. Those residents of Marks House who were present at the time the pun was made would offer their scores, and the arithmetical average (mean) would be used as the score, rounded to the nearest whole number. My bonus from rationing was that everyone was thinking puns all the time.

This system was soon found to be unwieldly. Residents lost interest in stopping whatever they were doing in order to vote on the score, and became disinterested in continuing the complicated scoring system. Thus ended the discriminatory period of pun rationing at Caltech. I was free to pun to my heart's content, un-pun-ished.

Ralph Y. Komai (MS '67)

SoCaltech

The iconic images by MIT's Harold Edgerton, inventor of the electronic flash, inspired **Ann Cutting** to find her own way to freeze time. Cutting, a technician in the Division of Biology and Biological Engineering, is also an award-winning photographer. To make this image, she released a drop of liquid into a shallow reservoir of water and captured the moment of impact with a synced high-speed strobe.

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

Four Questions for: Christy Salinas

Christy Lee Salinas, Caltech's new registrar, joined the Institute on December 1, 2017. Salinas, who grew up in Texas, has spent much of her career at colleges in Massachusetts, where she has managed student academic records, class scheduling, and degree auditing.

1. What is the scope of your job?

The Office of the Registrar oversees all of registration and grading, makes sure students are meeting all of their degree requirements, awards their degrees, works with the academic departments to ensure compliance, and supports department initiatives. Financial aid, athletics, and other departments are all dependent on registrar data and activities. The registrar's office is a huge resource to so many offices.

2. What are your goals as registrar?

My goals are to learn about "the Caltech way": to understand the culture, because the needs are unique here, and then to see if there is a way that I can use my experience and skill set to facilitate matters and prepare this school for the future.

3. What attracted you to Caltech?

I think I was most attracted to the community and the attention given to the student experience, which is the part that I enjoy the most. I was also attracted to being at a school small enough that I could get to know everyone, all the staff, every student, and help them throughout their journey to achieve their goals. These are people who are going to change the world. The students here are an inspiration because of how much they accomplish while they're here.

4. Why do you enjoy working with students?

I like seeing people who are working on their own goals and self-improvement. I was a student who had times when I was confused and didn't know what to do, and could have used some more guidance. I like to think of that when I am helping students. I focus on their experience and help them accomplish their goals.

For more of our conversation with Christy Salinas, go to **magazine.caltech.edu/post/christy-salinas**

"In bringing together Caltech's faculty, students, and researchers in this facility we will have the opportunity to enable even more powerful and meaningful interactions, which can lead to breakthroughs in our understanding of the inner workings of the brain."

—Steve Mayo (PhD '87), *William K. Bowes Jr. Leadership Chair of the Division of Biology and Biological Engineering and Bren Professor of Biology and Chemistry*

Chen Institute Breaks Ground

Caltech broke ground in December 2017 on the Tianqiao and Chrissy Chen Neuroscience Research Building, which will be located at the northwest corner of campus along Del Mar Boulevard and Wilson Avenue. The building is scheduled to open in the fall of 2020.

The three-story, 150,000-square-foot facility will house labs and offices for more than a dozen principal investigators and will be the administrative home of the Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech. The building will also house research support space, as well as a teaching lab and a 150-seat lecture hall. The research institute and building are both named in honor of the Chens, who donated $115 million to Caltech in December 2016 in support of advancing Caltech research in the field of neuroscience.

Object Lesson: Basic science

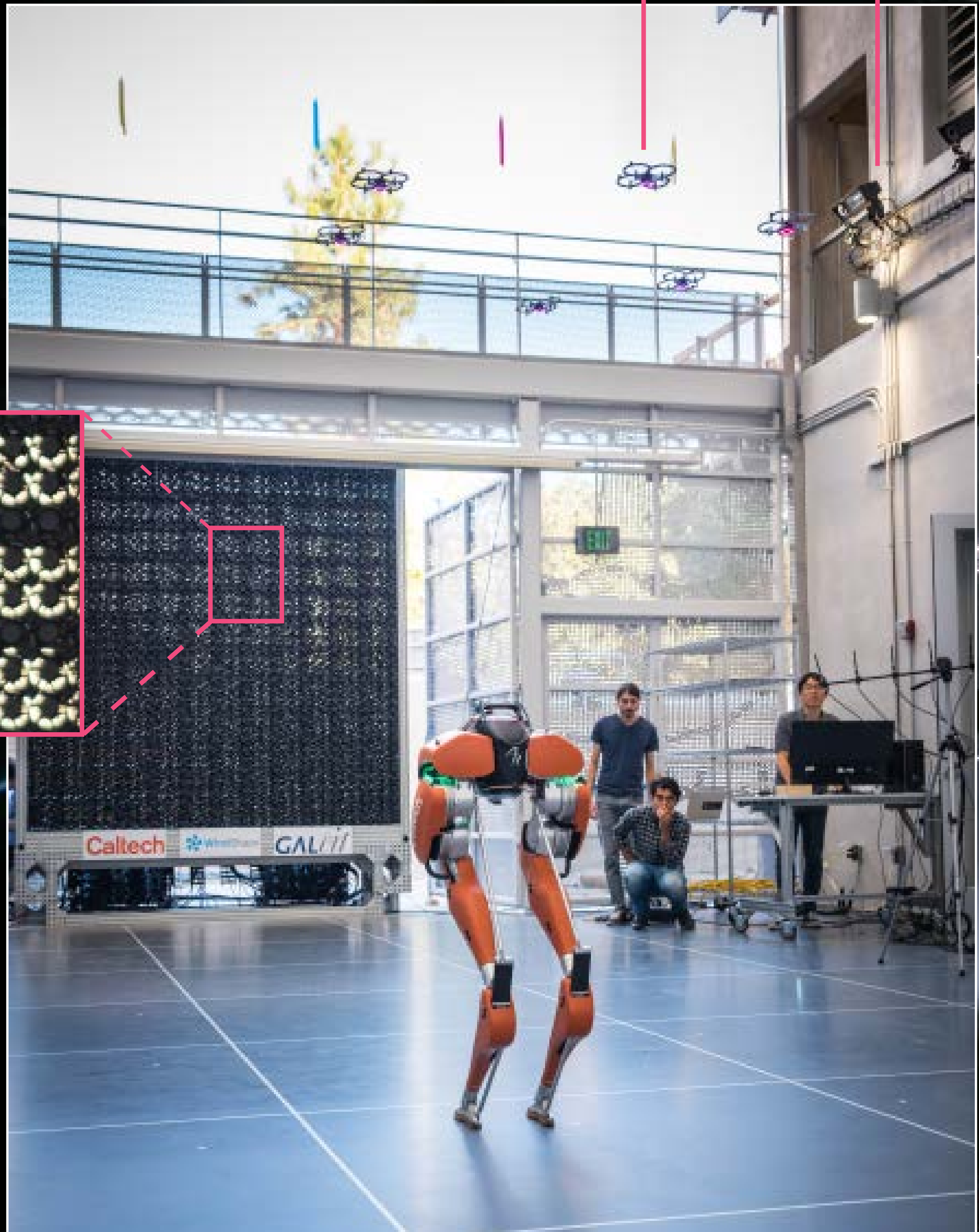
This simple drum microscope—on display in the Beckman Room, a science museum on campus that is open to the public on the first Friday of every month—dates from around 1850 and was a gift to the Institute from Donald S. Clark (BS '29), a Caltech metallurgist on the faculty from 1934 to 1975. The microscope is simple in that it has only one lens, in striking contrast to such highly sophisticated and complex instruments as the cryo-electron microscope featured in the Q&A with Caltech's Alasdair McDowall on page 32. Modern light microscopes have a magnification of around 1,000 to 2,000, compared to approximately 20 for a simple microscope of this era. "Our modern electron microscopes can magnify more than 500,000 times," notes McDowall, "and now, with the help of cool preparation techniques, extremely stable instruments, powerful cameras, and computers, can resolve the very building blocks of life."

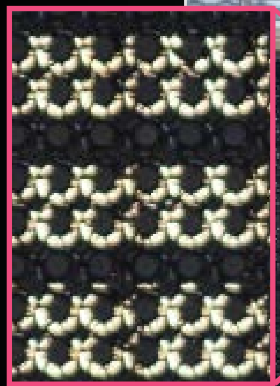
CAST:
A two-page tour

CAST's centerpiece is a three-story-tall, wholly enclosed aerodrome—the tallest of its kind—in which to test flying drones.

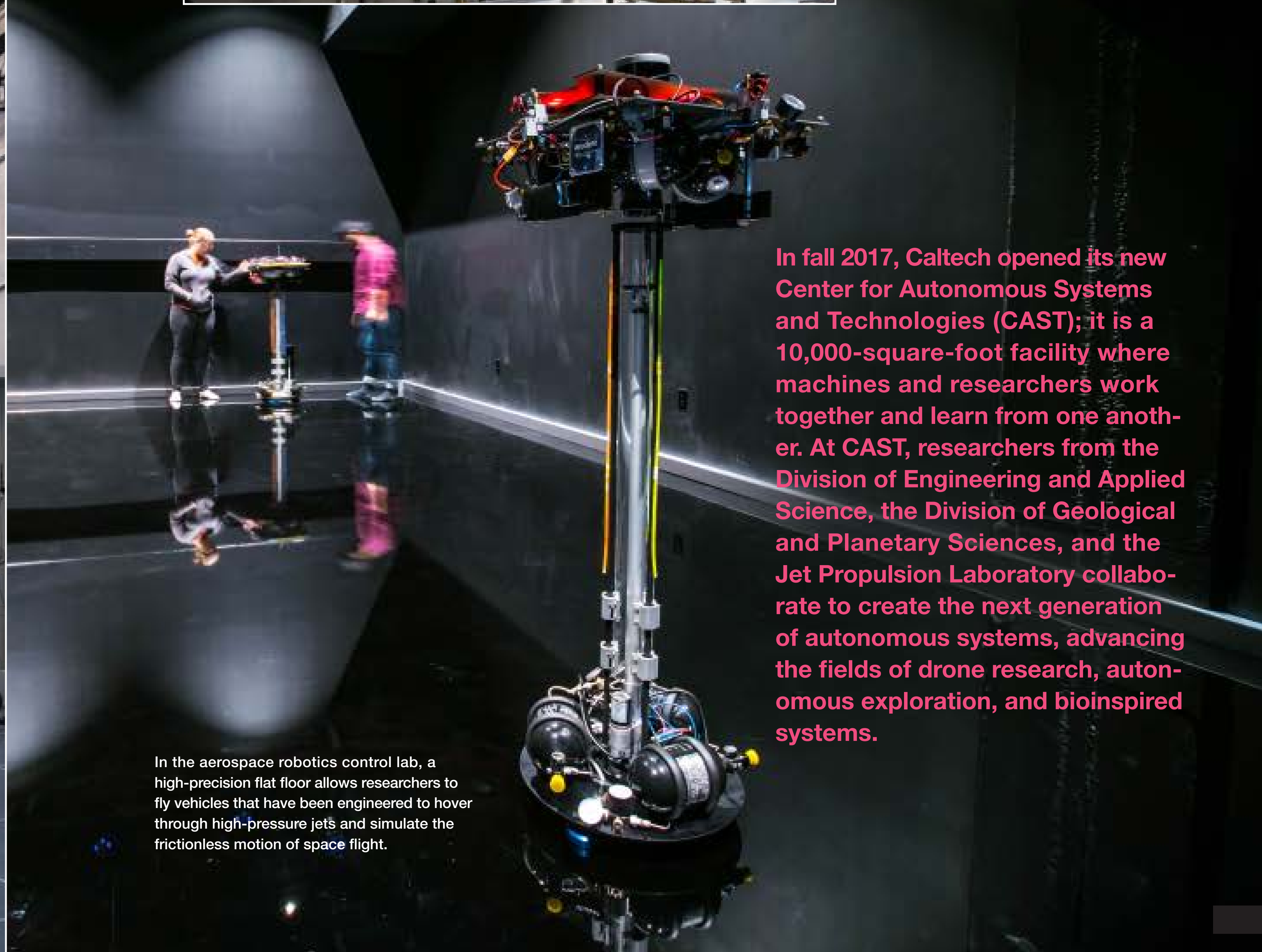
A total of 46 cameras provide complete coverage of the interior, tracking each robot's motion down to within 100 microns (about the thickness of a human hair).

The assembly room boasts a modular design and features an 85-foot-long overhead oval track for walking robots.





The aerodrome includes a wall of 1,296 fans, with a side wall of 324 fans to create a crosswind. The individually controllable fans can generate any type of wind that flying vehicles will face in the real world—from a light gust to a stormy vortex. The wall can also be tilted 90 degrees to simulate vertical takeoffs and landings. Bipedal robot Cassie struts her stuff in the foreground.



In the aerospace robotics control lab, a high-precision flat floor allows researchers to fly vehicles that have been engineered to hover through high-pressure jets and simulate the frictionless motion of space flight.

In fall 2017, Caltech opened its new Center for Autonomous Systems and Technologies (CAST); it is a 10,000-square-foot facility where machines and researchers work together and learn from one another. At CAST, researchers from the Division of Engineering and Applied Science, the Division of Geological and Planetary Sciences, and the Jet Propulsion Laboratory collaborate to create the next generation of autonomous systems, advancing the fields of drone research, autonomous exploration, and bioinspired systems.

A season of firsts:

Women's soccer takes the field at Caltech

Fall 2017 marked the launch of Caltech's first-ever women's soccer program, coached by Taylor Houck, a onetime professional soccer player and former coach at Oberlin College. Director of Athletics Betsy Mitchell, a driving force behind the establishment of the new program, says the players are "vocal and vibrant and engaged," and the addition of the program has had an energizing effect on the entire athletic department. Highlighted below are a few of the team's firsts.

First game:

September 1

The team's first match under the lights with a full crowd was an away game against the University of Redlands.

First goal:

September 13

The team's first goal came against Alvernia University in Reading, PA, with freshman midfielder Krystin Brown scoring two minutes into the second half of the game.

First win:

October 6

Their first win—an 8-0 victory—came during a home game against nearby Shepherd University, another first-year women's soccer program.

First time they really saw the future of the program:

October 9

The team regards their game against Whittier College to be their season's greatest victory . . . despite the fact that they were edged out 2-1. The Caltech players were proud of how hard they pushed their opponents (who went on to win the SCIAC title) and of how close they came to winning. "No one would expect a first-year program to play on such a competitive level," says Houck. "The women had a bravado about them after that."

For more on the women's soccer program at Caltech, go to **magazine.caltech.edu/post/a-season-of-firsts**

Joe Parker, entomologist, collector

New assistant biology professor Joe Parker is an entomologist interested in the mechanisms underlying evolutionary change, particularly those that involve symbiosis, the intimate, cooperative relationships between different species. In particular, he looks at rove beetles (*Staphylinidae*), a species-rich group of organisms that have repeatedly evolved symbioses with ants.

Recently, Parker talked with *Caltech* magazine about how his fascination with insects took off when he was a child growing up in Wales:

"I've been obsessed with insects fanatically since I was 7 years old. When you're that age you're impressed by big, flashy insects, which to this day I still sometimes find hard to resist collecting.

"At home in Wales I have a big insect collection I accumulated as a kid, and I used to keep all of these tropical species in my bedroom: scorpions, tarantulas, giant African land snails, hissing cockroaches, katydids. I had maybe 10 aquariums with tungsten light bulbs heating all these tropical insects in the cold Welsh climate. I used to go to sleep at night with the aquarium light bulbs blazing, hiding under the covers so I could sleep!

"Over time I became more focused on beetles in particular. Then, when I was 16, I collected my first specimen of these rove beetles that have this symbiosis with ants. Suddenly, all the other insects seemed a little bit less interesting."

Watch Joe Parker talk about his research at **magazine.caltech.edu/post/joe-parker**

From the Caltech Archives Oral History Project

To date, the oral history project has published more than 160 interviews. Read them at **oralhistories.library.caltech.edu**

> "In my chemistry classes, it was a combination of stuff I brought in with demos and stuff the students did. They rigged up the Tom Lehrer audio. They invited the Hare Krishna chanter. I put up with all of it, and we just had a great time together. The great thing was that if you weren't in 22 Gates at 10:30 a.m. for an 11 o'clock class, you didn't get a seat."
>
> – Harry Gray, *Arnold O. Beckman Professor of Chemistry and winner of the 2018 Richard P. Feynman Prize for Excellence in Teaching*

Matthew Orr
(fourth-year graduate student)

Caltech has launched #SoCaltech*, a social media series designed to celebrate the diverse individuals who give Caltech its spirit of excellence, ambition, and ingenuity. Matthew Orr, a fourth-year graduate student in the Theoretical Astrophysics Including Relativity and Cosmology (TAPIR) group, kicks off the series. Orr also serves as strategic communications chair for Caltech's Graduate Student Council.*

"On one of my recent projects, I spent an hour or two at Copa Vida in Old Town Pasadena trying to work out how I thought a very specific part of the galaxy might regulate itself. I took my work back to campus when free parking was over, and I plotted it up on my laptop and compared it with real observations and the simulations our group runs, and ... if it didn't line right up! I was only tentatively extremely excited because, more than once, I had taken a plot to my adviser, and he'd look at it and say, 'Oh, this can't possibly be right.' So, I took some time to work through some little sanity checks before I brought it down the hall. As it turned out, it seemed to do all right at describing line-of-sight velocity dispersions, star formation rate, and star formation efficiency in galaxies, which is not something you wake up every day and do. To take a couple of lines of algebra and some intuition, and make some statements about how star factories in the universe work is, to me, pretty exciting."

For more #SoCaltech, go to **magazine.caltech.edu/post?tag=%23SoCaltech**

Surveying the dynamic universe

This image shows the Horsehead nebula. The head of the horse (middle) faces up toward another well-known nebula known as the Flame. Computers searching these images for transient, or variable, events are trained to automatically recognize and ignore non-astronomical sources, such as the vertical lines seen here.

A new robotic camera with the ability to capture hundreds of thousands of stars and galaxies in a single shot took its first image of the sky—an event astronomers refer to as "first light"—on November 1, 2017.

The recently installed camera is part of a new automated sky-survey project called the Zwicky Transient Facility (ZTF), based at Caltech's Palomar Observatory in the mountains near San Diego. Every night, ZTF scans a huge swath of the northern sky, discovering objects that erupt or vary in brightness, including exploding stars (also known as supernovas), asteroids, and comets.

"ZTF surveys the dynamic universe unlike ever before," says Mansi Kasliwal, assistant professor of astronomy at Caltech and a member of the ZTF team. "It will give us a treasure trove of discoveries."

From the *This Is Caltech 2018* overview book:

"A careful attention to how things came to be imbues us with an appreciation for the possibilities of what might have been and opens us up to questions that people caught up in the current moment might forget to ask."

—Maura Dykstra, assistant professor of history

Read *This Is Caltech 2018* at **caltech.edu/content/overview**

Building community

This fall, undergraduate students from all four years will move into the Bechtel Residence. The new building is rapidly nearing completion on the north side of campus.

1st new student residence in more than two decades

1st time in Institute history that all undergraduates may live on campus

212 beds

95,000 square feet

6 structures built around a central courtyard

8 different room configurations [from singles to suites]

7 goals for residential life created by student committee:

- intellectual growth
- mentorship
- diversity
- identity
- support
- honor code
- choice

To learn more about the Bechtel Residence, visit **magazine.caltech.edu/post/bechtel**

Rethinking Redistricting

This year, as the U.S. Supreme Court tackles a slew of hot-button topics, its justices are receiving advice from two Caltech professors on an issue with huge implications for the nation's politics: partisan gerrymandering.

Morgan Kousser, the William R. Kenan, Jr., Professor of History and Social Science, along with Jonathan N. Katz, the Kay Sugahara Professor of Social Sciences and Statistics (both from the Division of the Humanities and Social Sciences), have helped prepare amicus curiae briefs in support of a group of voters from Wisconsin suing their state over an electoral map they say deprives them of their political voice.

That case stems from 2011, when Republicans redrew Wisconsin state-assembly districts in a manner alleged to keep Democrats out of power. In the 2012 election, Republicans gained 60 percent of the seats in the assembly while only receiving 49 percent of total votes cast.

In response, 12 Democratic voters in the state filed a lawsuit seeking to have the Republican-drawn map declared unconstitutional. When the plaintiffs prevailed in district court, the state appealed to the Supreme Court, which agreed to take up the case. Oral arguments were held in October 2017 with a decision expected in 2018.

Though Kousser and Katz have sometimes found themselves on opposite sides of cases, they are in agreement on the negative effects of partisan gerrymandering, which is achieved by adjusting the boundaries of districts to gain desired electoral outcomes—such as diluting the voting power of a racial or ethnic group, protecting incumbents from losing their seats to challengers, or keeping one political party in power.

Advances in computing technology have made gerrymandering much more effective, say Kousser and Katz. "They used to draw districts by hand using a slide rule," Kousser says. "Now you can create 10,000 district plans with a computer." Big data has also made it much easier for politicians to target which voters they want in a district, almost to the household level.

The last time a political gerrymandering case reached the Supreme Court, in 2004, a split court ruled against the voters, with swing voter Anthony Kennedy saying he believed partisan gerrymandering is an issue the court should decide if someone could develop an objective way to measure it. This is where Katz and Kousser come in.

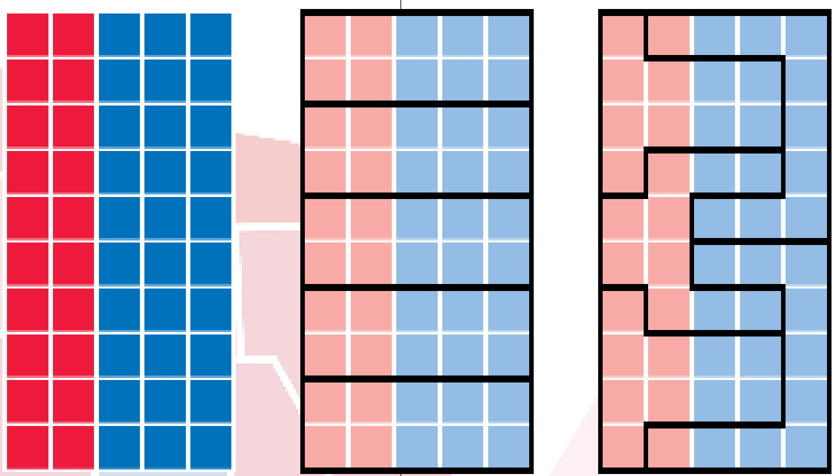
Kousser's brief lays out a case that gerrymandering in its modern form is a serious threat to democracy in the United States, and implores the court to step into an area where it has traditionally been reluctant.

"The argument we're making is that the historical precedent of the court deferring to state legislatures on these issues doesn't apply because the tools have changed," Kousser says.

Katz's brief proposes the court use something called the partisan-symmetry test, which is the idea that a share of total votes should result in the same number of legislative seats regardless of which party received them.

"Scientists are going to increasingly see issues they care about being litigated," says Kousser. "Professors and intellectuals can get involved in shaping public policy through contributing to amicus briefs. It's a way for scientists to actually put their expertise to use shaping public policies."

—Emily Velasco



How gerrymandering works: By adjusting the boundaries of electoral districts, political parties can gain votes and influence election outcomes dramatically. In this example, though the district is 60 percent blue, a redrawing of the boundaries results in the majority of the districts being controlled by red (far right).

Read more about the history and methods of gerrymandering at **magazine.caltech.edu/post/rethinking-redistricting**

CTLO Celebrates Five Years of Success

Created in 2012, the Center for Teaching, Learning, & Outreach (CTLO) was launched with ambitious goals: to improve the quality of teaching on campus, bolster instructional opportunities for students, and engage K–12 schools in educational outreach. At the time, Caltech lacked a center specifically devoted to those ends.

Timothy Liu, a senior in electrical engineering, says CTLO "has played a critical role in supporting and improving classroom instruction. Programs like TA training and cross-departmental discussions organized by CTLO have helped improve the classroom experience for students."

Almost half of all faculty now participate in programs annually, says Cassandra Horii, who has served as director of CTLO since its inception, showing "Caltech's depth of commitment to discussing meaningful questions about how students learn."

Xie Chen, associate professor of theoretical physics, is one of the program's participants. In January 2016, she sought help from CTLO to improve her Physics 129 b class.

"I was pretty new, and, after teaching the class once, I wanted to get my students more motivated and interested; I didn't want them to fall asleep," she jokes. CTLO's assistant director for instructional practice and technology, Jennifer Weaver, sat in on a class and offered Chen specific tips for improvement, such as engaging students with questions and allowing them the time to consider and respond.

> "I wanted to get my students more motivated and interested—I didn't want them to fall asleep."

Chen credits the experience with boosting her confidence and improving her students' interest and attendance—and also, in part, for her receiving a graduate student teaching award for her winter 2016–17 course.

CTLO's reach also extends into the community, where its programs cast students in the role of teachers as part of educational outreach efforts that engaged about 17,500 local K–12 students and teachers last year.

As part of the Science Night program, Celeste Labedz (pictured above), a geophysics graduate student, led students at Field Elementary School in Pasadena in a water and dry ice demonstration of how comets form.

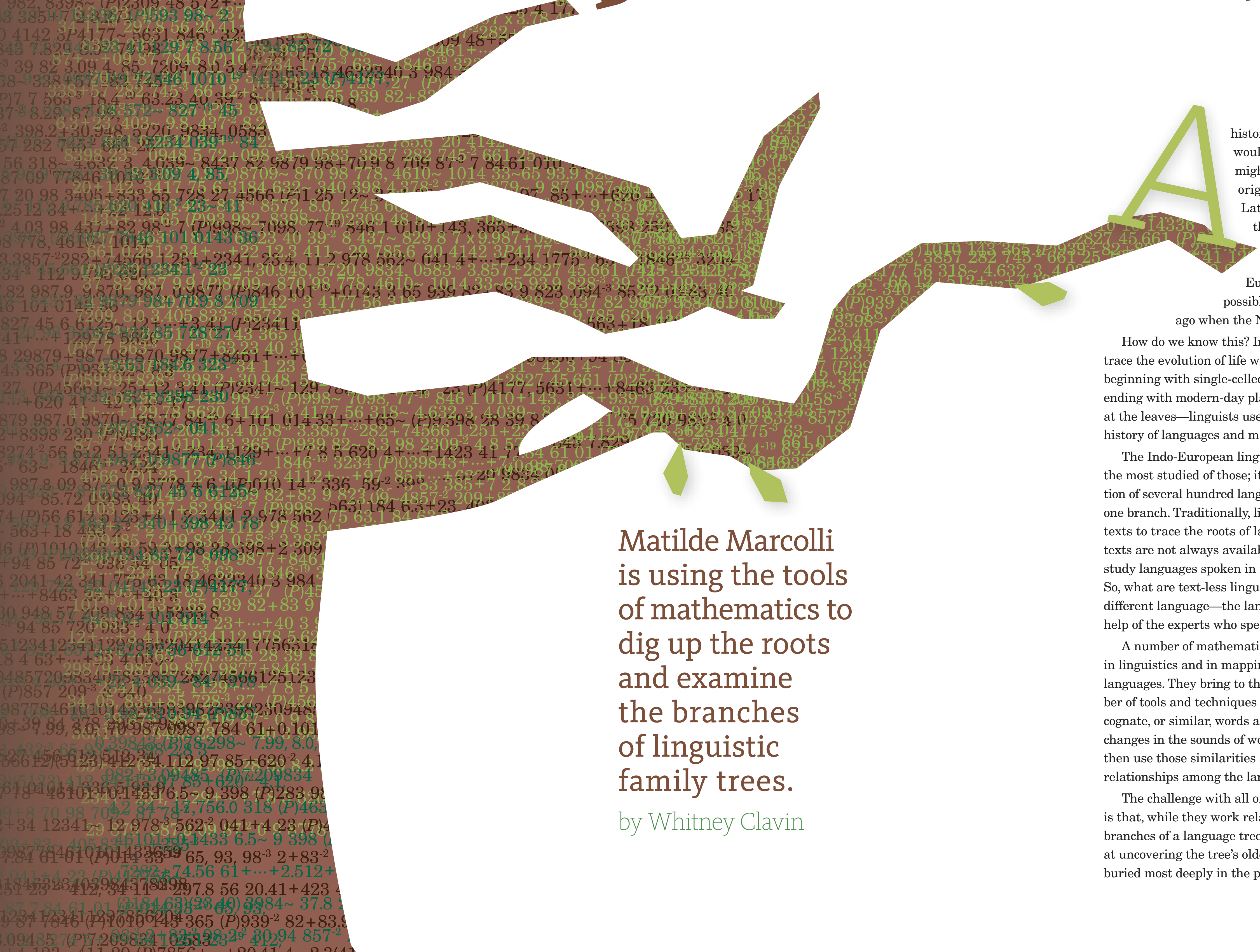
Labedz says she gained at least as much from the classroom experience as the children did. "When kids are excited about what they're hearing, you can see it. Sometimes they can't keep it to themselves and start bouncing around. It's awesome to see that learning can have that kind of effect on a kid," she says.

Horii says that, going forward, CTLO is aiming to deepen its collaboration with academic divisions and work to create more discipline-specific resources and programs: "We're really excited about partnerships that meet faculty and TAs where they are, and we're always looking for new ways to empower Caltech's community of educators."

—Jon Nalick

For more on CTLO go to **magazine.caltech.edu/post/ctlo-celebrates-five-years**

Branching Out into Language



Matilde Marcolli is using the tools of mathematics to dig up the roots and examine the branches of linguistic family trees.

by Whitney Clavin

A history of the words on this page would date back farther than you might think. Modern-day English originated from Germanic and Latin-based languages, which themselves evolved from an even more primitive language known as Proto-Indo-European, whose history stretches possibly as far back as 10,000 years ago when the Neolithic era began.

How do we know this? In the same way that biologists trace the evolution of life with the help of family trees—beginning with single-celled protozoa at the roots and ending with modern-day plants, birds, and other animals at the leaves—linguists use family trees, too, to study the history of languages and map out their common origins.

The Indo-European linguistic family tree is probably the most studied of those; it is a sprawling oak-like collection of several hundred languages, of which English is just one branch. Traditionally, linguists have used historical texts to trace the roots of languages like these, but such texts are not always available, especially when trying to study languages spoken in more remote parts of the world. So, what are text-less linguists to do? They can turn to a different language—the language of math—and seek the help of the experts who speak it.

A number of mathematicians have become interested in linguistics and in mapping out the relationships among languages. They bring to the metaphorical table a number of tools and techniques that allow them to compare cognate, or similar, words among languages and to track changes in the sounds of words, called phonetics. They then use those similarities and changes to tease out the relationships among the languages they are studying.

The challenge with all of these mapping techniques is that, while they work relatively well on the leaves and branches of a language tree, they are often less effective at uncovering the tree's oldest sections: the roots that are buried most deeply in the past.

Over the past several years, Caltech mathematician Matilde Marcolli, together with her students, has begun developing new computational methods that allow her to build and analyze linguistic trees—and, specifically, to hone in on their oldest sections. To do this, Marcolli is applying several different mathematical methods to the study of language: algebraic geometry, topology, and coding techniques, among others.

"Individually, some of these methods have been applied before," she says. "But in trying to tackle the structure of syntax in natural languages, you need a broad combination of different mathematical approaches."

So far, Marcolli's approach has proved successful. She has shown that algebraic geometry methods can be used to narrow down candidate linguistic trees and identify the ones that best follow evolutionary processes and thus are more likely to be correct. And by applying topological math techniques to these narrowed-down family trees, she has revealed how some of the branches, or subfamilies, have influenced one another through the years.

"What I'm most interested in is using mathematical methods to understand how human languages are structured and how the structure has changed over time," says Marcolli. "By applying different mathematical methods to languages, you can get the methods to talk to each other and provide a more comprehensive look at the tree's structure."

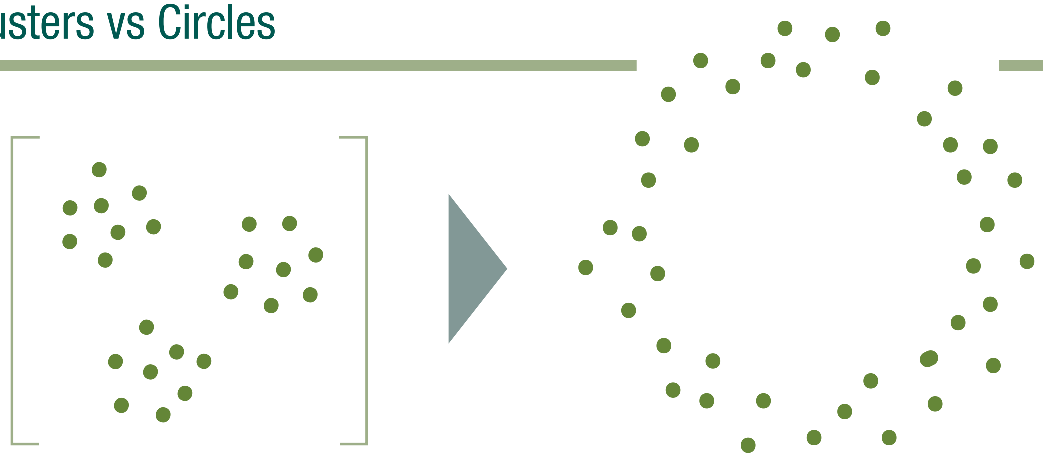
Layers of Language

Language, like matter, adheres to a detailed and many-layered structure. At its smallest scale, it is made up of different types of sounds, or phonemes. Different languages have different numbers of phonemes: the East Papuan languages of New Guinea use 11 different distinct phonemes, while the African language family called Khoisan has more than 140 basic sound units, including clicks.

At the next level of language structure are words and the varying ways in which words are not only formed but are modified to play different roles in a sentence—such as

The Shape of Data: Clusters vs Circles

In topological data analysis, researchers look for shapes, like circles, that organize the data. Traditionally, mathematicians have looked at clusters of data to group items by similarity, but with topological data analysis the data are viewed from a higher order (or higher dimension) and organizing shapes, or structures, emerge.



when the verb "run" changes to the past tense "ran." This latter process is known as morphology. While English has a moderate degree of morphology, German and Russian have a much higher degree. Vietnamese, on the other hand, generally does not alter its words; thus, this language is considered among the least morphologically complex.

An even higher-scale structure in language is syntax. While morphology is about the way words change, syntax looks at how the meaning of a sentence changes based on the ordering of those words. Syntax differs by language: For instance, many languages put the subject before the verb, as in English, while others, such as the Celtic languages, do the opposite. Another element of syntax has to do with "head directionality," or the positioning of the main part (or head) of a sentence—the subject and the verb. In head-initial languages such as English, the main part of the sentence comes first, and the rest of the sentence is appended to the end; in head-final languages such as Japanese, the main part of the sentence comes after its complement. For instance, when a Japanese person says, "I want to eat an apple," they would place the word apple and other words before eat, since eat is considered the head of the sentence.

It is in this area—syntax, or the large-scale structure of language—where the focus of Marcolli's language research lies. She and other linguistic researchers are looking at variations in the syntax of languages to better understand how they each splintered off from one another and evolved.

"What linguists have already been doing for many decades is trying to classify the way the syntax works in different languages on the basis of what are called binary variables," says Marcolli, referring to an idea originally introduced by philosopher and linguist Noam Chomsky in the 1960s and 1970s. "You basically ask a yes/no question for all the variables known—for example, does the language put the subject before the verb—and then you compare languages to see how different those variables are."

Mapping the DNA of Language

To this end, linguists have developed a database of 115 syntax variables for 253 world languages spread across several different language families. The Indo-European languages are well represented in the database, which includes not only English but Spanish, Punjabi, and Persian, to name a few. One way computational linguists use the database is through the "neighborhood-joining method," in which languages with a greater number of syntax variables in common are placed closer together on the tree.

"These syntax parameters act as a sort of DNA for language. You can apply phylogenetic ideas from biology in order to construct plausible histories of how these languages might have evolved," says Kevin Shu, a Caltech undergraduate student who worked with Marcolli on her linguistics research. The method is not infallible, of course. If an error finds its way into one of the branches of a family tree, it will propagate deeper and deeper, spreading back to the roots like an infection.

To solve this problem, Marcolli adopted a tool used by mathematical biologists; an algebraic geometry technique developed by UC Berkeley mathematicians Bernd Sturmfels, Lior Pachter (now the Bren Professor of Computational Biology and Computing and Mathematical Sciences at Caltech), and others. Marcolli is the first to apply this tool to linguistic trees to find which are the "healthiest," or have the fewest errors. The tool looks at the modern-day languages that make up the leaves of the trees and traces backward to the roots to see if the placement of the leaves makes evolutionary and mathematical sense.

"Whatever the modern languages look like now, they are a function of what happened according to some random evolutionary process that has been creating mutations in those languages along the way," says Marcolli. "The distribution of the binary syntax variables that we observe in language today—those at the leaves of the tree—is produced by that evolutionary process acting on that tree."

Using their algebraic geometry method, the Caltech researchers were able to narrow in on what is generally accepted as the most accurate of the Indo-European trees, demonstrating that the technique worked in this well-known language family. Marcolli plans to use the method next on languages that are not as well documented to see if she can better illuminate their murky origins.

One limitation of this geometric method, however, is that it makes a basic assumption that the binary syntactic parameters examined—the subject-verb order and the head directionality, for instance—evolve independently of one another. But, says Marcolli, "there are unknown relationships between the different syntactic parameters that will impact the way languages change and evolve."

The Shape of Language

To better understand the interconnectedness of the syntactic variables and to build the most accurate trees, Marcolli and colleagues are taking advantage of a suite of methods to "shape" the linguistic trees in the way an arborist uses a variety of tools to shape an actual tree. These methods include various forms of geometric data analysis and coding theory as well as some novel methods of topological data analysis developed by Stanford mathematician Gunnar Carlsson and others.

Topological data analysis is a mathematical technique that allows mathematicians to look at the higher-order structures, or shapes, that organize sets of data. The method, which has been growing in popularity in recent years, can reveal previously unseen connections between data points.

To look for these sorts of obscured connections within the Indo-European language tree, Marcolli and her students applied the topological method to the syntax variables they had already studied using algebraic geometry. They found something unexpected: when one branch of a linguistic family tree influences the growth of another, a loop or circle can show up in the topological data analysis, indicating lateral connections between those languages, as opposed to direct evolutionary pathways. For example, a circle in the data would indicate connections between a tree's different language branches—branches that had, for the most part, grown independently.

"We found that, in the Indo-European language tree, there is a circle in the data that is mysterious," says Marcolli. "What it seems to mean is that, at the syntax level, the ancient Greek languages may have influenced other branches of the family tree, such as some of the Slavic languages. This is a phenomenon that linguists have already observed in other ways, but you see it now in the topological data because there's a circle that comes up. And that means that this is a methodology that will become really useful in the study of linguistic evolution."

"Languages evolve over time and become separated, but they can come back together again and influence each other," adds Alexander Port, a Caltech undergraduate student of Marcolli's who is now doing graduate work at the University of Southern California. Port worked on this project with Marcolli as a part of a computational-linguistics class.

In the future, Marcolli hopes to use studies like these to develop models that describe the structure of languages and all the nuances as well as how groups of people acquire new languages or become bilingual. If scientists can better understand how people learn languages—or "how the 'syntax calculators' in our brains work," as Marcolli puts it—it might lead to new insights into how to create the neural networks needed for artificial intelligence.

But, for now, her focus is on language and its history. As Marcolli demonstrates, the best way to uncover the buried past of words may well be through the use of numbers. [C]

GREASY hairy Scuba-Diving flies

The flies of Mono Lake have long puzzled observers with their ability to stay dry while they crawl underwater. New research may solve this scientific mystery.

by Lori Dajose

More than a century ago, Mark Twain observed a curious phenomenon at Mono Lake, just to the east of Yosemite National Park: enormous numbers of small flies would crawl underwater to forage and lay eggs, but each time they resurfaced, they would appear completely dry.

In his travel memoir *Roughing It,* Twain wrote: "You can hold them under water as long as you please—they do not mind it—they are only proud of it. When you let them go, they pop up to the surface as dry as a patent office report."

Caltech biologist Michael Dickinson, Esther M. and Abe M. Zarem Professor of Bioengineering and Aeronautics, became similarly intrigued by these so-called diving flies—scientifically known as *Ephydra hians*—on a vacation to Yosemite 22 years ago. Now the principal investigator of a laboratory that specializes in insect flight, Dickinson teamed up with former Caltech postdoctoral scholar Floris van Breugel (now at University of Washington) to study the mysterious behavior of the Mono Lake flies.

"We were interested in the Mono Lake flies not only because their behavior is so unusual," says van Breugel, "but because they are a crucial species for the lake's ecosystem and food web . . . acting as a food source for spiders and for migratory and nesting birds."

Mono Lake is not an average freshwater lake. Three times saltier than the ocean, it is also full of sodium carbonate and borax—essentially laundry detergent—and the water's high pH gives it a slippery, almost oily texture.

No fish or other vertebrates survive in Mono Lake, though algae and bacteria are abundant. Thus, for a fly, the depths of the lake may seem appealing—there are no predators and plenty of food. There is just one hurdle to overcome first: how to stay dry while underwater.

To something the size of a fly, water's surface tension is powerful, making it a deadly sticky trap. All insects need to be water-repellent, or hydrophobic, in order to coexist with rain and dew in their environments. Most accomplish this by sporting a coating of short bristly hairs covered in a waxy substance, which allows them to repel water for the most part.

However, due to its peculiar chemical makeup, Mono Lake water is particularly good at breaking through an average insect's hairy defenses. Van Breugel and Dickinson discovered that this is because the surface of the lake contains a thin layer of negatively charged carbonate ions. When a regular fly gets too close to the water, the ions are attracted to positive charges on the fly's skin and the water is pulled between the protective hairs, wetting the fly.

How can the Mono Lake fly dive and stay dry in what Dickinson calls "perhaps the wettest water in the world"?

Using a combination of high-speed video and micro-force measurements in which they plunged flies into a variety of different chemical solutions, van Breugel and Dickinson found that the Mono Lake fly creates a protective bubble of air around its body when crawling into the lakewater. This bubble is a result of an extreme water-repelling phenomenon called superhydrophobicity. The flies are able to do this, the researchers discovered, because they are hairier than the average fly and coat their bodies and hairs with waxes that are particularly effective at repelling the carbonate-rich water.

The team compared the performance of Mono Lake flies with a variety of different flies. None of them could take a dunk into Mono Lake water without getting wet to a degree that would make escape from the lake unlikely. Additionally, when the Mono Lake flies were briefly rinsed with a solvent (hexane) to dissolve their wax, they lost their ability to form a superhydrophobic bubble, suggesting that the fly's waxes are critical to this phenomenon.

"It's not that Mono Lake flies have evolved a new and unique way of remaining hydrophobic—it's that they've amplified the normal tools that most insects use," says Dickinson. "It's just a killer gig. There's nothing underwater to eat you and you have all the food you want. You just have to dive in perhaps the most difficult water in which to stay dry on the planet. They figured it out, and so get to enjoy a unique life history." C

Funding for this research was provided by the National Geographic Society's Committee for Research and Exploration.

"It's just a killer gig. There's nothing underwater to eat you and you have all the food you want. You just have to dive in perhaps the most difficult water in which to stay dry on the planet."

If the [sports] shoe fits

by Judy Hill

Whether they are in sneakers, oxfords, or flip-flops, these alumni are stepping into a variety of roles in the competitive world of sports. While academia, technology, medicine, and business surely all beckon for Caltech alumni, combining a passion for athletics with skills honed at the Institute—discipline, innovation, insight, and an unstoppable work ethic—has led some to singular success in athletics, from the front court to the front office.

The team player

For **Nasser Al-Rayes** (BS '17), who now plays professional basketball in his native Qatar, college was always equally about basketball and academics. He chose Caltech because he wanted a challenging and fulfilling academic environment. He chose to play basketball at Caltech with, he says, "the vision of leading the team to its first SCIAC [Southern California Intercollegiate Athletic Conference] title in over 50 years." Although that did not happen, the team did shatter many program records during his tenure, including finishing fifth in the conference in back-to-back years.

Collaboration was a way of life for Al-Rayes at Caltech, where he pursued an option in mechanical engineering. "The very basic idea of collaboration, that two brains are better than one, has become very important to me, whether it's a group project or seeking another perspective on a big life decision," he says. "I always want to know others' perspectives since there is a good chance someone else will have looked at a situation in a different way than I have and can offer a varying perspective that I would not have considered on my own."

Surprisingly, he says, that sort of mind-set is rare in professional basketball, despite it being a sport predicated on the ideas of teams and teamwork. "Many athletes are quite headstrong and don't seek or want other perspectives, especially during times of adversity. I firmly believe that only when the ability to collaborate fails does adversity prevail. This is especially true when working on a team trying to achieve a common goal, like, in my case, winning a game."

The other big takeaway from Caltech for Al-Rayes was the importance of grit. "I remember upperclassmen warning me that this place would make it very hard to maintain a high-level training regimen in basketball and that I could run the possibility of burning out," he says. "But Caltech never crushed my love and passion for athletic competition."

Al-Rayes's dream of playing professionally began in high school and, after signing with an agent while at Caltech, he fielded interest and offers from teams in Denmark, Portugal, and Spain. Ultimately, he signed with the Al Sadd Sports Club in Doha soon after graduation, happy to be able to spend time back where he grew up but also preparing for his post-basketball life by taking online classes to continue his education. Al-Rayes admits the first few months of playing professionally were hard: his coaches expected more from him and were even harder on him than he was used to. Still, he says, "I never got discouraged. I kept my nose to the grindstone. Caltech taught me to be tough."

Nasser Al-Rayes (top) and Collin Murphy (bottom, #22)

The free safety

That ingrained ethos of hard work, of doing whatever it takes to get the job done, would benefit a Caltech alum in any profession. As **Collin Murphy** (BS '13) found, it is particularly helpful in the grueling and unpredictable environment of a start-up company.

A software engineer for the Pasadena-based BallerTV, a subscription streaming service for amateur-athletics events, Murphy spends his days putting out fires large and small. Though he gets to show up for work close to noon and wear flip-flops in the office, the work is demanding, he says. When not refining apps or working on coding, Murphy might be traveling to Dallas to guide a team contracted to broadcast a game, designing an email template for a colleague, or reviewing statistics for the weekend's events to make sure they make sense, "because sometimes data can be a little wonky." He also meets with coaches, knows how to set up a camera, and is, as he puts it, "pretty much just kind of a free safety covering anything that needs to be done."

From left: Dean Oliver; Eldar Akhmetgaliyev and Arian Forouhar; Ari Kaplan

Half the staff of Baller TV are Caltech alumni, many recruited by Murphy himself. "Yeah, I hired my friends," he says. "The lead developer, Christophe Kunesh [BS '13], played on the basketball team with me. Ping Chen [BS '14] and Chan-Hee Koh [BS '14] are both software engineers here, and all three of us were in Page House."

Beyond the easy camaraderie, Murphy, who was a double major in computer science and business, economics, and management at Caltech, says he likes to hire Caltech alumni because of their work ethic. "I think we just know how to work hard to get a project done," he says. "Working until two, three in the morning, or just through the night, that's the kind of thing you get used to as an undergrad, and I think that carries forward. We're not working on problem sets, but they are problems nonetheless."

With a Caltech grad, says Murphy, "the problem is never going to be 'we didn't give it a good-enough go, effort-wise.' That's not going to be a problem for us. I think everyone kind of knows how to push themselves through really tough 14-hour days, to work through it."

The scientist-analyst

The field of sabermetrics—which involves the analysis of data gathered during a sports game as a way to improve player value and game strategy—has grown by leaps and bounds since the early 2000s, gaining national recognition with Michael Lewis's 2003 book *Moneyball: The Art of Winning an Unfair Game.*

A year before that, **Dean Oliver** (BS '90) had written a primer on basketball analytics called *Basketball on Paper*, which laid out the statistical tools that could be used to build a better basketball team.

"That was effectively my business card," says Oliver. At the time Oliver's book came out, he was an environmental consultant; he leveraged its publication to get his foot in the door with sports organizations. By 2004, he had secured a position with the Seattle Supersonics, where he provided the front office, coaches, and scouts a statistical interpretation of what they were seeing on a game-by-game basis; he also advised on the draft. Stints with the Denver Nuggets, the Sacramento Kings, and ESPN—which started an analytics group in 2011—followed. Now Oliver is with TruMedia Networks, a data-analytics company that works across multiple sports, including football, baseball, and soccer. Oliver recently recruited another Caltech alum, T.J. Creath (BS '95), a former basketball teammate, to the company.

Oliver says his Caltech education gave him an edge in terms of learning how to see beyond the statistics. "A lot of people who get into this field come from a statistics or programming background, and those are very useful, but I think what I learned at Caltech was how to piece things together."

He adds, "Being an environmental engineer, I understand how water gets from here to there or how air gets from here to there. You have to understand the physical system and then you can apply statistics to it, and that perspective—that there is a physical mechanism, not just a statistical model—is something I don't see as much in other people who are doing sports analytics. They use statistical models and machine learning but are blind to the concept that basketball is played in groups—a system of players—which behave in a more deterministic way than people with purely statistical backgrounds can understand. I definitely feel that there is a fundamental science, a system of rules, that sits in sports. It's just not as obvious."

Read more about these Caltech alumni and meet others who have found their niche in sports at magazine.caltech.edu/post/if-the-sports-shoe-fits

The digital storytellers

Arian Forouhar (PhD '06), who founded MOCAP Analytics in 2012 with fellow Caltech alum **Eldar Akhmetgaliyev** (PhD '16), spent a lot of time "thinking of ways to apply the innovative technologies developed in the lab to sports" while pursuing his doctorate.

The Silicon Valley start-up (which was aquired by sports-data company Sportradar in 2017) focused on making sense of tracking data on professional players. "MOCAP's mission was to become the world's best sports data storytellers," says Forouhar. What the pair developed, explains Akhmetgaliyev was "a way to use machine learning and artificial intelligence to extract insights from tracking data."

In basketball, for example, they came up with a way to measure the quality of shot selection by estimating how much each team or player *should* have scored on these shots. By comparing actual scores with expected scores, they could estimate the amount of luck contributing to an outcome. MOCAP developed algorithms to measure on-court chemistry between players, create video-game-style player profiles, and describe similarities between players based on skill or style.

They started with the Golden State Warriors and have worked with other professional teams as well as leagues, data collectors, and athlete-management systems to process data from thousands of games. In football, for example, they are using data collected from RFID tags underneath player shoulder pads to build the most accurate model to predict a run or pass before the snap.

"During my doctoral work at Caltech, we used novel imaging tools and techniques to gain insights into heart development," says Forouhar. "The interesting thing is that we gained these insights about the system by studying moving dots—flowing blood cells and pumping myocardial cells. In our work at MOCAP and Sportradar, we've been able to make sense of sports systems by studying other moving dots—in this case, players and a ball."

The data visionary

A decade ago, when huge amounts of new data on baseball pitching—detailing everything from how the ball spins to how hard it is hit—became available, **Ari Kaplan** (BS '92) saw an opportunity to use that information to provide valuable insights to major league teams.

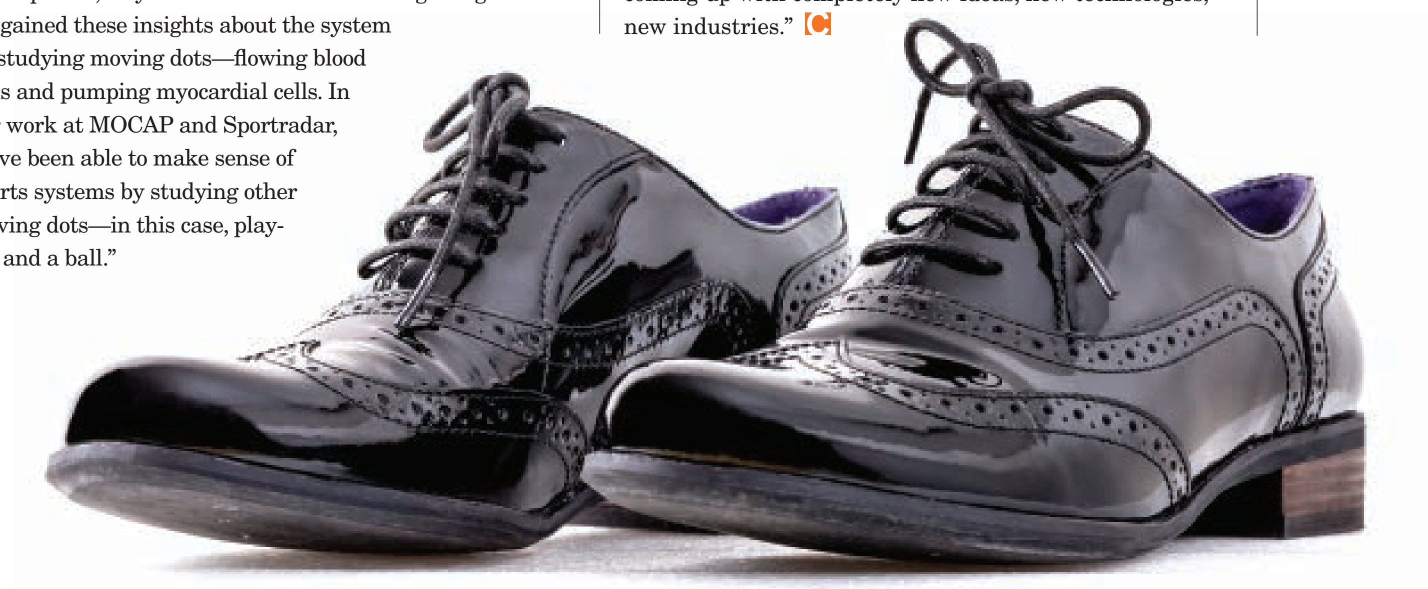
"For me, the fun is doing something that hasn't been done before, innovating," says Kaplan, who started his baseball career with a SURF project and then co-founded the sports-analytics company AriBall (now Scoutables). Kaplan, who has worked with two-thirds of Major League Baseball's teams, was recently hired by the Chicago Cubs to launch and run their analytics and research-and-development departments, helping the organization to become World Champions in 2016 for the first time since 1908. He is now special consultant to the general manager of the Baltimore Orioles.

"It's very exciting to give recommendations for signing a player based on your own insights. It's especially rewarding to find a player who everyone else is overlooking and make a recommendation to sign him, and then see him end up the home run champion of the year or in the All-Star Game."

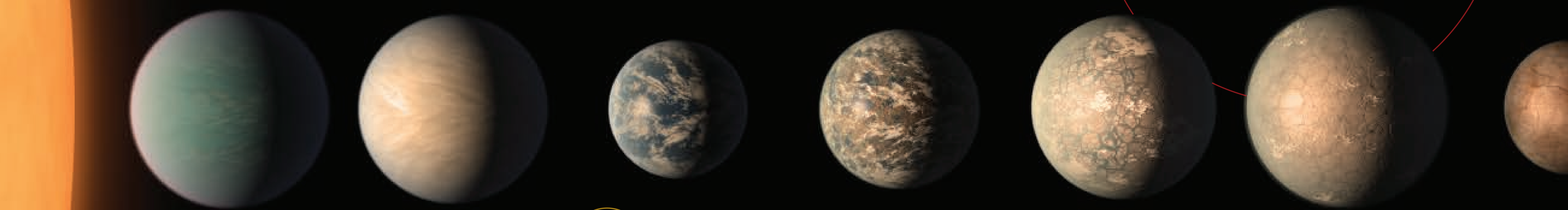
In addition to being involved with player recruitment, Kaplan also developed software to automate scouting reports and to use data to enhance game strategy on the field.

Lately, Kaplan has dived into the vast amounts of information available on fielding. "I'm trying to understand what the meaning of that information is," says Kaplan. "It's easy to get data, but it's hard to put meaning behind it and take action on it." He also is looking at behavioral science and the intangibles of personality, and how people work together as teammates.

"I like to try to use that innovative spirit that I experienced at Caltech," says Kaplan. "It's not just tweaking existing work and making it incrementally better. It's coming up with completely new ideas, new technologies, new industries."



Exploring the Rocky Worlds of TRAPPIST-1



In February 2017, the Spitzer Space Telescope—funded by NASA and managed by the Jet Propulsion Laboratory—revealed the first known system of seven Earth-size planets around a single star, with three firmly located in the habitable zone, the area around the parent star where a rocky planet is most likely to have liquid water. In February 2018, further research—which revealed that the planets in this exoplanetary system, known as TRAPPIST-1, are all mostly made of rock—offered the best estimates to date for the planets' densities, noting that some could hold up to 5 percent water; 250 times more than in the earth's oceans.

The form that water would take on TRAPPIST-1 planets would depend on the amount of heat they receive from their star, which is a mere 9 percent as massive as our sun. Planets closest to the star are more likely to host water in the form of atmospheric vapor, while the water on those farther away may be frozen on their surfaces as ice.

"We now know more about TRAPPIST-1 than any other planetary system apart from our own," said Sean Carey, manager of the Spitzer Science Center at Caltech/IPAC, and co-author of the new study. "The improved densities in our study dramatically refine our understanding of the nature of these mysterious worlds."

This artist's concept shows what the TRAPPIST-1 planetary system may look like, based on available data about the planets' diameters, masses, and distances from the host star, as of February 2018.

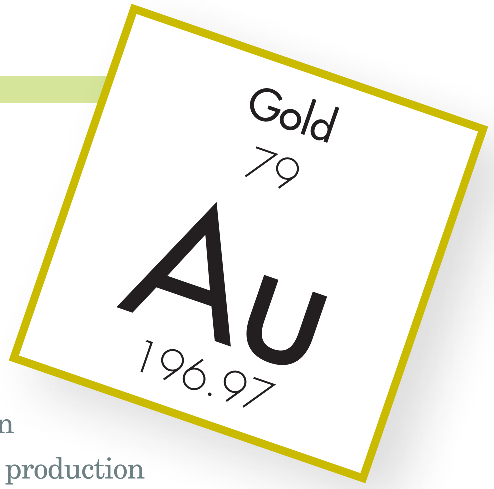
For more about TRAPPIST-1 and a video, visit magazine.caltech.edu/post/trappist

10 Insights from LIGO Insiders

LIGO (the Laser Interferometer Gravitational-wave Observatory) had quite a year in 2017. On August 17, scientists for the first time detected both the ripples in space and time known as gravitational waves as well as the light produced and emitted during the same cosmic event: the collision of two neutron stars. They did so using LIGO, the Europe-based Virgo detector, and approximately 70 ground- and space-based observatories.

But there was more. Over the year, LIGO made a total of four gravitational-wave detections and garnered a Nobel Prize for Caltech's Kip Thorne (BS '62) and Barry Barish, along with MIT's Rainer Weiss, for their "decisive contributions to the LIGO detector and the observation of gravitational waves."

Caltech magazine asked the scientists, engineers, and staffers on the LIGO front lines—at Caltech and at the observatories in Hanford, Washington, and Livingston, Louisiana—to look back at the year and at what the project has taught them. Here is what they had to say.



1 The birth of heavy metals

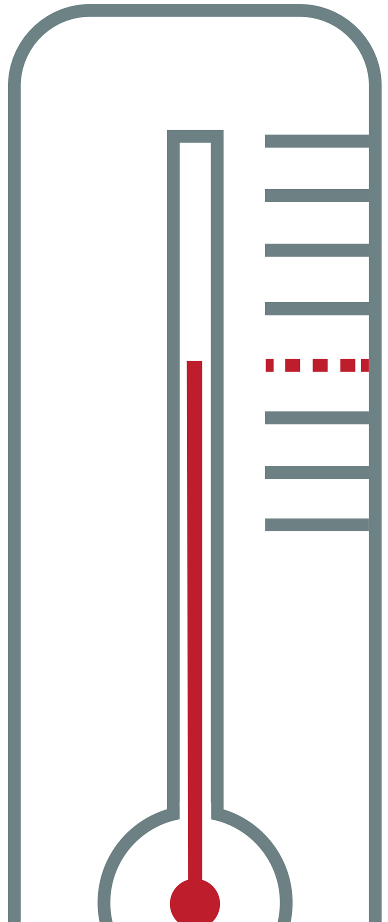
We learned that binary neutron star mergers are an important source of matter production in the galaxy. If you ask where the gold in your jewelry was made, the most likely answer seems to be a binary neutron star merger in the distant past. LIGO helped us observe this process in detail for the first time.

Jonah Kanner
Scientific Data Application Developer,
LIGO Caltech

2 It bends!

I was surprised that a mirror coating could bend a 40-kilogram piece of glass. The way LIGO mirror coatings are deposited means that this 6-micrometer-thick layer produces enough force to bend our 200-millimeter-thick optic! The mirror deforms by less than 10 nanometers, but the fact that it changed at all was a surprise.

Garilynn Billingsley
Senior Optical Engineer,
Advanced LIGO



3 One degree can throw everything off

The LIGO facilities and the maintenance performed there are critical to the quality of the scientific observations. This is especially true regarding temperature control. We are tasked with maintaining a 68°F temperature throughout the space year-round and, in south Louisiana, this is quite a challenge. Still, we are able to stay within half a degree of that target 24/7. Maintenance and temperature control were important in my previous job, but here at LIGO, a one-degree rise in temperature can mean hours of lost observation.

Tim Nelson
Facilities Team Lead,
LIGO Livingston

4 It takes a village

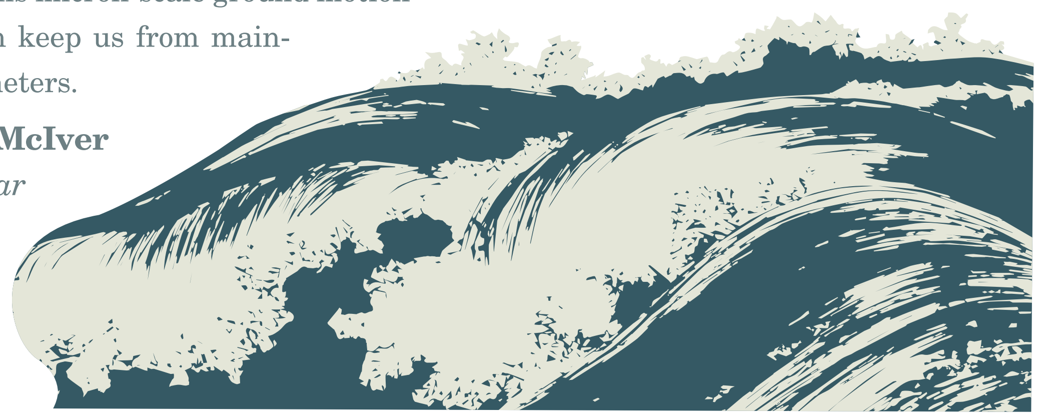
One person can make a difference and every role is important no matter how small. Whether you are a physicist, engineer, accountant, or custodian, your role within LIGO is just as important as the next guy's. We climbed to Nobel status as a team, and there is nothing that any and all team members wouldn't do to ensure that LIGO is successful in its mission to measure gravitational waves.

Nichole Washington
Property and Logistics Manager,
LIGO Caltech

5 Coastal weather shakes things up

I learned from working on the LIGO experiment that ocean waves beating on the shore induce ground motion with different characteristic frequencies depending on the body of water. We can see these "microseismic" ground motions with seismometers at the LIGO sites. For example, when the waves are high, it's easy to tell from the frequency peaks in the LIGO-Livingston detector's seismometers whether the sea winds are driving inland toward the site from the Gulf of Mexico, or the Atlantic Ocean, or both. In bad coastal weather, this micron-scale ground motion shakes the instruments around and can keep us from maintaining light resonance in the interferometers.

Jess McIver
Postdoctoral Scholar in Experimental Physics, LIGO Caltech



6 It's personal

I worked on the output optical system of the Advanced LIGO detectors. When I heard about the first detection, I realized that the gravitational wave, imprinted on the laser beam, had passed through my equipment as it was converted into an electrical signal. I felt a strong sensation of accomplishment when I thought about it.

Koji Arai
Senior Scientist, LIGO Caltech

7 LIGO and Virgo are *super* accurate

The biggest surprise for me was LIGO's detection, with Virgo, of gravitational waves from a binary neutron star merger. It is astounding to me that LIGO and Virgo could so accurately give the sky position and distance to the first-ever detection of gravitational waves from colliding neutron stars, and when the telescopes looked, they found the optical counterpart in the region we told them to search!

Greg Mendell
Senior Scientist, LIGO Hanford

8 Orders of magnitude

I enjoy seeing an experimental technique I am using being exploited for precision measurements in another field. That wouldn't have been possible without LIGO. When I heard that the suspension team had reduced the effects of Earth's vibration by 10 orders of magnitude, that was another "wow" moment.

Brittany Kamai
Postdoctoral Scholar in Physics, LIGO Caltech

9 It works!

LIGO is made up of many, many thousands of pieces. When you start to think about how many of these can and do go wrong, it is testimony to the team that not only does it work but that it can also detect!

Calum Torrie
Senior Systems Engineer, LIGO Caltech

10 Waves of wonders

The universe is full of nice surprises. I'm sure that no one would have predicted that the first gravitational-wave detection would happen the day we turned on the Advanced LIGO detectors, or that the signal from the first black hole merger would be large enough to see in the raw data. Not to mention that the first detection of two neutron stars colliding with each other would also be captured by astronomers here at Caltech and around the world. The universe, it seems, wants to tell its story in gravitational waves. I can't wait for the next chapter!

Dave Reitze
Executive Director, LIGO Project

The Inside Story

A Q&A with Alasdair McDowall, cryo-electron microscopist

Alasdair McDowall has been working in the field of electron microscopy for 45 years, starting at the European Molecular Biology Laboratory (EMBL) in Heidelberg, Germany, and in 2008 joining the Caltech laboratory of Grant Jensen, professor of biophysics and biology and a Howard Hughes Medical Institute Investigator. He was on the scientific front lines when Jacques Dubochet—one of the three scientists awarded the 2017 Nobel Prize in Chemistry "for developing cryo-electron microscopy for the high-resolution structure determination of biomolecules in solution"—was establishing how best to keep cells in an electron microscope hydrated, given that the scope's vacuum evaporates liquid. The solution? Vitrification, the cooling of water so rapidly that it doesn't create cell-and-organelle-destroying crystals.

McDowall played a key role in optimizing the process of vitrification, which made cryo-electron microscopy (cryo-EM) possible. McDowall was first author on several of the early papers from the Dubochet lab that the Nobel Prize recognized and was considered so integral to this work that Dubochet invited McDowall and his wife, Leta, to attend last year's Nobel ceremonies: Dubochet also gave McDowall one of the three replica medals offered to each Nobelist.

Caltech magazine caught up with McDowall just before his trip to Stockholm, Sweden, to talk about the evolution of cryo-EM, the next challenges researchers in that field will face, and how he, Jensen, and their colleagues are working to bring cryo-EM to the next level.

Caltech Magazine [CM]: Tell us about how cryo-EM evolved.

Alasdair McDowall [AM]: The history of cryo-EM more or less started for me back in the early '80s. I grew up in Scotland, and did my undergrad work in Edinburgh. I was introduced to electron microscopy there at a young age. I became interested in it, and then after my master's, I accepted a position at the EMBL.

They were just setting up, and their focus was driven by the director at the time, John Kendrew, who had won the Nobel Prize for the structure of myoglobin. His goal was to bring in groups that could look at structures in their more realistic native state.

They invested a lot in getting specific lenses and microscopes that would better protect a sample. The vacuum of an electron microscope is very alien for biological samples. We don't live in a vacuum, so putting biological samples into a vacuum is not natural. That's the way we have to look at them with electrons, but they don't like going in that environment, so we have to protect them. That's what one of these new instruments that Kendrew was building was hopefully going to help us do.

I was there in the background, trying to prepare better samples from biological materials that would work in this new superconducting helium-cooled lens electron microscope. Up to that point, from the '30s to the '80s, everything was dry when it went into the electron microscope. It was dead. It was pickled. It was cut. It was cooked. We wanted to see more subtle things in the microscope, and so we had to think of better ways of saving this liquid that we all live in.

That's what the goal was, and that's where the big quantum leap came. We managed to take cells or parts of cells and immobilize them by freezing them very fast. It was believed by the physicists and the theorists that vitrification was impossible at ambient pressures. Generally, when you cool water, it will form crystals, and that will just damage everything.

CM: So, by freezing the water quickly, you preserve its structure in solid amorphous water.

AM: That's right. The water molecule doesn't have the chance to arrange itself into a crystal. The minute you freeze something successfully in that state, it's stable, and life in that state looks very real. It looks as if it was still in the biological system outside.

This was a big jump, being successful in getting that to work. Many others were trying other things with metal salts or sucrose to support structures, and getting close, but nobody had done the vitrification of cells for electron microscopy until we did it at Heidelberg.

Then the research took off for the next 10 years, and the Dubochet team worked on that, and we had lots of success and trained a lot of people. Many of the group leaders who are working in the field now came to that lab to learn how to do the work, including Richard Henderson, one of the three 2017 Nobel laureates in chemistry.

CM: When did you work with Jacques Dubochet?

AM: I joined the Dubochet group in 1978, and I worked with him in Heidelberg for 10 years. I became an assistant professor at UTSW [University of Texas Southwest] Dallas, and then I went to a director professorship in Brisbane, Australia. Jacques came out and did a sabbatical with me there. We collaborated, and we published a bit more throughout the years.

CM: Why was achieving vitrification so important?

AM: Because the cells go into the microscope vacuum dry, you had to somehow support the sample. You just can't remove the liquid and expect to see the structure as it is. It's like seeing a sun-dried tomato and a vine tomato. They are totally different.

We struggled with making vitrification work. We were using all sorts of different cryogens, cold liquids. Nitrogen is one obvious one. When it's liquid, it's very cold, but it doesn't remove the heat fast enough. This is where the success came in the early '80s, when I tried different cryogens and eventually found one or two that could cool the sample in a freezing action much faster than liquid nitrogen. We now use liquid ethane, propane. These hydrocarbons are much more effective in removing the heat before the water can crystallize.

CM: What are some of the other challenges?

Center: Alasdair and Leta McDowall attending the Nobel Prize ceremonies at the Stockholm Concert Hall in December 2017.

AM: One other challenge is that the beam is like a nuclear reaction on the biological samples. Really, it's like a nuclear bomb going off inside a cell when a beam goes in there. It's burning and cooking the cell. Yes, we got a prep that was well frozen, but now we have to find machines in which we can control the beam dose, the dose of the number of electrons that are bombarding the sample. We have to record enough electrons just to sensitize the camera but not to boil the sample.

Stability is another challenge. You cannot afford to have anything drifting around or moving during a few-microsecond exposure or something like that.

CM: What kind of things do you think researchers will be able to look at using cryo-EM?

AM: There is a huge explosion of information coming out. Structures are being solved so rapidly now as opposed to even just five years ago. And medicine will be helped along the way by understanding what's happening inside the cell or nucleus when it's dividing and replicating and doing all sorts of its operations.

The Jensen Lab has been working for the last 10 years on bacteria and viruses, and some of the bacteria that cause problems in the Third World in terms of health and disease. Cryo-EM is opening up this window inside the cells that we never knew existed.

We're trying to also correlate the information we obtain from cryo-EM with what we see with the other microscopies—fluorescence and light microscopy, that is—with which you can look at a live cell. This is called correlative light electron microscopy. That's one very strong area.

CM: What about the microscopes themselves? How are they improving?

AM: The environment that the microscope is in is being controlled better. Now, if you go over and look at the new microscopes in Caltech's Beckman Institute, they put them in their own cabinet, so you don't see the microscope anymore. You operate outside the room, and the human body heat, the human noise, the human airflow is taken out of the equation. Those advances, together with better stability, cameras, and computers have made the new microscope much better. It is more expensive, of course.

CM: When did Caltech get its first cryo-EM?

AM: I think the Jensen group was formed around 2003.

CM: Pretty recently then.

AM: Yes. They've been here 15 years. The microscope arrived soon after that in the form of this 300 kV Polara, still an excellent workhorse cryo-electron microscope. They bought two under the Moore Foundation and Agouron Institute grants. Then the new microscopes just arrived a couple of months ago.

CM: It must be exciting seeing the cryo-EM field getting so much recognition now after the Nobel Prize.

AM: There is a lot of gratification, because the field struggled for quite a while to get going. Now there's this tsunami of information coming out from the data from so many labs. I was just on the phone this morning with the salespeople who sell the microscopes, who said they just can't keep up. The instruments are not cheap. They're $10-million-plus, each one. Labs are desperately trying to get hold of these machines.

Grant Jensen's group here actually realized that there aren't enough people to train those who want to use his microscope, so Grant is putting a lot of his effort into teaching now and very successfully making YouTube videos of how to actually prepare samples, to drive the microscopes. He's redoing them and creating more advanced ones for the new microscopes this year.

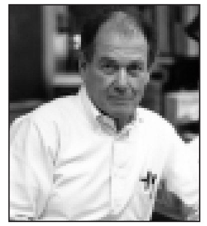
We spent many years training people in our little institutes, wherever we were, in groups of 10 or 15 or 20, and that's just never going to work for the hundreds of people who need to know how to get into this field now. The YouTube videos are hands-on, very specific, detailed. A beginner can learn how to do it.

CM: That is great.

AM: That's what the goal is now, to get everybody educated. It's exciting times. [C]

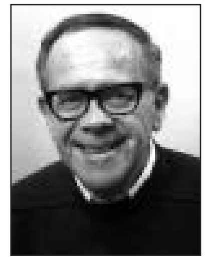
In Memoriam

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



Jerry Pine 1928–2017

Jerome "Jerry" Pine, a Caltech professor of physics, emeritus, passed away on November 8. He was 89 years old. Pine served as a professor at Caltech for more than 50 years. In his early career, he undertook research in particle physics at several particle colliders, improving our understanding of the structure of elementary particles. Later, he transitioned into biophysics, developing new ways to study and visualize living neural cells. Pine was also passionate about science education.



J. N. Franklin 1930–2017

Joel (J. N.) Franklin, who taught mathematics at Caltech for nearly a half century, passed away on November 18 at the age of 87. Franklin joined Caltech in 1957 and worked closely with Gilbert McCann, professor of applied science, who was one of the early champions of computing at Caltech. Franklin was the author of textbooks on methods of mathematical economics and matrix theory, and was the recipient of Associated Students of the California Institute of Technology (ASCIT) Teaching Awards for the 1977–78 and 1979–80 academic years.

Kevin Austin 1953–2017

Kevin Austin, longtime director of Caltech's health and counseling services, died on November 4. He was 64. Austin, who retired from Caltech in December 2015 after more than 25 years of service as a therapist and administrator, worked with countless students, faculty members, and student-affairs professionals during his tenure at Caltech.

Joseph Polchinski 1954–2018

Joseph Polchinski (BS '75), the Pat and Joe Yzurdiaga Professor of Theoretical Physics, Emeritus, at UC Santa Barbara, passed away on February 2. Polchinski was perhaps best known for his discovery of D-branes in string theory. In 2017, with two other physicists, he won the prestigious Breakthrough Prize in Fundamental Physics.

Endnotes

What was the most surprising thing you learned during your time at Caltech?

Nature is simple. Therefore, complicated explanations are problematic.

Oreste Lombardi (BS ’55)
LAKE CITY, FL

I delight in recalling that we were enrolled in the very first graduate program in rocketry and jet propulsion—under the guidance of Robert Millikan’s son, Clark, with visiting lecturers Theodore von Kármán and Wernher von Braun—eight years *before* Sputnik!

Dick Boera (MS ’49)
ESSEX, VT

A few things stand out:

1. I don’t need to wear makeup.
2. I can handle failure.
3. I can teach myself pretty much anything I need to know.

Debi Tuttle (BS ’93)
ALTADENA, CA

As an undergraduate physics student, I struggled to understand quantum mechanics. As a grad student at Caltech, I spent a year with Dick Feynman, who explained it to me in a way that was both a surprise and a relief. He said, “Nobody understands quantum mechanics.”

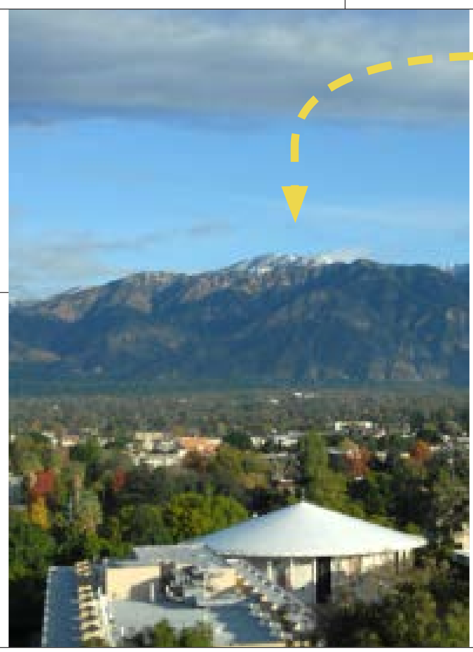
Frank Mullen (MS ’86)
WOODSTOCK, VA

There were enough of us ex-pats and former colonials to make up a cricket team!

Hugh Kendrick (MS ’62)
ANACORTES, WA

That math was not purely algorithmic: that there is a place, and indeed a need, for the educated guess in solving math problems.

Larry McClellan (EX ’64)
PORTLAND, OR



Three months after arriving at Caltech, on a clear morning after an overnight storm, I discovered there was a 5,715-foot-high mountain virtually in the backyard that I had not seen before.

Alvah Strickland (MS ’65)
HONOLULU, HI

Caltech’s motto, “The truth shall make you free,” was not just a pretty phrase, but an actual, ultimate “truth” in itself. Life and work are much easier and most satisfying if one sticks to the truth all the time.

Robert Tait (BS ’62)
PASADENA, CA

When a 13-foot-long cannon barrel elevated to around 40 degrees is filled with a raspberry Jell-O, ice, and water mix on a November night only the first few feet of the mix will gel.

Tom Trinko (BS ’76)
FREMONT, CA

Humbleness.

Erin White (BS ’08)
NEW HAVEN, CT

Connect with us

Join the conversation

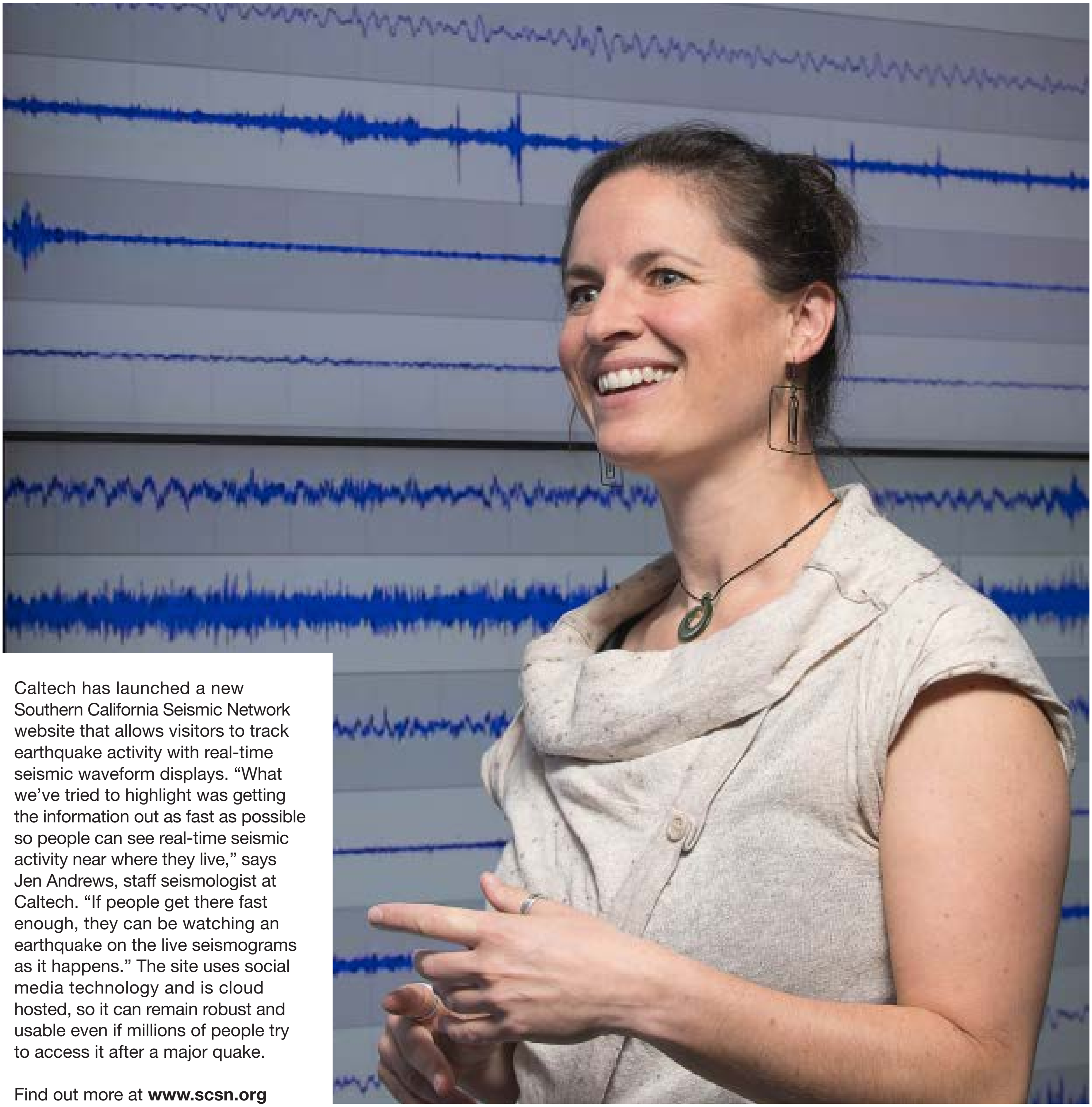
Email us at **magazine@caltech.edu**

And remember to get social:

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

Caltech
magazine

1200 East California Blvd., Pasadena, CA 91125



Caltech has launched a new Southern California Seismic Network website that allows visitors to track earthquake activity with real-time seismic waveform displays. “What we’ve tried to highlight was getting the information out as fast as possible so people can see real-time seismic activity near where they live,” says Jen Andrews, staff seismologist at Caltech. “If people get there fast enough, they can be watching an earthquake on the live seismograms as it happens.” The site uses social media technology and is cloud hosted, so it can remain robust and usable even if millions of people try to access it after a major quake.

Find out more at **www.scsn.org**