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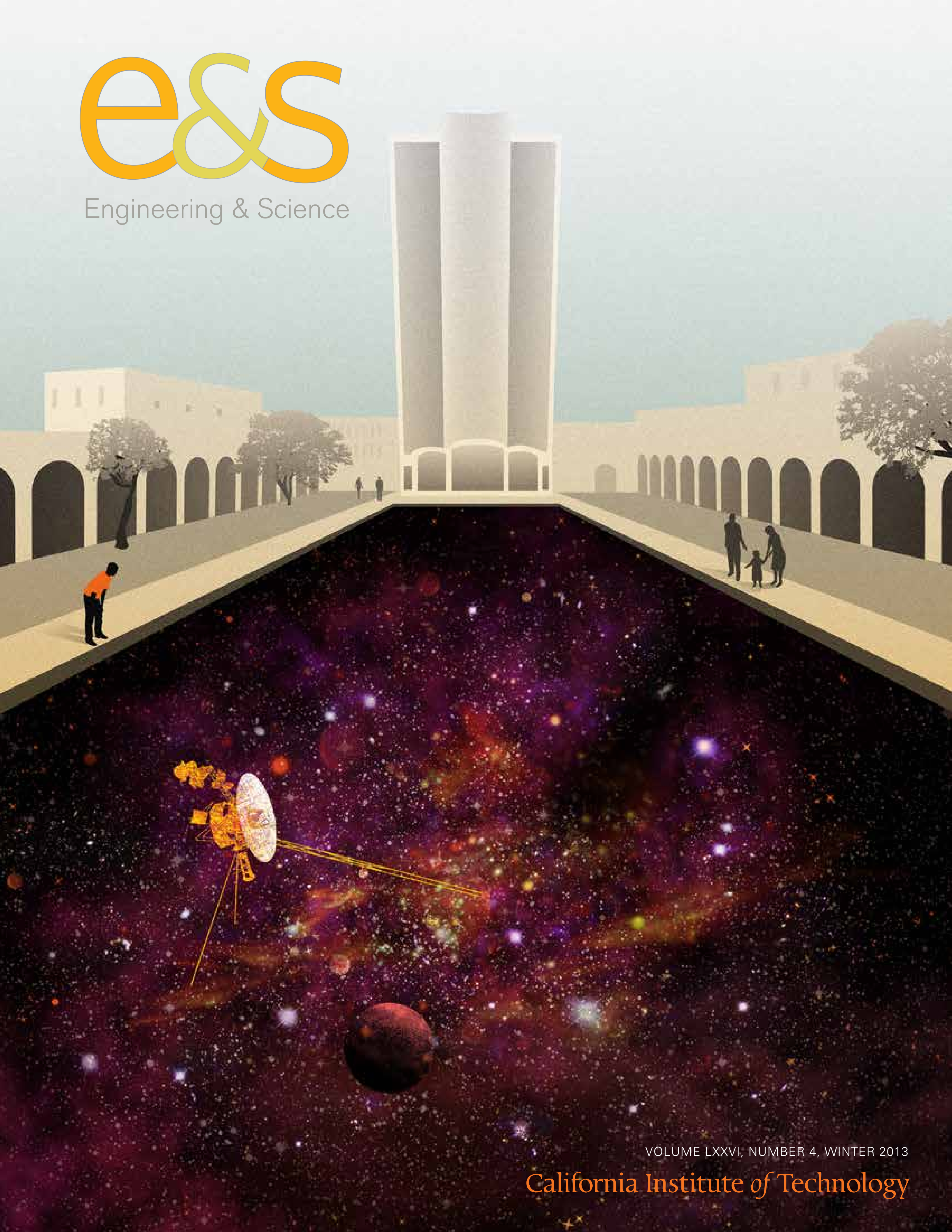

VOLUME LXXVI, NUMBER 4, WINTER 2013

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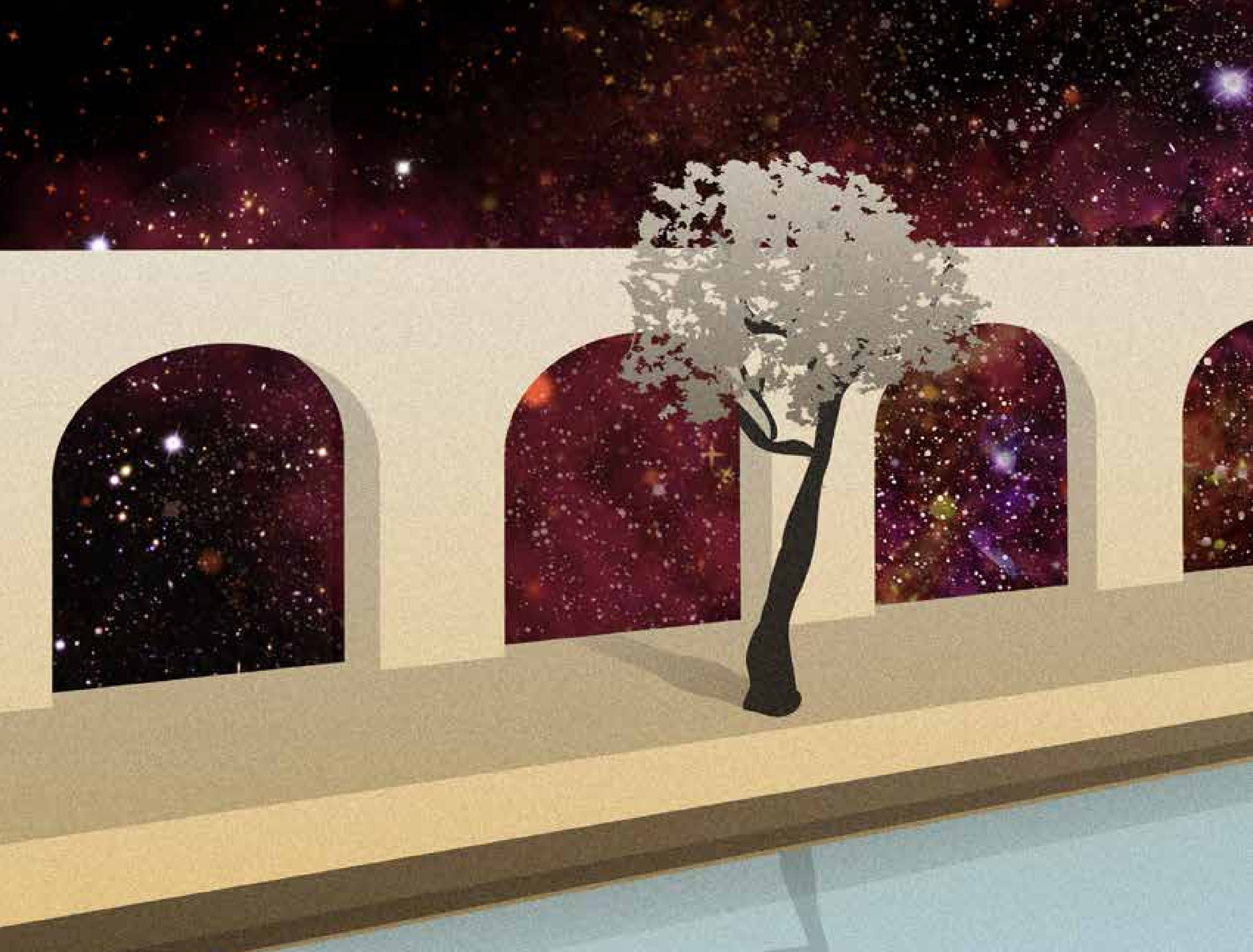

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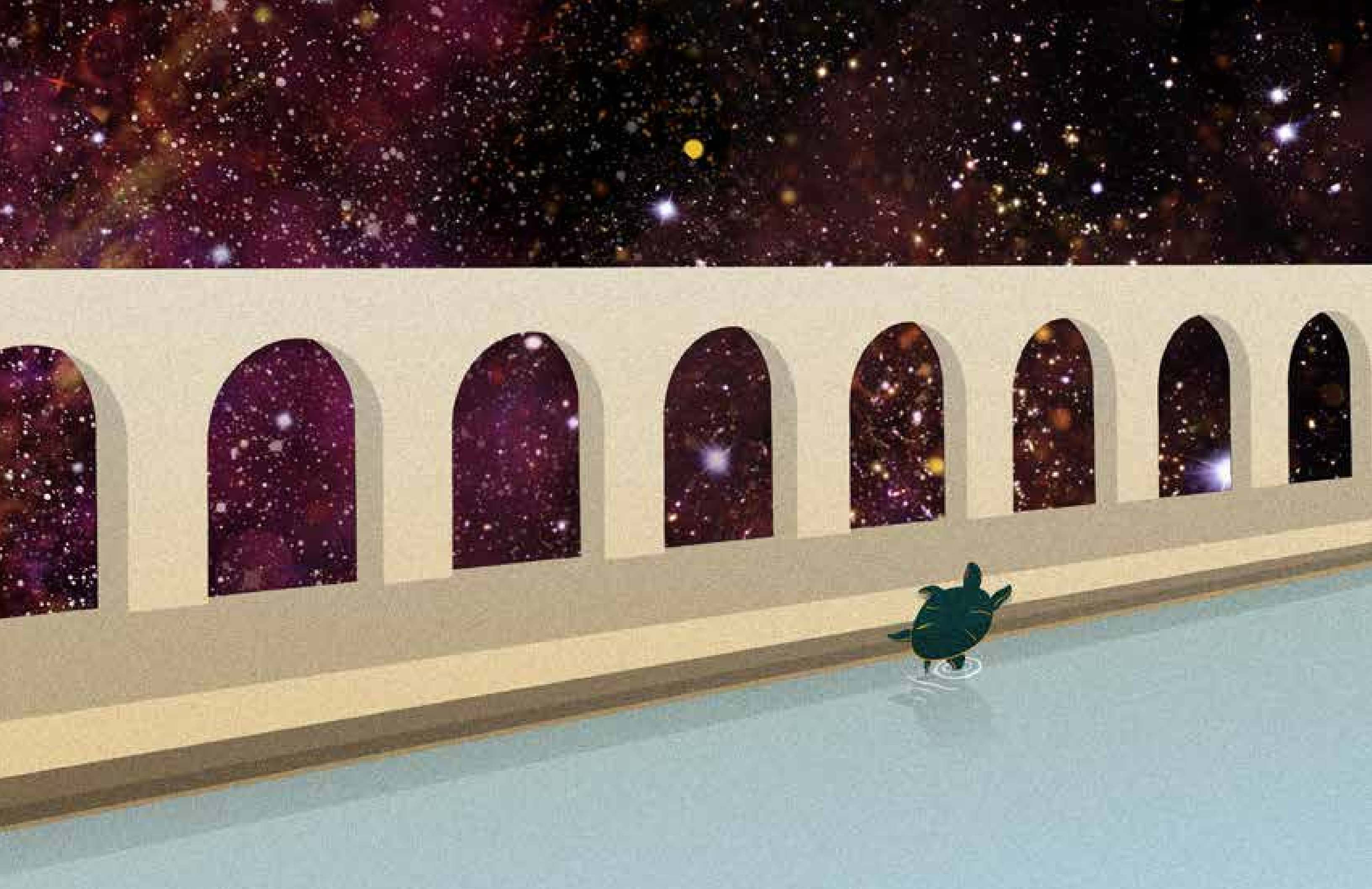

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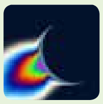
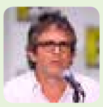
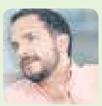
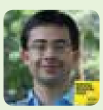
@CaltechHoops: Welcome to the team, President Rosenbaum. @Caltech pic.twitter.com/2kYsuwBebQ

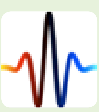

@NASAJPL: Welcoming @Caltech's new president, Thomas Rosenbaum, to our corner of the universe. pic.twitter.com/39VgLk99vl

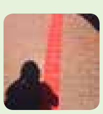
@THEworldunirank: Congratulations to Thomas F. Rosenbaum, the new president of the world's #1 university, @caltech.

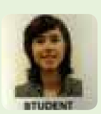

@BrannonBraga: Filming Cosmos at the BEST university in the universe. CALTECH! http://t.co/aSxB5BoMJJ


@JoseAndrade79: @Caltech ranked No. 1 again by @THEworldunirank ahead of Harvard, Oxford, Stanford, MIT. It's lonely at the TOP guys :)


@freiheitsfreund: @Caltech has just released the first book of the #Feynman lectures on #Physics on the internet. Great stuff! http://t.co/D0AVijarFI


@photonchoma: I had a great visit to @Caltech. I gave a seminar about optical coherence. Also, physics discussions at the bar. http://t.co/BhyuJ9jDTp


@ecapra: Time to start doing science again! #newlab #caltech #vacationsover http://t.co/PAcOSvQLy6


@genevievemp: My favorite place at @caltech is the humanities library.

@acsnano: Welcome Harry Atwater @Caltech editor of @acsnano's new sister journal ACS Photonics! http://t.co/LzZDGKZcJn @cenmag #nano #photonics/PSW

Tweets may have been edited for spelling and grammar.

Engineering & Science

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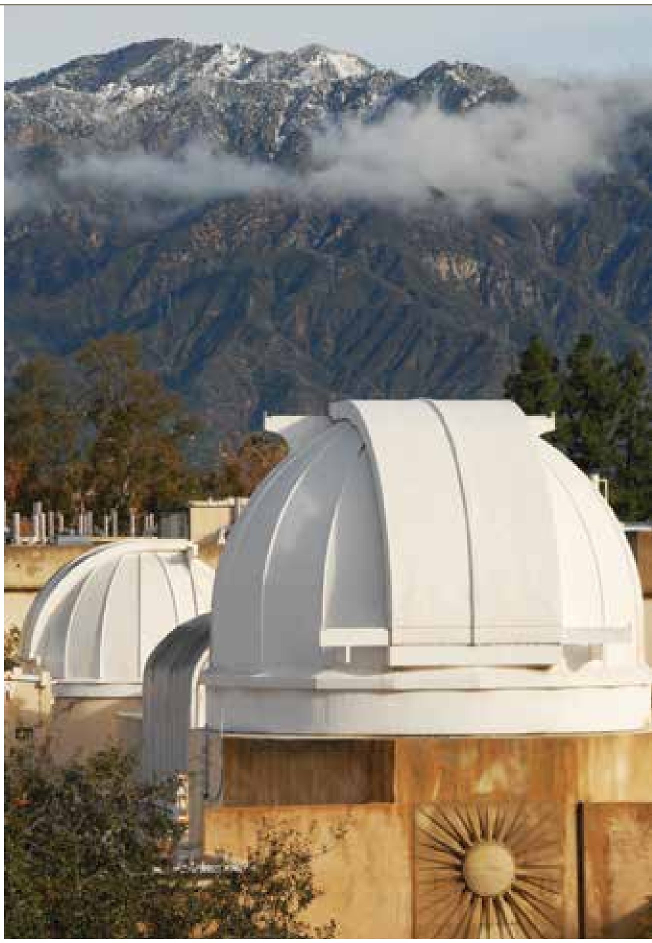
The Spaces Within



As a science writer and the editor of this magazine, I get a unique view of the places and spaces on the Caltech campus, a view not limited by which classes I sign up for or which lab I work in. In fact, one of the true perks of my job is that I get *paid* to show up at the laboratories and offices of as many scientists and engineers as possible, asking as much as I want about their work. It is a delightful way to experience Caltech—I get a one-on-one education from top researchers, and I don't have to worry about my GPA.

I'm not the only one. For this issue of *E&S*, our newest science writer, Jessica Stoller-Conrad, got to tour some of the most noteworthy labs on campus (see "Lab Spaces," page 20), the spaces in which our scientists and engineers explore the intriguing and sometimes recalcitrant questions facing our world and our society.

This issue of *E&S*, which looks at "space" in its myriad forms, also examines how Caltech's scientists and alumni collaborated with their JPL colleagues to send the Voyager spacecraft out into the interstellar medium in which it now finds itself (see "The Other Side," page 10). In addition, observational astronomers are observed getting us closer to glimpsing stars that are not only far away but so old they may well be among the first ever formed (see "Lighting Up the Dark Ages," page 24).

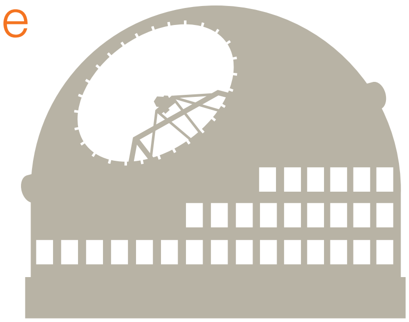
The issue considers the ways in which structural engineer Sergio Pellegrino and his team are looking at space both literally and as a more abstract concept as they try to build a large space telescope that can assemble itself once it's reached orbit (see "Using Space Wisely," page 14). And it looks at how Caltech scientists are manipulating the spaces between particles of soil, snow, and rock to better understand how our landscapes—and the natural disasters that plague them—come into being (see "The Spaces Between," page 30).

For this issue's Endnotes (see page 40), we asked our alumni about their favorite Caltech spaces. One of mine is pictured above: the Linde + Robinson building, with its stately dome that slides open to give the coelostat—or solar telescope—inside a view of the sky and the sun above. Now that's what I call making the most of the spaces within.

Random Walk

HIDDEN GEMS ON CAMPUS Move over, turtle pond: there's a new display of shells on campus. Eggshells, that is. In September, the newly remodeled Division of Geological and Planetary Sciences "gem room" in Arms Laboratory was updated to include several new additions, including this set of dinosaur eggs, thought to be the 100-million-year-old fossilized offspring of a Therizinosaur. This feathered beast walked on two legs, had a tiny head, and—in spite of its three-foot-long front claws—was likely an herbivore, according to many scientists. The eggs, originally discovered in China, were donated to the Institute in 2004, but the reopening of the GPS gem room marks their first time on display. Other new items include several meteorites and a rare gold nugget that bears a crystal structure visible to the naked eye. These curiosities represent only a fraction of the Caltech mineralogy collection's 30,000 items. The rest are kept behind closed doors to be used as research specimens.

BY THE NUMBERS: The Thirty Meter Telescope



In its 2001 decadal survey, the National Academy of Sciences listed the construction of a 30-meter segmented-mirror telescope as its highest priority for the advancement of ground-based astronomy and astrophysics. Caltech has since taken a lead role in designing that giant, known as the Thirty Meter Telescope (TMT), and construction is slated to begin next year. Upon completion, the TMT will be the world's largest and most capable ground-based observatory, offering astronomers the ability to study everything from the birth of stars and the evolution of galaxies to the nature of dark matter and the possibility of life elsewhere in the universe.

5

▲ Years it took to select Mauna Kea in Hawaii as the ideal site for the TMT.

10

▲ Meters in diameter of each of the W. M. Keck Observatory's twin telescopes—the world's current largest optical and infrared telescopes.

492

▲ Number of hexagonal mirror segments that will make up the TMT's primary mirror. The Keck telescopes' mirrors are made up of 36 segments each.

0.31–28 microns

▲ Range of the electromagnetic spectrum—spanning from the ultraviolet to the mid-infrared—in which the TMT will be equipped to make observations.

10–100x

▲ Number of times more clearly TMT will see compared to existing telescopes, thanks to its large light-collecting area and advanced adaptive optics.

Volume one of Richard Feynman's famous lectures on physics has gone digital. First presented in the early 1960s as an introductory physics course given at Caltech, the lectures quickly became a classic reference book. Now, anyone with a computer can try his or her luck at learning physics from a Nobel laureate at feynmanlectures.caltech.edu.

> "We now know Mars offered favorable conditions for microbial life billions of years ago."
>
> *—John Grotzinger, Caltech's Fletcher Jones Professor of Geology and project scientist for the Mars Science Laboratory mission, on August 6, the one-year anniversary of MSL's landing on Mars.*

FACULTY FOOTNOTES

This fall, the Division of the Humanities and Social Sciences welcomed new faculty member Frederick Eberhardt to its ranks. Though he's a professor of philosophy at Caltech, his multidisciplinary work integrates ideas from machine learning, statistics, and cognitive science, identifying statistical features that could indicate when a correlation actually signifies a causal relationship. This work could lead to big changes in the way we evaluate research studies.

Here are a few things about Eberhardt that you might not learn from his résumé:

▸ He had an international upbringing. *"I was born in the Galapagos Islands—sort of. There was no decent hospital there at the time, so my parents flew to the mainland for the actual birth. I grew up in Germany, studied philosophy and mathematics in England, and then philosophy and machine learning at Carnegie Mellon in Pittsburgh."*

▸ Southern California was not his first choice for relocation. *"But I am very curious about L.A.—it is such a different beast from anything else. I suspect it is going to grow on me quickly."*

▸ He loves to travel. *"Not the relaxing kind of travel, but the kind where you end up stuck in a bus with chickens and screaming kids on a dirt track somewhere without running water."*

Of Ancient Cats and Collagens

When mass spectrometrist Sonja Hess was asked if she'd like to analyze prehistoric fossils recovered from the famed La Brea Tar Pits in Los Angeles, she enthusiastically agreed to help. In 2011, Hess, the director of the Proteome Exploration Laboratory (PEL) at Caltech, began a collaboration with the Tar Pits' George C. Page Museum to study one ancient predator in particular: the saber-toothed cat, or *Smilodon fatalis*. Smilodon has long been extinct, last roaming the California wilderness more than 11,000 years ago. Researchers at the museum are interested in discovering how these cats are evolutionarily related to today's tiger species, whose "family trees" are still somewhat of a mystery. The museum's paleontologists were able to excavate the fossils and anatomically compare them to modern tigers, but techniques at Caltech's PEL have allowed the investigators to dig even deeper—into the ancient cat's protein makeup.

Although researchers have difficulty finding intact DNA samples from fossilized prehistoric animals, Smilodon's collagen proteins are extremely stable and easy to access. Researchers at the PEL have been able to extract the collagens from fossilized bones and analyze them with mass spectrometry, a technique used to discern the molecular makeup of materials. Combining these techniques with other types of data analysis, Hess and her colleagues hope to reconstruct the entire protein sequences of Smilodon collagens. With this information, the museum should be able to gain molecular insights into the evolutionary lineage of modern tigers—and Caltech researchers hope to develop new methods for extrapolating information from proteins when DNA sequences are not available.

"We are always excited about unique samples and what we can learn from them," Hess says. "Who would *not* be excited about the first look at a 10,000-plus-year-old sample?" —*JSC*

Insider Info

The humming noise made by booming sand dunes (see page 30) can hit

105

decibels—about as loud as a rock concert!

There are

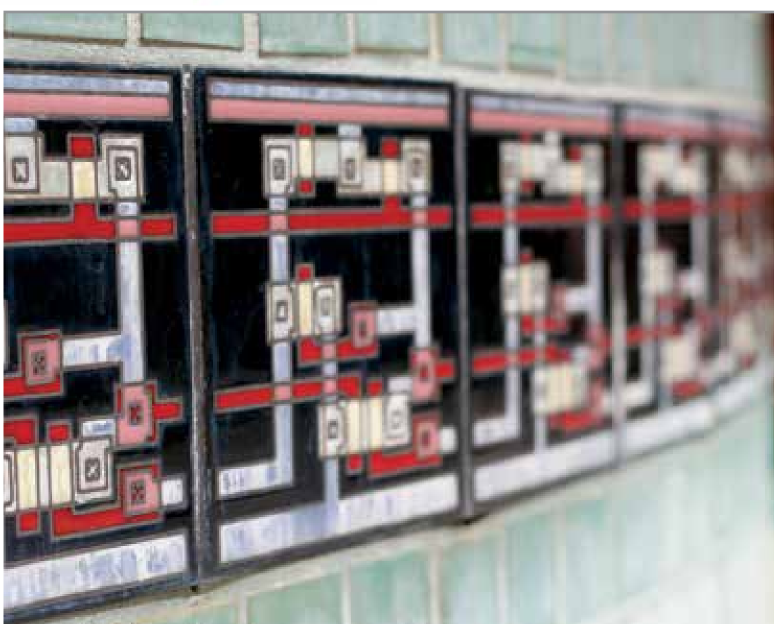
1,083

lab spaces on campus. We've highlighted a few of our favorites, starting on page 20.

The strength of the signal we receive on Earth from Voyager 1 (see page 10) is only

10^{-16}

or 0.0000000000000001 watts.



On the Grounds

These tiles, located somewhere on campus, reflect a symbolic representation of an analog integrated circuit developed in the lab of Carver Mead, Caltech's Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus. Designed by a graduate student in Mead's lab in collaboration with a staff engineer, the pattern was inspired by research exploring how the owl uses hearing to locate its prey—a focus of Bing Professor of Behavioral Biology, Emeritus, Mark Konishi. So where at Caltech can you get a glimpse of these intriguing slates? See below for the answer.

The tiles are part of the fountain in the entrance courtyard of the Moore Laboratory.

Birds of a Feather

When Voyager scientist Alan Cummings isn't thinking about space and crunching numbers related to the mission (see page 10), you might find him scanning the skies and crunching numbers related to another of his passions: bird-watching. Since 1986, he has led a casual group of Caltech birders on weekly walks around campus, keeping a tally of the feathered friends they observe along the way. Cummings posts data and reports from the walks on a Caltech birding website (birdwalks.caltech.edu) and has many plots related to the group's observations pinned up on the walls of his office.

"You see, you can almost set the calendar by yellow-rumped warblers," he says, pointing to one plot that shows the likelihood, by week, of observing the species. "They depart pretty much around week 16 of the year, and they reappear around week 40."

But it's not just seasonal variations that have caught the birders' attention. They've also noticed long-term trends—both dips and bumps—in some of the bird populations. Take the spotted dove; once seen regularly on campus, the species hasn't been spotted at Caltech since 1996.

"Also, we used to see rock pigeons, scrub jays, mockingbirds, and house sparrows without fail," Cummings says. "A lot of these more common birds are declining on campus, but we're seeing some other species more frequently as well." For example, the group sees many more black phoebes and parakeets than it used to, he says.

All told, Caltech's bird enthusiasts have spotted 123 species on campus, ranging from birds like the rock wren and the golden-crowned sparrow, which each have only been seen once, to the American crow, which has been tallied more than 1,100 times. "Occasionally, we still find a new species," Cummings says. In fact, he marked a major milestone on his "life list" of birds seen around the world, spotting his 1,000th species—a red-lored parrot—on campus in October. —*KF*

Fast-tracking Discoveries

Artificial photosynthesis offers a potential route to the green pastures of affordable energy in a sustainable, environmentally friendly manner. Standing between those verdant fields and us are several new and undiscovered materials that are needed to drive the efficient and cost-effective splitting of water by a solar-fuels device.

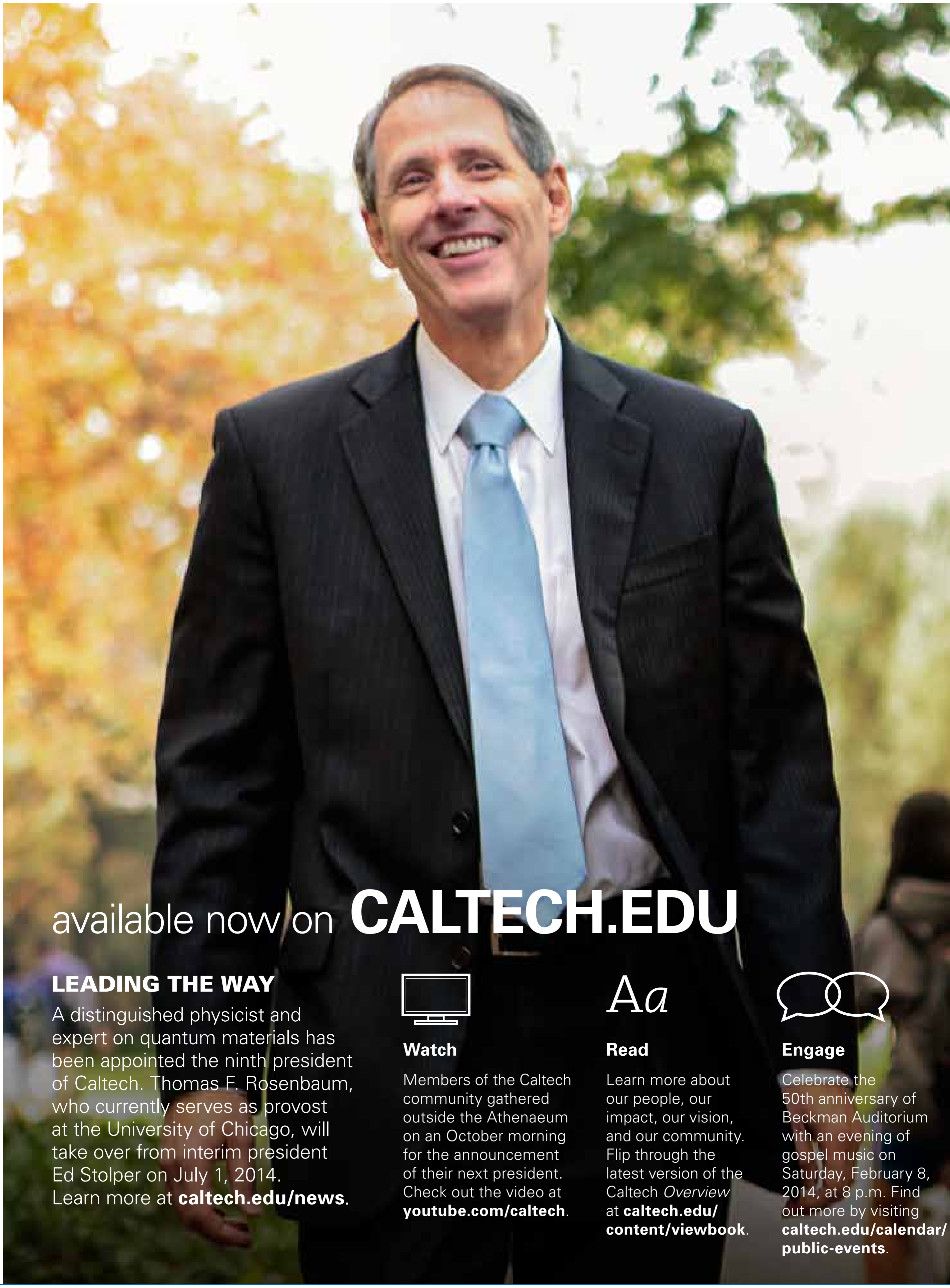
Inside the renovated Jorgensen Laboratory, researchers from the Joint Center for Artificial Photosynthesis (JCAP) Energy Innovation Hub are using a high-throughput discovery process to expedite their search for new semiconductors that can function as light absorbers and new catalysts that are up to the task of efficiently evolving oxygen and chemical fuels such as hydrogen.

These scientists have replaced the inks in an ink-jet printer with salt solutions of Earth-abundant materials such as iron, cobalt, and nickel, to print out alloys made of varying concentrations of those materials on glass plates. Their selections are based on their knowledge of which mixtures work naturally, which have been tried previously, and which ones theoreticians would put their money on to succeed. Then, using custom-designed instruments, the JCAP teams screen thousands of compounds to see how well they perform as the catalysts and semiconductors that would form key pieces of a solar-fuel generation device.

Thanks to this fast-tracking process, the researchers have already discovered a critical component for artificial photosynthesis, a new, highly efficient oxygen-evolving catalyst made of only Earth-abundant materials.

"What's unique about JCAP is that we're accelerating the discovery of new materials to a rate that is much faster than has ever been done before in the field of artificial photosynthesis," says Will Royea, assistant director for strategy and communications at JCAP. "We are also, in parallel, working toward the development of a fully functional device in which all of the components work together to produce fuel safely, efficiently, and cost effectively."

Those greener pastures may not be so distant after all. —*KF*



available now on **CALTECH.EDU**

LEADING THE WAY

A distinguished physicist and expert on quantum materials has been appointed the ninth president of Caltech. Thomas F. Rosenbaum, who currently serves as provost at the University of Chicago, will take over from interim president Ed Stolper on July 1, 2014. Learn more at **caltech.edu/news**.

Watch

Members of the Caltech community gathered outside the Athenaeum on an October morning for the announcement of their next president. Check out the video at **youtube.com/caltech**.

Read

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

Engage

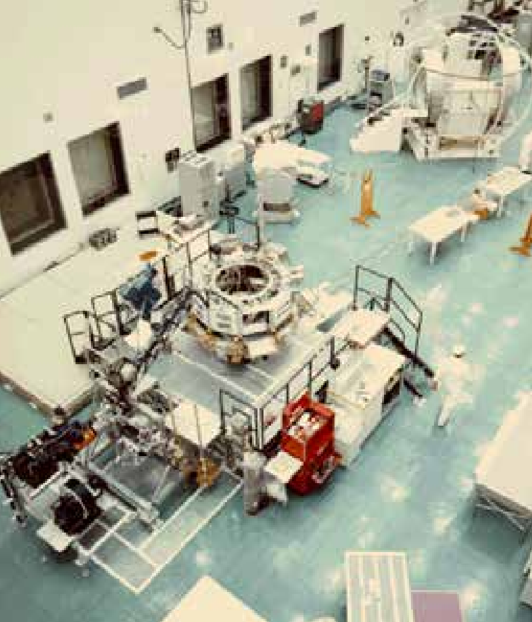
Celebrate the 50th anniversary of Beckman Auditorium with an evening of gospel music on Saturday, February 8, 2014, at 8 p.m. Find out more by visiting **caltech.edu/calendar/public-events**.

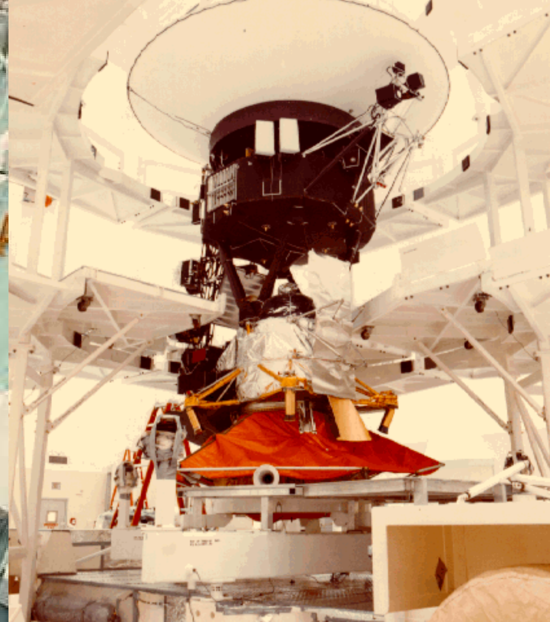
THE OTHER SIDE

by Douglas Smith

In a press conference on September 12, NASA announced that Voyager 1 is now officially cruising among the stars. This resilient robot, built by NASA's Jet Propulsion Laboratory (JPL), had burst through the sun's magnetic "bubble" and crossed into interstellar space on August 25, 2012—almost 35 years to the day after its launch on September 5, 1977. It's now more than 11 billion miles from home and still going strong.

"We got there!" exulted Ed Stone, the Voyager mission's project scientist, principal investigator for the Voyager Cosmic Ray Experiment, and Caltech's David Morrisroe Professor of Physics. "We all hoped, when we started on this 40 years ago, that this would happen. But none of us knew how big this bubble was, and none of us knew any spacecraft could last as long. . . . Setting sail on the cosmic seas between the stars, Voyager has joined other historic journeys of exploration such as the first circumnavigation of the earth, and the first footprint on the moon."





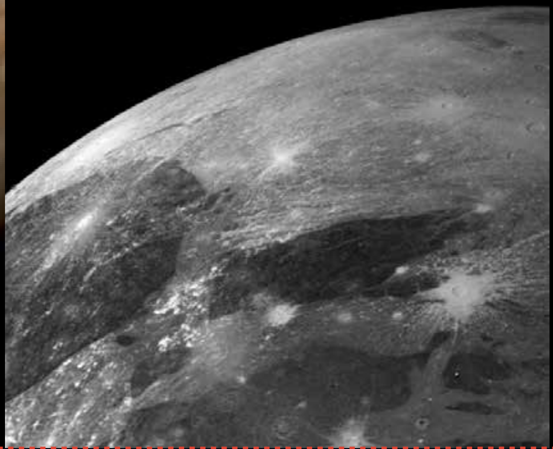
Just how *did* we get there?

As the outer planets plod through the frozen void, once every 175 years they line up in such a way that Jupiter's gravity can be used to fling a properly aimed spacecraft on toward Saturn, and thence to Uranus and Neptune. In the spring of 1965, Caltech aeronautics grad student Gary Flandro (MS '60, PhD '67) was working part-time up at JPL analyzing so-called gravity-assist trajectories when he realized that such a four-for-one alignment would occur between 1976 and 1979; intrigued by the possibilities, he set about matching possible paths of departure from one planet to lines of approach to the next one. All the path segments had to align perfectly in time and space; like Tarzan swinging from vine to vine through the jungle, missing a transition by even the smallest of margins would spell disaster. A few months and several reams of graph paper later, Flandro had worked out hundreds of itineraries—some reaching all the way to then-planet Pluto—for the upcoming launch window. His boss, Elliott "Joe" Cutting, booked him a meeting with the chief of JPL's advanced technical studies office, aeronautics professor Homer Stewart (PhD '40). Stewart embraced the idea, christening it the Grand Tour.

But despite Stewart's passionate promotion and some glossy publications, the Grand Tour failed to get off the ground. In 1965, simply hitting the broad side of the moon was hard enough, and getting Mariner 4 close enough to Mars to take a handful of decent pictures had pushed JPL to the limit. Still, the notion lingered out on the fringes—much like Uranus and Neptune themselves—waiting for time, technology, and human expertise to catch up.

JPL formally proposed the Grand Tour in 1970, with Harris M. "Bud" Schurmeier (BS '45, MS '48, ENG '49) as the project manager. This was an A-team effort: Schurmeier had just presided over the Mariner 6 and 7 flybys of Mars, and his collaborators included JPL's planetary program director, Robert Parks (BS '44), and its spacecraft systems manager, Raymond Heacock (BS '52, MS '53). It was also a gold-plated Cadillac of a mission—a flotilla of four mother ships carrying probes on parachutes to be dropped off at the various planets en route. The billion-dollar price tag (much of it for technology development) proved too much, and the Tour was axed in December 1971; the following month President Nixon signed a NASA budget authorizing $5.5 billion to be spent developing a space shuttle instead.

But all was not lost. "They told us, 'If you guys can come up with something less grandiose, we'll consider it,'" Schurmeier recalls. "So we went home and quickly put together what we called Mariner Jupiter Saturn [MJS] '77." Saturn was a mere three-year journey instead of 10; instead of four spacecraft, only two would be built, largely

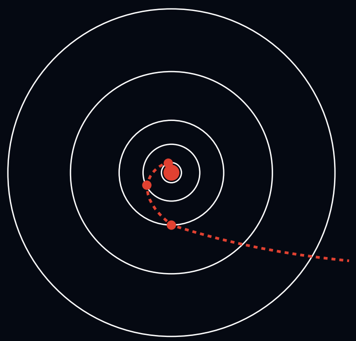

with existing technology; and the probes were deep-sixed. The scaled-back proposal was worked up within weeks, and MJS was officially approved in May 1972 by NASA administrator James Fletcher (PhD '48).

JPL had promised Saturn, but still intended to deliver the full Tour. "One of the Grand Tour's key objectives had been to measure cosmic rays that were unmodified by the sun," Schurmeier says. "Of course, the scientists then didn't really think the heliopause was so far away. So we thought, OK, if we can make it to Saturn, maybe we can last long enough to get out there." The heliopause is the theoretical boundary where the sun's outward flow of charged particles meets a counterflow from the Great Beyond—the unmodified cosmic rays that Voyager 1 is now sampling. "The Cosmic Ray Experiment was proposed by [Caltech physics professor Rochus] 'Robbie' Vogt," says Stone, who inherited the instrument when Vogt became provost in 1984. "He pushed hard for it, and succeeded in making the hunt for interstellar cosmic rays a goal of a *planetary* mission. We thought maybe we'd only have to go twice as far out as Saturn, but it turned out to be twelve times farther away than Saturn."

But first, MJS had to make it to Saturn itself.

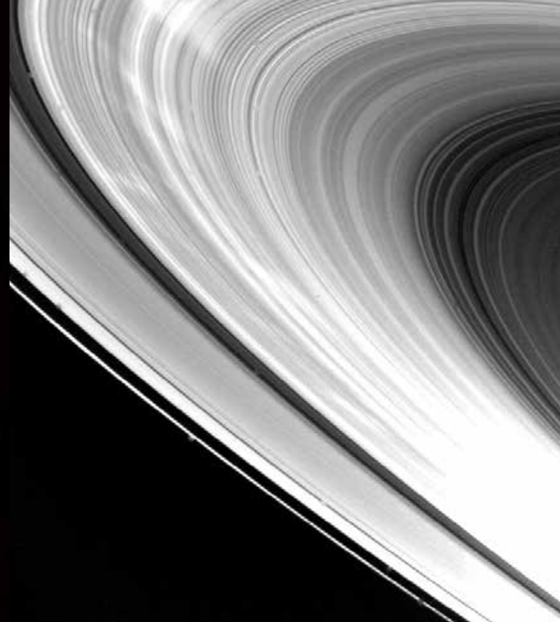
Caltech had organized JPL to develop rockets for the Army, and the Lab had maintained its engineering-based approach when it became part of NASA in 1958—if something doesn't work, tweak it and try again. JPL's first steps into space had had a 50 percent success rate, perfectly reasonable for the times. But after going one-for-eight in the early 1960s, director William Pickering (BS '32, MS '33, PhD '36) had assigned Schurmeier and Jack James, who had overseen the Lab's only recent success—Mariner 2's 1962 flyby of Venus—to write an operations manual that might have been subtitled *How to Build a Spacecraft Without Embarrassing Yourself.* Says Schurmeier, "In the early days, people would say, 'Oh, gee—I had a glitch, but it's gone now, so forget it.' We said, 'Any glitch—any time the electronics don't do what they're supposed to—we find the reason and fix it. And if we can't find it, we've got to create work-arounds for all of the possible failures that could have caused it.' And that had to be done before launch."

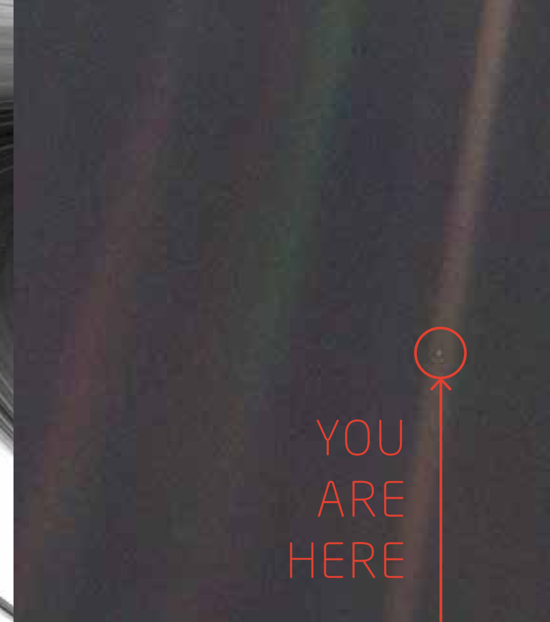
Schurmeier practiced what he preached. "On Voyager, we were very meticulous about looking at the individual electronic components," he says. "They had to be thoroughly tested before they could be used. Even before you started to build the electronics, the parts had already cost us a bundle. But we knew their pedigrees, how they'd been manufactured, what kind of failures they'd had. It was a big, big effort, but I think it was key to the lifetime we've had."



Of course, components that work flawlessly on the ground can still get fried in deep space, so each Voyager carries A and B copies of every critical system. "For the Grand Tour, we'd designed a triply-redundant computer that would control everything," Schurmeier says. "With Voyager, we couldn't afford to do that, but we did make dual radios, dual computers, and a lot of other dual equipment." The Voyagers' computers were designed to be reprogrammable to an unprecedented degree—and over unprecedented distances. Space is a harsh mistress, and despite rigorous quality assurance, scan platforms sometimes stick, radios die, power converters short out . . . and JPL engineers need to uplink new software that works around the damage.

Detailed design work had begun in earnest in October 1972, and the entire project almost went out the window a little more than a year later, when Pioneer 10 took humankind's first close-up look at Jupiter in December





1973 and encountered intense radiation. Although the Grand Tour proposal had called for "hardened" spacecraft to be built with armored shielding around delicate instruments and military-grade electronics designed to withstand nuclear war, this fiendishly expensive option had been discarded in favor of simply keeping a safe distance. After all, no one had known how strong Jupiter's radiation belts actually were. Now they did. "If we flew far enough away to need no radiation-hardened parts, we wouldn't have a mission," Schurmeier says. "That forced a very large change very late in the process, but we got enough hardening so we could fly close enough for a decent mission."

Mariner Jupiter Saturn was officially renamed Voyager in March 1977; Voyager 1 was launched that September and flew by Jupiter in 1979. In November 1980, it dove around and behind Saturn's Mercury-sized moon, Titan, in order to study its atmosphere before skimming past Saturn's rings on a track across the planet's southern hemisphere that would fling the spacecraft up and out of the plane of the solar system.

On Valentine's Day, 1990, Voyager 1 took one last look over its shoulder, snapping a family portrait of the solar system from about 32 degrees above—and 4 billion miles away from—it. The cameras were then turned off for good.

The ship is now flying blind, but it's not deaf. On August 25, 2012, the cosmic-ray data changed dramatically and Voyager's magnetic-field readings jumped by 60 percent—both signs that the spacecraft *might* have reached the heliopause. However, the key data—the plasma measurements proving that Voyager had left the hot, diffuse "solar wind" behind and entered the cold, dense interstellar medium—was unobtainable because Voyager's plasma science experiment had died just after the Saturn encounter 20 years earlier. Fortunately, on April 9, 2013, Voyager's plasma-wave antennas began picking up oscillations of the plasma that had a steadily increasing pitch. "These oscillations were triggered by a solar eruption that traveled outward through the solar wind like a tsunami crosses the ocean," says Stone. "Although the solar wind ions don't travel out to Voyager, the wave energy does, and our antennas pick up the plasma oscillations caused by the arriving wave. The frequency of the oscillation tells us the density of the plasma Voyager is traveling through."

The plasma team members at the University of Iowa realized that they were hearing the reverberations of the cold, dense interstellar medium from within. They went back through their data, and found a fainter signal with the same rising pitch that had been recorded from October 23 through November 27, 2012. The pitches fell on a line pointing straight back to August 25 as the date of entry to be stamped on Voyager's interstellar passport. "Voyager is now on a 10-year journey through the space between the stars," says Stone. "We should have enough power to keep all of the instruments running for another six years, and we'll turn the last one off in about 2025. Who knows what we'll find before then?" e&s

SNAPSHOTS OF A VOYAGE *On page 11, from left to right: Voyager gets its initial system test at Cape Canaveral Air Force Station prior to launch in 1977; the robot spacecraft at the Kennedy Space Center, where it was assembled and encapsulated; Voyager's first attempt at photography, showing a crescent-shaped Earth and moon, taken on September 18, 1977, 13 days after liftoff. On page 12, from left to right, images taken by Voyager: a dramatic view of Jupiter's Great Red Spot taken in February 1979; Ganymede, a satellite of Jupiter and the largest moon in the solar system; and Saturn, taken from a distance of 11 million miles in October 1980. The graphic on page 12 shows an illustration of Voyager's path through the solar system. On page 13, Voyager captured, from left to right: a montage of images of Saturn and a few of the planet's 60 moons, taken in November 1980; a close-up of Saturn's ring system; and part of the first ever "portrait" of the solar system taken by Voyager, with Earth showing up as a pale blue dot.*

USING SPACE WISELY

BY KIMM FESENMAIER

When you first enter the Space Structures Laboratory in the Guggenheim building, you can't help but be struck by the diversity of models—some suspended from the ceiling, some displayed like museum artifacts behind glass, some just laid out on tables. There are those that look like intricately folded origami creations, those that resemble oversized, metallic Chinese finger traps, and others—like the 4-meter-diameter model of NASA's superpressure balloon—that look as if they came straight out of some fantastical toy store.

Welcome to Sergio Pellegrino's lab, the place where the structural engineer and his postdocs and graduate students build and test all sorts of lightweight, shape-transforming structures, and where they study the relationship between structural form, stability, and ability to package and deploy into a required configuration. As different as they may look, however, these structures share at least one key trait: all of the models represent studies of how objects *fill* space, and most are designed for applications *in* space.

"The goal for much of my work," says Pellegrino, "is to make simpler and cheaper spacecraft. I want to use clever structural engineering to make access to space more affordable."

In that vein, one of Pellegrino's most ambitious projects focuses on an idea he and his colleagues first started contemplating several years ago: how to more easily build large or very large space telescopes at a lower cost than has been possible.

To understand the idea, you need to first recognize that the heart of any space telescope is its primary mirror—and that the larger the mirror is, the more photons it can collect and focus, and the farther into the cosmos it can help astronomers see. That's why astronomers would like to launch telescopes into space with enormous mirrors—mirrors larger even than the record-breaking 6.5-meter-diameter one on the James Webb Space Telescope (JWST), which is currently being built for launch in 2018.

It's quite challenging to build and integrate flawless mirrors on such a scale, however. Plus, a given launch vehicle can carry only so much cargo, in terms of both volume and mass. Take the JWST. In order to fit the spacecraft within the Ariane 5 rocket scheduled to lift it into orbit, the telescope's mirror is constructed in a segmented fashion out of lightweight beryllium, with sides that fold down and lock in place for launch and extend once in space. But even with such a design, its full 6.5-meter span is at the upper limit of what is possible with today's technologies and launch vehicles.

That's why, Pellegrino says, a new approach is needed—an approach that moves most of the telescope-assembling from Earth to the scope's ultimate destination. "We are trying to demonstrate the paradigm of assembling telescopes in space," he says.

"We" is a team of engineers and scientists that includes program area manager John Baker of the Jet Propulsion Laboratory (JPL), who joined this new effort in 2010. The team has become convinced that a different approach is needed to build the giant space telescope of the future. They envision launching a number of identical spacecraft, each bearing its own mirror segment and each having the ability to maneuver independently. Once in space, those smaller vehicles could use thrusters to reconfigure and position themselves so that they dock and become mechanically interconnected to form a giant mosaic mirror.

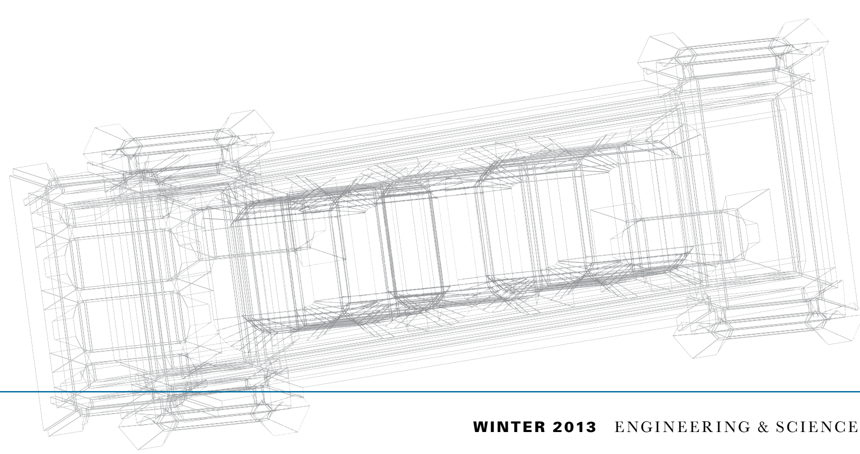
Aside from making it possible to get ever-larger mirrors into space, team members say, this strategy would also allow a damaged mirror segment or part simply to be plucked out of the configuration and swapped for a new one. Plus, the diameter of the mirror could be expanded as funding and additional launches became available.

"There's a whole history that says if you're going to build a large telescope in space, the cost will be a function of the weight of the mirror," says Baker. "But with this alternative approach, we would have the ability to actually fly very lightweight, low-cost mirrors. We could, in theory, end up building really large telescopes for a lot less money."

Before anyone is going to fund or undertake a full-blown mission using this new approach, however, someone needs to prove that the technological pieces of the concept are feasible on a smaller scale. Pellegrino, along with his colleagues and students, intends to be that someone.

"We want to show a path so that others can get inspired and go from there," Pellegrino says. "That's my goal. We will say, 'Here is a concept

Left to right: Sergio Pellegrino, Manan Arya, Keith Patterson, and John Steeves discuss the design of various test hardware, like the docking test robot and the deformable mirrors, and models for AAReST in Pellegrino's lab.



AAREST PROTOTYPE

A rendering of AAReST shows the black backdrop behind the CubeSats, which will open into a sunshade, while the black boom, folded around the spacecraft for launch, will deploy out straight, as shown, holding the telescope sensors and camera (shown in gold to represent multilayer insulation).

that you might want to start from. By all means, go and make it better.'"

AN AARESTING IDEA

Pellegrino and his team have been working on just such a technology-demonstration mission, a project called AAReST—Autonomous Assembly of a Reconfigurable Space Telescope. It's not a NASA mission. Think much smaller. To date, it's an effort that has been funded largely by Caltech's Keck Institute for Space Studies (KISS), Division of Engineering and Applied Science, and Innovation in Education Fund.

Despite the mission's modest budget, it has some rather ambitious goals. The plan is to launch several individual spacecraft all bundled together and command them to separate from one another in orbit before independently repositioning themselves. Then those smaller vehicles will have to dock back together in a wholly new configuration—one that creates a wider mirror. And, finally, since the individual mirrors will be made identical to one another, they will need to be adjusted while in orbit to create one focused, coherent image. Therefore, the mission also needs to demonstrate a feasible technology for actively deforming and controlling the shape of these lightweight mirrors.

As currently envisioned, AAReST will begin its journey as a compact cluster of three nanosatellites—two 3U CubeSats attached to a 9U CubeSat. CubeSats are small, standardized spacecraft that have been used over the past decade for various educational missions. A 1U CubeSat is a standard box 10 by 10 by 10 centimeters in size. The whole cluster can be stowed in a launch vehicle in a configuration that would take up no more space than a minifridge. This should allow the mission to limit costs by piggybacking as a launch vehicle's secondary payload.

Ten-centimeter deformable mirrors will sit one atop each of the two 3U CubeSats; additional rigid glass mirrors will sit on the 9U CubeSat. Once in space, the 9U CubeSat will extend a hinged, carbon-fiber boom carrying the telescope's instrumentation package—including a camera, corrective optics, and a mirror shape sensor—away from and above the rest of the CubeSats. These instruments will then help correct the shape and focus of the deformable mirrors.

From its new position on high, the camera will snap photographs of the stars and other objects that the mosaicked mirror brings into view, showing that the four mirrors, getting feedback from the sensor package, are capable of correcting their own shape and improving the quality of captured images.

In a grand finale of sorts, the two 3U CubeSats will detach from the rest of the spacecraft and usegas propulsion systems to reposition themselves atthe sides of the 9U CubeSat. Once complete, that partial do-si-do will have created one extended mirror; the telescope then will recalibrate itself to adjust to the new configuration, making any needed adjustments to the mirrors before taking new images.

Sound like a lot to demonstrate with one small mission? Baker thought so too. "The thing that was most intriguing to me about AAReST was that it didn't look possible at first," he says. "Creating an adaptive optics element at pretty low cost and then actually using it on a very small spacecraft to test it out? Both of those things seemed pretty impossible."

NEVER UNDERESTIMATE CALTECH STUDENTS

What might also have seemed impossible to Baker was that much of the work on this most difficult and innovative of projects would end up being done by a talented and dedicated group of students. That's right … students.

Around 2010, following two KISS studies that looked into the idea of self-assembling space telescopes, including those with large primary mirrors, Pellegrino recognized that there was a real opportunity to incorporate an educational component into the mission that he was beginning to envision.

The result is that, in addition to its technological goals, AAReST has an important educational objective: to help train new aerospace engineers by giving them hands-on experience working out the details of an actual space mission. As a result, today's AAReST team is made up almost entirely of Caltech students and postdocs joined and guided by Pellegrino, Baker, and Caltech instructors. Professors Craig Underwood and Vaios Lappas from the University of Surrey in England complete the team.

Pellegrino has even incorporated the mission into the curriculum of Ae 105—Aerospace Engineering—a graduate-level course. Over each of the past three years, students in the class have spent the second half of their academic year working on various aspects of the AAReST mission—improving the design of the telescope and its components, producing and testing prototypes, and otherwise refining the mission. Last year's class conducted a detailed thermal analysis of the telescope's components, determined how to arrange the mirrors after launch to ensure that the telescope would be able to image its target star (which will most likely be Sirius), evaluated the detailed design of the lenses in the optical system, and used physical and computer models to measure the small disturbances that would be created by a reaction wheel—which would control the direction of the spacecraft without the use of fuel-consuming rockets—provided by the University of Surrey for stabilizing the telescope's orientation.

"Unlike a typical space mission, it has been our main objective to involve students, to teach classes, and to have students build the spacecraft and to do it openly so that *every* student can participate," Pellegrino says.

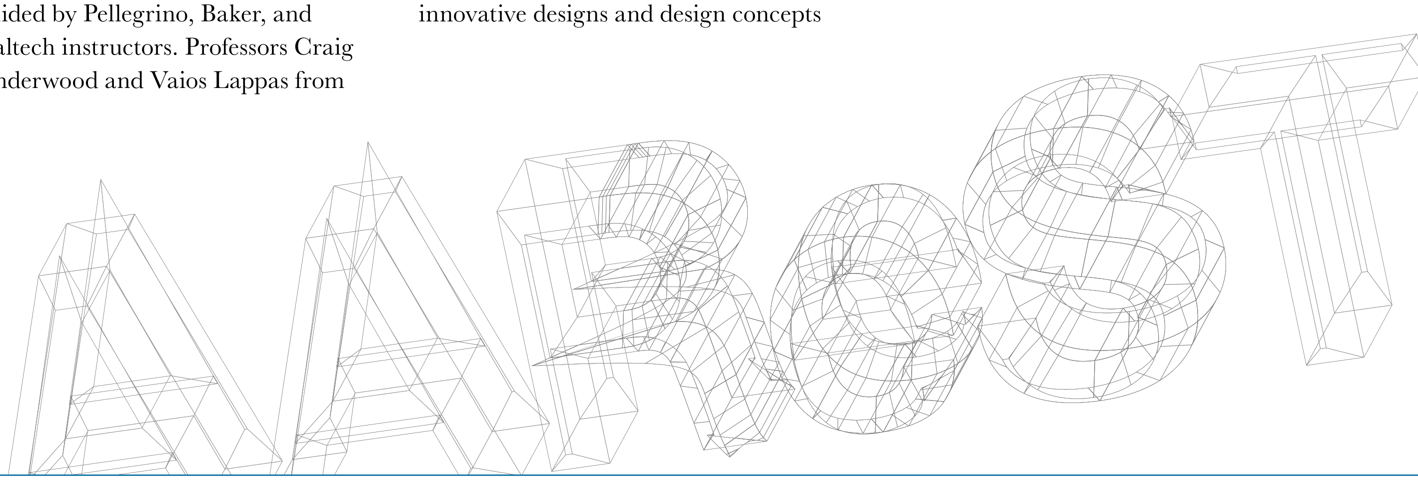
The team is currently on target for a 2015 launch of AAReST, although they're not sure exactly which rocket will take the telescope up into space. Logistics aside, Baker says, the design is looking better all the time. "We have innovative designs and design concepts

This early prototype of a deformable mirror was used by researchers to test the concept of AAReST.

for the camera, the mirror elements, and the boom," he says. "And the students have done all of the design, all of the thermal analysis, all of the shading and baffling, the covers, and the electronics. It's quite impressive."

MIRROR, MIRROR

Among those impressive students is Keith Patterson, a graduate student who has been working on AAReST since its earliest days. Despite having been fascinated by space since childhood, Patterson says he "knew nothing about mirrors, adaptive optics, or any of this stuff" when Pellegrino first mentioned needing help on a project that would involve developing thin, lightweight mirrors for a potential space mission. Still, Patterson jumped in without hesitation. "I'm pretty much open to working on anything as long as it has to do with space," he laughs.



Today, Patterson knows plenty about mirrors—he's one of the leads in the development of the novel technology behind AAReST's small deformable mirrors—as well as about the ins and outs of the mission. He's been a teaching assistant for Ae 105 several times and spends about half his time in JPL's Microdevices Lab clean-room facilities, designing and fabricating and then refining mirror concepts with the help of his mentor, Risaku Toda of JPL.

The first ultrathin mirrors Patterson and his colleagues developed were made of silicon wafers coated with a reflective material. More recently, however, they've switched away from silicon and are developing a technique for using glass wafers instead, since glass is softer and can therefore take on a curved shape more easily. All the mirrors, being less than 0.3 millimeters thick, are quite lightweight.

Behind the wafer—be it silicon or glass—the engineers deposit alternating layers of metal electrodes and piezoelectric polymers, which are materials that will deform when an external electric field is applied. These electrodes allow the researchers to apply different voltages to specific points on the mirror, altering its curvature in just the right spots. By patterning the electrodes in different ways—forming a series of concentric circles, a triangular lattice, or, most recently, a floral pattern called "the Notre Dame"—the researchers can create mirrors that have the ability to be adjusted precisely as needed to produce the best images possible.

"When I first started working with Sergio, basically all I knew was that there was going to be a project on thin mirrors," Patterson said. "To start from something so vague and then try a bunch of things and find that sweet spot where something actually works … and *then* to have the potential for these things to actually fly and be demonstrated in space … that is pretty exciting."

APPLICATIONS BACK ON EARTH

As the AAReST mission has progressed, aspects of the work have overlapped with and inspired separate but related projects in Pellegrino's lab. The small mirrors that will top the CubeSats, for example, motivated other students to consider using similar techniques to make much larger lightweight mirrors.

"The mirrors in a telescope are the most difficult mirrors to make because they have to be so precise," Pellegrino says. "We thought, Why don't we try to develop some bigger mirrors for an application that isn't as demanding but actually needs big solar-collecting surfaces? So we started looking at solar concentrators—lenses that focus sunlight to collect heat."

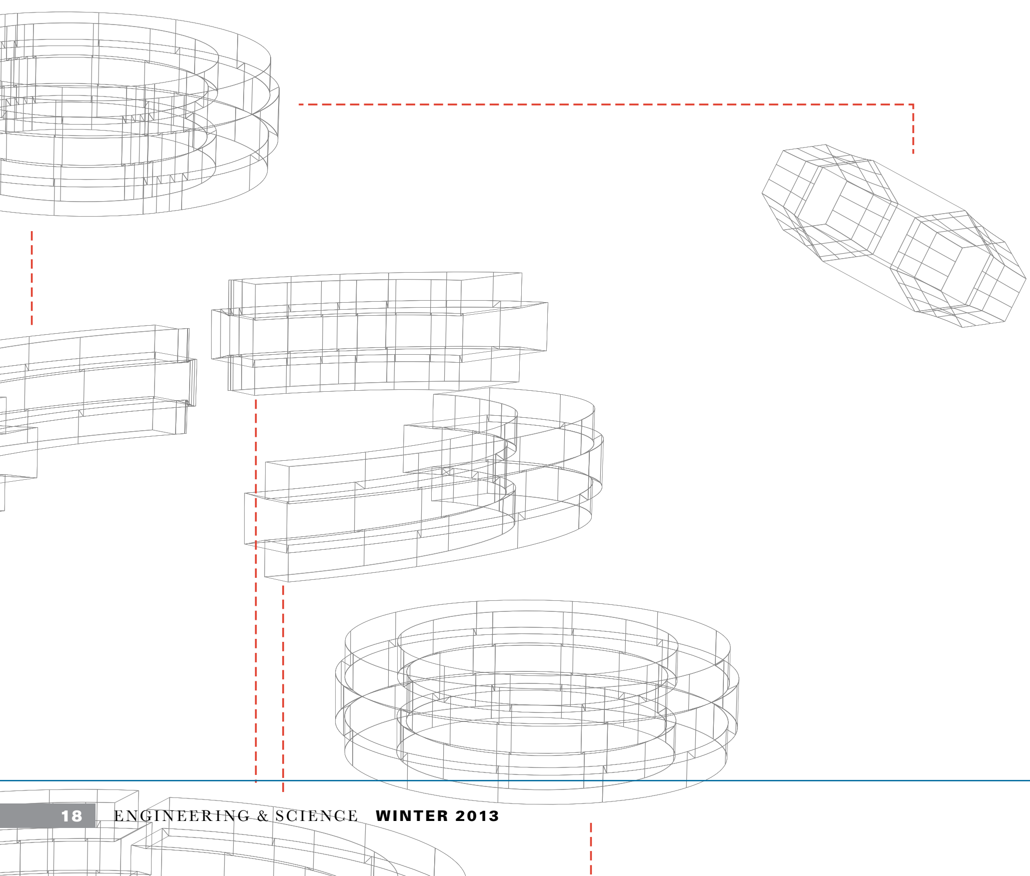
With funding from the Resnick Institute and the Dow Bridge Innovation Fund, the Pellegrino group's pursuit of this line of research has led to the production of large, more-durable carbon mirrors for solar concentrators.

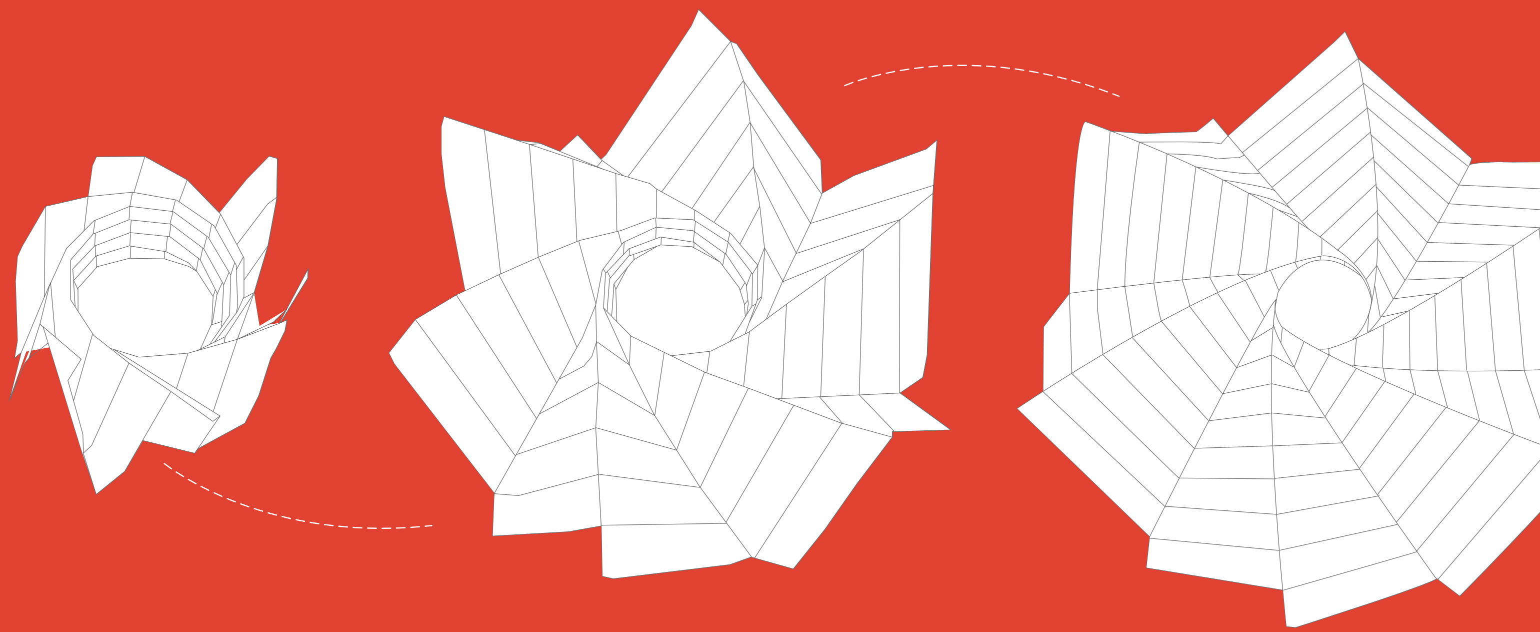
"We are doing work on some rather fundamental research while we work on the AAReST mission," says Pellegrino. "In fact, we often get inspiration from AAReST's problems to try out new things in the lab. It's interesting and exciting that our technology-demonstration mission can also inspire our research." e&s

John Baker is program area manager of the Human and Robotic Mission Systems Architecture Office and also the Planetary SmallSat lead at JPL.

Sergio Pellegrino is the Joyce and Kent Kresa Professor of Aeronautics and professor of civil engineering at Caltech. He is also a senior research scientist at JPL.

Funding for the Ae 105 class comes from the Keck Institute for Space Studies, Caltech's Division of Engineering and Applied Science, and the Innovation in Education Fund, which is made possible in part by the Caltech Associates.





You can hear small crackling sounds echo—pop, pop, pop—in the Pellegrino lab as graduate student Manan Arya pulls two corners of a shiny silver sheet of Mylar in opposite directions. Ideally, the intricately folded sheet in his hands would unfurl without a sound. But there's still work to be done before those pesky little pops will be silenced. Arya is tinkering with the design for a new solar sail—an extremely lightweight reflective sheet that would be propelled through space by the force of photons hitting it as they stream away from the sun. Solar sails are nothing new, and the idea behind them is simple: if you can extend a large enough sail in such a way that it is always getting pushed even just slightly by the sun's light, it—and anything attached to it—will eventually pick up momentum and ultimately travel at exceedingly high speeds.

"I believe it's the only viable way we have right now for properly exploring the solar system and places outside the solar system," Arya says.

His inspiration comes from a Japanese experimental spacecraft called IKAROS, which successfully deployed the first functioning solar sail in space in 2010. Rather than attempting, as others have, to deploy booms that could guide the unfurling of segmented sails, the IKAROS team used centrifugal force, simply spinning the spacecraft to unwrap one large sail.

"They went a completely different route and surprised everybody," Arya says. "Without supporting structures, the spacecraft as a whole becomes much lighter, which means it can accelerate faster and get to destinations faster."

Currently, Arya is thinking along those same lines while trying to devise an even better way to package a sail so that it can be even larger while still deploying seamlessly; such a sail, he says, might carry a more capable spacecraft into the farthest reaches of the solar system.

"I like the fact that there is exactly one problem here and that it's something I can contribute to," Arya says. "The problem is: how do you package something that's very large into a small space? That's it. Once it's large enough and light enough, it will fly."

For now, Arya is experimenting with miniature sails to see how they behave when they are folded in different patterns and when they have different sizes and thicknesses. Over the summer, Caltech alumnus Robert Lang (BS '82, PhD '86), one of the world's leading origami experts, stopped by the Space Structures Laboratory to chat with Arya about his work and what he might try next.

Still, there are some difficulties to overcome before the sail can set sail. "Different folding patterns behave very differently," Arya says. "The problem with my current models is that there is definitely strain—a real problem for the sail's ability to function properly—while they are being deployed. You know about the strain because of the popping sounds. You could do complicated measurements and look at the forces jumping around. But you can also just hear it by the pops."

LAB SPACES

BY JESSICA STOLLER-CONRAD

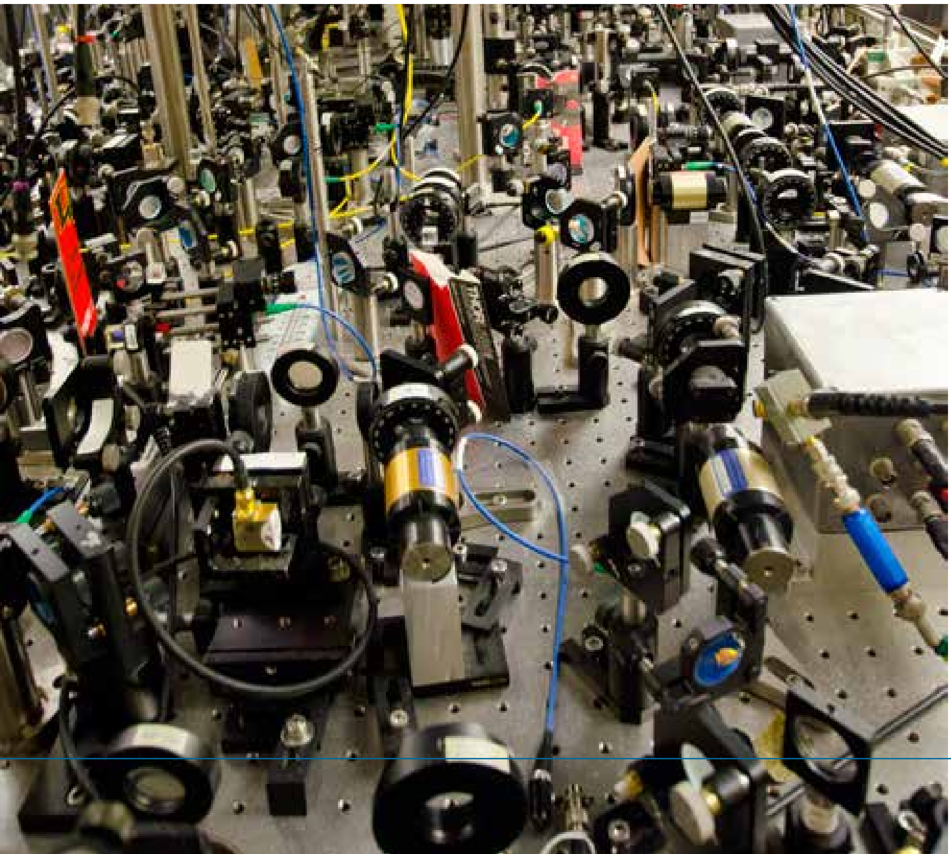
When asked to envision a typical workspace, most of us imagine neutral colors, generic cubicles, and fluorescent lights. The work done in Caltech's offices and laboratories, however, is anything but typical—and that uniqueness is often reflected in the design of the spaces within which the Institute's researchers do their most creative work. Some labs were designed to include artistic elements that reflect a specific research interest; in others, sophisticated instruments are themselves objects of beauty. Here are some examples of Caltech's uniqueness and creativity at work—literally.

◀

When Markus Meister, Lawrence A. Hanson, Jr. Professor of Biology, came to sunny California from Boston in the fall of 2012, he quickly noticed that his new laboratory, ironically, had very poor lighting. Even more ironic? Meister studies the neurobiology of the visual system, or how our eyes process images. When he met with architects to redesign the space, they proposed not only optimizing the flow of natural light but also adding another prominent light source in the form of the long, luminous wall seen at left. Though light from the wall isn't used in experiments, Meister considers it an important design feature, facing the laboratory's common area and inspiring the researchers in their adjacent glass-walled offices. But don't worry about Meister getting tired of a bright blue wall shining into his office. "My only contribution to the design was to require that the color be able to change to anything we want," he says. "Most of the time we use all colors of the rainbow in a slow rotation."

▶

The cleanroom at the Kavli Nanoscience Institute—designed to be as free of dust and microbes as possible—is an important resource for Caltech's nanotechnology researchers, who design high-tech components 10 to 100 times smaller than any floating piece of dust. Right, Pawel Latawiec, a former undergraduate student in the laboratory of Axel Scherer, Bernard Neches Professor of Electrical Engineering, Applied Physics and Physics, uses a tool in the cleanroom to produce plasmonic chips—devices that increase the intensity of light—for use in the precise study of viruses and small biological systems. And that golden glow? It has a purpose, too: because the chips' photoreactive polymers are put into their functional patterns using ultraviolet (UV) light, those bluish-purple waves must be filtered out of white light in the room to prevent unwanted pattern changes. The resulting UV-less rays cast a yellow hue.



◀

This tangle of wire, glass, and metal is actually a carefully positioned network of optical instruments that Caltech scientists use to study the interactions between our macroscopic world and the realm of quantum mechanics—the set of physical principles that govern the behaviors of tiny subatomic particles. Researchers in the laboratory of Jeff Kimble, William L. Valentine Professor and professor of physics, use the blue fiber-optic cables in this setup to transport laser light through a series of optical instruments that can control and change the frequency, direction, intensity, and path of the light. The trip through the maze manipulates the light so that it can be used to cool atoms to less than 30 microkelvins—just shades away from absolute zero. The cold atoms resulting from this process can then be localized one by one within nanoscale structures fabricated at the Kavli Nanoscience Institute—allowing researchers to control the quantum interactions of single photons and atoms.

▼ *John Seinfeld, Louis E. Nohl Professor and professor of chemical engineering, studies where particles in the air come from and what they are made of. The atmosphere around us, he says, is a giant chemical reactor; the airborne particles that are the result of these atmospheric reactions generally contain a great deal of organic material that comes from the volatile organic compounds found in motor vehicle exhaust as well as in emissions from trees and vegetation. Seinfeld's research group simulates these organic reactions in the large transparent teflon chamber pictured below, which is surrounded by lights that mimic sunlight. The data gathered from these experiments at Caltech—which is a general source of much of the world's information on the formation of atmospheric aerosols—will help researchers understand where the constituents of smog come from and how they can be reduced.*

◀ *It would be difficult to walk into the lab space of Paul Sternberg, Thomas Hunt Morgan Professor of Biology, and not quickly realize that he's spent the last several decades at Caltech studying worms—specifically,* Caenorhabiditis elegans, *a tiny roundworm whose compact genome and easy-to-follow development have made it an excellent model for determining gene functions. Sternberg's laboratory features a wiggling worm design tiled into the floor, a worm-shaped desk (seen left, with Sternberg), and even a detailed representation of the worm's anatomy in a wall decal, a flattened computer rendering the worm's skin made transparent so that its organs are visible.*

▲ *Jennifer Jackson's basement laboratory is underground, but her research digs even deeper to discover the properties of minerals that are nestled more than 600 kilometers below Earth's surface. Because researchers can't physically get down that deep—even the deepest drill hole only descends about 12 kilometers—Jackson, professor of mineral physics, has to simulate the high-pressure conditions of the interior of the planet. She does this using a tool called a diamond anvil cell—a schematic of which is represented in the floor tiles of her laboratory. In the photo above, the structures in blue represent the two diamond anvils. A mineral sample—represented by the red tile—is then compressed between the two anvils. Diamonds are used to compress the mineral sample because they are hard enough to stand up to the crushing pressures they themselves create, and transparent enough that Jackson and her team can shine a laser (represented in yellow) and X-rays through them—as well as through the sample—to measure physical changes in the sample.*

▲ *This fluorescent column of water is more than just an attractive design element in John Dabiri's lab space—it's also an experiment in progress. Dabiri, professor of aeronautics and bioengineering, uses this four-foot-tall water tank to study the effect that vertically migrating swarms of small organisms, such as brine shrimp, may have on the transport and mixing of nutrients in the ocean. Once the brine shrimp are released from a cage at the bottom of the tank, they are lured by the blue lights to try to reach the top, a process that involves a combination of passive floating and active swimming. This mimics their behavior in the wild, where various species of plankton migrate daily to the water's surface to eat, and swarm back down to avoid predators. The researchers then use a high-speed camera to measure the flow field and determine how much food and water from the bottom is dragged to the top by each swarm. While the effects of a single shrimp are, well, shrimpy, the millions of shrimps and other tiny swarming organisms that rise from the ocean floor each day may play a significant role in distributing the ocean's nutrients.*

LIGHTING UP

THE DARK AGES

by Marcus Y. Woo

NOT LONG AFTER THE BIG BANG—a mere 370,000 years later—the universe entered what astronomers now call the dark ages. The cosmos had yet to see the light of stars and galaxies; in fact, a cloak of hydrogen haze smothered almost any photon that might have tried to illuminate the infant universe.

After about 200 million more years, however, that hydrogen gas began to coalesce into increasingly dense clouds—coaxed together by the gravitational pull of dark matter, the unseen and unknown stuff that accounts for most of the universe's mass. Those hydrogen clouds eventually collapsed into dense balls that were hot enough to ignite nuclear fusion, thus giving birth to the first stars.

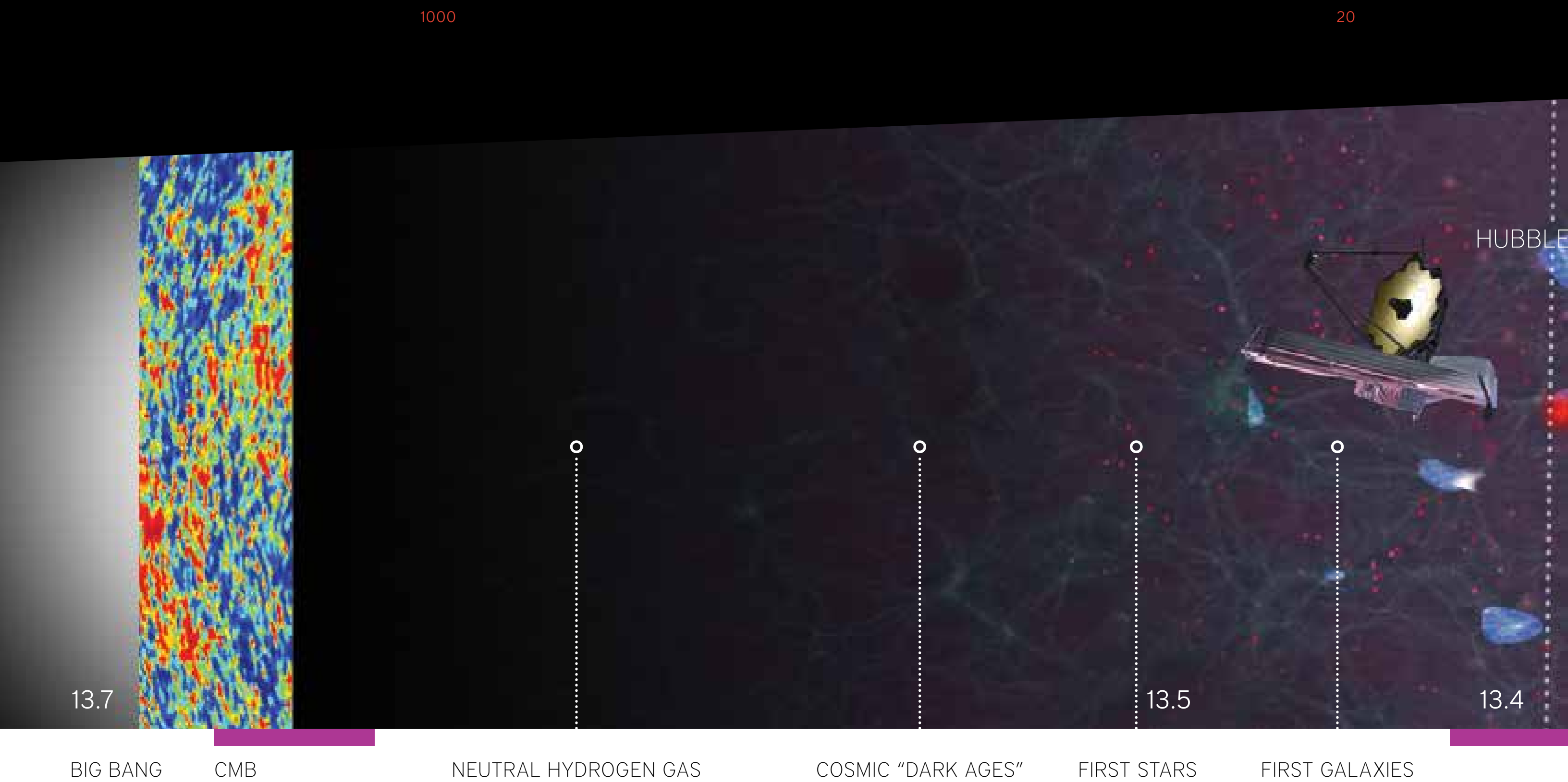
Over the course of another couple of hundred million years, more and more stars flared into existence and galaxies formed, flooding the universe with high-energy photons—ultraviolet light that carried enough energy to strip the single electrons from the hydrogen atoms that pervaded the cosmos. At this time, most of the hydrogen gas in the universe was electrically neutral—a single electron joined with a proton—and neutral hydrogen blocks light by absorbing it. But with the influx of ultraviolet light, the neutral hydrogen lost its electrons and became ionized. Without neutral hydrogen to absorb them, photons could now travel freely.

This epoch—the one that saw the first stars and galaxies and the ionization of hydrogen—is known as the cosmic dawn, and its light brought an end to the dark ages. Together, both periods represent the last frontier of observational cosmology—an era so distant and therefore so faint that it's out of reach (though only just so) of today's telescopes. But because astronomers, ever the pioneers, love a good frontier, scientists like Caltech's Richard Ellis are pushing the limits of those present-day telescopes, trying to capture images of the first generation of stars right after they formed.

Recently, they got tantalizingly close when Ellis led an international team of astronomers as they discovered seven of the earliest galaxies ever seen—the first-ever census of such primitive galaxies. The observations offered a glimpse of the cosmic dawn, setting the stage for the next generation of telescopes to peer even deeper into this mysterious era of cosmic history. "It's exciting," he says. "We're very close now."

FILLING THE GAP

The universe is roughly 13.8 billion years old—a staggering number compared to our human timescales. But, remarkably, scientists have been able to sketch out its general history pretty well. The beginning of the dark ages, for instance, is marked by the omnipresence of the cosmic microwave background (CMB)—a microwave-frequency glow that provides a snapshot of the universe when it was 370,000 years old. Studying the CMB allows astronomers to piece together a blow-by-blow account of the early universe beyond that snapshot, down to the first fractions of a second after the Big Bang. There have been a variety of increasingly advanced experiments,



such as the balloon-borne BOOMERanG project, which was led by Caltech's late Andrew Lange at the turn of the century, as well as other Caltech-led balloon and Earth-based programs at the South Pole, and experiments on the Planck spacecraft (whose U.S. participation is based at JPL). Thanks to these efforts, astronomers have been able to probe the CMB and the baby universe with startling precision over the last couple of decades.

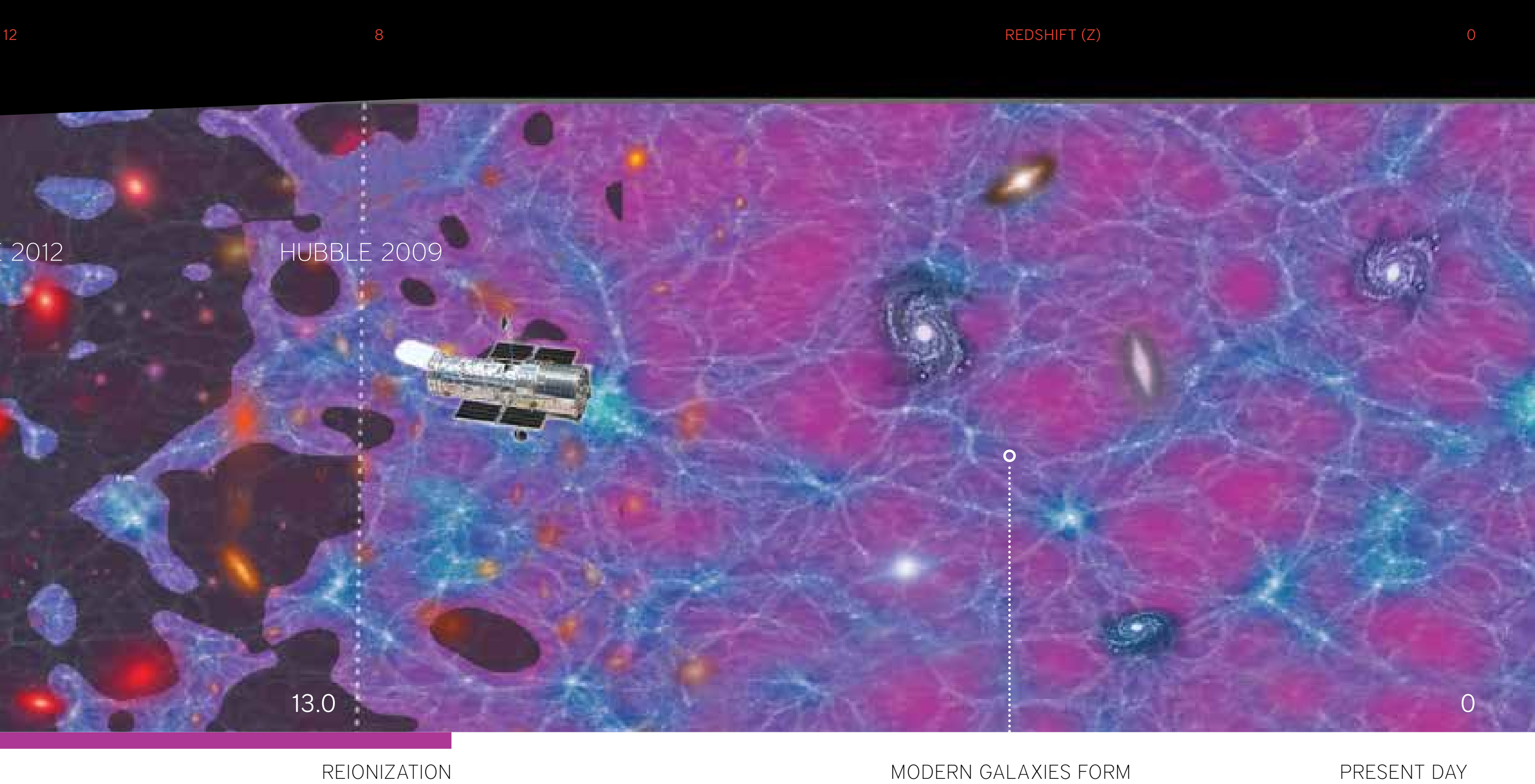
While such experiments are telling, telescopes offer the ability to actually peer back into different stages of cosmic history. The light that reaches astronomers' telescopes is an image from the past: the more distant a galaxy, the longer its light will have to travel; so the farther away the object, the more primitive it is. Bigger and better telescopes have allowed astronomers to chronicle periods of cosmic history deeper into the past—as far back in time as about 12.8 billion years ago. But, until recently, telescopes hadn't been able to reach much farther than that.

Between the window the CMB gives us into the earliest days of the universe and the telescopic record going back more than 12 billion years from today, however, there's a gap. And in that gap are the dark ages and the cosmic dawn. As Ellis says, “it's the last uncharted period of cosmic history.”

Which isn't to say that nobody's tried to chart it, nor that they haven't had some success. In 2009, for instance, a team of astronomers led by Garth Illingworth of UC Santa Cruz and Rychard Bouwens of Leiden University pointed the Hubble Space Telescope at what's known as the Hubble Ultra Deep Field. Hubble had first observed this tiny patch of sky in the constellation Fornax—only about 1/50th the area of the moon as it appears in the sky—between 2003 and 2004. The astronomers had chosen that region because it lacked bright foreground stars and nearby galaxies, which would have overwhelmed the faint galaxies they wanted to study. During that original set of observations, which were made almost 10 years ago now, the astronomers had kept the telescope trained on that same region for 400 orbits—amounting to 11.3 days of total exposure time. Only with such a long exposure time could they hope to see the cosmic dawn.

What they found was an impressive initial haul of galaxies, containing a total of about 10,000 of the most distant galaxies ever seen—which meant they were some of the earliest ever detected. But astronomers weren't quite able to see back to the cosmic dawn. By the fall of 2009, however, astronauts had upgraded Hubble with the Wide-Field Camera 3 (WFC3); Ellis says its larger field of view, smaller pixels, and overall improvements made it 40 times more efficient at taking astronomical surveys than its predecessor. Using this new instrument, Illingworth and Bouwens's team was able to observe galaxies that were even more distant—including about three dozen from a time when the universe was just under 800 million years old. The astronomers were also able to pinpoint one galaxy that appeared to be from 480 million years after the Big Bang, making it the single most distant galaxy ever seen.

The astronomers were able to date these newly discovered, very distant galaxies by measuring their colors. Astronomers can determine the colors



of galaxies using filters that block light at certain wavelengths. For instance, massive stars that quickly burn through their nuclear fuel are hotter, and therefore bluer, than others. Since they use up their fuel so fast, they die faster as well—after only a few hundred million years, compared to the lifespans of other stars that last billions of years. If you see a blue star, then, it must necessarily have been young—i.e., caught early in its lifespan—otherwise, it would already have died. Redder stars, which burn slower, will have lived longer and therefore must be older, caught later in their lifespans. Because the galaxies in the 2009 observations appeared blue, they were likely newborns. That the galaxies were also extremely distant led the scientists to ask whether they might be the long-sought first-generation galaxies of the cosmic dawn.

PUSHING THE FRONTIER

To see if this was truly the case—and to see if they could reach even further back in time—Ellis and his colleagues pointed Hubble at the same area once again in 2012, taking more exposures over the course of two months and thus gathering an additional 128 orbits of data. They used an additional filter to better narrow down the colors—and therefore the ages—of the galaxies.

The team also used a "drop-out" filter technique to confirm that the distant galaxies were indeed extremely far away. The neutral hydrogen gas that permeated the early universe absorbed any light that was bluer than a wavelength of 121.6 nanometers. Because the expansion of the universe stretches the wavelength of light, the more distant a galaxy is, the more its light's wavelength gets shifted—a phenomenon known as the cosmological redshift.

To measure this shift, the astronomers use different filters to observe each galaxy at shorter and shorter wavelengths until the galaxy is no longer visible—because the hydrogen around it has completely absorbed its light. At that point, the galaxy is said to have "dropped out." The wavelength at which a galaxy drops out tells the astronomers how much its light has redshifted, which tells them how far away it is. Caltech's Lee A. DuBridge Professor of Astronomy Chuck Steidel was the first to demonstrate this technique on a large sample of galaxies at the Palomar and Keck Observatories.

The results of the 2012 observations, Ellis says, were a breakthrough. The team doubled the 2009 number of known galaxies that existed less than 800 million years after the Big Bang—there are now a total of 74 such galaxies. More importantly, he says, the team found seven new galaxies that date from just 500 million years after the Big Bang. With the better data, the 480-million-year-old galaxy that had been previously identified as the most distant galaxy ever spotted now looks as if it came into being when the universe was a mere 380 million years old. (At least for now, says Ellis. Because this galaxy is especially faint, the astronomers aren't as confident about its age; in the future, more

Above: A timeline of the history of the universe, with the numbers denoting billions of years. The location of Hubble 2012 and Hubble 2009 represents the era targeted by the Hubble Ultra Deep Field in 2012 and 2009.

powerful telescopes may help them pin it down for sure.)

These observations—and, in particular, the sighting of the seven galaxies dating back to no more than 500 million years after the Big Bang—are as close to the cosmic dawn as anyone has ever gotten. "It's truly amazing that we can look this far back," Ellis says.

What's even more surprising (and slightly disappointing), he adds, is that the galaxies his team found in 2012 aren't as blue as those measured in the 2009 observations. This means they are older, containing stars that had already been shining for 100 million to 200 million years. "These galaxies are not, sadly, the very earliest galaxies," he says. What's less sad is that the findings suggest astronomers are close to finally capturing the earliest galaxies. And they tell us that the cosmic dawn must have happened earlier than we thought—perhaps as early as 200 million years after the Big Bang.

Unfortunately, that's a time beyond the reach of today's telescopes. With the 2012 observations, Ellis and his team pushed Hubble to its limits. To finally capture the cosmic dawn will require the next generation of telescopes: the James Webb Space Telescope (JWST), which is slated for launch in 2018, or the Thirty Meter Telescope (TMT) in Hawaii, scheduled to start observations by 2022. But the current data already hint at what these higher-tech scopes might see—and possibly provide a rich hunting ground for finding even earlier galaxies.

For instance, the 2012 observations show a steady decline in the number of galaxies the further back in time you go. That means the birth of the first stars and galaxies must have been a gradual process—not a single dramatic event that suddenly flooded the cosmos with light. The future telescopes should be able to track this entire transition.

Astronomers also expect JWST and TMT to help solve a related mystery about a cosmic event called reionization. When hydrogen first formed after the Big Bang, it was ionized, i.e., missing an electron. As the universe expanded and cooled, the hydrogen nuclei joined up with their lost electrons to form the so-called neutral hydrogen gas that blanketed the universe during the dark ages. It was only when that gas became ionized (or *re*ionized, since the hydrogen was initially in an ionized form) that the fog of the dark ages lifted. Today, almost all of the hydrogen gas in the universe is ionized. According to scientists' observations of the CMB, this ionization happened sometime after the cosmic dawn, as more and more galaxies began to populate the universe.

The question is, how did all that hydrogen become reionized in the first place? The process would have required a flood of ultraviolet light, which many astronomers think simply radiated from the growing number of galaxies that characterized the cosmic dawn. But were there enough galaxies to do the job?

The data from the Hubble Ultra Deep Field seem to say that there weren't enough galaxies—not at all. But there's a catch: the galaxies sighted in 2012 are among the biggest and brightest ever seen. And yet it was the

Above: Richard Ellis (left) and Matthew Schenker are leading the way to find the very first galaxies.

ASTRONOMERS WILL HAVE TO WAIT UNTIL THE NEXT GENERATION OF TELESCOPES BEFORE THEY CAN COMPLETELY EXPLORE THE DARK AGES AND THE COSMIC DAWN.

faintest of those bright galaxies—the ones at the very limits of Hubble's galaxy-finding abilities—that appeared to be most numerous. That could mean that there's a large population of small, dim galaxies out there that Hubble just can't see. According to Ellis and his colleagues, there should have been enough of these feeble galaxies—as they call them—to have reionized all the hydrogen gas in the universe.

If future telescopes fail to find these feeble galaxies, Ellis says, astronomers will then have to consider more exotic sources of ultraviolet light—such as massive black holes that produce high-energy radiation as they gobble up gas and dust. But for now, he says, "galaxies are the best bet."

BEYOND THE HUBBLE

To study this epoch of reionization more closely and pinpoint exactly when the universe emerged from its dark ages, Matthew Schenker, a graduate student at Caltech working with Ellis, has been using the Keck observatory in Hawaii and, more specifically, its multi-object spectrometer for infrared exploration, or MOSFIRE—a state-of-the-art instrument built by Caltech's Chuck Steidel and instrument expert Keith Matthews along with a team from UCLA. Together, Schenker and Ellis have been measuring a specific wavelength of light from galaxies, called the Lyman-alpha emission line, which corresponds to the wavelength of light that's absorbed by neutral hydrogen—the same 121.6-nanometer feature used to determine galactic distances in the drop-out filter technique.

Reionization and the end of the dark ages go hand in hand, it turns out. This is because the dark ages were characterized by the presence of that neutral, nonionized hydrogen gas. Once ultraviolet light appeared on the scene, the hydrogen became ionized again (which made it transparent to—or unable to absorb—ultraviolet light), more photons were able to light up the universe, and the dark ages were no more.

And so, by measuring how readily the 121.6-nanometer light was absorbed by neutral hydrogen over the course of cosmic history, Schenker and Ellis are able to gauge how the amount of neutral hydrogen waned over time, and thus witness—in a sense—the ushering out of the dark ages. What they've found so far is that at around 1 billion years after the Big Bang, the emission line, which had appeared in 50 percent of the galaxies previously, dropped to only 10 percent—a sudden decline that marks the end of the dark ages.

In addition to Hubble and Keck, Ellis and his colleagues are also using the Spitzer Space Telescope to probe the cosmic dawn. While Hubble is good at detecting those younger, bluer stars, Spitzer—which observes in longer, redder wavelengths—is good at detecting the relatively older stars. Old stars are important because they reveal the past rate of star formation, which is how much "star stuff"—the combined mass of stars—has been produced over time. For example, if you see a bunch of stars that are 200 million years old and collectively weigh as much as a billion suns, then that means the equivalent of a billion suns is formed over the course of 200 million years, a rate of five suns per year (by comparison, the Milky Way is forming stars at a rate less than one sun per year).

And while Hubble has already been pushed to its limits, Ellis says, Spitzer has not. The astronomers have applied for telescope time to point Spitzer at the Hubble Ultra Deep Field soon to gather data on older stars and complement the census of younger stars taken during the 2012 Hubble observations.

In addition, astronomers working at the Atacama Large Millimeter/submillimeter Array (ALMA), an array of dishes in Chile that began operation in 2011, will conduct their own survey to find the first stars and galaxies. Because the first-generation galaxies are so distant, their light has been stretched to millimeter and submillimeter wavelengths, making them prime targets for ALMA.

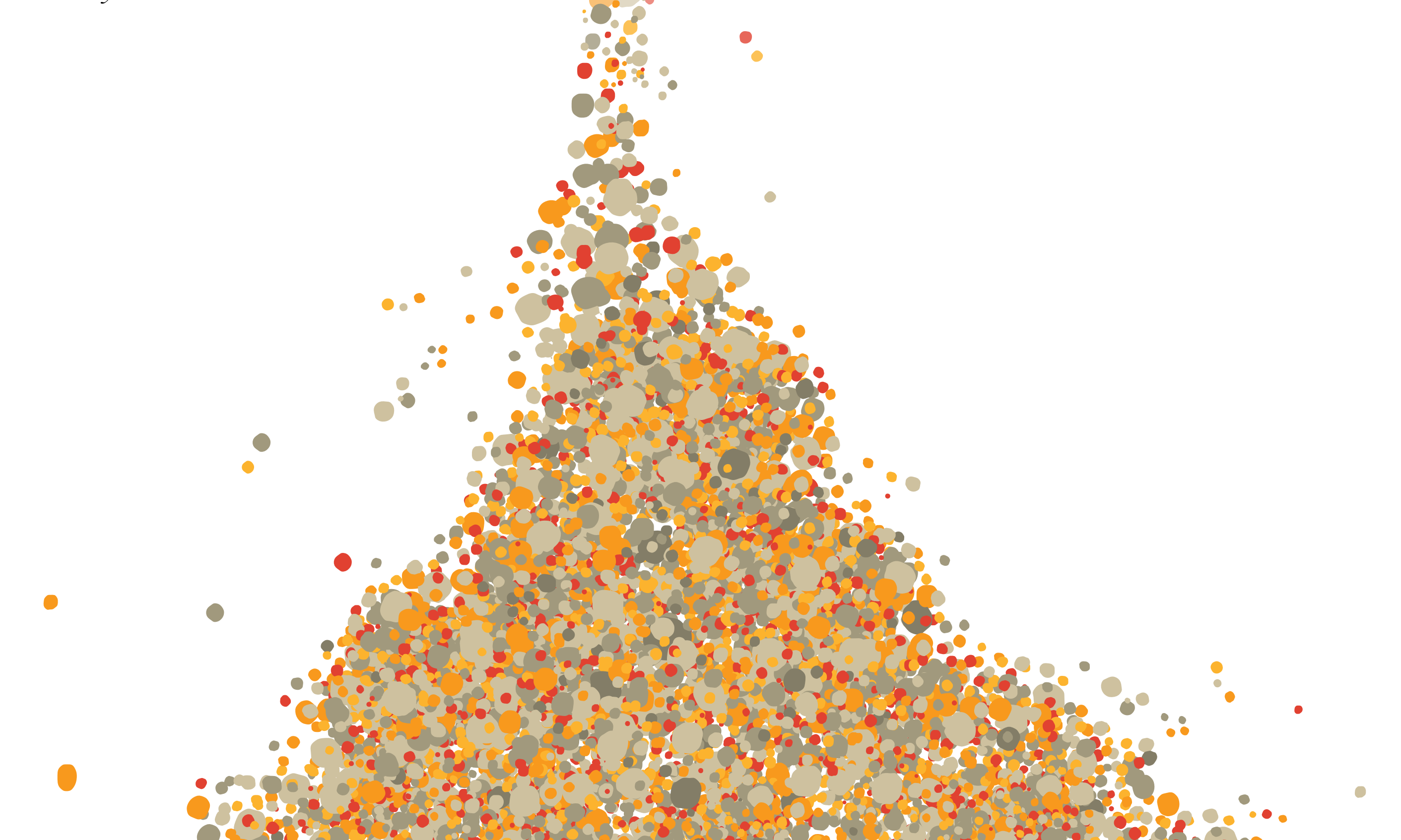
Still, despite the promising data that ALMA and Spitzer may soon yield, astronomers will have to wait until the next generation of telescopes before they can completely explore the dark ages and the cosmic dawn. They'll look for the first stars with JWST and TMT and try to map the neutral hydrogen throughout the dark ages with radio telescopes such as the Square Kilometre Array—an arrangement of radio dishes to be built in South Africa and Australia that won't start observations until after 2021—and the Owens Valley Long Wavelength Array in eastern California. These radio telescopes will be used to try to reveal how clouds of gas in the infant universe clumped together to form the very first stars. And then, hopefully, astronomers will finally be able to answer some of the most profound questions about cosmic history. After all, Ellis says, "finding the very first objects is, in essence, exploring our very origins." e&s

Richard Ellis is the Steele Family Professor of Astronomy. This work is funded by the Space Telescope Science Institute.

The Spaces Between

Caltech geologists and engineers are exploring how the nooks and crannies amid particles help create Earth's most beautiful landscapes—as well as its most dangerous landslides and avalanches.

By Katie Neith



At first glance, an hourglass filled with sand appears to be a simple object. If all the sand is at the bottom of the apparatus, you can flip it over and watch as the grains trickle back down, marking a set amount of time.

"It flows the way you would intuitively expect—when half the time is gone, half the sand will be at the bottom," says mechanical engineer Melany Hunt. And yet, that intuitive sense only applies to sand; as Hunt points out, "If it were a liquid, it wouldn't work that way—the rate of flow would depend on factors like the liquid's height above the neck, which would change the liquid's discharge speed."

Sand is much more low-maintenance and predictable: its particles just sort of temporarily lock together and tumble down into the bulb below at a set rate, making it the ideal timekeeping material. And yet, no one knows exactly how to predict the flow field. Indeed, the simple-yet-complex mechanics of an hourglass encapsulate some of the most intriguing questions in geophysical science and engineering: Why and how do granular materials behave differently than liquids? And what happens when we combine the two?

Natural Grains

Mechanical engineer José Andrade is on a mission to understand the mechanics and physics of granular materials—how individual grains in nature, like those we see in soil, snow pellets, and porous rocks, interact with one another and the environment around them. Understanding that interaction is important because such insights are useful for everyone from geotechnical engineers trying to build structures on different types of soil to space engineers interested in figuring out how a rover or spacecraft might interact with martian landscapes (see "On Alien Soil," page 33).

"You also have things like avalanches, or the way earthquakes nucleate in faults due to granular processes, or the extraction of hydrocarbons and the injection of fluids into reservoirs for geologic CO_2 sequestration—they're all related," says Andrade.

And what they're all related *by*, he says, is space. It's the space between the particles that controls each and every one of these processes—and more. Without the spaces between particles, there would be no movement—no giant canyons worn by wind and water, no flowing rivers, no landslides or sand dunes. In short, it's the liquids and gases located in between bits of granular material that are critical in determining how these substances move over land and through time.

For field geologist Mike Lamb, who works primarily on questions about how the movement of material changes the shape of Earth's surface, the spaces between particles become really important when, for example, rock turns into sediment.

"Rock doesn't have much space between its grains," explains Lamb. "Rock turns into sediment when it either gets broken apart physically, or chemically through dissolution and weathering. We study all the steps in those processes: from how rock turns into soil to how the sediment or soil then makes its way down the sides of mountains, through rivers, and out to ocean basins."

Lamb does many of these studies in Caltech's Earth Surface Dynamics Laboratory (or the Flume Lab), a giant room he designed that's filled with chutes and tanks—a place where scaled-down versions of major landscape features like waterfalls and river deltas can be created.

"Most of the processes that shape Earth's surface happen over a long time compared to PhD dissertations or even our lives," says Lamb. "If we want to understand how a system works in its natural state—such as how and when a typical delta shifts over time—we have

Above, top: Hima Hassenruck-Gudipati, a senior studying mechanical engineering, pours sediment into a feed system for Mike Lamb's delta experiments in the Earth Surface Dynamics Laboratory. Above, bottom: To better understand the damage flowing water can cause, Lamb built several different kinds of artificial waterways, called flumes. The tilting flume pictured can be slanted to a steep 18 degrees; Lamb and his team can then send up to 10,000 gallons of water per minute—enough to transport fist-sized rocks and other types of debris—down the incline. The setup allows the researchers to gain insights into the consequences of mountain flooding while also predicting the impact of water erosion and its role in the evolution of mountain ranges over geologic time.

Students from Melany Hunt's lab, along with a few volunteers, set up an array of 50 geophones for a seismic refraction experiment that allowed them to measure wave speeds within the dune, located at Dumont Dunes, California. The geophone setup was borrowed from Rob Clayton, professor of geophysics at Caltech, who uses it in earthquake studies.

to make it evolve faster. Only then can we see these processes unfold."

One of the processes Lamb is exploring is how waterfalls help rivers cut into canyons over geologic time. Although waterfalls may seem like they're fixed in space, he says, they actually move upstream over long periods of time, as a sort of wave that cuts into the landscape. Because it's a process so slow that it can't really be observed in the field, Lamb has built a waterfall in the Flume Lab, using artificial rock made of polyurethane foam that erodes much faster than regular rock, but otherwise acts just like the bedrock on any local mountainside. In this way, he can speed up the processes and evaluate them as they are happening.

"We have found that coarse sediment is necessary to erode the pools at the base of waterfalls," Lamb says. "However, too much sediment will form a protective layer shielding the rock from erosion. This work suggests that the rates of waterfall erosion are set by a dynamic balance between the inputs of both water and sediment, both of which evolve under changing climate and tectonics."

Another tank in the lab models the way a river flows into an ocean or other large body of water, and what happens to sediment at that intersection. What happens, it turns out, is a delta—a fanlike landform made from sediment deposits at the mouth of the river. Over time, sections of the delta called lobes, as well as the river channel, shift around—a process whose dynamics are not well understood.

"I think our research speaks to people's desire to know what created and what impacts the beautiful landscapes around them," says Lamb. "Over geological time, we know that mountain ranges are rising and rivers are cutting through them, creating features like the Grand Canyon, but we still don't have a good understanding about how they formed, or how *fast* they continue to evolve."

Dune Songs

The same spaces between grains that shape what we see around us also sometimes shape what we hear. That's what Melany Hunt discovered when she first began, in the early 2000s, to try to pin down the conditions that lead to a unique phenomenon that occurs in some sand dunes, in which the dunes "boom." Loudly.

Called booming dunes, these mountains of sand play single notes—most often G, E, or F—when vibrations move through the sand grains. Those sounds can become amplified in the dune until the boom they create echoes across the desert. This phenomenon has been reported in more than 40 locations around the world, including South America, North Africa, and China.

What Hunt wanted to know is what makes these booming dunes different from the average silent pile of sand. "So we went out to the desert in Death Valley, generated the sounds, and tried to record them using seismic instruments. At the same time, we imaged the dunes using ground-penetrating radar," she says.

Generating the sounds on cue, however, required a little ingenuity. "You need an avalanche of sand to generate the sounds. That can happen naturally, with the wind just coming up and starting a slide on the surface. But the way we did it was to simply slide down the dunes on our back ends."

What their studies have shown is that in order for a dune to boom, there must be a top layer of relatively loose and very dry sand. When that dry top layer begins to slide, the friction between grains generates a whole range of sound frequencies on the dune's surface. If there is a wetter, more tightly packed layer of sand below the surface layer, that dense lower layer will reflect the sound waves, creating what is called a waveguide—a structure that conducts waves in a particular direction—in the loose top layer.

But if that entire range of sounds is emerging from the top layer, why is the boom a single note? "There's only a certain frequency that's transmitted efficiently through this waveguide, which is what you hear with this booming phenomenon," explains Hunt. And it doesn't happen every time. "You have to have the right conditions," she adds. "The dune has to be large enough—at least 150 feet tall; it has to be very, very dry; and you have to have a slide to generate the sound in the first place."

Debris Dangers

Of course, research into granular flow—the movement of discrete, solid particles—is not all fun and flumes. Beyond hourglasses and deltas and creating avalanches by sliding down sand dunes, there are processes involving granular materials that not only result in the movement of materials but in threats to lives and property—processes such as big-time avalanches and landslides, and an earthquake-related phenomenon called liquefaction.

In addition to his work on the movements of waterfalls and the effects of river flows, Lamb also uses his Flume Lab to look at specific kinds of large-scale slides—mostly debris flows, or landslides.

On Alien Soil

Researching the way grains flow through space and time on Earth has led to some far-reaching applications—literally. Geologist Mike Lamb, for instance, has used results from his lab's sediment transport experiments on Earth to do calculations for features on Mars, which has a number of dried-up channels.

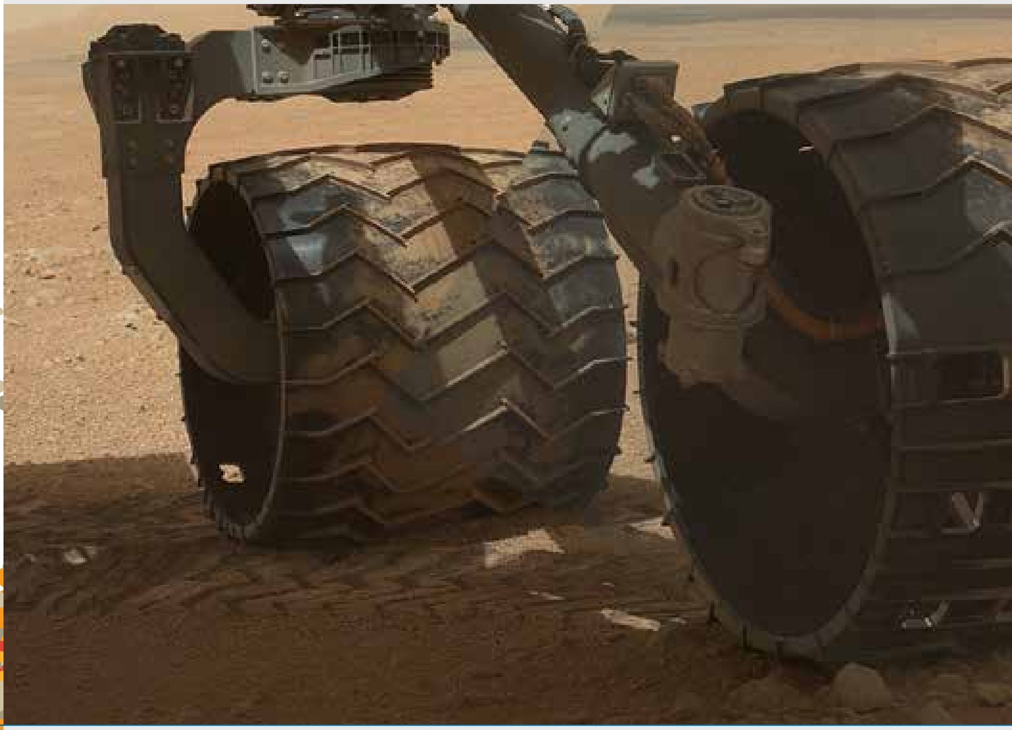
"If you see a big river canyon on Mars, you know that to carve that canyon, water must have at least been sufficient enough to move the sediment that's in the canyon," explains Lamb. "Sediment transport constraints allow us to put a minimum bound on the water discharges that might have carved these ancient river canyons on Mars."

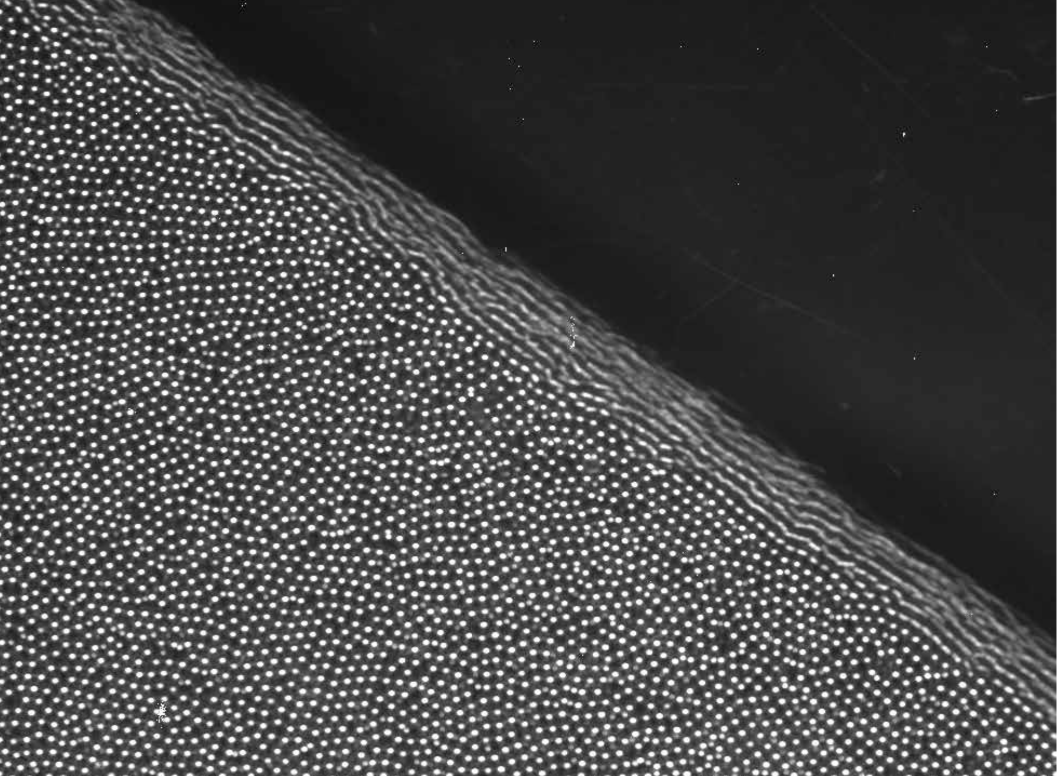
Mechanical engineer Melany Hunt has been involved in granular-flow simulations for planetary missions as well as research into terramechanics, or how different vehicles—including those like the Curiosity rover on Mars—interact with various terrains.

"Getting a vehicle to move over granular materials, or loose grains, is always much less effective than anything else we can envision—they travel at incredibly slow speeds and are extraordinarily inefficient in terms of energy conversion." she says.

Mechanical engineer José Andrade points out that a deep knowledge of how foreign materials are likely to behave is essential for these scientific missions to other planets. He and his team are working on modeling the best way for a penetrator, or mole, to dig itself into martian soil; such a piece of equipment is likely to be a key part of the InSight mission to Mars being planned for 2016.

"We love our planetary science projects," Andrade says. "What's really exciting is that the understanding of the mechanics and physics of granular materials—understanding how the spaces between particles control both mechanical and behavioral features—is extremely important. In fact, it's mission crucial in some cases . . . no matter what planet you're on."





Above: A high-resolution image of a tiny, granular avalanche as it occurs in José Andrade's laboratory shows a blurry, flowing layer of material on the surface. Video recordings of his benchtop experiments give important clues into the lifecycle of an avalanche.

"When streams are steep enough, like in mountain areas, sometimes debris flows or landslides occur after a large storm in areas where we would normally expect to see a river," says Lamb. "In the Flume Lab, we are doing experiments in steep river flumes by directing flowing water over grains to see what conditions result in 'normal' river transport of sediment, versus conditions that produce catastrophic debris flow in which tons of material come barreling down."

In rivers, Lamb explains, sediment grains suspended in water rarely touch each other when they are flowing downstream—it's only on the riverbed that they come in contact with each other. But in a debris flow, the grains collide with and scrape against one another and, somehow, that makes the behavior of debris flows quite different from that of rivers. It's that difference that allows debris flows to pick up and carry large boulders long distances; it's that difference that makes them so destructive.

"We're trying to understand why mountain channels that usually transport sediment by river processes—which aren't typically hazardous—sometimes switch to produce debris flows," says Lamb. Understanding this switch, he adds, could also help explain why landslides often occur after wildfires. "It must have something to do with the spaces," he says. "The key thing that makes debris flows different is that the spaces between grains are small. We hope our work can lead to better predictive models for helping response teams decide when, after a wildfire, to call for evacuations out of fear of debris flows."

He notes that his research can have other, less disaster-oriented applications as well—such as in efforts to restore fish habitats in rivers.

"River restoration involves understanding how sediment movement works, since fish spawn in the spaces between gravel and cobbles," says Lamb. "Salmon, for example, build nests out of certain-sized gravel by moving it around with their tails. If the gravel is too big, they can't move it, and if it's too fine there's no space for the eggs. By understanding how sediment moves, we are developing better strategies to restore river habitats."

The Life of an Avalanche

In his work to dig deeper into the workings of major avalanches, José Andrade, like Melany Hunt, utilizes benchtop experiments to create tiny versions of such events. He uses a rotating drum to spawn a mini avalanche and a video camera to record the lifecycle of the event—when it's born, how long it takes to get to its peak velocity, and when it dies, which in avalanche parlance means coming to a final halt. The movies these recordings create help him construct mathematical models that not only reproduce those events but also provide the means for possibly explaining *why* the avalanche was born, why it peaked when it did, and why it died. In this way, Andrade says, his work isn't just about trying to mimic behavior, but also about trying to understand it.

"Avalanches are a neat problem, because for some reason they connect with humans—everyone thinks that they know what you're talking about," he says. "They can imagine something rushing down a slope and eventually hitting either people or infrastructure downstream."

And yet, as it turns out, we know a lot less than we think we do. The surprising thing about avalanches, Andrade says, is that they are very ordered . . . that there is structure in the middle of all the chaos. But it depends on how you look at it. Somewhat ironically, if you watch an avalanche closely, he says, you'll see what seem to be disordered grains of snow bouncing all over the place. It's only when you zoom out a little bit that you begin to see how organized avalanches actually are. In the laboratory, avalanches show a very distinct and repeatable pattern, flowing roughly at the same angle and stopping at an angle several degrees lower. This pattern is very ordered and consistent, Andrade says.

"We're at a very basic science

“That’s the thing that keeps me excited about the work we do—the beauty of the behavior of these materials that are so very complex and difficult to understand.”

level with our research, but essentially what models are trying to do at the end of the day is make predictions,” he says. “You’re always trying to get to the point where you can give a tool to decision makers so they can evaluate when and how bad things could be for a given environment.”

Andrade also looks at the often-destructive and typically earthquake-induced transition of sandy ground to a more fluid phase, a process called liquefaction. One essential ingredient for liquefaction to occur is space, or pores in the ground—relatively loose soil or sand makes the perfect terrain for liquefaction. But that’s not enough, says Andrade. Those pores have to be saturated with a fluid—usually water—and then something needs to “excite,” or shake, the soil, like an earthquake.

“When the ground is deforming because of an earthquake, the space between the grains wants to contract, but it can’t because the water is there,” explains Andrade. “And so the grains squeeze the fluid that lives in these spaces, which increases pressure in the water, which then pushes back on the grains, keeping them apart. Since the way that these grains transmit forces is by contacting each other, when a sand grain cannot contact its neighbor, it cannot transmit force anymore, and it starts effectively floating in this water—that’s what liquefaction is.”

By understanding those basic mechanisms, Andrade has been able to start building models to help identify the precise conditions under which liquefaction might occur. This type of information would be particularly useful in earthquake-prone Southern California, where many homes and businesses are built on sandy ground.

“We’ve been very successful in predicting when liquefaction will occur in the laboratory, but we haven’t been able to explain *why*,” he says. “One of my students is working ferociously on a model that seems to be able to explain why, so we’re very excited about that.”

The Basics of Flow

Melany Hunt and some of her students have also recently begun to take a closer look at how liquids and sands mix, but from the other way around. They’re looking to see what happens when you have a pure liquid and you start adding particles to get to a granular flow.

“As you add solids to a liquid, what are the forces involved in moving that material?” asks Hunt. “For example, there are tanks full of nuclear waste—solids and liquids that need to be moved using a pump. It’s not pure liquid by any means, so how do you move a liquid with potentially heavy particulate matter in it? What are the forces that will be involved? What do you do with this stuff when you can’t predict its properties? These are the problems that we’re trying to figure out.”

She points to the Deepwater Horizon / BP oil spill in the Gulf of Mexico in 2010 as an example of how little people know about the interaction between solids and liquids.

“In trying to stop the spill, they were just injecting different substances—like drilling fluids or cement—into the pipe, hoping to clog it, without any real knowledge about what these things were going to do when they got into the well hole and mixed with the liquid,” Hunt says. With more information—information Hunt and her colleagues are currently trying to gather—future spills like this might be easier to halt or even reverse.

Whether it’s snow tumbling down a mountainside, “solid” sandy ground suddenly acting like a liquid, or solutions of liquids and solids in need of transportation, the elusive and mysterious behaviors of these ubiquitous granular materials have yet to be cracked, but the effort continues.

“That’s the thing that keeps me excited about the work we do—the beauty of the behavior of these materials that are so very complex and difficult to understand,” says Andrade. “They give us gorgeous puzzles to work on.” e&s

José Andrade is professor of civil and mechanical engineering. His research on granular materials is funded by the National Science Foundation (NSF), the Defense Threat Reduction Agency, the Air Force Office of Scientific Research, and the Keck Institute for Space Studies (KISS).

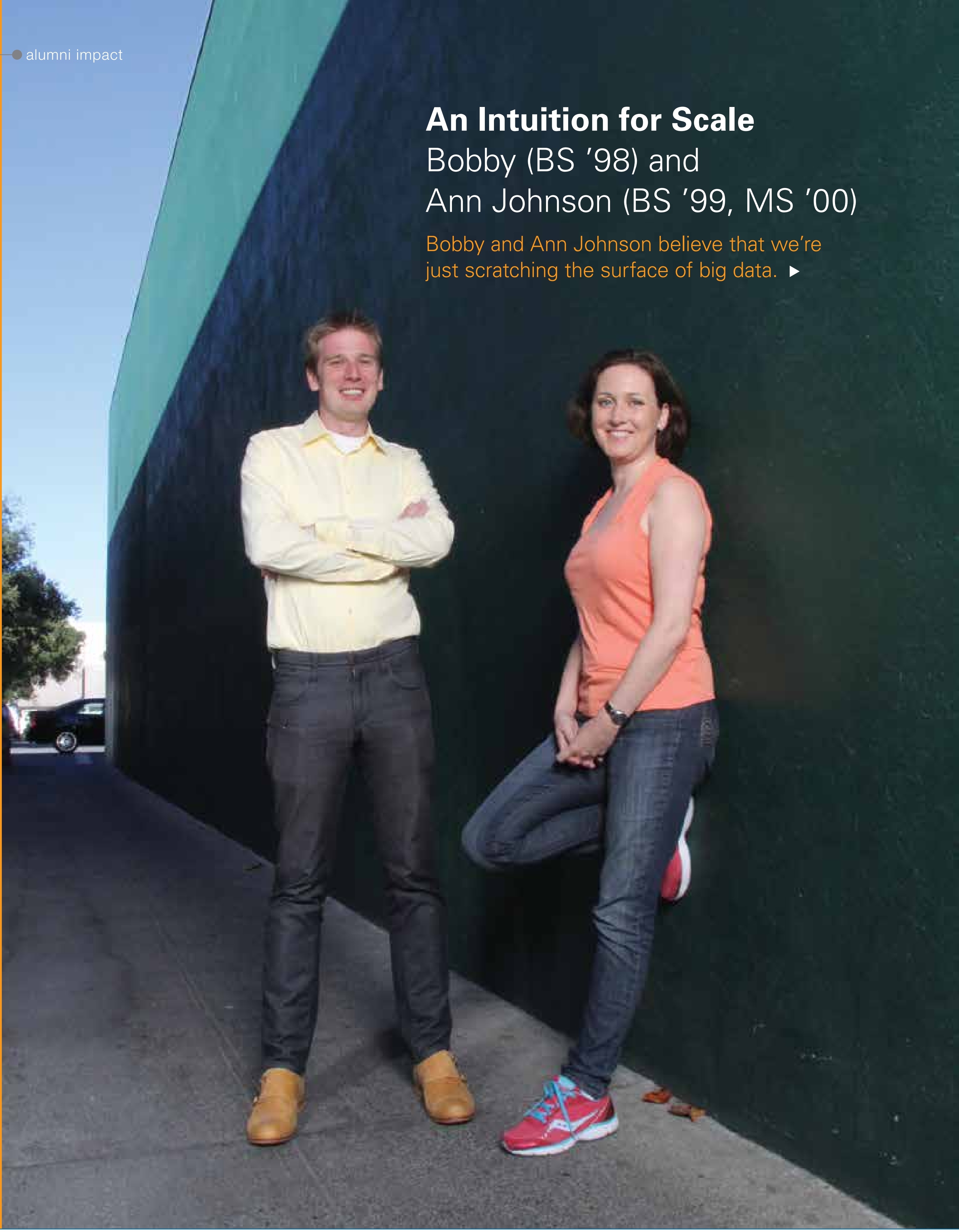
Melany Hunt is the Dotty and Dick Hayman Professor of Mechanical Engineering, and a vice provost at Caltech. Hunt’s work described in this article was funded by the NSF and NASA.

Michael P. Lamb is an assistant professor of geology whose work is supported by the NSF, NASA, the American Chemical Society, KISS, and Caltech’s Terrestrial Hazard Observation and Reporting Center.

An Intuition for Scale

Bobby (BS '98) and Ann Johnson (BS '99, MS '00)

Bobby and Ann Johnson believe that we're just scratching the surface of big data. ▶



"A lot of the things that you think a company like Facebook is doing with its data right now, it turns out that it can't," Bobby Johnson says. "The tools that exist just aren't good enough."

He ought to know. Bobby served for six years at the social media giant, rising through the ranks to become director of engineering, charged with scaling the technology as the site grew from hundreds of thousands of users to nearly one billion.

With its exponential growth, Facebook was often in jeopardy of being crushed under its own digital weight. Bobby helped develop software, build infrastructure, and grow an army of engineers to keep the site humming as hundreds of millions signed on. Then, to collect the massive amounts of data coming in from servers around the world, he wrote a program called Scribe, which was so effective that Facebook eventually made it open source.

"Most people don't have a good feel for scale," says Ann, who met Bobby while the two were students at Caltech in the late '90s; they married right after graduation. "Many think that after a million, the next large amount is a billion, without understanding how enormously different those numbers really are. Bobby has a strong intuition for it."

Now that the race is on to analyze the huge troves of data collected by services around the world, Bobby's intuition tells him there's a flaw in the existing system for doing so.

"Most information still ends up in standard databases," he says. Such systems were built to put data into neat boxes, making them less useful for finding relationships in these large, amorphous, and interconnected streams. "You can track statistics, but you can't really draw meaningful patterns."

So Bobby and Ann joined with one of Bobby's like-minded colleagues from Facebook to form Interana, a company created with the goal of designing a next-generation platform capable of analyzing extremely large and loosely structured data sets. Ann serves as the chief executive, while Bobby directs the technology development. Still in its early stages, the company has grown quickly, quietly generating buzz.

"Caltech trains us to take an unknown, break it down to first principles and solve it," says Bobby. "Starting a business isn't some magical thing, it's a real skill to be taken seriously. It can be learned, but it's important to find the people you trust to give you support and advice."

The Web as Canvas

Niniane Wang (BS '98)

To you, it's a card for your mother's birthday. But to Niniane Wang, it's a social-media canvas.

Wang is the chief technology officer at Minted, a social-commerce company that discovers artists and graphic designers, curates their work through online competitions, and then connects them with customers who can personalize these designs to their own taste and have them produced in the form of such items as wedding invitations, framed art, and more.

"The first challenge was to create tools that any artist can use in any browser," says Wang. "Then they need to maintain pixel-perfect fidelity when creating a high-resolution print file." The resulting artwork is then submitted to competition, where Wang's team applies customized algorithms to weight audience responses. This, Wang says, leads to a tighter connection between the artist and customer, and to a collection of products that emerge as a cohesive brand.

Wang has always felt most comfortable at the intersection of technology and art. After graduating from Caltech at the age of 18 with a degree in computer science, she began her career in games, earning notice for her innovative graphics work on *Flight Simulator*, Microsoft's popular game for Windows.

Wang then moved to Google, where she led the team that integrated ads into gmail. She took advantage of the company's famous "20-percent time"—which encourages the company's engineers to pursue personal projects—to create Lively, a popular web-based virtual environment often compared to Second Life. Users could design digital rooms in which they could hang YouTube videos or Picasa photos, personalizing their space with virtual wall art. Google eventually closed the service, but Wang's reputation as an innovator grew.

At Minted, Wang now concentrates on helping artists sell their designs in the physical world. Since its founding in 2007, the company has grown into a global artistic community that has caught the eye of the business world.

"I love building technology to enable self-expression," Wang says. "It's important to focus on something you love. You do your best work that way."

Alumni stories provided by the Caltech Alumni Association. For more about these stories and to read about other alumni in the news, go to *alumni.caltech.edu*.

Bruce Murray 1931–2013

Bruce Murray, Professor of Planetary Science and Geology, Emeritus, and former director of the Jet Propulsion Laboratory (JPL), passed away August 29. He was 81.

Murray, who served on the imaging teams for the Mariner 4, 6, 7, and 9 missions, and helped found infrared planetary astronomy, led JPL from 1976 to 1982 during the Viking landings on Mars and the early missions of the Voyager 1 and 2 spacecraft. Long an advocate for planetary exploration, Murray, along with Carl Sagan and Louis Friedman, in 1980 cofounded The Planetary Society, a nonprofit organization dedicated to exploring the solar system and expanding public advocacy for space exploration.

"Bruce was really dedicated to exploring the frontiers," says Ed Stone, the David Morrisroe Professor of Physics, director of JPL from 1991 to 2001 and Voyager's project scientist. "He recognized the power of scientific imaging, and the opportunity it provided to engage the public."

Murray received his SB, SM, and PhD degrees from the Massachusetts Institute of Technology. He came to Caltech in 1960 as a research fellow in space science, became an associate professor of planetary science in 1963, and a professor of planetary science in 1968. In 1992, he was named professor of planetary science and geology; he retired in 2001.

Murray was a fellow of the American Academy of Arts & Sciences and the American Association for the Advancement of Science, and a member of the American Astronomical Society and the American Geophysical Union. One of his books, *Journey Into Space*, won two awards for science writing. His other honors include NASA's Exceptional Scientific Achievement Medal, NASA's Distinguished Public Service Medal, and two NASA Distinguished Service Medals.

He is survived by Suzanne, his wife of 41 years; five children; and 10 grandchildren.

To learn more about the Bruce Murray's life and work, visit caltech.edu/content/bruce-murray-0.

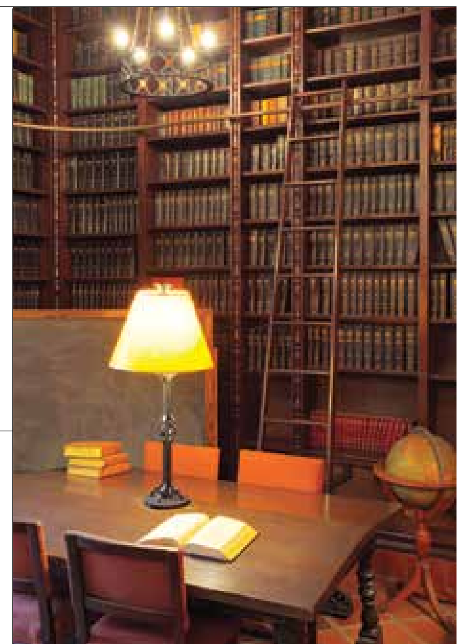
THE BEST SPACES ON CAMPUS

We asked alumni to tell us about their favorite spaces at Caltech. Here is what some of them had to say.

The **RED DOOR CAFÉ**

DABNEY LOUNGE. Back in the 1980s, community folk-dance recreation sessions were hosted there on Tuesday nights, and I used to walk over from my grad-student office in South Mudd to meet my Dad, who was a longtime participant. Eventually I started dancing there too. In late 1987 I married a JPL engineer in Dabney Lounge and Gardens. We all danced, of course.

The **GATES LIBRARY** because of the architecture and ambiance. It is the perfect place for quiet study.



The statue of Ten Jin in **DABNEY GARDENS**. Can't forget him or his patient ox.

The lounge in the **ANNENBERG BUILDING** on the second floor. It feels like a treehouse.

When I was a grad student in the early 1990s, I used to sit on a rock in the middle of the **POND IN THROOP GARDEN** and read physics papers. It was very peaceful and pretty, and people wandering by would wonder how I'd gotten out there.

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