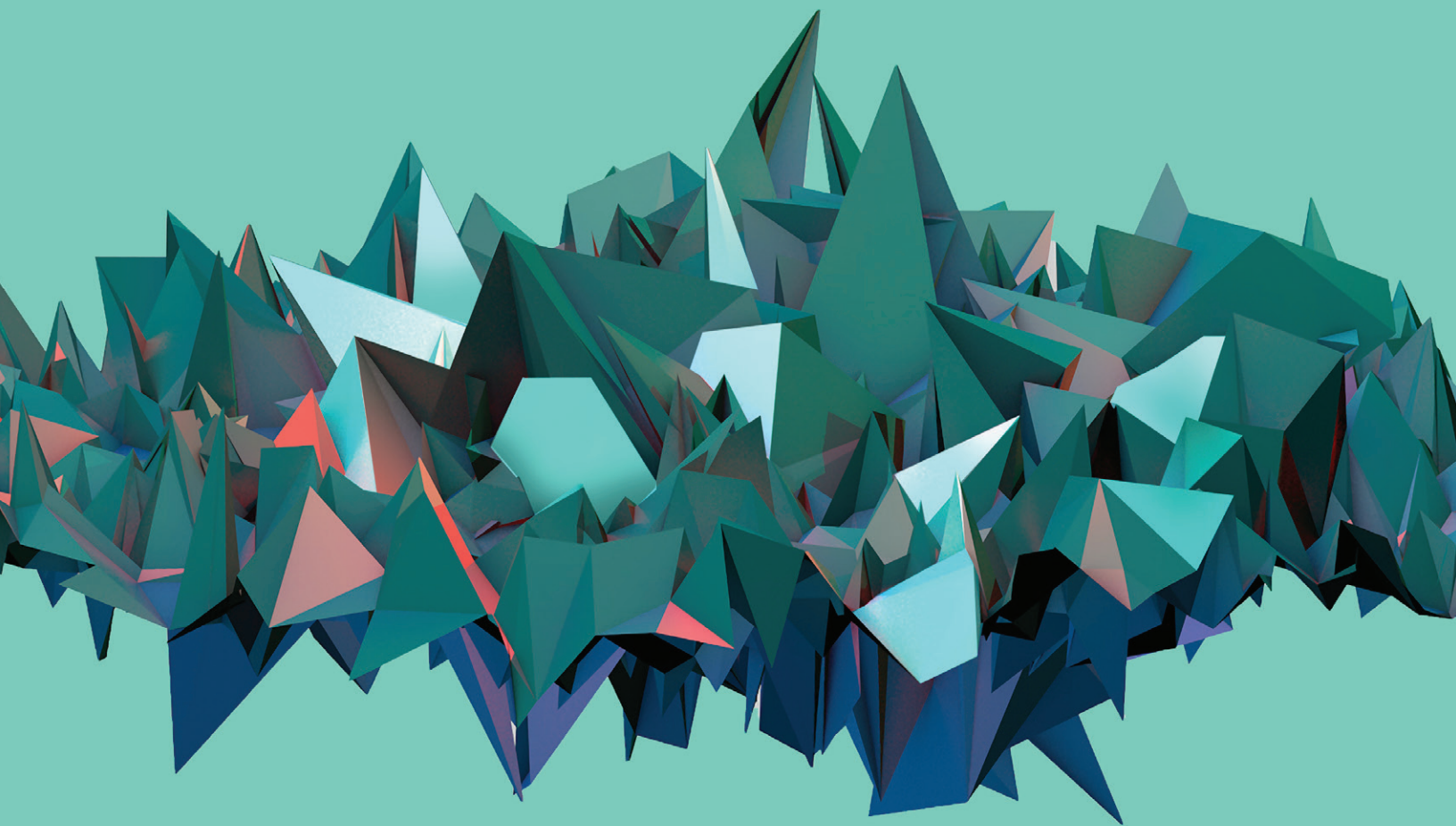


e&S

Engineering & Science



Caltech

VOLUME LXXVIII, NUMBER 2, SUMMER 2015

e&S

Engineering & Science

VOLUME LXXVIII, NUMBER 2, SUMMER 2015

- 2 Caltech on Twitter
- 3 From the Editor
- 4 Random Walk
RoboSimian ▪ Thirsty Brains ▪ Ant-Man Physics ▪ And More
- 10 Origins
A look back at *E&S*'s own beginnings
- 11 Available Now on Caltech.edu
- 12 Good Vibrations
BY KATIE NEITH
Caltech researchers seek to ride the power of sound waves to a better way to diagnose and treat disease.



18 The Sounds of Science

BY KATIE NEITH

Even at its quietest, the Caltech campus is buzzing, booming, and chirping with research and discovery.

20 Everything Noise

BY KER THAN

At Caltech, scientists and engineers are tapping into the power of noise to push their research forward.

26 Take It to the Crowd

BY JESSICA STOLLER-CONRAD

A look at how Caltech scientists get by with a little help from their friends ... as well as a whole lot of strangers and other citizen-scientists.

32 Tracking Down Infections

A Caltech alum uses social media to help map disease outbreaks in real time.

34 In Memoriam

Charles H. Townes
Fredric Raichlen
Don L. Anderson

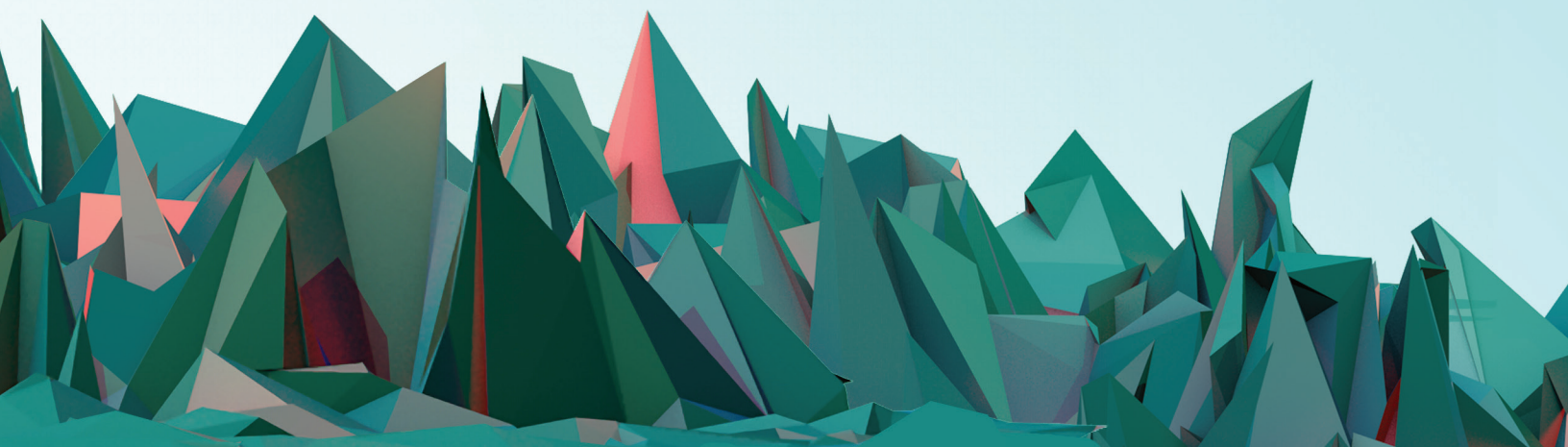
36 Endnotes

What were the most memorable sounds from your time at Caltech?

On the Cover: The “noise” depicted on the cover is a screenshot from a video representation of Richard Wagner’s “Ride of the Valkyries,” which is played at ear-splitting volume at 7 a.m. on the dot every morning during finals week at Caltech. The image was created for E&S by motion-graphics designer Ryan Luse.

But that’s not all it is. In keeping with the issue’s theme—noise, and finding the signal within the noise—we’ve hidden a signal on the cover as well. It is, appropriately enough, the word noise. Can you find it? Here’s a hint: Check out the light-colored “spikes.”

Still can’t see it? You’re not alone. We’ve created a highlighted version for you on E&S+. Just visit eands.caltech.edu.



Caltech on Twitter

Follow us, retweet us, and let us know you're talking about us by including @Caltech in your tweets.



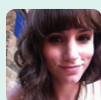
@loveplanets Overheard at @Caltech: "100% sure the first business to set up on #Mars will be a casino. There's no taxes out there."



@dgtedford I didn't know what graphene was until today and it (and @Caltech) might change the world



@JoseAndrade79 "Only the best go to #Caltech. One day I will go to #Caltech."
—Samuel, 6 year old.



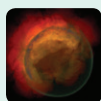
@HannaloreJoy The best part of #Caltech exams is getting to snack during them without anyone giving you dirty looks. #gradschool



@hollyaprilb Only @Caltech theater can you: A) sing a song to graphene & B) receive a graphene necklace made in a castmate's lab!



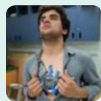
@mananarya Overheard at @Caltech: "But I don't know how to make surface charge calculation sexy!"



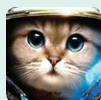
@fisherastro My Ph12c stat mech Caltech prof @preskill is a "snake charmer" of physicists. In a good way. bit.ly/1IODYUK



@farazmahboob When your prof casually drops in the fact that she was head researcher at Caltech and now she's here, teaching us Biochem . . .



@ChicaliDude @Caltech's cafeteria is way cooler in real life than in 'The Big Bang Theory'.



@Space_Mog I'm working in Kip Thorne's office during my stay at Caltech #awesome #hero



@CaltechBeavers @caltechbaseball @MITengineers @Caltech @MIT Doesn't get much better than two of the top schools in the world playing @d3baseball #d3b

Tweets may have been edited for spelling and grammar.

Caltech

Engineering & Science

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Of Signals and Noise

When we were talking about the stories we wanted to tell in this issue of *E&S*, we invariably found ourselves talking, instead, about the theme itself and, more specifically, the word it revolves around: noise.

It's a bit of a pejorative, after all, usually defined as a loud or unpleasant sound. And yet, it's a critical part of what Caltech is about. Science is a noisy business. There are pings and pops and booms and bangs. And there is a steady, unrelenting stream—an almost-audible hum—of information, from which researchers need to tease the important, relevant bits.

It is in this attempt to find the signal within the noise that science really shines, that it helps make the world understandable. The world is all noise until you can begin to make sense of it, to push aside or tamp down the chaos so that you can find patterns and meanings.

Still, noise in and of itself can have value and meaning, even if we're only just beginning to understand it. As science writer K. C. Cole remarks in her book *The Universe and the Teacup: The Mathematics of Truth and Beauty* (Houghton Mifflin Harcourt, 1998), "One person's data is another person's noise, and knowing which is which in any particular instance is not a simple matter. Indeed, what's noise today may be viewed as an important signal tomorrow, and vice versa."

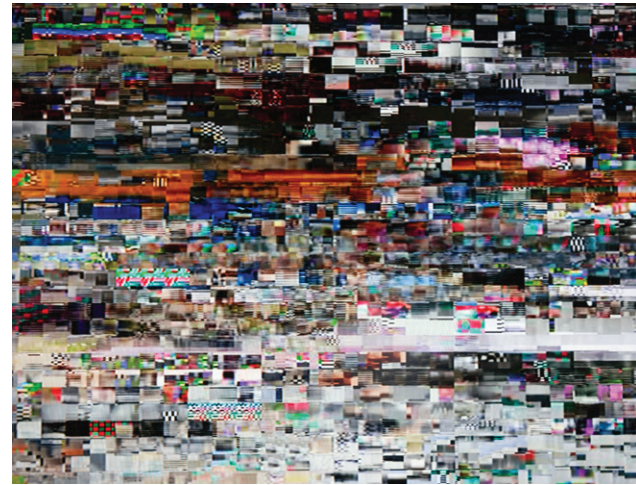
For example, Caltech scientists have shown that noise can play a key role in gene expression, demonstrating that almost identical genes under almost identical conditions will sometimes produce significantly different proteins, thanks entirely to random, noisy fluctuations in their signaling. And noise—or at least the sound waves of which it is made—can be used therapeutically to diagnose and explore and even potentially to heal the human body.

So, yes: noise is more than some loud and unpleasant sound, which is why we've devoted the features in this issue to looking at it in all of its guises and with all of its implications.

As for our decision to put a bit of "Ride of the Valkyries" on our cover to represent this particular theme? As Samuel Johnson once said, "Of all noises, I think music is the least disagreeable." We most heartily agree.



—Lori Oliwenstein, Editor in Chief



Random Walk



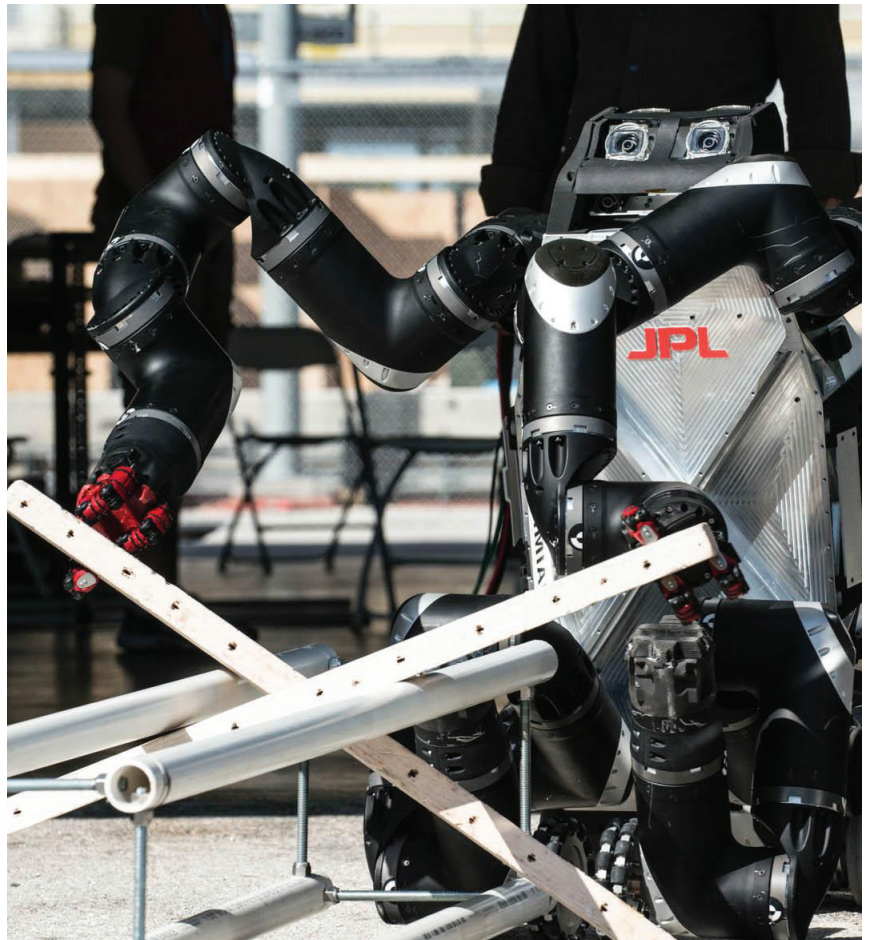
FIRE AND ICE

Graduate student Peter Gao took this photograph in Iceland while on an enrichment trip offered by the Division of Geological and Planetary Science and led by faculty members Mark Simons, Bethany Ehlmann, and Robert Clayton. The image features a sheer face of columnar basalts that is part of a series of dramatic rock formations found at Jökulsárgljúfur within Vatnajökull National Park. The terrain in the area is shaped by a volcanic eruption that took place about 8,000 years ago. The eruption led to flooding and subsequent erosion that swept away much of the volcanic edifices. When the magma cooled and contracted underground, it fractured, producing the hexagonal patterning seen here. The 15 students on the trip got to see the earth in action as Iceland's Bardarbunga volcano began to stir the day they arrived and erupted at Holuhraun on the day they flew out.



“I encourage all women with ambition to come solve the great problems we face: climate change, energy, environment, healthcare—basically how do we provide a better life to 7 billion people without destroying our beautiful planet? We cannot do it without you.”

—Frances Arnold, Caltech's Dick and Barbara Dickinson Professor of Chemical Engineering, Bioengineering and Biochemistry, blogging for the Huffington Post about women in science and engineering.



Robots to the Rescue

When disasters strike, first responders—often highly trained emergency medical staff—risk their lives to rescue victims and secure damaged structures. However, an apelike robot named RoboSimian could one day provide a safer alternative.

RoboSimian is JPL's entry in the Defense Advanced Research Projects Agency (DARPA) Robotics Challenge. The competition, motivated by the radiation dangers posed to response crews at Japan's Fukushima Daiichi nuclear power station after a tsunami struck in 2011, challenges teams to design a robot that can perform many of the same emergency procedures as a human rescue worker.

Composed of researchers from JPL, Caltech, and UC Santa Barbara, the RoboSimian team crafted a machine featuring four equally strong and dexterous limbs that allow the robot to drive a vehicle, climb over debris, turn valves, and even cut through walls when instructed by a human operator. At the final competition this June in Pomona, RoboSimian's performances on these tasks will be judged against at least 10 other competitors. Scoring will also include the competitors' performance during a surprise task that won't be revealed until the day of the competition.

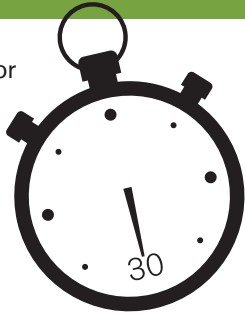
Although robotic rescue workers might seem outlandish now, the reality might be closer than we think. Several previous DARPA challenges of the last decade—in which Caltech and JPL have both participated—led directly to advancements in the driverless car technologies that are being explored today. —JSC

Insider Info

It took *E&S*'s senior editor more than

30

minutes to be able to see the message hidden in this issue's cover. How long did it take you?

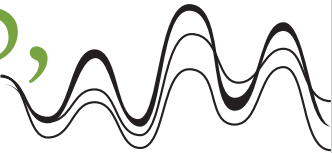


The 1.7-ton Fleming Cannon, a favored noisy campus memory (see page 36), has been stolen twice by rival institutions.



115, 200

Vocal cord vibrations, with conversational frequencies averaging 115 hertz for men and 200 hertz for women, could one day power medical implants. To learn more, see page 12.



Techie Talk

Genevieve Bell, Intel's in-house cultural anthropologist, is this year's commencement speaker. She studies the various ways in which people use technology—including what they love about it, what frustrates them, what they wish it would do—and processes and shares that information with the designers and engineers at Intel in hopes of creating products that can integrate more seamlessly into our lives. "I think our biggest challenge as technologists is sometimes we forget about people and all of their dimensions. We forget about families and art and love and beauty and poetry, and all that stuff," Bell says. Her top tip for keeping all of that in mind when working in the technology field? "Read more poetry."

Here are some other fun facts about the speaker at Caltech's 121st annual commencement ceremony:

- ▶ **She knows how to get water from frogs.** Bell's mother was an anthropologist who worked with aboriginal Australians, so Bell spent quite a bit of time in their settlements. Some of their survival techniques have stuck with her in part because they highlight the fact that different people think about and experience the world in different ways. "For me, there was something extraordinary as a kid to be immersed in that radically different worldview than the one I was accustomed to," says Bell. "It set me on a path of thinking about and paying attention to the ways in which people see the world differently."
- ▶ **She has an "embarrassingly large" personal collection of more than 5,000 books.** A lifelong avid reader, Bell's prized possession as a child was her library card, and she read every book in her high school library, alphabetically by author.
- ▶ **Her favorite question to ask herself and colleagues at the end of the day is, "What surprised you today?"** "There's something in the gift of still being surprised that's about being curious and allowing that there are things that you don't know," she says. "I don't want to ever become fixed in place or static."

On the Grounds

These water droplets, caught dancing in the sun's rays, are from numerous fountains that arch over a long pool lined with bright, mosaicked tiles that resemble the double helix structure of a strand of DNA. Nicknamed the "gene pool," this aquatic feature is flanked by benches and trees, providing space for a shaded nap or peaceful lunch with a soundtrack reminiscent of light rain. Where can you find this refreshing spot on campus?

Answer: The pool is found between the Beckman Institute and the Beckman Auditorium.

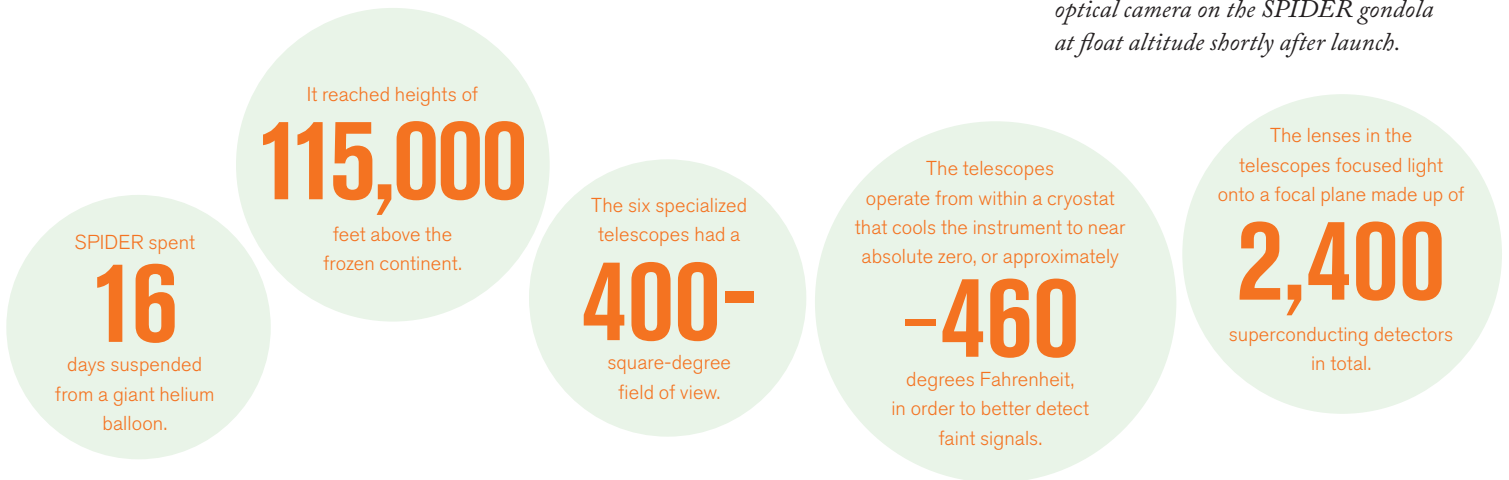


BY THE NUMBERS: SPIDER

Earlier this year, a scientific instrument dubbed SPIDER landed in a remote region of Antarctica. Conceived of and built by an international team of scientists, the instrument was launched on a balloon from McMurdo Station on New Year's Day. Caltech and JPL designed, fabricated, and tested the six refracting telescopes the instrument used to map the thermal afterglow of the Big Bang, also known as the cosmic microwave background (CMB). SPIDER's goal: to search the CMB for the signal of inflation, an explosive event that, in the first fraction of an instant after the birth of our universe, blew the observable cosmos up from a volume smaller than a single atom. The instrument appears to have performed well during its flight, said Jamie Bock, head of the SPIDER receiver team at Caltech and JPL. "Of course, we won't know everything until we get the full data back as part of the instrument recovery."



A view of Antarctica, seen from an optical camera on the SPIDER gondola at float altitude shortly after launch.



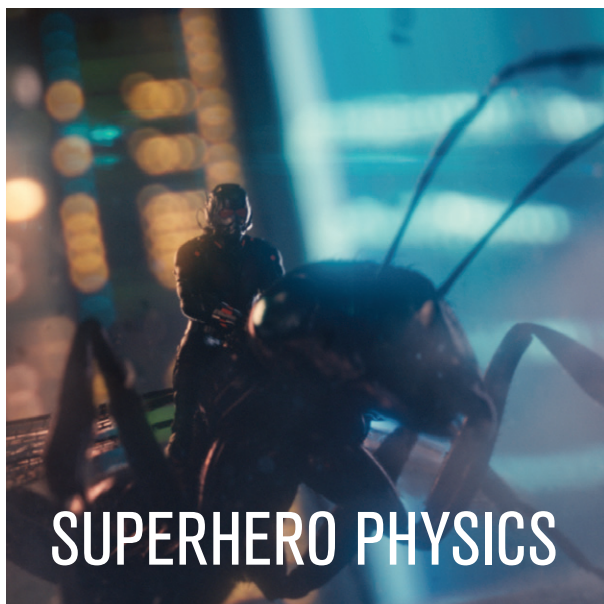
* FACULTY FOOTNOTES



By day, Konstantin Batygin (MS '10, PhD '12), assistant professor of planetary science, is developing a theoretical understanding of how planetary orbits evolve—from start to finish—by studying the dynamical structure of our own planetary system. By night, he's the lead singer of a band called The Seventh Season. Earlier this year, Batygin's impressive research reputation—he had published 21 first-author papers by the age of 28—coupled with his musical interests earned him a spot on the Forbes "30 Under 30" list in the science category, where he's described as "the next physics rock star."

We asked Batygin for a few other facts that probably don't appear on his résumé:

- ▶ **He grew up surrounded by scientists in Japan, where his dad was a physicist at a research institution called RIKEN.** "At the time, I had grown to believe that becoming a scientist is simply something that you do when you grow up. However, this had nothing to do with my own career choice as I am now keenly aware that other jobs do exist—for example, one can also become a musician!"
- ▶ **but at the time the coolest thing about Dmitry's dad was that he took us to Disneyland in Tokyo, and we got to go on all the rides, including Space Mountain. My mind was totally blown when I finally realized in grad school that Dmitry's dad, Nikolai Shakura, was a world-famous astrophysicist who developed the standard theory of disk accretion.**
- ▶ **His first trip to Disneyland was with a famous astrophysicist.** "When I was about 10 years old, I had a good friend named Dmitry. I knew Dmitry's dad studied something related to black holes,
- ▶ **He met his wife, Olga, on the day he arrived in the United States as a teenager.** "Meeting her that day confirmed what the USA brochure had said: America really is a great country."



One day last year, Spiros Michalakis, a staff researcher at Caltech's Institute for Quantum Information and Matter, found himself having a serious conversation with actor Paul Rudd about conservation of mass and energy. Rudd stars in this summer's Marvel flick, *Ant-Man*, playing a character who steals a suit that shrinks the wearer down to the size of an ant while allowing him to retain his usual strength.

Rudd was part of a team, including writers, producers, and special effects experts working on the film, who met with Michalakis, a quantum physicist, to get his scientific input on various plot points in the script.

"The *Ant-Man* suit has to do a lot of work to keep the hero alive," says Michalakis. After all, a lot could go wrong if a 160-pound man suddenly became the size of an insect. Everything from his metabolism, to his breathing, to his sight (he would see in the ultraviolet) would change.

Then there was the issue of mass. In order for the character to be able to ride on a flying ant (as the original Marvel character did), he would have to lose almost his entire mass. How would one account for that?

"I gave them a visually stunning way to represent the loss of mass through energy dissipation," says Michalakis. "That would lead to nuclear explosions that would destroy the earth, but who is counting?"

The filmmakers identified Michalakis as the expert they needed through the Science and Entertainment Exchange, a program of the National Academy of Sciences aimed at elevating the level of scientific accuracy in Hollywood productions. Michalakis says he doesn't think the goal should necessarily be to get the science in the movie exactly right but to make some fundamental aspects accurate.

"It is in the conversations after the movie that the fans get into the actual science," he says. "That's when the experts should be front and center to answer the questions and to create wonder." —KF

NEED A DRINK?

After taking your dog for a run on a warm sunny day, it's likely that your first instinct upon returning home is to gulp down a whole glass of water. Fido slurps from his bowl, too, as you're both driven to the same specific behavior by a signal that the body's healthy ratio of salt to water is getting out of balance. But how does that signal result in the desire to drink water? Assistant Professor of Biology Yuki Oka has pinpointed specific neurons in the brain that control this response, at least for mice.

Oka and his colleagues focused a recent study on the circumventricular organs—the regions related to the hypothalamus that were previously suggested to play a role in thirst. Using optogenetics, a technique that allows the control of neural activities with light, the researchers found two distinct populations that controlled the animal's water-drinking behavior. When the researchers "turned on" the first group of neurons, it evoked an intense drinking behavior even in fully water-satiated mice. The activation of a second group of neurons, on the other hand, could block the desire to drink even in highly water-deprived animals.

Although the work was done in mice, Oka says the finding suggests that there are innate brain circuits that can act as "switches," creating or erasing the desire to drink water—and that these circuits could act as a thirst control center in humans, too. —JSC

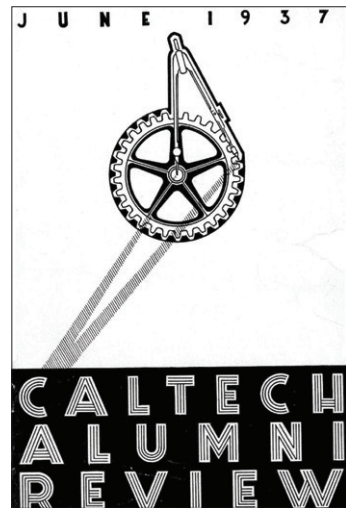


ON THE MOUND

Mel Levet (BS '39, MS '40) returned to campus in February to throw out the first pitch for a Caltech ball game against Occidental College. The last time that Levet, 97, squared off against Oxy in a baseball game, Franklin Roosevelt was in his second term as the nation's president and *Gone with the Wind* had just won the Oscar for best picture. During his three years on the varsity squad, Levet led teams to 15 wins—including a 2–0 shutout of Occidental College in his final season.

BEGIN AT THE BEGINNING

“As this, the first issue of the Caltech Alumni Review goes to press we feel like the frosh who has just purchased a bright new beanie and is trying it on in front of his mirror. Admiring his reflection he is happy at the thought that he is now old enough to be a college man and proud of his new colors—when the terrible thought occurs to him that as soon as he steps from the privacy of his room he will be laughed at, criticised, and paddled by the sophs, ignored by the upperclassmen.”



So began the “Foreword” of the enterprise that begat the *E&S* magazine in your hands—or on your computer screen or tablet or smart phone. Edited by Albert W. Atwood Jr., BS ’32, and published by the Alumni Association of the California Institute of Technology, the very first issue of the Institute’s very first magazine—published in June of 1937—was not that very different from the *E&S* of today.

It began with a message from the then president of the Alumni Association, H. Fred Peterson, BS ’27: “A forward step being watched with great interest is the publication of this first copy of the Alumni Review. The Board of Directors of the Association have decided to dispense with the

California Tech as a medium for Alumni news and expect to publish a magazine, this being the initial and experimental issue.”

The issue also included a note about its cover, which was created “by Harold Graham, ex ’24, who has left the ranks of pure science and engineering to achieve note in the field of industrial design. . . . All thanks to a busy Tech man who has wholeheartedly cooperated in making this first issue artistically successful.”

In September 1943, the *Caltech Alumni Review* became *Engineering and Science Monthly*, kicking off with a note from its editor in chief, Donald S. Clark. “With this issue for September, 1943, we present *Engineering and*

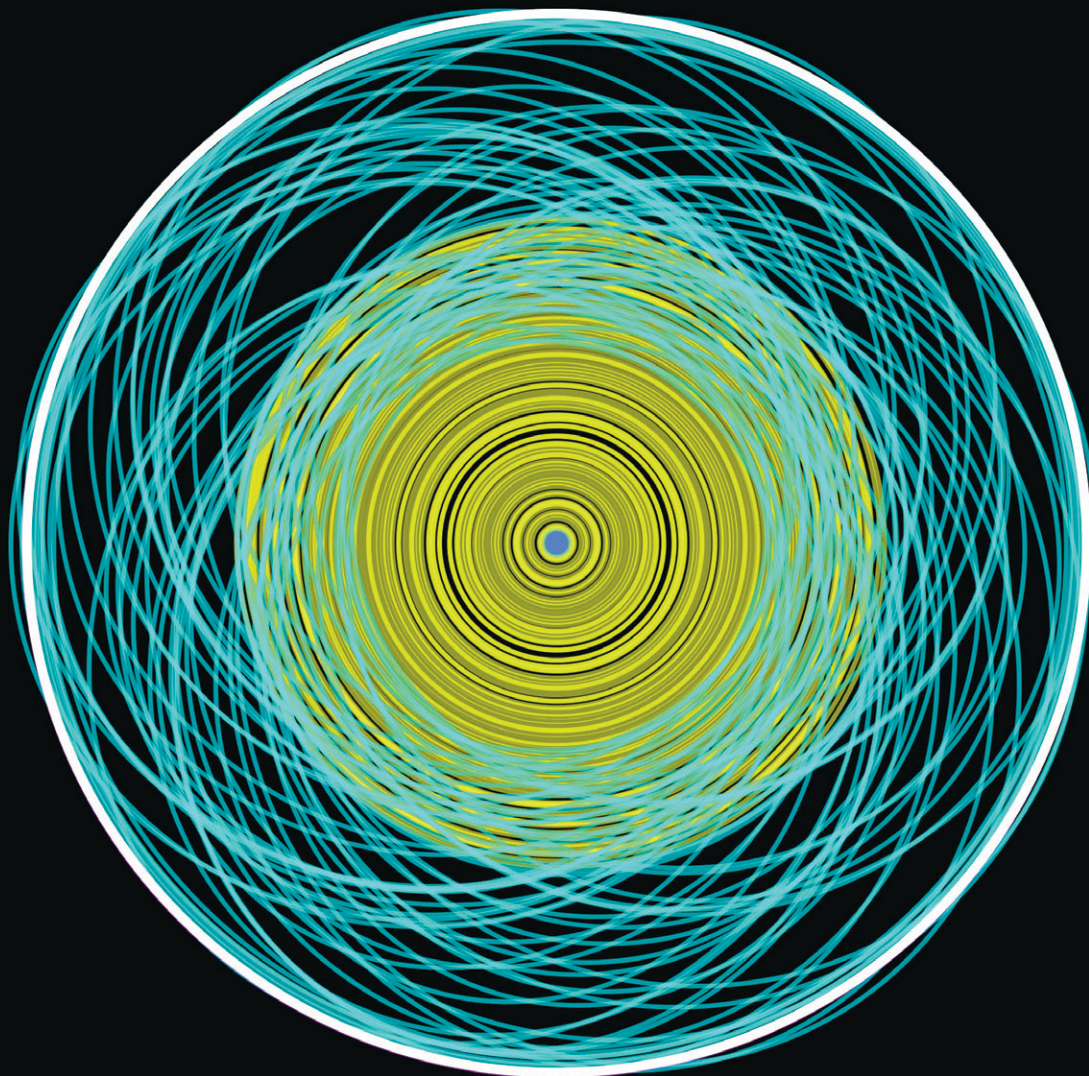
Science Monthly, which takes the place of the *Alumni Review*,” he wrote. “*Engineering and Science Monthly* has the endorsement of the California Institute of Technology, as well as the Alumni Association, and will endeavor to reflect all current development in the fields of engineering and science.” He then added, “We plan that each issue of *Engineering and Science* will be a well-balanced expression of the theoretical and the practical.”

In that same issue, Robert Millikan himself declared that, “With the inauguration of this magazine . . . a new means has been provided for the dissemination of information on the technical work of Institute graduates in the general field of engineering and science.”

In mid-1967, *Engineering and Science* disappeared for a few months, presumably while it underwent a redesign. When it reappeared in October of that year, it carried the first-ever *E&S* logo on its front cover and, in its interior, a continued focus on the Institute’s science (that done by its faculty as well as that done by its graduates), its students and alumni, and the campus itself.

It was, of course, not even close to the last time the magazine would evolve in look and tone and focus, but it was the last of the name changes and thus—in many ways—the end of *E&S*’s beginning. —LO





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SUPERSIZED WORLDS

A Caltech research team has hypothesized that long before Earth and our neighboring planets formed, the inner solar system may have been home to a number of super-Earths—planets larger than our own but smaller than Neptune. Learn more at caltech.edu/news.

Watch

No need to count sheep anymore! You probably already know that taking a melatonin supplement may help you sleep, but do you know why? Caltech scientists have found the answer. Find out more at youtube.com/caltech.



Read

Explore Caltech's new interactive campus map to learn more about the Institute, including the history of the buildings, the architects who designed them, the year they opened, and what is housed in them. Check it out at caltech.edu/map.



Engage

Enjoy music under the stars when MUSE/IQUE returns to the Caltech campus for its Summer of Sound series, kicking off Saturday, July 11, at 7:30 p.m. Find out more at caltech.edu/calendar/public-events.



GOOD VIBRATIONS

CALTECH RESEARCHERS
SEEK TO RIDE THE POWER
OF SOUND WAVES TO A
BETTER WAY TO DIAGNOSE
AND TREAT DISEASE.

by Katie Neith

For their 1966 song “Good Vibrations,” the Beach Boys assembled an unusual mix of instruments—including a jaw harp, a cello, and an Electro-Theremin—to produce one of their biggest hits. By arranging sound waves in a unique and particular way, they were able to elicit a positive response.

Many doctors and researchers have the same goal. After all, the same “excitations” that helped the Beach Boys usher in an era of feel-good pop—the sound waves that propagate through air and water, bringing notes of music to our ears—are also non-invasively able to explore body tissues, helping to visualize babies in the womb, heal back pain, or even deliver chemotherapeutics to targeted tumors.

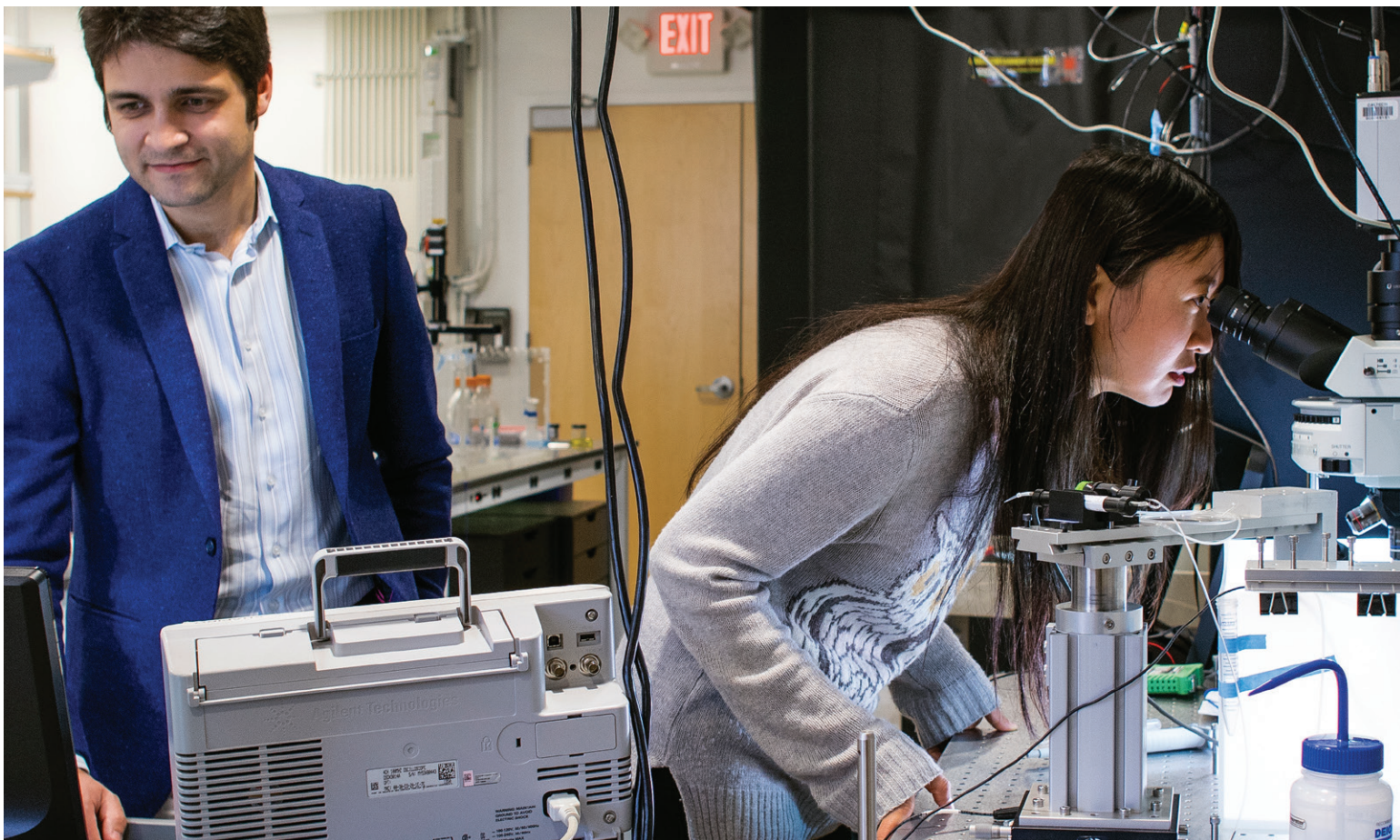
One of the most-used “good vibrations” in medicine is ultrasound—sound waves delivered at a frequency inaudible to the human ear. Ultrasound has been used in medical settings since the 1940s for diagnostics and in recent years has gained popularity for use in physical therapy and to speed up drug delivery.

But that, say chemical engineer Mikhail Shapiro and biologist Doris Tsao, isn’t all that ultrasound can do. The two, who met shortly after Shapiro was hired to the Caltech faculty in late 2013, have joined forces to develop a new technology that uses ultrasound to both map and determine the function of interconnected brain networks. Their goal: to one day be able to change abnormal neural activity deep within

the brain using pulses of sound. The idea is so intriguing that, in September 2014, theirs became one of 58 projects nationwide to be awarded funding by the National Institutes of Health (NIH) as part of President Obama’s Brain Research through Advancing Innovative Neurotechnology—or BRAIN—Initiative.

They are an ideal pair for this project: Shapiro’s lab focuses on ways to use different forms of energy—like magnetic fields or sound waves—to penetrate deep into the brain in order

As part of their research on the microscopic interactions of sound waves and neurons, Mikhail Shapiro (left) and Doris Tsao use custom instrumentation that allows detailed programming of acoustic pulses and high-speed microscopy to observe the effects of sound waves on neural excitation and signaling.





people hesitant to use implants. If you can have a more permanent power source that continuously powers the devices, it would be a big advantage. So I've been looking for an energy source that we could reliably and easily harvest, or capture and store."

Choo thinks he's found a solution, one we use all the time: our voice. He wants to harness the vibrations that vocal cords make when we talk, and use them to power implantable devices. So, for example, a deaf person could sing a song to charge up their cochlear implant.

Last summer, Choo tasked undergraduate Sophia Chen with testing this idea—that our voices could be used to power devices—as part of her Summer Undergraduate Research Fellowship (SURF).

"First, I analyzed the vocal cord vibrations throughout the skull, which basically showed that we could harness those vibrations and turn them into

storable energy," explains Chen.

To then test the strength of the vibrations, she simply attached tiny accelerometers to different areas of the head in eight volunteer participants, one of whom was Choo. She asked the volunteers to hum at a constant frequency; then hum on a scale, from lowest to highest frequency; and then read aloud.

"Sophia found that, no matter the vocal activity being performed, the acousto-mechanical vibrations were concentrated at a single frequency for 80 to 90 percent of the time," says Choo. "By focusing on one frequency, we can really optimize the harvesting process."

This suggests that—instead of having wires running from the brain to a power source typically placed under the skin of your chest for deep-brain stimulation, or batteries mounted behind the ear for cochlear implants—a device harvesting energy from vocal cords could also be implantable.

"There would be no wires sticking

Caltech student researcher Sophia Chen attaches sensors to the face and head of volunteer Sagar Vaidyanathan, a visiting undergraduate researcher from UCLA. The sensors are accelerometers used to characterize the magnitude of vocal cord vibrations at different locations on the head.

out or anything; everything would be inside the head," says Choo. "That would be an advantage of this approach."

He is now working on building such a vibration-harnessing device, inspired by an off-the-shelf piezoelectric setup—a device that harvests energy from pressure, including that derived from sound vibrations. The team's challenge is to scale down that technology so it can be implanted in the body while leaving it sizeable enough to generate the power needed, utilizing the energy provided.

"Best we can tell right now from



Senior postdoctoral scholar Carly Donahue is surrounded by granular materials and other items that represent the fundamental building blocks of an acoustic lens.

the data we have, a person would have to sing their favorite songs for about 10 to 20 minutes twice a day to keep their device powered,” says Choo.

He notes that there is no worry of overdoing it, should one want to sing an entire opera or gab with friends for hours. A safety feature can be built into the device to cut off the charging process once the implant has enough juice.

Because Chen—now finishing up her sophomore year at Caltech—has coursework to deal with, Choo and his lab are taking the SURF work she did and running with it. But Choo gives Chen all the credit for what he calls “a very viable option” for solving this medical challenge.

“The right project for the right

student makes a big difference,” says Choo. “We are continuously working on this project, and when the time comes to test the energy-harvesting device that we fabricate, I hope Sophia will come back and help us again.”

SOUND IT OUT

Ultrasound machines and energy harvesters use regular old sound waves in unique and novel ways. But Caltech senior postdoctoral scholar Carly Donahue has taken a different tack. She helped devise techniques to try to change the way those sound waves *behave*, with the goal of giving sound more power in medical applications.

In a research group lead by Chiara Daraio, Donahue and graduate student Paul Anzel worked to produce highly focused, high-amplitude acoustic signals called sound bullets because of their destructive power. The manipulated sound waves act much like a tidal wave, appearing to move by pushing all their energy forward in a single

crest instead of in the classic squiggly (and weaker) waveform. The hope is that these focused packets of energy could one day be used to destroy unwanted tissue or trim away tumors, all without doing the kind of damage to the body that a real bullet would do.

This work really began in 2010, when Daraio and her lab reported that they had learned how to control the way in which sound travels, using granular materials—in their case, macroscopic stainless-steel ball bearings, or spheres, assembled into a chain. An array of 21 such parallel chains created what the researchers call an acoustic lens—a pulse of sound pressure initiated at one end travels down each chain in much the same way motion in the Newton’s cradle children’s toy travels from the first ball to the last in a chain without moving the ones in the middle. The point of it all? To use the lens to focus all that pressure, all that sound, at one spot, creating a sort of bullet of sound.

“It’s a simple concept, but it has

such incredibly interesting physics,” Donahue says. “The whole idea of the lens is being able to control acoustic signals in a completely different, nonlinear way.”

According to Anzel, who is studying applied physics, the best way to focus sound at a specific point is to shape the way the signal moves through space.

“What we took advantage of is that, just by squeezing a row of bearings, you can cause a signal to travel through it faster,” he says. “So, if you create rows of ball bearings and squeeze the outer rows more than the inner ones, you can control the speed of the sound pulses so that they arrive at the same time from a bunch of different directions to target an area.”

Building on the 2010 results, which focused the sound waves to penetrate a solid material, Donahue and a team of colleagues began testing the concept in liquid. They also began thinking about applications: sound bullets traveling through liquids could be used to image and evaluate the structures of bridges, says Anzel, or solid objects on the floor of the ocean, much like weaker ultrasound waves are used to image the body.

“We wanted to try this in liquid because, if we want to do medical applications, we have to deal with the fact that obviously the body is not solid,” Donahue explains. “For liquid, we had to think about how to actually transmit a wave from a solid material into a fluid and the extra complications involved.”

To create the lens in water, Donahue, Daraio, Anzel, and others first aligned the same spheres they’d used in their solid lens, but put each chain into individual tubes. Then, they constructed a waterproof interface—made of a glass disk and polymer encasing—so that they could submerge part of the tubes in water without the

spheres falling out. After arranging the tubes next to each other to form the same kind of array they’re created in the solid version of the lens, they then generated a sound pulse, controlling each wave’s timing and amplitude.

“The most surprising part of the study was how important the materials used in the lens-water interface were for controlling how the sound travels,” Daraio says. “We knew it would play a substantial role in the formation of the sound bullet and the energy transfer to the water, but we had not fully realized the complexity required in its design. This is something Carly really made important progress on.”

A much smaller setup would be needed for use in the human body, so Daraio’s research group is investigating solutions for the miniaturization of such a device. And Donahue is now exploring how contacts between different materials work on smaller scales—at the microscale or even the nanoscale—where different forces may come into play.

“We want to know the basic forces and how things behave to see if it will work,” she says.

If successful, these tiniest of sound bullets might one day be used to noninvasively blast kidney stones and gallstones, remove blood clots, and potentially provide a more accurate imaging alternative, one that could produce even clearer views of the body than do current ultrasound technologies.

“Reducing the device’s size would enable us to reach wavelengths of interest for medical applications, and I hope to see this realized in the next few years,” says Daraio. “It is exciting to see many years of hard work and passion for fundamental research leading to the creation of an instrument that may improve everyday life for many people.” **eS**

Mikhail Shapiro is an assistant professor of chemical engineering. Doris Tsao is a professor of biology. Their collaboration is funded by the National Institutes of Health.

Hyuck Choo is an assistant professor of electrical engineering. Sophia Chen will be entering her junior year at Caltech in fall 2015, and her work in Choo’s lab was funded by a Student Undergraduate Research Fellowship and the Aerospace Corporation. Choo’s continuation of their energy-harvesting research is funded by Caltech’s Grubstake program.

Chiara Daraio is a professor of aeronautics and applied physics at Caltech and professor of mechanics and materials at ETH Zurich in Switzerland. Paul Anzel is a graduate student in applied physics and Carly Donahue is a senior post-doctoral scholar in applied physics and materials science. The sound-bullet project was originally funded by U.S. Office of Naval Research. Daraio’s current work on the acoustic lens is funded by the U.S. National Science Foundation and the Army Research Office.

The Sounds of Science

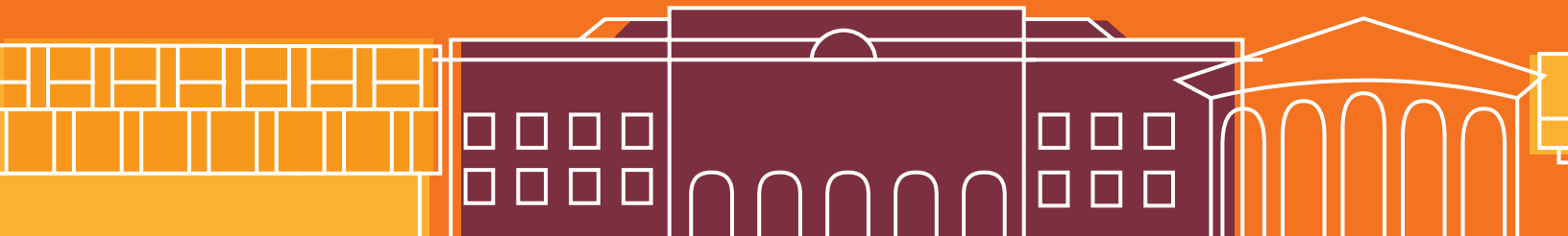
Take a walk around the Caltech campus on any given day—save perhaps Ditch Day or commencement—and it is unlikely to reveal itself as a noisy place. However, step into any of a number of labs, and you can hear the sounds of science at work, from buzzing brain-scanning technology to music-like signals from space, and many whirs, bleeps, and booms in between. Since it's impossible for us to embed those sounds into these pages, we asked a sampling of researchers to describe what their work sounds like. You can also tune in to our E&S+ website to hear recordings of the sounds that we could gather.

“It sounds kind of like a cross between a **car alarm** and an **angry squirrel**, with some **drums** in the background.”

Ralph Adolphs, Bren Professor of Psychology and Neuroscience and professor of biology, describes the sound of the pulse sequence used for functional imaging of the human brain at Caltech's Brain Imaging Center.

“We listen for changes in the separation of mirrors over the 4-kilometer length of each laser-interferometric detector. But thermal energy in the 0.4-millimeter-diameter glass strings that hold up 40-kilogram mirrors also causes **ringing** sounds that we call ‘violin modes.’ And a **hiss** comes from the quantum nature of the light: fluctuations in the nothingness of empty space that interfere with our pure laser beam.”

Rana Adhikari, professor of physics, talks about noises from the Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors. The aim of LIGO is to measure the stretching and squeezing of space-time. Scientists listen to the detector outputs—which are sometimes disturbed by things from the earth, such as earthquakes or traffic—using headphones.



“Experiments in T5, one of the GALCIT Hypersonics Group facilities, begin with a **siren** . . . to alert the building. Sometimes it’s mistaken for an earthquake warning. A few seconds later the tunnel fires, accelerating gas to the velocities required to simulate planetary entry flows. The gunshot-like sound and vibrations can be heard and felt through the building.”

Joanna Austin, professor of aerospace, uses pistons and explosives in large test tunnels to compress gases. She studies the mechanics involved in compressible flows, which come into play in problems ranging from the logistics of a spacecraft’s entry into a planet’s atmosphere to the hows and whys of volcanic eruptions.

“The tsunami causes the ionized gas that is out there to resonate — ‘**sing**’ or vibrate like a bell.”

Edward C. Stone, the David Morrisroe Professor of Physics, characterizes the sounds of “tsunami waves” that helped signal Voyager 1’s entrance into interstellar space. These waves of pressure are caused by coronal mass ejections from the sun. Stone is the project scientist for the Voyager mission, based at Caltech.

“My research literally includes the sound of **waves crashing** on the beach, the **bubbling** of a brook, and the **crackling** of glacial ice disintegrating as it flows into the ocean.”

Victor Tsai, assistant professor of geophysics, studies the seismic noise of ocean waves and rivers as well as glacier mechanics.



EVERY THING NOISE

by Ker Than

“I like everything noise.”

Jonas Zmuidzinas's new favorite saying is a phrase that's been running through his mind a lot lately. A physicist at Caltech who develops instrumentation for use in astronomy, he spends an inordinate amount of his waking hours thinking about noise—but not in the way you might expect.

For the average person, thinking about noise might mean trying to ignore the loud neighbors on a Sunday morning or using sound-cancelling headphones on a flight full of babies. But for many scientists and engineers, a broader definition also assigns the term to the fluctuations in a measured signal that can obscure or reduce its clarity.

“For people like myself who build instruments and detectors, noise is at the heart of what we do,” says Zmuidzinas.

That's because in engineering, for example, fluctuations, or noise, can arise from the random motions of atoms or electrons, and can manifest as heat or electronic static. And that can lead to malfunctioning machines. A clearer understanding of noise sources and ways to minimize it in circuits can lead to more efficient microchips and to telescopes that are capable of probing structures in the universe that were previously beyond reach.

At the same time, Zmuidzinas and his Caltech colleagues believe that noise can also be a useful scientific tool; some are investigating ways to harness the literal power of noise to create artificial cells that can function as powerful computers, while others

are starting to uncover the important role noise plays in gene expression, research that suggests noise is vital to life itself.

SPACE NOISE

Zmuidzinas's focus on noise is helping him learn how to reduce it and thereby improve the ability of instruments to detect previously indiscernible signals and objects in astronomy.

“Big progress is made when you advance the frontier of detection,

from the ground up.”

The construction of improved submillimeter instrumentation could help answer many of modern astronomy's outstanding questions, such as when and how did stars form in galaxies over the history of the universe. Large clouds of gas and dust give birth to stars, but when stars blaze to life, the clouds enveloping them absorb their starlight and convert it into a longer and weaker wavelength before reemitting it back out into the universe in

“FOR PEOPLE LIKE MYSELF WHO BUILD INSTRUMENTS AND DETECTORS, NOISE IS AT THE HEART OF WHAT WE DO.”

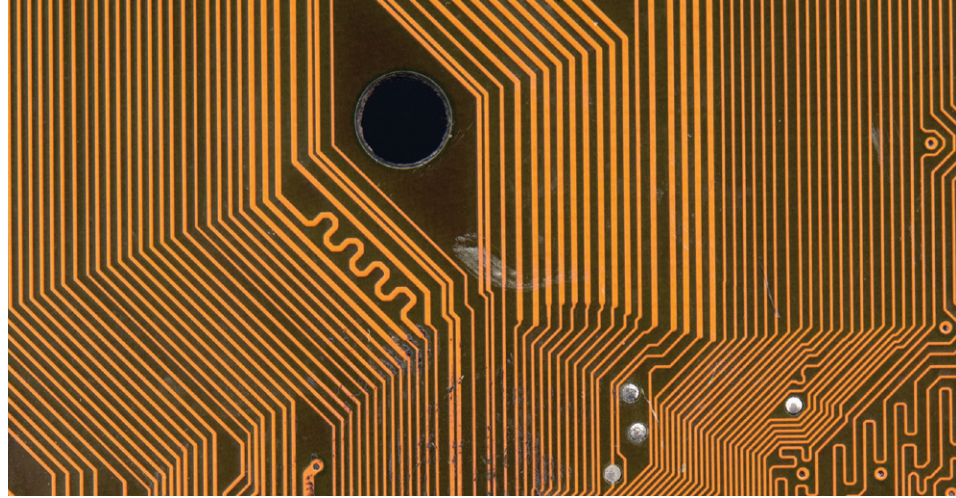
when you start measuring signals and detecting objects that have not—could not—be seen before,” he says.

Zmuidzinas's lab focuses on submillimeter astronomy, the branch that deals with wavelengths of light that are both invisible to the human eye and lie between the wavelengths that radio telescopes and optical telescopes observe.

“Submillimeter astronomy straddles these two very different domains of astronomy. It's a mishmash of both,” says Zmuidzinas. “All of the physics that enables the detectors that you use in visible-light astronomy get tossed out the window when you're designing instruments for submillimeter astronomy. You have to start completely fresh and invent everything

the submillimeter band. Still, astronomers were shocked to discover—in the 1990s—that the universe is as bright in submillimeter light as it is in optical-infrared light, which are the primary wavelengths that stars emit. “The surprise was how much of the energy produced by stars gets shifted to the far infrared and submillimeter range. Very few astronomers would've believed it if the measurements didn't clearly show that this was the case,” says Zmuidzinas.

Building detectors sensitive enough to make this case—or, rather, to discern submillimeter light—is technically difficult. That's because the particles of light, or photons, in the submillimeter band are 1,000 times weaker than optical photons,



since the gas clouds and other celestial objects that emit them are typically cold and dark. Instruments intended to ensnare these feeble photons must be similarly cooled, so that they do not radiate any heat that would interfere with signal detection. To build their detectors, Zmuidzinas and his team have turned to superconducting materials that can operate at temperatures well below 1 kelvin (−458 degrees Fahrenheit).

At such frigid temperatures, the natural motions of the atoms that make up the superconductors slow to a near standstill, thus minimizing thermal vibrations. These vibrations—which are a kind of noise—can break the fragile bond between the electron pairs in the superconductors that form the core of the detectors Zmuidzinas’s team develops, and create false positives in their measurements.

“Understanding the origins of the noise allows us to engineer our detectors to reduce it,” says Zmuidzinas, who helps lead Caltech’s Submillimeter Astrophysics group, which operates the Caltech Submillimeter Observatory (CSO) in Mauna Kea, Hawaii.

Zmuidzinas’s immersion in the study of noise has resulted in some surprising collaborations. While researching a type of noise originating from atoms hopping around on the surfaces of their detector circuits, particularly in the capacitors—electrical components that store energy—Zmuidzinas and his coworkers discovered a common ground with physicists working on

quantum computing, which aims to use the weird laws of quantum mechanics to process information.

“It turned out that the noise we were investigating also strongly influences the performance of the superconducting circuits that people interested in quantum computing have been using,” says Zmuidzinas, “and so we’ve had this nice back and forth that has helped us both.”

PHONON NOISE

Delving into the mechanics of noise also resulted in new insights for mechanical engineer and applied physicist Austin Minnich. He and his team recently identified a source of electronic noise that sometimes affects the functioning of electronic instruments that operate at very low temperatures, including devices used in radio astronomy and in airport security scanners. The findings could also have implications for the future design of circuit elements, such as transistors, which amplify and switch electronic signals and electrical power.

The electronic noise Minnich’s team identified is related to the transfer of packets of vibrational energy, called phonons, which are present in all materials that have a crystal structure. “In a crystal, from those in ordinary table salt to the indium phosphide crystals used to make transistors, you have atoms that are arranged in an orderly lattice,” Minnich says. “Those atoms can vibrate in different ways, and you can break down those vibrations into

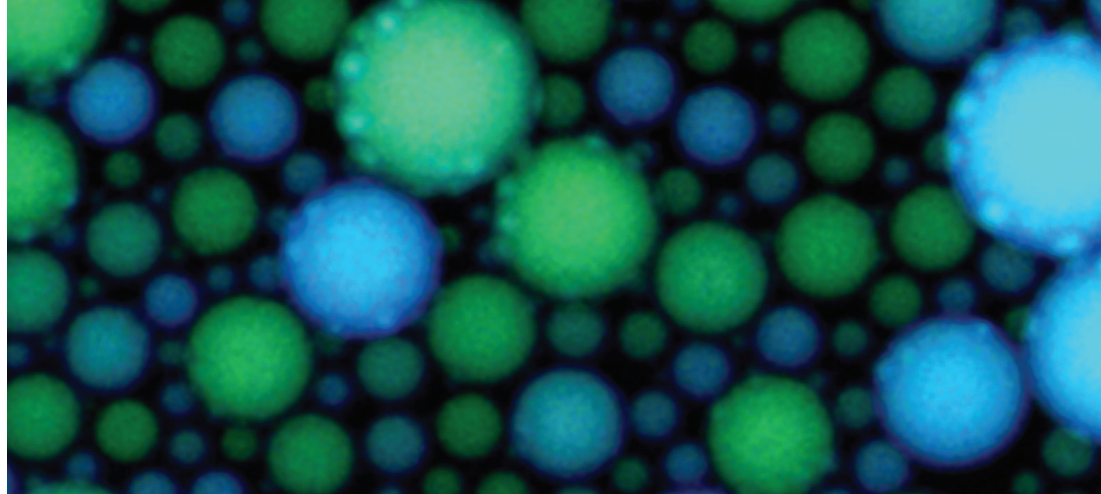
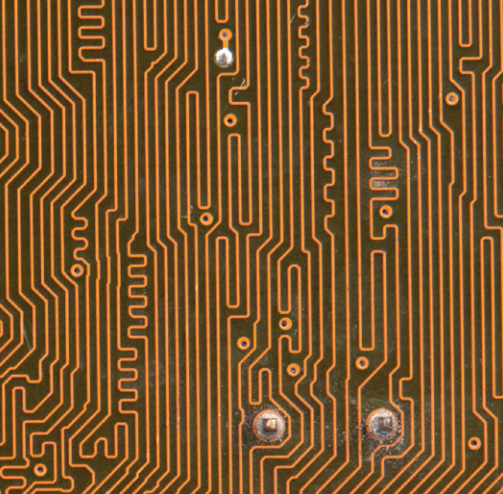
modes. A phonon is a discrete packet of these vibrational modes.”

Phonons are important for electronics because they help carry away the thermal energy, or heat, generated by electrical currents. When electron flow is restricted, some of the energy involved in moving the electrons forward is converted to heat. How swiftly and efficiently phonons ferry heat away from a circuit element and into the environment is partly dependent on the device’s operating temperature: at high temperatures, phonons are more energetic and are more likely to collide with one another and with imperfections in the atomic structures of electrical components. This noisy phenomenon, called scattering, results in phonon traffic jams that prevent phonons leaving the device and therefore lead to a temperature rise.

“Phonons can interact with each other, and you can imagine that if their direction is randomized, a lot of scattering will occur, and that makes it hard to move heat energy around,” Minnich says.

One way that engineers get around this problem is to operate electronics in extremely cold conditions, because scattering drops off dramatically when the temperature dips below about 50 kelvins, or about −370 degrees Fahrenheit.

But the new findings by Minnich’s team showed that while phonon scattering ceases at low temperatures, another mechanism kicks in and severely restricts heat transfer



away from a device.

In a study published last fall in the journal *Nature Materials*, Minnich and his colleagues demonstrated that at around 20 kelvins, or -424 degrees Fahrenheit, the high-energy phonons that are the most efficient at transporting heat away quickly become deactivated. The remaining low-energy phonons don't have enough energy to carry away the heat and, as a result, the transistors warm up until eventually the temperature rises enough that the high-energy phonons become activated again.

Minnich says the solution may be to design transistors that don't heat up as much at low temperatures in order to find an equilibrium where scattering doesn't come into play again either. "The heat turns out to be generated in a very small region under a device. So if you can figure out how to spread out the phonon generation, you could, in principle, decrease the temperature rise that occurs," Minnich says.

A better general understanding of phonon scattering could also lead to improved thermoelectrics: devices that can convert heat directly to electricity and that could lead to efficient waste-heat recovery, environmentally friendly refrigeration, and more capable rovers and other robots for space exploration.

ARTIFICIAL NOISE

Understanding noise—and harnessing its power—also is a goal for computer scientist Erik Winfree, who sees noise

as an intrinsic aspect of synthetic artificial cells that are designed at the molecular level. Winfree and his team of international collaborators want to create biochemical circuits that use DNA, proteins, and other biological molecules instead of silicon chips to perform programmed tasks, such as computations or signal processing, that control the activity of the artificial cell.

"I tend to think of cells as really small robots," Winfree says. "Biology has programmed natural cells, but now engineers are starting to think about how we can program artificial cells. We want to program something that can interact with its chemical environment and carry out the spectrum of tasks that biological things do but

“UNDERSTANDING THE ORIGINS OF THE NOISE ALLOWS US TO ENGINEER OUR DETECTORS TO REDUCE IT.”

according to our instructions.”

Because the components in their circuits are so tiny, the scientists have to contend with sources of noise—such as Brownian motion, which is the random jiggle of atoms and molecules suspended in fluid—that can be ignored in macroscopic systems. Another source of randomness that comes into play at very small scales is partitioning noise, which results from small differences in how particles end up in each place when a large volume of

Above, a false-color image from Erik Winfree's research shows fluorescence within water-in-oil droplets containing a biochemical oscillator. Droplet-to-droplet variability in the fluorescence indicates noise in the preparation and operation of the oscillator circuitry.

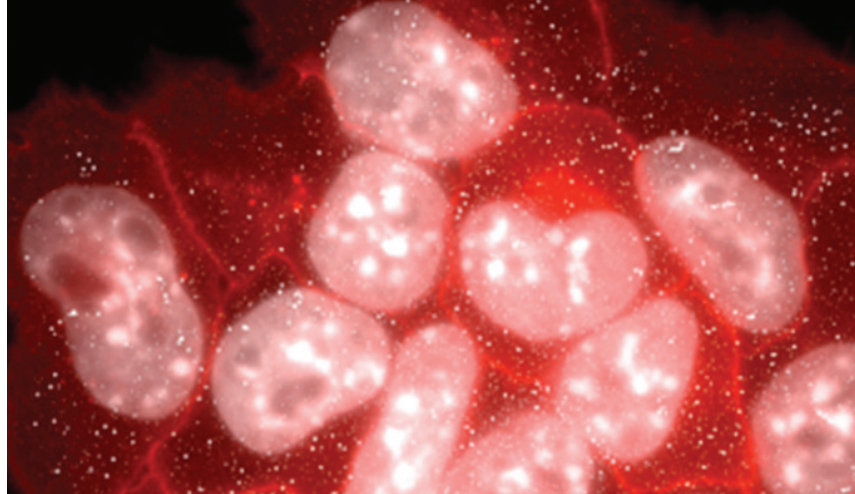
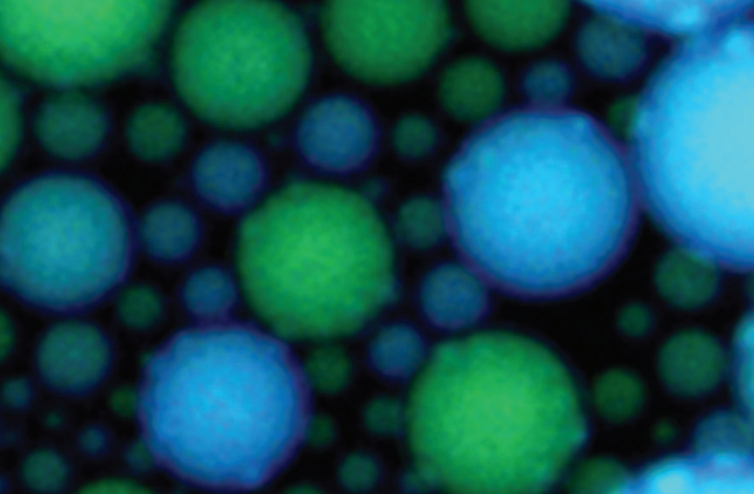
liquid gets divided, or partitioned, into many tiny compartments.

Winfree ran into an example of this kind of partitioning noise when he and his team recently tested the effect of small sample size on biochemical processes using a fluorescent biochemical oscillator circuit capable of pulsing rhythmically for several hours.

First, they designed the oscillator, a solution composed of small synthetic DNA molecules that are activated by

RNA transcripts and enzymes. When the DNA molecules are activated by the other components in the solution, a biological circuit is created. The researchers then “compartmentalized” the oscillator by reducing it from one large system in a test tube to many tiny oscillators isolated within droplets surrounded by oil.

During their experiments, they found that the size of the droplets really mattered: large droplets fluoresced mostly in sync with one another, as



though they were acting in concert and similarly to how the larger circuit acted in a test tube, while smaller droplets were much less consistent—their pulses quickly moved out of phase with the larger droplets.

The scientists think the main reason for this is partitioning noise: some of the droplets initially had more molecules when they were created, while others had fewer. Also, the ratio of the various elements differed among the droplets. The smaller the droplets, the more important these differences became since, with fewer molecules, slight differences in the timing of reactions were amplified.

“In one sense, partitioning noise is a nuisance, because it prevents you from knowing how any given droplet is going to behave because it could have different starting conditions compared to its neighbors,” Winfree says.

But Winfree thinks the data gleaned from this natural variability could also be useful for characterizing molecular circuits and measuring their behavior. “You can think of the randomness as a resource,” he says. “For example, if you have 1,000 droplets, and each one has a slightly different initial condition, you can essentially perform 1,000 different experiments in parallel.”

Other scientists are using the molecular circuits and design principles developed in Winfree’s group to create biomolecular systems that might one day operate within cells to diagnose or treat disease. But Winfree

says he is interested in more fundamental questions, such as what kinds of computation are possible using chemical and biological systems, what the limits are of such computations, and how can noise either hinder or help the molecular circuits function.

“We have a rich theory about deterministic computation like the kind performed by electronic computers,” he says. “But the universe is made out of molecules, and I want to understand what are the computational capabilities of these natural systems.”

NOISY BIOLOGY

Bioengineer Michael Elowitz also investigates noise in nature. He and his team focus on gene expression—the cellular process by which

whether it is driven mostly by random, noisy fluctuations in gene signaling.

The ideal way to test for this kind of randomness in genetic circuits would have been to place two identical cells in the same environment and see whether their behavior differed. “But you can’t really perform this experiment,” says Elowitz, “because no two cells are ever identical. Even two sister cells differ from one another and do so in many ways.”

So Elowitz’s team did the next best thing. They took two almost perfectly identical genes that coded for differently colored fluorescent proteins—call them green and red—and inserted them into single cells in a population of the bacteria *Escherichia coli*.

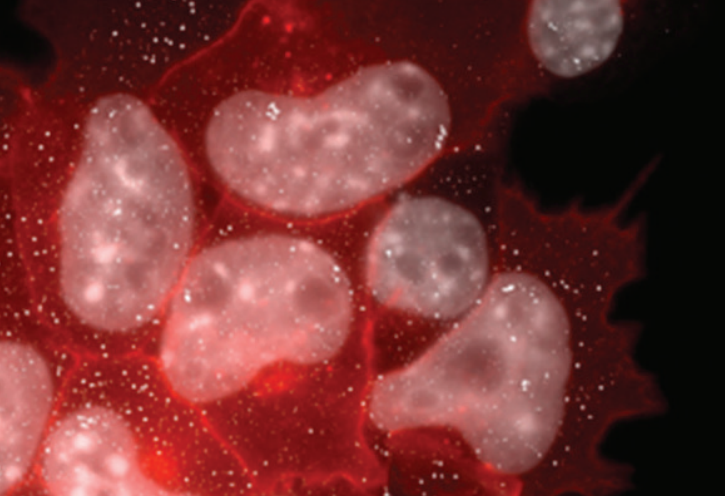
Their hypothesis was that, if

“OUR EXPERIMENT SHOWED IN A VERY VISUAL WAY THAT CELLS ARE NOISY. IT ESTABLISHED THAT NOISE IS REAL . . . IN GENE EXPRESSION.”

DNA instructions get translated into proteins—and on better understanding and even designing genetic circuits composed of interacting genes and proteins; such circuits are already beginning to enable researchers to program new behaviors in living cells.

Back in 2002, his lab was looking specifically at the question of whether gene expression is deterministic—whether a specific gene action always leads to a specific protein outcome—or

gene expression is deterministic, the cells would treat the two genes in the same way and express equal amounts of the two proteins. In that case, all cells would appear yellow, since the equal amounts of red and green protein produced would combine to make yellow. What happened instead was that the cells exhibited a much broader spectrum of colors, ranging from neon green cells to very red cells, with plenty of oranges and yellows in



At left, an image taken by Zakary Singer in Michael Elowitz's lab shows how closely related embryonic stem cells can show variable levels of gene expression. The white dots in the cytoplasm are individual messenger RNA molecules for a gene that maintains the stem-cell character of these cells, but whose expression level (number of dots) varies substantially from cell to cell.

between. This color variation indicated that cells expressed widely varying amounts of the two genes, despite the cells' similarity.

"Our experiment showed in a very visual way that cells are noisy," says Elowitz. "It established that noise is real and in many cases is the dominant source of variation in gene expression between cells."

Subsequent research by Elowitz's lab has indicated that bacteria have evolved ways to exploit this kind of noise in order to hedge their bets against an uncertain future. For instance, his team showed in another experiment that genetically identical bacteria raised in the same environment nonetheless employ different survival tactics when stressed. Some enter a state in which they are more receptive to infusions of DNA from other bacteria, while others transform into spores—a dormant state that makes the cell extremely resilient and able to survive for hundreds of years. In many ways, this is a clever strategy, Elowitz says.

"The cells don't know the future, so what they've evolved to do is diversify by having different fractions of the population enter into different states," he says. "The cells use their own internal noise to roll the dice, if you will."

Elowitz's research suggests that the decision about which state to enter seems to be governed by random chance at the level of gene expression, depending on what else is happening inside a cell at the time. His team has

identified specific kinds of gene circuits in the cell that initiate specific cellular behaviors or programs in response to random fluctuations of protein levels—i.e., noise—within a cell.

Under conditions where the environment itself fluctuates randomly, noise-based strategies can be more advantageous than deterministic strategies. This makes sense, says Elowitz: a population of cells whose members can switch randomly between different states will be better prepared for future changes in the environment than one that just responds to current conditions.

But noise is not just for bacteria. Elowitz's team has begun taking the techniques they've developed for studying noise in bacterial cells and applying them to embryonic stem cells. These undifferentiated cells from the earliest stages of fetal development can go on to produce a wide range of different cell types, even when put in identical cell cultures. Elowitz's group is now studying how noise could enable this type of cell differentiation and development in mammals.

Elowitz's research strongly suggests that noise—far from being a nuisance—is essential for healthy cell functioning. "Computers function with essentially no noise. But cells are built very differently. They wouldn't function without noise, or if they did, it wouldn't be life as we know it," he says. "I think we're just beginning to scratch the surface of the many different roles that noise plays in living systems." **e&s**

Michael Elowitz is a professor of biology and bioengineering and an investigator with the Howard Hughes Medical Institute (HHMI). His work receives support from HHMI, the Army Research Office, the Human Frontier Science Program, the National Institutes of Health, the Paul G. Allen Family Foundation, and the Gordon and Betty Moore Foundation.

Austin Minnich is an assistant professor of mechanical engineering and applied physics. His research is funded by a Caltech start-up fund and by the National Science Foundation (NSF).

Erik Winfree is a professor of computer science, computation and neural systems, and bioengineering. His work receives support from the NSF and the Gordon and Betty Moore Foundation's Programmable Molecular Technology Initiative.

Jonas Zmuidzinas is the Merle Kingsley Professor of Physics and chief technologist at NASA's Jet Propulsion Laboratory. His research is funded by NASA, NSF, JPL, the Gordon and Betty Moore Foundation, and the Keck Institute for Space Studies.

Take it to



by Jessica Stoller-Conrad

When you have a question about your health or your finances, you go to a doctor or an accountant for advice; you figure they have the knowledge you need to get the answers you're looking for. But what about when you're wondering where to go for dinner in a new city? Rather than hiring an expert chef to individually rate each restaurant—a pricey and time-consuming endeavor—you'd probably find it far more practical and efficient to trust the recommendations of the thousands of local diners who've already voluntarily rated the restaurants online.

Today, crowdsourcing—in which many individuals work toward the collective goal of narrowing down a large amount of information—has indeed made it easier to choose a good restaurant or pick a movie you'll likely enjoy. But the concept has also found an application in areas of research where numerous scientists have collected far more data than they could ever analyze on their own.

By taking this data to the crowd, researchers at Caltech have found a way to engage the public while also allowing so-called citizen scientists to investigate a variety of research topics—from very tiny cells on Earth to massive star clusters in our galaxy.

The Solar Army

Chemist Harry Gray and his colleagues at the National Science Foundation's Center for Chemical Innovation in Solar Fuels (CCI Solar) are looking to answer one important question as quickly as possible: How can we tap the sun's energy to power the planet? Gray and the CCI Solar group believe that the answer will involve using solar-powered devices to produce fuels. These environmentally friendly systems would use energy from the sun to split water molecules on sunny days, generating storable hydrogen as fuel that could be used later to produce electricity.

Although the technology has the potential to satisfy all of humanity's energy needs, it's been difficult to find

the world

an abundant and cost-effective source for the catalysts needed to drive the essential water-splitting reaction. Platinum catalysts work well, but they are also rare and expensive. By mixing together different combinations of metals, scientists hope to find an alternative to platinum that is just as effective but is also cheap enough for worldwide use.

But testing the many combinations of metals on the periodic table is a task that Gray admits he and his colleagues need some help to complete. So, in 2009, Gray proposed that students around the world—which he calls his Solar Army—could add to his group's research efforts using an inexpensive apparatus to perform experiments similar to those that he and other chemists were doing in the lab.

Initially, the idea depended upon the Solar Hydrogen Activity Research Kit (SHArK), an inexpensive tool developed by CCI Solar colleague Bruce Parkinson for research in his laboratory at the University of Wyoming and distributed to science

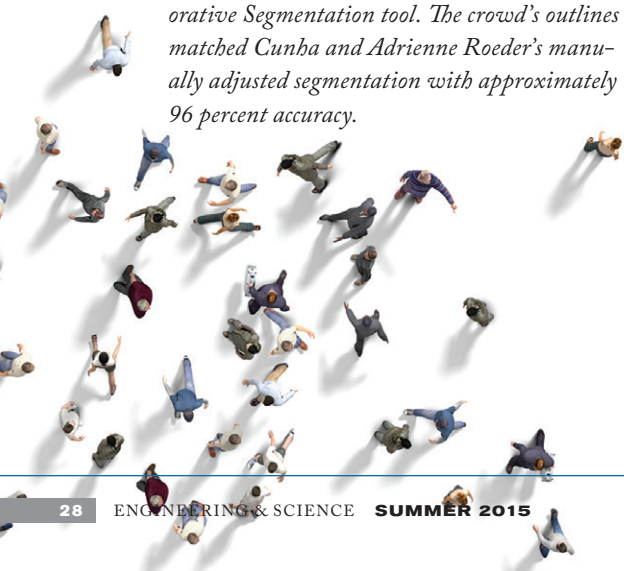
undergraduates by Gray. Using a modified inkjet printer, the students would first create tiny dots of metal oxide combinations, which were then targeted by a light source—a commercial laser pointer. A current detector could then determine each mixture's catalytic potential; if the light source spurred a large increase in electrical

High school students from Polytechnic School in Pasadena perform experiments with a Solar Energy Activity Laboratory, or SEAL, kit. With the kit, the students search for new catalysts that can use sunlight and water to make storable hydrogen fuel.





The 2,571 cells of this *Arabidopsis thaliana* sepal, shown above, were outlined by students using data scientist Alexandre Cunha's Collaborative Segmentation tool. The crowd's outlines matched Cunha and Adrienne Roeder's manually adjusted segmentation with approximately 96 percent accuracy.



current, the mixture might be a good candidate catalyst.

The program then expanded into an after-school activity at local high schools in Southern California, with CCI Solar graduate students and postdocs serving as mentors. And after several years of experimentation with SHArK, the CCI Solar team at Caltech created a more streamlined version—called the Solar Energy Activity Laboratory, or SEAL—which could test compounds faster and allowed students to learn hands-on laboratory skills, such as pipetting and solution preparation.

Now, after more than five years, Gray's Solar Army has expanded to include students from more than 90 schools worldwide—meaning that more than 500 “recruits” are contributing to the search for these game-changing catalysts.

“The Solar Army is something special,” Gray says. “A lot of crowdsourcing and citizen science projects are so focused on the educational component that very little real data are being produced. But using SHArK and SEAL, our students have discovered some interesting new materials that are being tested at Caltech and other universities.”

The Plant Pack

Gray isn't the only Caltech researcher who has entrusted work to budding young scientists. A few years ago, former Caltech postdoctoral scholar Adrienne Roeder was working on a time-consuming project in developmental biology that relied on outlining, counting, and measuring the cells within plant tissues. When Alexandre Cunha, a data scientist at the Center for Data-Driven Discovery at Caltech, learned that, to complete the project, Roeder had been manually tracing the outlines of cells in samples of plant tissue, he knew he wanted to find a way to help.

Cunha first devised computer programs to semiautomatically generate the cell outlines. The program enabled

a computer to do most of the outlining work, but a final human touch was necessary to perfect the results. Since crafting a fully automatic solution would be extremely difficult, he came up with a compromise: a way to combine his computer program with a crowdsourcing approach by enlisting the help of several local classrooms as his crowd.

Roeder was working with cells from the sepals of the flowering plant *Arabidopsis thaliana*—a model organism for geneticists and developmental biologists. Sepals, or the leaflike structures that protect delicate flower petals during development, are made up of small cells that divide normally during development and big cells that continue to multiply their DNA without ever dividing.

In her research, performed in the lab of Elliot Meyerowitz, Roeder aimed to understand which genes were involved in the development of each cell type and what specific factors determined a cell's fate. This meant that she had to measure and count the cells from many normal and genetically mutated plants to determine which mutations affected the sizes and quantities of these cells.

“If you have a tissue with lots of cells and you want to measure the size of each cell, you mark the cell wall with a fluorescent dye, take a picture of the tissue with a laser scanning confocal microscope, and then you outline the boundaries of each cell,” says Cunha, who, as a data scientist, helps researchers across campus analyze their data in new ways. Although computer programs have been developed to identify, measure, and count cells in a tissue, they often have difficulty spotting the boundaries of cells with absolute certainty. So the time-consuming outlining process was still at least partially done by hand.

Inspired by other crowdsourcing successes, Cunha, with the help of grad students from the Brazilian lab of his colleague Tsang Ing Ren, created an interactive web tool called

Collaborative Segmentation—or CoSe—so that school children could help researchers with the outlining process while also learning about plant biology and creating data to eventually help train a new computerized tool in the outlining process.

The students, including fourth- and fifth-graders from Hamilton Elementary School in Pasadena and high school students from Orthopaedic Hospital Medical Magnet High School in Los Angeles, were trained to outline, on a computer, the boundaries of cells in images of plant tissue. The students had minimal information about the nature of the images and were told to trace the contours as they appeared on the screen. They were nonexperts who nonetheless collectively produced remarkable results.

When the combined results from the students were compared to Roeder's earlier traced outlines, Cunha saw that the composite of the crowd's tracings closely matched those of a trained expert like Roeder. Cunha says this success opened the possibility of delegating outlining projects like these to a larger crowd anywhere in the world—allowing researchers to collect results in a fraction of the time it would take a single individual.

“Crowdsourcing allowed us to develop an interactive and far-reaching tool that can save researchers lots of time in the lab,” Cunha says. “In this case, the crowd may still miss some of the difficult outlines, but a researcher could always go back and correct them. In the end, correcting a few outlines is much faster than tracing every single cell by hand.”

Flock Focus

Plant cells, of course, aren't the only things that computers can be trained to “see.” In fact, Pietro Perona has been working on computer learning based on the human visual recognition system for more than 20 years.

People can seamlessly assign names to images; when we see a familiar object, we can quickly recognize that

object and say what it is. This process of translating an image into text is a problem for computers, however, so Perona wanted to find a solution.

To do this, Perona and his collaborators—including postdoctoral scholar Steve Branson, graduate student Grant Van Horn, and Cornell Tech professor Serge Belongie (BS '95)—designed a crowdsourcing project in which computers could learn from the way humans process visual information.

The ultimate goal of the project, called Visipedia, is to be able to harvest, organize, and make available visual expertise and visual knowledge on any topic. Because bird-watching is a popular hobby with a dedicated and enthusiastic following, the researchers began their project by collaborating with the Cornell Lab of Ornithology to create a version of Visipedia that acts as a sort of image-driven field guide for bird-watching.

In order to train Visipedia software to identify the approximately 1,000 species of birds in North America from images alone, Perona calculated that he would first need humans to label the species in more than 300,000 bird photos—representing a variety of different poses and lighting situations for each species. To reach this number, he used a paid crowdsourcing service, called Amazon Mechanical Turk, where workers are paid a very small amount to complete simple human intelligence tasks—or HITs. In this case, they were asked to identify the birds in Perona's photos.

Although the project did depend on the majority of participants correctly identifying the birds in the images, Perona also gathered interesting information from wrong answers.

“When people make mistakes, they have very different styles of making mistakes,” he explains. “Using modern statistical techniques, we can analyze the patterns of responses that people give, and just by looking at the pattern of the answers you can get into the heads of these people and figure out what they're thinking as they're

annotating these images. And that helps you develop a computer program that can label the pictures better.”

After five years of learning from the crowdsourced human responses, Visipedia can now identify more than 500 species of North American birds simply from uploaded photos. (However, it helps if the user can tell the program where on the continent the photo was taken and also pinpoint certain features—like the bird's beak and feet—so that the computer can understand the orientation of the image.) Visipedia then processes the visual and geographic information to provide the name of the species in the photo.

On-the-fly bird identification is just one application of the technology, Perona says. For example, it could also be used for e-commerce. When an online shopper chooses, say, a chair that he likes, a visual-based recommendation system might one day be able to automatically group together all chairs that have the same shape. Or a medical version of Visipedia could use photographs of patients' symptoms to help nurses diagnose diseases in resource-limited settings.





Milky Way Project volunteers were the first to notice so-called yellow balls—seen in the center of this image—and bring them to the attention of professional astronomers. Later, in follow up work, researchers showed that the yellow balls represent an intermediate phase of star formation.



A Coral Crew

After Perona's success with crowdsourcing human vision through Amazon Mechanical Turk, chemical oceanographer Jess Adkins thought that he too might have a good project for a crowd to take on.

Adkins and his team study the history of global climate change via ancient fossilized corals deep beneath the waves, on the ocean floor. Global changes in climate have a direct impact on deep ocean circulation patterns, and the varying ages and chemical makeups of these corals can provide clues about past oceanic behavior—and thus, shifts in climate—over many different periods of the past 100,000 years.

“However, we can't do any of that if we can't find the corals,” Adkins says. “And it turns out that it's pretty difficult to just blindly try to find corals lying in the sediment a mile below your boat.”

So over the years Adkins and his colleagues have used manned and unmanned underwater vehicles to take thousands and thousands of detailed photographs of specific regions of the ocean floor to try to pinpoint key areas of coral clusters.

“In the past, I've tried to have experts

examine these photos to look for corals, but you can never get through all of them. And often these scientists spend way too long looking at each picture,” he says. “They'll look at a photo and say, ‘Oh what's that interesting thing over there? And what is that?’ And I want to tear my hair out after a while because I just need to know one thing: Are there corals in the picture or not?”

After talking to Perona about his experiences with crowdsourcing, Adkins also turned to Amazon's Mechanical Turk. He found that the participants—or “turkers”—had goals directly aligned with his own: because they are paid according to the number of photos they score in a certain amount of time, the turkers would look for corals in each photo and nothing else. In fact, after the researchers uploaded the photos and provided a few simple instructions, the turkers were able to view and score the first 10,000 images in just 36 hours.

The specific corals the turkers were asked to spot are sessile filter feeders, meaning they are fixed to the ocean floor and rely on currents to bring their food. By comparing the photographs to detailed topographical maps of the area in which the



photos were taken, Adkins and his team can determine what topographical characteristics seem to be the best at funneling food to the corals. The researchers' end goal is to figure out, from a formula of slopes, elevations, and other factors, the percent likelihood of finding corals in an area.

Sending underwater vehicles down to collect corals is an expensive endeavor, Adkins says. "And with a percent likelihood map, we could remotely sense the topography of the seafloor anywhere and very quickly know where the coral hotspots are. This will be helpful as we decide how to wisely use these precious assets." And, ultimately, the more corals he finds, the more he can learn about our planet's response to past changes in climate.

Swarming Space

Just as Adkins uses crowdsourcing to survey the vast deep ocean while sitting on a boat atop the waves, researchers who study our galaxy using the Spitzer Space Telescope have also been drawn to crowdsourcing to address a similar challenge: how do you study an entire galaxy if you're always sitting right inside of it?

One big development came in 2008 when a team of scientists revealed that they had created the largest and most detailed portrait of our galaxy by essentially piecing together more than 800,000 photos taken from within the Milky Way by Spitzer.

Although this large composite image allowed scientists to answer some big-picture questions about the Milky Way's structure—for example, they determined that our galaxy has only two spiral arms rather than four, as was previously thought—the researchers knew that there was almost no way they'd be able to closely examine the nearly 1 million photos that were being curated by the Infrared Science Archive, part of the Infrared Processing and Analysis Center (IPAC) at Caltech.

"The amount of our galaxy that we've imaged so far is so large that if we printed it in full resolution, it would circle the Rose Bowl," says Luisa Rebull, a staff scientist at IPAC. "It's an enormous amount of data, and there are only a total of about 8,000 professional astronomers in the U.S. We don't have time to go through all of

this data by hand, but with the broad use of the Internet in schools and in people's homes there are now a lot of ways for people from the general public to get their hands on data."

Based on this concept, a multi-university team of researchers created the Milky Way Project in 2010. The project, which is hosted on the Zooniverse citizen science web portal, allows the general public to analyze approximately 440,000 of the images from Spitzer that are archived at IPAC.

When users sign up to participate in the Milky Way Project, a tool first shows them examples of what they'll be looking for: star clusters, which are groups of stars that have been pulled together by gravity; bubbles, thought to be regions of early star formation; and extended green objects, which appear often in the Spitzer images but are still a bit of a mystery to astronomers. Participants then view individual images from the Spitzer survey and circle and identify the different types of features they see.

"The idea is that you train your eye. If you're a novice, maybe you're worried that the first 20 or so you looked at, you didn't get them right. But each image is being looked at by at least 20 other people," Rebull says. "So even if one individual gives the wrong answer, the consensus of everyone who looks at the image will be correct. And if there are objects that almost no one can agree on, then we know that the scientists will need to look at those objects in detail."

So far, this strategy has worked well for the Milky Way Project. Over 900,000 citizen scientists have identified nearly 1.5 million objects in the Spitzer images—allowing professional astronomers to spend their time studying the features that matter most for their particular research.

Follow-up studies have found that these results from the crowd are quite reliable, and further analyses of the observations have actually been published in four papers that provide new information about star formation in our galaxy. In fact, a paper published in January 2015 revealed that the project's participants had uncovered a class of previously unrecognized features—

dubbed "yellow balls" for their appearance in the infrared Spitzer images—that may provide a new way to detect the early stages of the formation of massive stars.

The kind of information that projects such as the Milky Way Project provide can enable professional researchers to more quickly find the information they need in order to make discoveries, Rebull says. And, she adds, thanks to crowdsourcing "these projects have also allowed thousands of people to learn a bit more about the world—and even the galaxy—in which they live." [ES](#)

Harry Gray is the Arnold O. Beckman Professor of Chemistry and the founding director of the Beckman Institute. CCI Solar is a program of the National Science Foundation.

Alexandre Cunha is a computational scientist at the Center for Data-Driven Discovery. His crowdsourcing work with Adrienne Roeder and Elliot Meyerowitz, George W. Beadle Professor of Biology and Howard Hughes Medical Institute Investigator, was funded by the Gordon and Betty Moore Foundation, the U.S. Department of Energy, and the Biological Network Modeling Center of the Beckman Institute. The Collaborative Segmentation project is an ongoing collaboration with Tsang Ing Ren from UFPE, Brazil.

Pietro Perona is the Allen E. Puckett Professor of Electrical Engineering. His work on Visipedia is funded by Caltech and the Office of Naval Research Multidisciplinary University Research Initiatives Program.

Jess Adkins is a professor of geochemistry and global environmental science. His work with using crowdsourcing to map the ocean floor is funded by the National Science Foundation and Caltech's Davidow Discovery Funds.

Luisa Rebull is a staff scientist and member of the professional staff at the Spitzer Science Center and the Infrared Science Archive at IPAC. She is also the director of the NASA/IPAC Teacher Archive Research Program. The Milky Way Project is a collaboration between the University of Oxford, the Adler Planetarium, and the Spitzer Space Telescope.



Tracking Down Infections

A Caltech alum uses social media to help map disease outbreaks in real time.

Today, when there is an outbreak of disease, the first reports of it are likely to be online, through Facebook or Twitter. And as word in cyberspace goes viral, it can map closely to the spread of the actual virus in the physical world. That's the conclusion of NYU researcher Rumi Chunara (BS '04), whose paper analyzing Twitter and other online activity surrounding the 2010 outbreak of cholera in Haiti made waves in the public health world. So much so that in 2014 she was named to *MIT Technology Review's* "35 Innovators Under 35" list for her work in digital disease detection. Ben Tomlin from Caltech's Alumni Association spoke with Chunara about her research and the emerging area of crowdsourced health data.

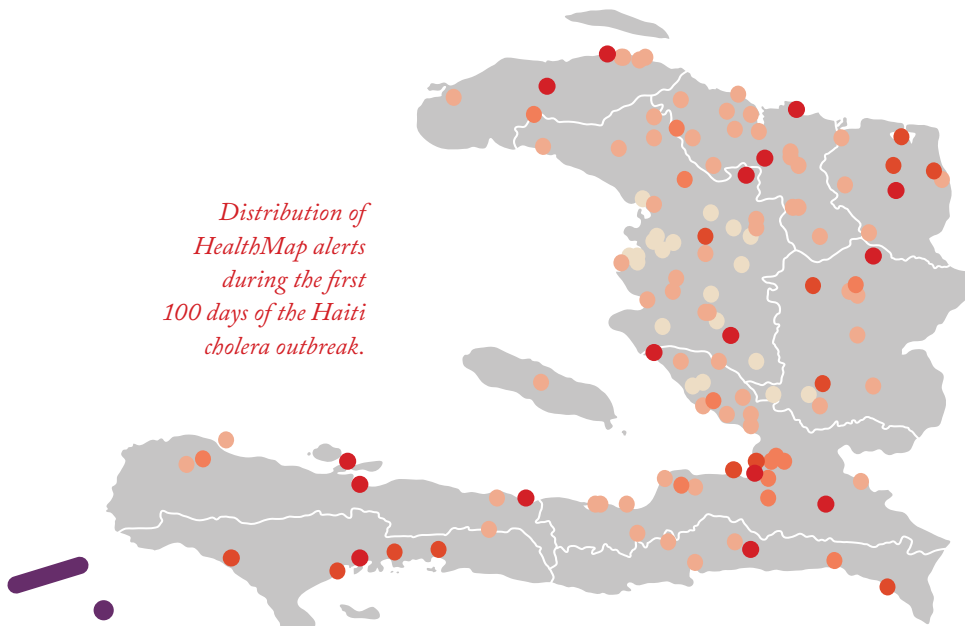
What is the focus of your work?

The goal of my research is to try and understand how infectious disease spreads in populations. Traditional health systems are really the gold standard for collecting and analyzing information on viral outbreaks, but information can travel slowly. With the proliferation of mobile Internet-based systems, we can crowdsource real-time information to offer clinicians and the public an enhanced picture of the path and progress of an outbreak.

Your study of the cholera outbreak in Haiti was one of the first to compare online activity with the movement of disease. What did you find?

In January of 2010, Haiti suffered a catastrophic earthquake. Nine months later, the Haitian Ministry of Public Health and Population (MSPP) announced an outbreak of cholera, which eventually affected nearly half a million people.

Distribution of HealthMap alerts during the first 100 days of the Haiti cholera outbreak.



- October 10, 2010–November 5, 2010
- November 6, 2010–November 22, 2010
- November 23, 2010–December 10, 2010
- December 11, 2010–January 2, 2011
- January 3, 2011–January 28, 2011

Wearable technology and mobile apps are starting to collect more data on health and fitness. Will this affect your research?

Absolutely. There has been a lot of discussion surrounding the development and implications of those products. This field of research will continue to grow as we acquire new capabilities to collect information. At the same time, there are significant issues to be thought out regarding privacy and security, which will take some time.

We are seeing a faster pace of information sharing between the tech industry and academic research, overall. Hopefully it will offer more opportunities for scientists to examine data and then see results from their research deployed.

You are advocating for more crowdsourcing of public health data. Why?

I think that we can do more than just monitor data from social media traffic. We can also ask the public directly for their help in collecting health information. Our early work with GoViral shows that they can be willing and effective partners. By actively crowdsourcing, we can collect information at the point of care. We can also learn about other things, like contact patterns and social interactions that affect disease dynamics.

And there is another advantage to this approach: while conducting research, we can engage and educate individuals to become more proactive in their own health—which is ultimately the best way to curb the spread of disease. [eSS](#)

Rumi Chunara is an assistant professor of computer science and engineering at New York University's Polytechnic School of Engineering and Global Institute of Public Health.

While I was at my previous post with HealthMap (a real-time disease surveillance website) and the Children's Hospital Informatics Program at Harvard Medical School, my fellow researchers and I reviewed the first 100 days of the outbreak. We took data from HealthMap and Twitter and compared it to Haiti's official reports, which were published daily. We then developed epidemiological models to try and get a sense of the rate at which things were changing.

Overall, we found strong correlation between the Twitter data and official reports. Moreover, we also found points when the Twitter data could be used to estimate the trajectory of the outbreak. That's particularly useful because data from social media is publicly available in real time.

Since we published that study, we have continued to improve on these efforts, as have a number of groups.

What are the challenges to this type of research?

First, we have to keep in mind that this data is not a replacement for traditional methods of disease tracking but meant to augment them.

We also have to be careful to isolate the relevant data. In 2013, Google Flu

Trends, a terrific service that monitors web searches to predict outbreaks of the flu, overestimated the number of cases in the U.S. by a good margin. It was a good cautionary example. Online searches are just a proxy for what might be happening. Is a person searching for themselves or someone in their household? Are they really sick? If they are sick, do they really have the flu? Are they influenced by the media or other social networks?

These questions led me to launch GoViral last year, a research program that combines online data from mobile apps with home diagnostic kits. This is the first time that we have actually crowdsourced to get diagnostic samples from people. We're able to get a clearer picture of a person's online activity correlated with their actual health.

How do you imagine this kind of research being used?

The main advantages are in speed of access to medical information. That's important, because in our era of increased mobility, diseases can spread globally more quickly. First responders could leverage information to target emerging situations or create public health infrastructure.

Charles H. Townes 1915–2015

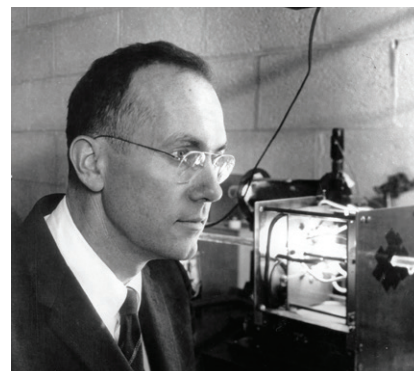
Laser pioneer Charles H. “Charlie” Townes (PhD ’39), a life member of the Caltech Board of Trustees and a recipient of the 1964 Nobel Prize in Physics, died on January 27, 2015. He was 99 years old.

Townes, a professor of physics, emeritus, at UC Berkeley, won one-half of the Nobel Prize in Physics for his role in inventing the maser (for “microwave amplification by stimulated emission of radiation”) and its cousin, the laser, in which light is emitted instead of microwaves. He shared the award with Aleksandr M. Prokhorov and Nicolai G. Basov, who independently developed the idea for a maser.

A native of Greenville, South Carolina, Townes graduated from Furman University in 1935 with a BS in physics and a BA in modern languages. He completed a master’s

degree in physics at Duke University in 1936 and in 1939 received his PhD in physics from Caltech. A member of the technical staff at Bell Labs through World War II, he joined the faculty at Columbia University in 1948. There, he built the first working maser. From 1959 to 1961, Townes served as vice president and director of research at the Institute for Defense Analyses in Washington, D.C.; he then served for six years as provost and professor of physics at the Massachusetts Institute of Technology.

In 1967, Townes moved to UC Berkeley, where he was named University Professor. At Berkeley, Townes transitioned into the field of infrared astronomy. Along with his colleagues, he carried out the first detection of three-atom molecules (water and ammonia) in interstellar space, and the first measurement of the



mass of the black hole in the center of our galaxy. He also served as principal investigator for a pioneering program in radio and infrared astronomy, the Infrared Spatial Interferometer Array.

Townes was named a Caltech trustee in 1979 and became a life member of the board in 1987.

To learn more about Townes’s life and work, visit caltech.edu/news/charles-h-townes-45519.

Fredric Raichlen 1932–2014

Fredric “Fred” Raichlen, professor emeritus of civil and mechanical engineering in Caltech’s Division of Engineering and Applied Science, passed away on December 13, 2014. He was 82 years old.

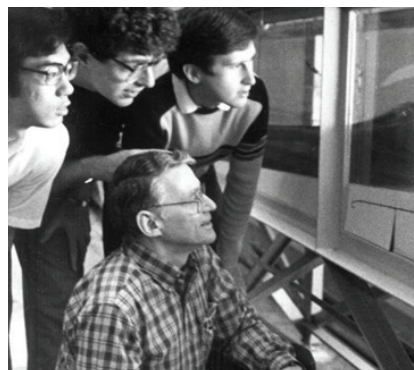
Raichlen was an expert in coastal engineering whose pioneering studies of tsunami mechanics have led to standards for designing tsunami-resistant structures that have saved lives around the world.

Upon arriving at Caltech in 1962, Raichlen built a set of wave tanks to analyze how tsunamis originate, how they propagate through the open ocean, and what happens when they run up on shore. The data from these experiments enabled him to develop a comprehensive, three-dimensional computer model of tsunami behavior.

Raichlen earned his bachelor’s degree in engineering from the Johns Hopkins University in 1953 and his

master’s and doctoral degrees at MIT in 1955 and 1962. He also served in the Air Force as an environmental health officer from 1956 to 1959. He came to Caltech as an assistant professor of civil engineering in 1962; he was promoted to associate professor in 1967 and to professor in 1972. In 1969, he became one of the founding faculty members of Caltech’s doctoral program in environmental engineering science. He was appointed professor of civil and mechanical engineering in 1997 and professor emeritus in 2001.

Raichlen was inducted into the National Academy of Engineering in 1993, and in 1994 he received the John G. Moffatt–Frank E. Nichol Harbor and Coastal Engineering Award from the American Society of Civil Engineers (ASCE). In 2003, he was given the ASCE’s International Coastal Engineering Award, the most prestigious honor in the international



coastal engineering community.

Raichlen is survived by his wife, Judy; his sons, Robert and David; their wives, Amy and Sarah (respectively); his sister, Linda Millison; his brother, Sonny; and two grandchildren.

To learn more about Raichlen’s life and work, visit caltech.edu/news/remembering-fredric-raichlen-45402.

Don L. Anderson 1933–2014

Don L. Anderson, the Eleanor and John R. McMillan Professor of Geophysics, Emeritus, passed away on December 2, 2014. He was 81 years old.

Anderson's work helped advance our understanding of the composition, structure, and dynamics of the earth and of earth-like planets. He was a pioneer in the use of seismic anisotropy—variations in the velocities of seismic waves as they move at different angles through materials—to study the earth's interior. This allowed him and others to learn more about the boundaries of the planet's mantle.

In 1981, Anderson developed, with Adam Dziewonski of Harvard University, the Preliminary Reference Earth Model (PREM), a one-dimensional model representing the average properties of the earth, including seismic velocities, attenuation, and density, as a function of planetary radius. PREM continues to be the most widely used standard model of the earth.

Born in Frederick, Maryland, on March 5, 1933, the son of a

schoolteacher and an electrician, Anderson received his BS in geology and geophysics from Rensselaer Polytechnic University in 1955. He earned a master's degree in geophysics in 1959 from Caltech and a doctorate in geophysics in 1962 under the supervision of Frank Press.

Upon his graduation, Anderson was hired as a research fellow; he became an assistant professor in 1963, an associate professor in 1964, and a professor in 1968. From 1967 to 1989, Anderson was director of Caltech's Seismological Laboratory. Anderson was the Eleanor and John R. McMillan Professor from 1989 until his retirement in 2002.

A fellow of the American Academy of Arts and Sciences and a member of the National Academy of Sciences and the American Philosophical Society, Anderson was also the recipient of the Emil Wiechert Medal of the German Geophysical Society, the Arthur L. Day Medal of the Geological Society of America, the Gold Medal of the Royal Astronomical Society, the William Bowie Medal



of the American Geophysical Union, and the Crafoord Prize of the Royal Swedish Academy of Sciences.

In 1998, Anderson was awarded the National Medal of Science and was cited for his “immeasurable influence on the advancement of earth sciences over the past three decades nationally and internationally.”

Anderson is survived by his wife, Nancy; a daughter, Lynn Rodriguez; a son, Lee Anderson; and four granddaughters.

To learn more about Anderson's life and work, visit caltech.edu/news/remembering-don-l-anderson-45138.

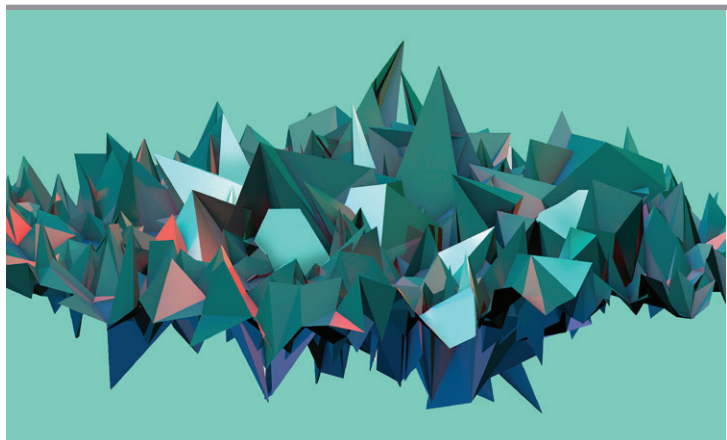


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What were the **MOST MEMORABLE SOUNDS** from your time at Caltech?



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The **CLANGING** of someone beating on a **CHROME-PLATED BRAKE DRUM**.

It was a trophy hidden by whoever possessed it. It was rung at random whereon a riot for possession ensued.

A **CANNON-TYPE EXPLOSION**, anywhere.



THE PRICE IS RIGHT THEME SONG. The Ricketts seniors play this song to wake up the house for Ditch Day (and fakes). I can sleep through loud music and fire alarms, but I’m conditioned to wake up to that song.

I remember playing football in the Rose Bowl, and all our fans had 50-yard-line seats. **THEIR CHEERS WERE ECHOES**, the best being the Caltech cheer: “e to the x du dx, e to the x dx, secant cosine tangent sine, 3 point 1 4 1 5 9, square root cube log of e, let’s go get them C I T.”

Corny though it may be, for me it is the school anthem. “In Southern California with grace and splendor bound, Where the lofty mountain peaks look down to lands beyond, Proudly stands our Alma Mater, glorious to see; We **RAISE OUR VOICES** proudly, hailing, hailing thee!”



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