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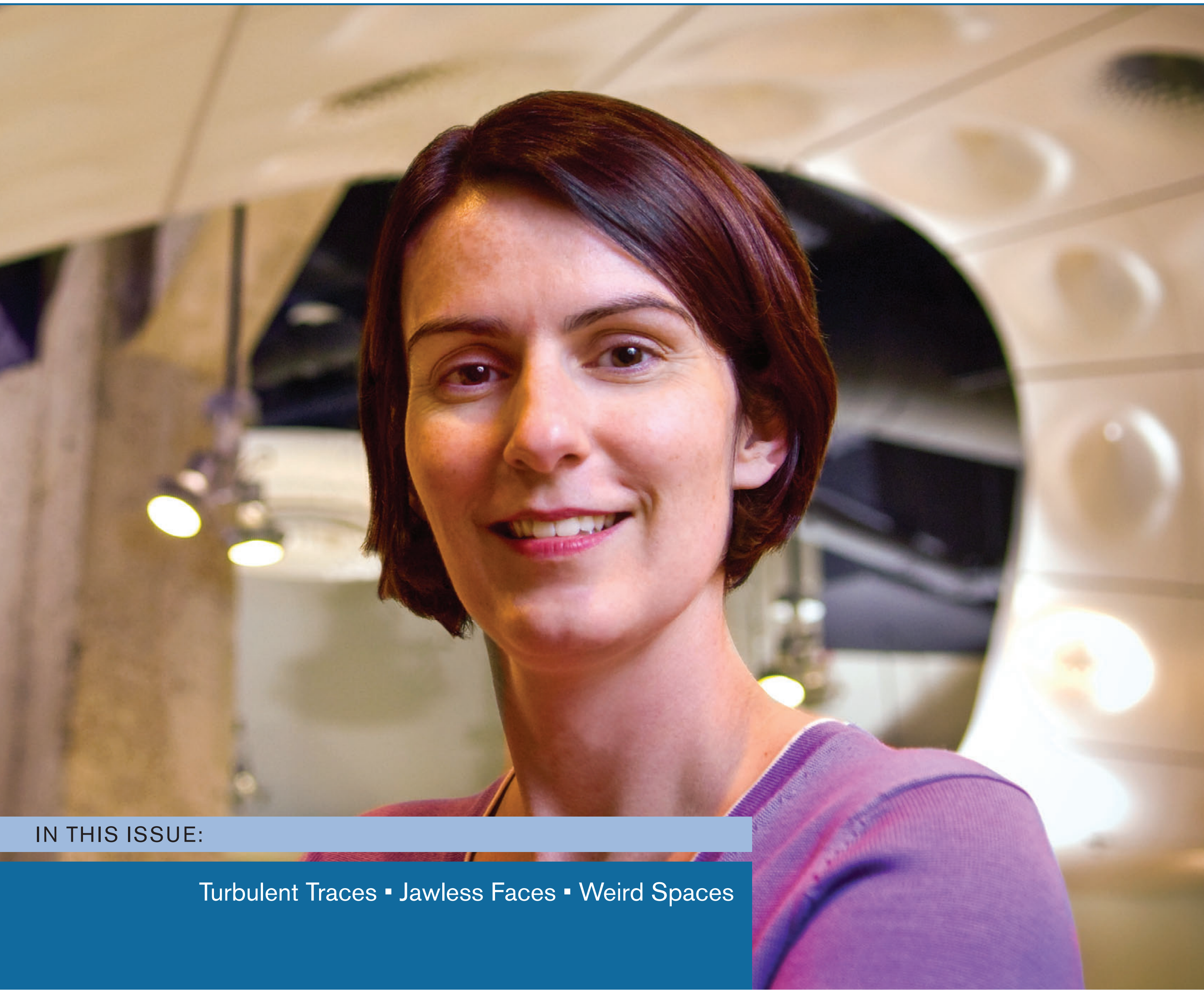
Engineering & Science



IN THIS ISSUE:

Turbulent Traces ▪ Jawless Faces ▪ Weird Spaces

VOLUME LXXIV, NUMBER 1, WINTER 2011

California Institute of Technology

ON THE COVER

Beverley McKeon, assistant professor of aeronautics, in the foyer of the recently renovated Guggenheim Aeronautical Laboratory. The dimpled ceiling behind her is a nod to her work—McKeon studies how roughened surfaces alter fluid flow, keeping golf balls flying true and perhaps one day steering airplanes. For more, see the story on page 16.

DEAR ALUMNI AND FRIENDS OF CALTECH,

Engineering & Science magazine began its life in 1937 as the *Caltech Alumni Review*. In the almost 75 years since, the magazine has undergone changes in length, publication schedule, writing style, and, of course, in name. I'm pleased to let you know that with this issue, Caltech is making three small but important changes:

- The magazine remains a quarterly, but with a new, fixed publication schedule. Look for issues following this one to appear annually in mid-March, just before commencement, at the start of the new school year, and in mid-December.
- Starting with this issue, you'll see enhanced photography accompanying the feature articles, to better tell our remarkable stories.
- Finally, you'll find the voice of alumni returned to the magazine with the new "EndNotes" piece serving as the back anchor.

To quote from the foreword of Vol. 1, No. 1, "We also realize that there will be criticism, comment, and worse yet, those who ignore us." (See http://calteches.library.caltech.edu/view/year/ for a complete online collection of past issues.) Together, Caltech and the Alumni Association will continue to work to improve *Engineering & Science* in ways that embody the spirit with which the publication began.

Tom Lloyd
President, Caltech Alumni Association

To the far left: That was our first look and this (to the left) is our newest feature—check it out on page 36!

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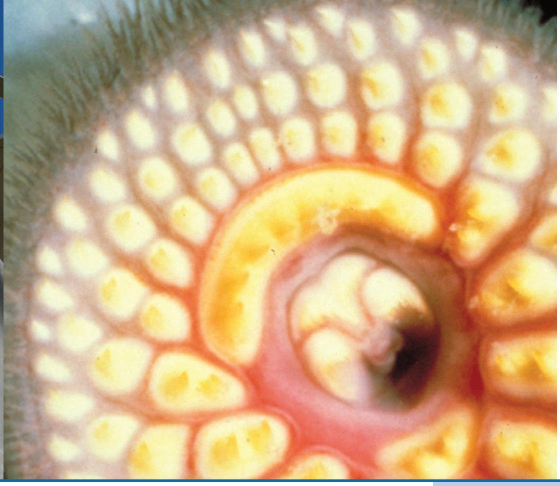

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Engineering & Science (ISSN 0013-7812) is published quarterly at the California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125. Annual subscription $20.00 domestic, $30.00 foreign air mail; single copies $5.00. Send subscriptions to Caltech 1-71, Pasadena, CA 91125. Third-class postage paid at Pasadena, CA. All rights reserved. Reproduction of material contained herein forbidden without authorization. © 2011, California Institute of Technology. Published by Caltech and the Alumni Association. Telephone: 626-395-8371.

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JUNIOR ACHIEVEMENT

Caltech's Theresa (Teri) Juarez is the face of college athletics—at least on the cover of the winter issue of the NCAA's *Champion* magazine. The magazine highlights the junior mechanical engineering major's accomplishments on the basketball court and in the classroom. Making the cover is not just an honor for her, Juarez says: "It's an extension of our whole team and the athletics department." Sandra Marbut, head coach of the women's basketball team, adds, "It's great because it continues to validate that our kids are many things. Yes, they're brilliant, but they're also athletes, musicians—so many things."

Indeed. A Gates Millennium Scholar, Juarez worked at JPL last summer, where she did thermal engineering on a proposed Venus lander and contributed to the book *Thermodynamics for Dummies*.

She's also recruiting for Caltech. A Latina from El Paso, she had never heard of Caltech until she participated in the Youth Engineering and Science Scholars (YESS) program. The three-week, on-campus program is designed for exceptional, underrepresented high-school students.

Juarez says she wants to connect with underrepresented minorities and other students who otherwise might never consider going to Caltech. She has visited her high school to spread the word, and she has recently started to help recruit students from the Los Angeles area as well. —*MW* E&S

Faces of the NCAA

Caltech athlete engineers well-rounded experience

By Gary Brown

Ask Caltech basketball and volleyball student-athlete Teri Juarez how she got from El Paso to Pasadena, and she'll say it's because she never felt like she couldn't accomplish anything she wanted.

That same spirit that drove this Latina math and science whiz to land at one of the most prestigious engineering schools in the country likely will be what brings her home, too.

"Giving back to my community is high on my priority list," said the determined mechanical engineering major. "Being able to take all these research ideas and the experiences I've had out here back to my community would be exciting for me."

If the effort she has put into her life is any indication, Juarez figures to have a lot to give back. She's come a long way from the ballet class she hated as a little girl to improving the thermal architecture design to keep the electronics on a Venus lander at a functional temperature for as long as possible.

Say what?

That's right. Caltech is not your typical college, and Juarez is not your typical college student. "I've wanted to work for NASA from the moment I decided to be an engineer," she said. Having the leading center for robotics so close to the Caltech campus certainly helped. The internship at NASA's Jet Propulsion Laboratory also involved contributing to "Thermodynamics for Dummies," which her mentor is authoring.

But to Caltech head women's basketball coach Sandra Marbut, Juarez's life reads more like "The Little Engine That Could." She was excited to have a player with Juarez's experience, even though the 5-foot-6-inch forward missed her senior year of high school ball because she blew out her knee.

Juarez actually credits that injury for her ending up at Caltech. "Being injured took me away from being so dedicated to my athletics in high school," she said. "I got a chance to focus on my academic side. My teachers were telling me that I had the potential to go anywhere I wanted."

That included MIT, which is where Juarez had set her sights. But a summer engineering program at the 900-student campus in the city better known for the Rose Parade changed this Texan's mind.

Juarez is attending college in part on behalf of a Bill and Melinda Gates Foundation Scholarship, a highly competitive grant that funds schooling based on need for 10 years – enough to carry Juarez through her master's and doctoral degrees.

With her admission to Caltech secured, Juarez heard from Marbut about playing basketball, which rekindled an athletics flame that had been snuffed by necessity. As for the volleyball part, freshman orientation at Caltech involved a couple of days at the beach, which included some volleyball, naturally. The team captain who was there said to Juarez afterward, "See you at practice on Wednesday."

For Juarez, sports is not just a passion, but a relief. She said if she did nothing but go through the academic rigors at Caltech every day, she would "go a little crazy."

But she's no different from other Caltech student-athletes in that she knows athletics has its place. "We all know academics come first here, but we are able to express ourselves in various ways by using sports to just have fun and improve ourselves in something different," she said.

Among the activities on her demanding schedule is a job with the admissions office focusing on informing and attracting under-represented populations to Caltech. People always ask her what it takes to get admitted, beyond just having some school smarts.

"We actually reject more applicants with perfect SAT scores than we accept," she said. "You have to show that you are passionate about math and science, that you want to get out there and try new things and collaborate and push the envelope. Those who can show that spirit the best – even if you don't have a perfect SAT score – are who we want here."

Which is why Juarez is there, and why she'll likely make Pasadena – and El Paso – better for it.

Teri Juarez bio

SPORTS: Basketball and volleyball.

SCHOOL: Caltech.

CLASS: Junior.

MAJOR: Mechanical engineering.

ACADEMIC ACCOMPLISHMENTS: Earned a Bill and Melinda Gates Foundation Scholarship for low-income students and students of color; interned at NASA's Jet Propulsion Laboratory; contributed to the book "Thermodynamics for Dummies."

ATHLETICS ACCOMPLISHMENTS: Averaged more than nine points and eight rebounds for a basketball team that won a school-record-tying six contests in 2009-10; ranks among volleyball team's kills leaders and is tops in aces.

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JAMIE SCHWABEROW / NCAA PHOTOS

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VOLUME 4 • ISSUE 1

NCAA CHAMPION

WINTER 2011

The Right Stuff

Caltech's Teri Juarez keeps her eyes on the stars

Art school gets creative with athletics

Behind Turner broadcasting

1981 governance plan anniversary

www.NCAAChampionMagazine.org

Move over Tennessee, UConn, and Louisiana Tech—Caltech women's basketball, in the person of junior Theresa Juarez, made the cover of the latest issue of the NCAA magazine. A quarterly, *Champion* gives this honor to only one Division III athlete (from any sport!) per year.

A NEW STREAK

They did it! With a 46–45 victory over Occidental College, Caltech's men's basketball team won its first Southern California Intercollegiate Athletics Conference (SCIAC) game in more than 26 years, breaking its 310-game losing streak.

With the score tied at 45–45, Caltech had the ball for the final possession of the game. Senior Ryan Elmquist was fouled on a layup with 3.3 seconds left. Having already made 14 free throws in the game, he sank the first of two to give the Beavers a one-point lead, sending the crowd into a frenzy. After the second attempt rimmed out, Oxy rebounded and missed a desperation heave at the buzzer. Fans, players, and coaches stormed the court, embracing and high-fiving one another. Techers everywhere rejoiced.

With four nonconference wins early this season, and several nail-biters in conference play, hopes were high that this would be the year that Caltech snapped the SCIAC streak. And with this victory, coming on the last game of the season, the Beavers finally triumphed. —*MW* E&S

HAIL FROM THE CHIEF

In his 2011 State of the Union address, "Winning the Future," President Obama pointed to Caltech as a model for innovation, saying: "We're issuing a challenge. We're telling America's scientists and engineers that if they assemble teams of the best minds in their fields, and focus on the hardest problems in clean energy, we'll fund the Apollo projects of our time.

"At the California Institute of Technology, they're developing a way to turn sunlight and water into fuel for our cars. At Oak Ridge National Laboratory, they're using supercomputers to get a lot more power out of our nuclear facilities. With more research and incentives, we can break our dependence on oil with biofuels, and become the first country to have a million electric vehicles on the road by 2015."

"It is a great honor," says Caltech president Jean-Lou Chameau, "that President Obama has recognized the Institute's game-changing solar energy research as a prime example of how America is investing in innovation to confront 'our generation's Sputnik moment.' Caltech's Jet Propulsion Laboratory designed and built the first U.S. satellite in just a few short months after Russia's launch of Sputnik 1 in 1957, leading our country into the Space Age. When America wins this new innovation arms race—developing efficient ways to cleanly power our planet—we will not only 'win the future,' we will make a better future." —*KB* E&S

Above: Head coach Oliver Eslinger hugs Elmquist after the game.

Right: President Barack Obama gave a shout-out to Caltech in his State of the Union address to a joint session of Congress on January 25. Behind him are Vice President Joe Biden (left), in his role as president of the Senate, and Speaker of the House John Boehner.

This galaxy, Messier 99, is 60 million light-years away and is home to a transient named PTF10fqs (inset). Called a luminous red nova, this oddball transient is brighter than an ordinary nova but too faint to be a supernova. Its visible light dimmed after only a few months, but it still glows in the infrared and may do so for a couple of years.

A SUPERNOVA SURPRISE

Strange explosions in space keep Mansi Kasliwal (MS '07) awake at night. As a graduate student at Caltech, Kasliwal has been pointing a half dozen telescopes at the sky to catch these cosmic blasts—fleeting flashes of light that last from a few days to a few months. She's a member of the Palomar Transient Factory (PTF), a project whose automated telescopes on Mount Palomar continuously scan the heavens, looking for bright spots that weren't there just a day or two before.

Many of these fleeting flashes belong to a class of explosion called a Type II supernova, something that forms when a dying star spends the last of its fuel and collapses. Another sort of explosion, known as a Type Ia supernova, happens in a binary system consisting of a bloated red-giant star and its white-dwarf partner. About the same size as Earth, a white dwarf is a low-mass star at its last life stage. As the red giant, which has health issues of its own, sloughs off its outer layers, some of the matter accumulates on the white dwarf's surface. Under the right conditions, a nuclear explosion can ignite. A third class, the classical nova, is a calmer version of a Type Ia supernova that's 1,000 times fainter.

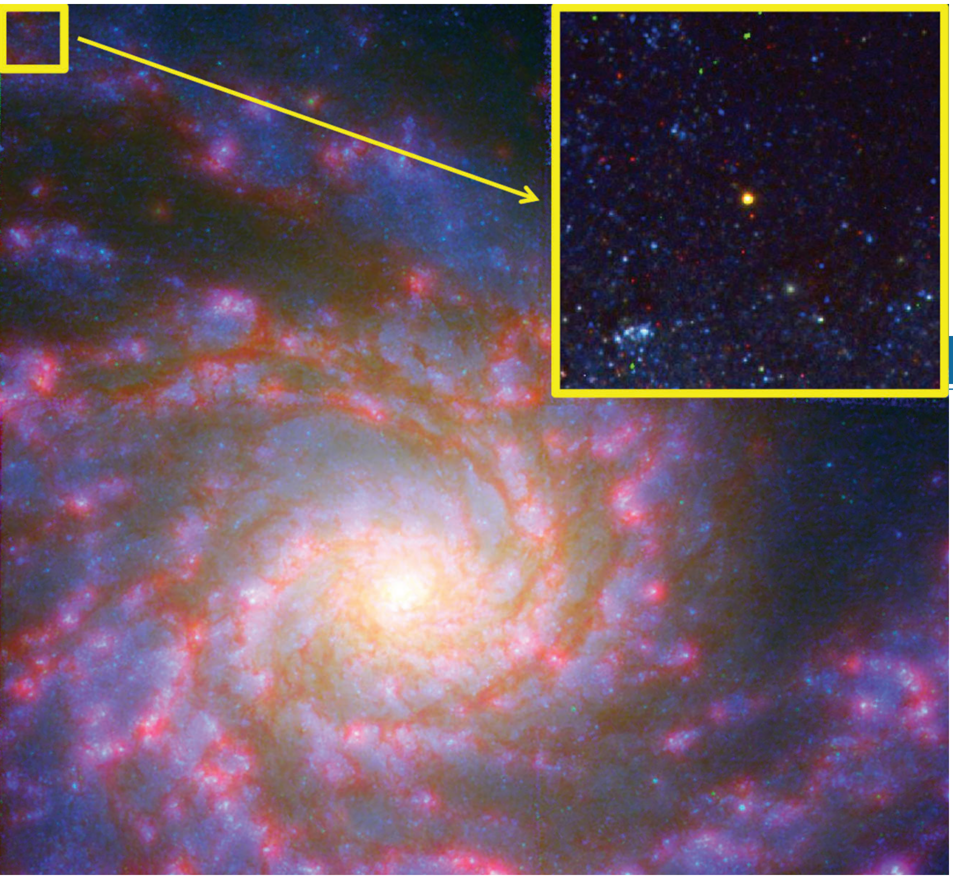
Astronomers classify supernovae by a dozen or so characteristics: their maximum brightness, the time it takes for them to dim, and the wiggles and bumps found in their spectra—which are like supernovae fingerprints, revealing the chemical composition of the explosion. Members of the PTF team measured spectra of their finds during follow-up observations using the Palomar Observatory, the MDM Observatory on Kitt Peak in Arizona, the Gemini telescopes in Hawaii and Chile, and the W. M. Keck Observatory, also in Hawaii.

In just about a year's worth of observing time, the PTF has found over 1,000 so-called transients. Most are likely to be novae and supernovae—when confirmed, they will account for nearly a fifth of the total number discovered in the past century—and 97 percent of them fit the profiles of one of the three usual suspects. Among the remaining 3 percent are half a dozen explosions that are complete mysteries. A few last for several months, like Type II supernovae do, but they are about 100 times dimmer. Others are as brief as regular novae, but as bright as supernovae. They're nothing like any cosmic explosions we've seen before, so what are they? "There are lots of stories, lots of ideas that people have thought of," Kasliwal says. But none of these theories can explain everything about each object—except for one.

In February 2010, an amateur astronomer named Douglas Rich discovered a supernova that was quickly confirmed by another amateur, Paul Burke. Soon after, the PTF made the same discovery independently. The object, dubbed PTF10bhp, was particularly short-lived, shining for only about five days before fading away—rivaling only one other supernova as the fastest ever known. It turns out that all of the characteristics of this supernova—such as its peak luminosity, decay time, and spectrum—perfectly match those of a theoretical model devised by astrophysicist Lars Bildsten at UC Santa Barbara.

In this scenario, two white dwarfs zip around each other in a tight orbit, taking less than an hour for each revolution. One white dwarf is composed of helium, while the other

The explosion is called a Type .Ia supernova—pronounced "point one A"—because it's about one-tenth as bright, lasts one-tenth as long, and has about one-tenth the amount of nickel as a Type Ia supernova.



teach you about new physics you could never have dreamed of. There's so much territory that's completely unexplored. Nature always catches you by surprise—it's fantastic."

Kasliwal will finish her PhD in June. Having been awarded a prestigious Hubble Fellowship and a Carnegie-Princeton Fellowship, she will begin her postdoctoral work this fall at the Carnegie Institution for Science, just up the street from Caltech. —*MW* e&s

is made of carbon and oxygen. Helium from the lower-mass star spills over to the higher-mass one. When all the mass has transferred over, the system can become unstable, and runaway reactions can lead to a thermonuclear explosion. The explosion is called a Type .Ia supernova—pronounced "point one A"—because it's about one-tenth as bright, lasts one-tenth as long, and has about one-tenth the amount of nickel as a Type Ia supernova.

Bildsten's model makes very specific predictions about the supernova's peak luminosity, how long the supernova takes to brighten and decay, and the presence of calcium and titanium lines as seen in its spectrum—the latter a weird feature not observed in ordinary supernovae. One by one, Kasliwal was able to check each prediction off the list, as PTF10bhp satisfied every requirement from the model. More work will be needed to confirm that PTF10bhp is indeed a Type .Ia, but such a perfect fit between observation and theory is a reason to rejoice. "It's very interesting because there have been very few theoretical models for these things," she says. "It's certainly very rare, and certainly exciting."

Kasliwal has discovered some other oddballs, as well. For example, she's found two supernovae about 130,000 light-years away from their host galaxies—farther than the diameter of the Milky Way. These supernovae appear to be massive stars, and their shorter lifetimes are insufficient for them to have made the long voyages from their host galaxies. They must have formed near their current locations, out in the galactic boonies surrounded by nary a wisp of gas or dust—perhaps similar to the conditions in which the first stars in the universe were born. Studying these supernovae, then, is a way to understand the evolution of the very first stars.

"I really did not think before I came to Caltech that I could actually be a part of a project where you start with some crazy brainstorm and see it happen," Kasliwal says. "Mother Nature's revealing these rare opportunities to

BETTER THAN A POKE IN THE EYE

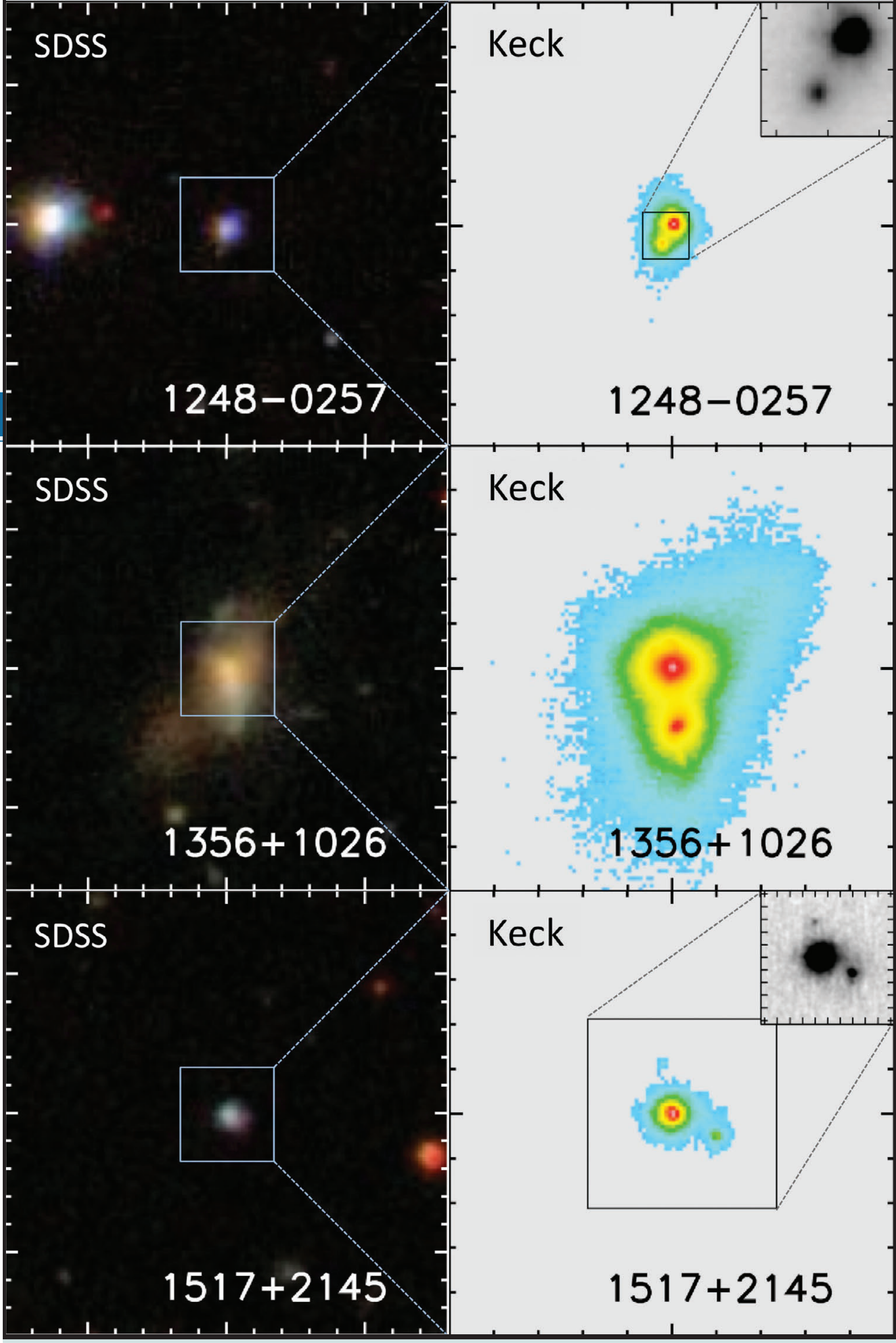
For most of human history, cataract surgery has consisted of pushing the clouded lens aside or scraping it out altogether with a needle jabbed into the patient's eyeball. A lensless eye was better than a blind one; at least the patient could make out shapes and colors. Today's techniques are slightly less cringeworthy and considerably more effective. They generally involve fragmenting the lens with ultrasound, and implanting a synthetic replacement through a tiny incision in the cornea—the clear part of the eyeball.

Like contact lenses, these implants can be made of hard or flexible plastic; and like contact lenses, the prescription is "baked in" when they're manufactured and can't be altered later. Not so with the laser-adjustable lens (LAL), whose optical properties can be fine-tuned days or weeks after surgery. The LAL is the product of a multi-institute collaboration that includes Daniel Schwartz, an associate professor of ophthalmology at UC San Francisco, as well as Caltech's Robert Grubbs and Julia Kornfield (BS '83, MS '85). Grubbs, a 2005 Nobel laureate, is the Atkins Professor of Chemistry; Kornfield is a professor of chemical engineering. Kornfield studies how a polymer's microscopic structure dictates its macroscopic properties; Grubbs is an expert on making polymers to order.

Kornfield and Grubbs make their implants from photosensitive macromers (short-chain polymers), allowing the lenses' optics to be tweaked post-op. (See "Squishy Is Good," *E&S* 2002, No. 2.) Once the incision has healed, there's a follow-up eye exam. Then the ophthalmologist briefly illuminates selected regions of the lens with a pattern of near-ultraviolet light. This activates the macromers in those areas, creating a chemical imbalance that osmotically attracts free macromers from nearby regions. Over the next day, the influx of material alters the lens's shape, and thus its refractive power. A final lenswide dose of ultraviolet light locks in the new configuration.

Although the LAL isn't yet approved for use in the United States, it's taken off overseas. "Sales in Europe are doing well," Grubbs remarks. Meanwhile, recent clinical trials have confirmed the lens's ability to correct astigmatism. Says Kornfield, "It's exciting to be involved in a technology that might soon be giving people over 45—like me!—near and distance vision without glasses or contacts."

So keep an eye out—er, as it were. *—DZ* E&S



S. G. Djorgovski, H. Fu, et al., Caltech

COSMIC COLLISIONS

Newly discovered black-hole pairs provide a rare glimpse into the later stages of how their host galaxies collide and merge. The images on the left, from the Sloan Digital Sky Survey, each show a single blurry object. Now the Keck telescope's adaptive optics have resolved each smudge into two active galactic nuclei (right), each of which is powered by a supermassive black hole. These binary black holes are a hundred to a thousand times closer to each other than most previously observed pairs—and these 16 pairs are the largest population of such objects discovered with a systematic search. Postdoc Hai Fu, Professor of Astronomy George Djorgovski, Member of the Professional Staff Lin Yan (PhD '96), and Alan Stockton of the University of Hawaii at Manoa, reported their observations at the American Astronomical Society meeting in January. E&S

AUTOMATA IN OUR MIDST

Pity the poor service robot. It has its marching orders; it knows where to go, but to get there, it must thread its way through a mob of humans. We all face that same problem daily, in malls and museums, on boardwalks and boulevards: navigating a living, jostling obstacle course. Only this purposeful pedestrian is electronic.

"I see crowds as swarms of massive particles with random trajectories," explains Caltech graduate student in control and dynamical systems Pete Trautman. "Picture a hapless robot wading into the melee. It takes baby steps. It backpedals frantically." And one stubborn human, motivated by obstinacy, curiosity, or simple obtuseness, can detain it indefinitely.

Not that most of us flesh-and-blooders wish our mechanical friends ill. Adults frequently try to engage them in conversation, no doubt having been conned into thinking they are sentient by the melodious bleeps and burbles of R2D2 and WALL•E. And University of Washington researchers have observed infants responding to social cues from robots. But crowds are chaotic, and even a mind-reading android capable of predicting each person's every move might never find a clear path. All the obvious strategies have limitations. "Make an aggressive beeline? That's obnoxious," Trautman cautions, "and potentially dangerous. Wide, evasive detours? Inefficient or impossible." What about simply waiting for the seas to part, then making a dash for it? "And if they never part?" he shrugs. "You'd wait forever. We call that the Freezing Robot Problem."

Yet humans navigate crowds routinely—how? "First," Trautman says, "I collected mountains of data by filming pedestrians negotiating a crowded sidewalk." Their motions revealed details of the hidden logic known as cooperative collision avoidance: the subconscious twists and turns we all execute to keep from continually bumping into one another. Next, he constructed a mini-robot of intentionally disarming cuteness (a laptop computer on wheels, with stereo camera "eyes") and turned it loose among the lunchtime crowds in Caltech's Chandler Dining Hall. Some days he hovered nearby, maneuvering it remotely; other times, the WALL•E wannabe moved autonomously. Hearteningly, the seething mass of humanity accepted the newcomer. Far from running interference, they simply flowed around it as if it were any other (very short) chow seeker on a mission. Some even professed not to have noticed it.

These observations led Trautman to a key insight. "We all expect cooperative collision avoidance from robots," he says. "It turns out they can also expect it from us." People are surprisingly predictable creatures, he explains. "We want to get where we're going, we can only change direction so fast, we don't like touching strangers. Some metal gizmo whizzes up. Maybe we noticed someone with a joystick nearby—whatever. We're busy, we're distracted, we make way and move on." The only exception is when the robot dawdles or appears lost. "Then folks notice it and crowd around. Certain individuals even try to prevent it from moving off again."

Trautman presented his crowd-navigating algorithm at January's TEDxCaltech conference. Using probability theory to predict the behavior of others, it charts assertive courses. "In fact," he notes, "the algorithm generally selects shorter, smoother paths than most humans do." So next time you hear "Last orders!" or "Look, it's Brad Pitt!" or "70 percent off in housewares!" . . . follow the nearest robot. *—DZ* E&S

In this overhead view of part of Chandler's food-service area, a small crowd gathers around Trautman's robot (green circle) the moment it stops moving. For videos, see http://www.cds.caltech.edu/~trautman.

THE PHYSICIST WHO CAME TO DINNER

Top: Every year since 1992, famed physicist Stephen Hawking has spent about a month at Caltech. And every year since 2000, a group of Caltech students have cooked dinner for him. This year, on January 25, the students—led by Rosemary Macedo (BS ’87) as part of a cooking class taught by Tom Mannion, senior director for student activities and programs—prepared an Indian feast.

Left: From left: Anguel Alexiev (’11), Wesley Chen (’12), and Laura Decker (’11) prepare Goan-style seafood curry in Mannion’s backyard.

Below: From left: Pengsu Jiang (’12), Jenny Xiong (’11), and Skylar Cook (’12) stir up beef in black-cardamom tomato sauce and pork vindaloo in Mannion’s backyard. Afterward, the students carried the steaming pots and trays to Chandler Dining Hall, where dinner was served.

DUNE THE MATH

Despite its name, the Arroyo Seco (Spanish for "dry streambed") meandering past Caltech's Jet Propulsion Laboratory does actually contain water. But even if it were bone-dry, perpetually so, you wouldn't need a planetary scientist like JPL's Serina Diniega (BS '03) to deduce that at one time something liquid this way came.

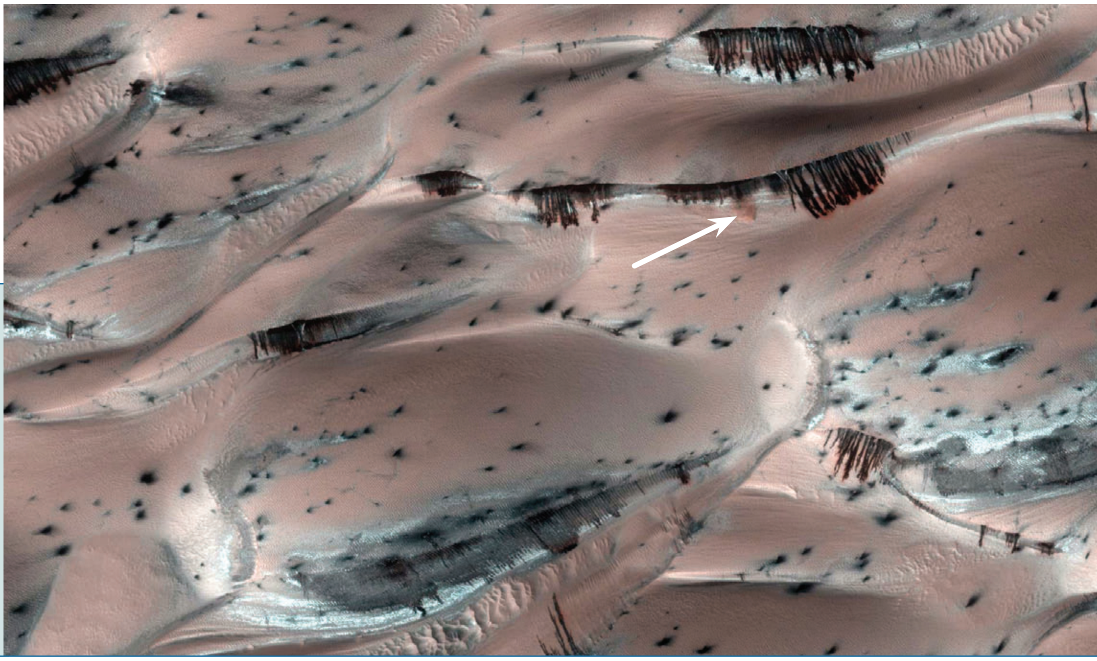
Shift now to Mars. Its empty riverbeds mark where water once flowed; its towering sand dunes don't. Yet, observes Diniega, the dunes' faces are scarred by deep channels—elongated hourglass-shaped gullies sluicing from crest to base. The wind eventually smoothes everything over; a decade's worth of orbiter images confirms that. But eerily, new gouges keep appearing.

What's flowing up there? Groundwater? Snowmelt? Condensation? All physically improbable, Diniega says: though those processes are common on Earth, "Mars is a different planet with its own mysteries." The most likely culprit, she's concluded, is carbon dioxide: the layer of dry-ice frost that blankets the planet's vast dune fields through the Martian winter.

In recent papers in *Science* and *Geology*, Diniega and her collaborators postulate that as the spring thaws approach, the warming sands heat the frost layer from beneath, causing its underside to vaporize before its surface does. Trapped, the newly liberated carbon dioxide gas rushes sideways, picking up sand particles as it accelerates, until it reaches a crack—such as the ones typically found along the crests of dunes. There the sand squirts out like feathers from a ruptured mattress; falling back, it triggers miniature landslides that gash the dune's face.

Diniega's current focus is on the dynamics of lava flows here on Earth—quite a shift from Martian dunes. Diniega is fascinated by the dynamics of everything from lava flows to river channels. "My interdisciplinary research path has been an interesting one," she acknowledges. At Caltech she was a math major—unusual for a planetary scientist. "I knew from my undergraduate experiences that I wanted to study how landforms evolve on different planets, and that I wanted to use mathematical techniques to do it. During my first year at the University of Arizona, I attended a math colloquium about 'coalescence dynamics,' in which you start with a large number of small things, but end up with a small number of large things—the way droplets of water collect, for example. That same week we discussed sand dunes in my planetary geomorphology class. Small sand dunes move faster than larger sand dunes, as there's less sand to move, so the small ones catch up to the big ones and sometimes get absorbed. I decided I wanted to know more, and fortunately Karl Glasner, the applied mathematician who'd given the colloquium, was also intrigued. He ended up serving as my PhD advisor."

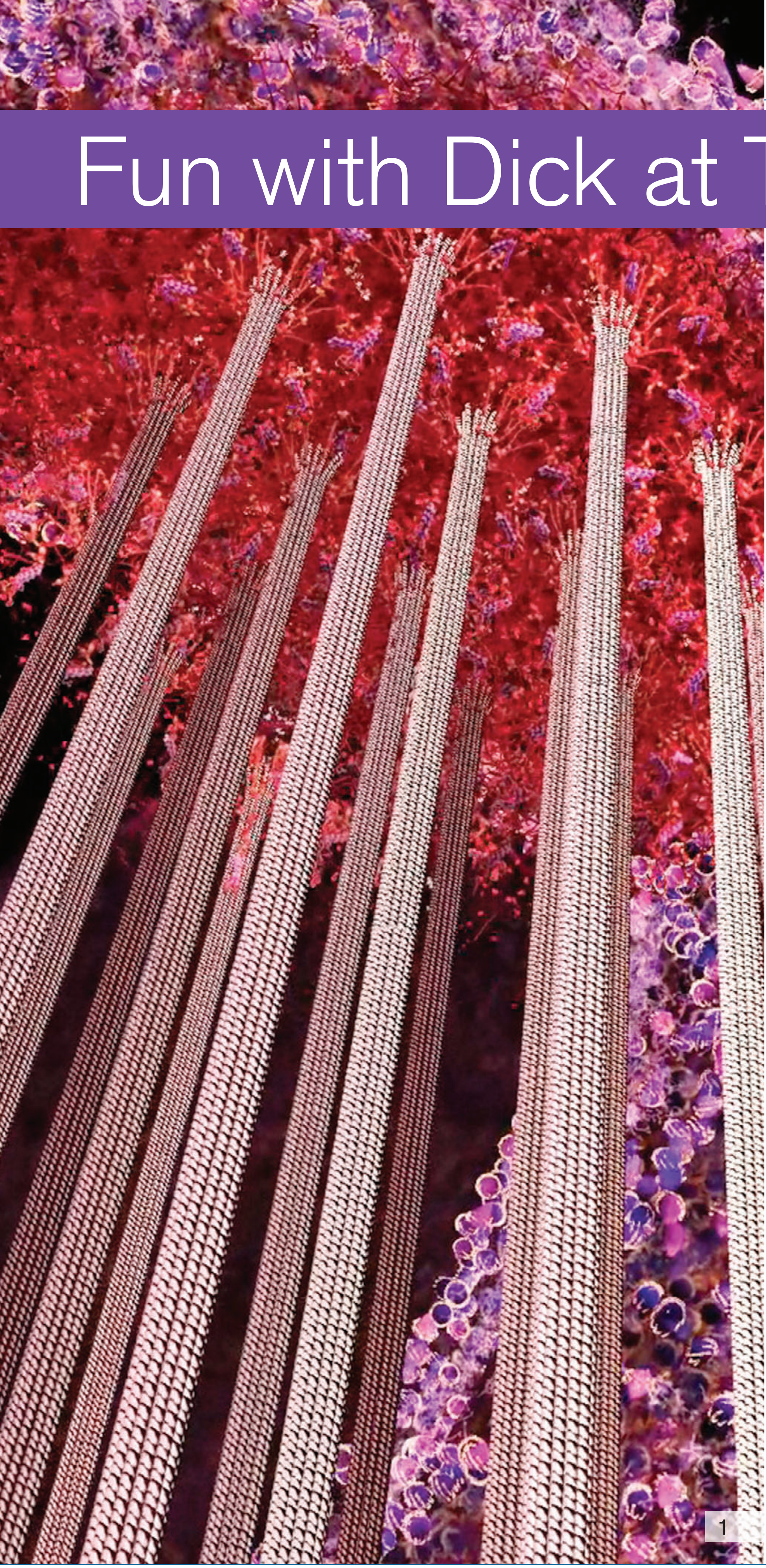
So for the native Hawai`ian (whose interests include hula and who once captained Caltech's fencing team, specializing in saber), the transition from Galois fields to lava fields wasn't much of a lunge. "I've always enjoyed showing how I use math," she explains, "in studies of more 'real' questions about how the world works." *—DZ* e&s



This Mars Reconnaissance Orbiter view of a dune field in early spring caught a dust cloud (arrow) kicked up by a mini-avalanche down a dune face some 40 meters tall. The dark streaks are believed to be landslides triggered by sand squirting from the dunes' crests. The bright patches are carbon-dioxide ice remaining from winter.

Fun with Dick at TEDx

By Douglas L. Smith



Richard P. Feynman, Caltech's Renaissance man—visionary, artist, teacher, showman, safecracker, raconteur, bongo drummer, and winner of some award for physics that they hand out every year in Stockholm—was the subject of Caltech's first independently organized TED event. *Feynman's Vision: The Next 50 Years* drew 1,035 people to Caltech's Beckman Auditorium on Friday, January 14, for a daylong amalgam of science, music, and some just plain silliness. The (un)dignified professor himself, who died of cancer in 1988, made numerous appearances in video clips, giving those of us who had never had the opportunity to meet him a glimpse into the mind of a very curious character indeed. TEDxCaltech also marked the 50th anniversary—more or less—of Feynman's prescient "There's Plenty of Room at the Bottom," an exploration of the possibilities of nanotechnology published in these very pages in February 1960; and of the 1961–1963 *Lectures on Physics*, his classic introductory physics course released in 1964 as a set of iconic red textbooks.

Emceed by Rives, who cohosts the annual TEDActive conference in Palm Springs, the day was divided into three sessions. The first focused on taking the world from another point of view, as it were. The second session revolved around strange theories of light and matter, from quantum computing to cosmology. And the third revisited the room at the bottom, showcasing the coming intersection of nanoscience and biology. Here are some highlights.

Session One: Conceptualization and Visualization in Science

After an introduction by Feynman's daughter Michelle and Feynman documentarian Christopher Sykes, the session settled into talks on making sense from complexity and communicating with clarity: Caltech biologist Pamela Björkman's presentation featured a long-armed cartoon Elmo to demonstrate how a successful HIV antibody has to grasp widely spaced marker molecules on a virus's surface—an insight made possible by accurate 3-D renderings of the proteins involved. "When the imaging is good enough, solving some problems in biology becomes, 'Hey, just look at this!'"

Microsoft's Curtis Wong demoed the World Wide Telescope, an interactive atlas of the universe downloadable to a browser near you. Caltech astronomer George Djorgovski noted that scientists are migrating into cyberspace, where data, literature, and computational tools are just mouse clicks away. Humanity and society coevolve with science and technology, he said. "The rapid pace of technological change may accelerate our evolution as a species."

But for now, we still have to learn the old-fashioned way. Shuki Bruck, the 2009 winner of the Feynman Prize for Excellence in Teaching, talked about engaging students' curiosity. Adam Cochran, Caltech's intellectual-property counsel, previewed the electronic *Lectures on Physics*, where users can not only zoom in on any equation, but see photos of Feynman's actual blackboards or hear a recording of him giving the lecture. (In tribute to the master practical joker, the audio—which had worked fine at rehearsal—refused to play.) A surprise announcement followed: The Ralph M. Parsons Foundation is underwriting the renovation of 201 East Bridge, the venue for said lectures, to be renamed the Richard P. Feynman Lecture Hall.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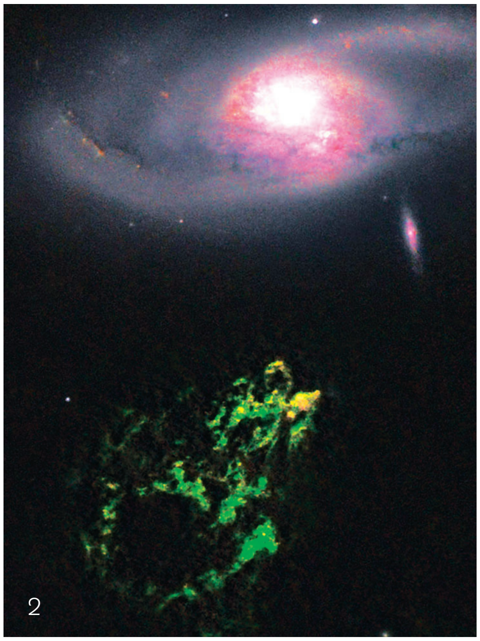
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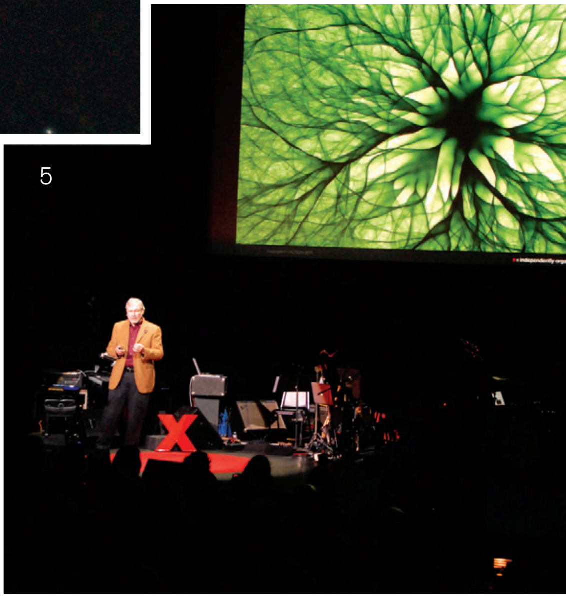
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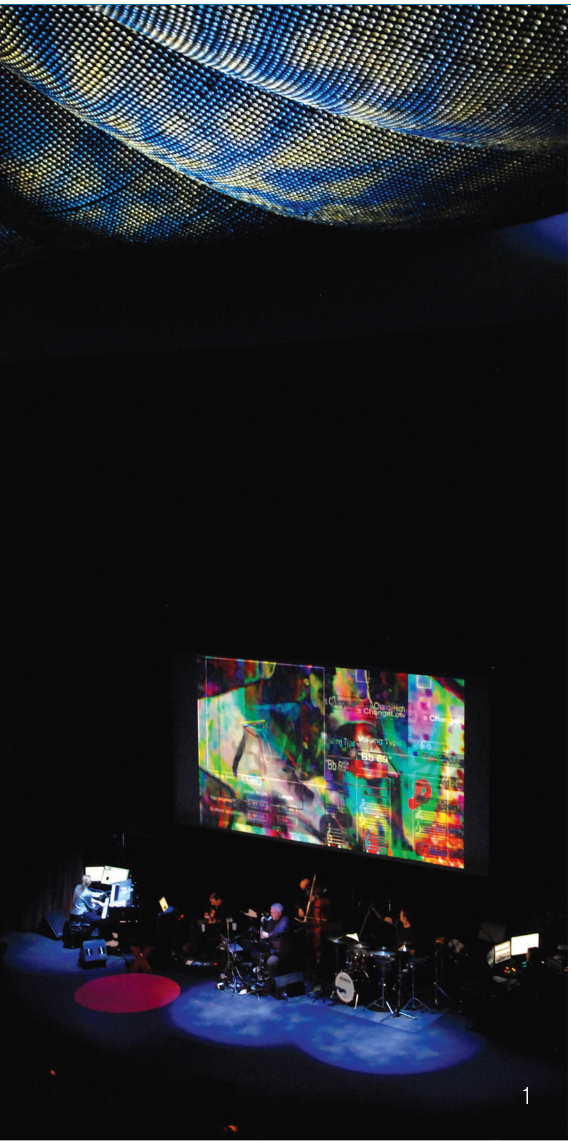
1. Drew Berry showed three-dimensional digital animations derived from scientific data—"a whole semester of biology in only three minutes." Here the white pillars are the microtubules that connect a pair of chromosomes as they detach from each other during cell division. The red region is a megacomplex made of thousands of proteins on the chromosome that senses the degree of tension in the microtubules and gives the go-ahead for separation to proceed.

2. With large data sets easily accessible on the 'Net, average folks can make discoveries almost as a hobby. In July 2007, Johns Hopkins astronomer Alex Szalay helped launch the Galaxy Zoo, a website where volunteers could classify the million or so galaxies photographed by the Sloan Digital Sky Survey. In the first three days the site had 300,000 users, and within a month a Dutch schoolteacher named Hanny van Arkel found this bizarre blob known as Hanny's Voorwerp—a part of a streamer of gas encircling galaxy IC 2497 that has been made visible by the searchlight beam of its central quasar.

3. MIT's Sanjoy Mahajan (PhD '98) demonstrated how to solve complex problems with educated guesses—a skill for which Feynman was famous. Here he drops two coffee filters of different diameters to estimate the force of aerodynamic drag en route to approximating the fuel efficiency of a 747.

4. Feynman himself made an appearance, as channeled by JPL attitude-control engineer and veteran Theater Arts at Caltech performer Steve Collins, dressed in the Ladakhi monk's robe and hat that Gweneth Feynman sewed for her husband to wear to a costume party.

5. Harvard's Eric (Rick) Heller creates simulations of the paths of electrons through a semiconductor—which he likens to tracing light rays through "a drawerful of bad lenses"—and turns them into works of fine art. Heller followed grad student Dennis Callahan, a two-time winner of Caltech's Art of Science competition, who showed microscope images from various labs around campus.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Session Two: Frontiers of Physics

With the exceptions of cosmologist Sean Carroll's exploration of the universe's increasing entropy, and an excursion to Mars with grad student Jeff Marlow, the frontiers in question tended to be quantum. Simon Fölling of the Max Planck Institute for Quantum Optics talked about building the hardware for quantum computers, which are widely expected to be the Next Big Thing. However, as UCLA's Zvi Bern remarked in his talk about Feynman diagrams, "A good idea will always kick the pants off of a supercomputer." Scott Aaronson, a designer of quantum-computing algorithms from MIT, asked rhetorically, "Is there *anything* we can discover in the 21st century that would not have been deeply obvious to this man? We might as well quit physics and take up bongo drumming. . . . Oh, never mind—he had that covered, too." Aaronson compared the state of quantum computing today to Charles Babbage's hand-cranked difference engines of the 1830s. Feynman, he noted, did not have much respect for pure mathematics (or pure mathematicians?), possibly because "quantum mechanics is incredibly easy once you take the physics out."

The physics was leavened by the TEDx Jam Band, led by Lyle Mays, 11-time Grammy-winning keyboardist and longtime creative partner of Pat Metheny. The ensemble also included bassist Tom Warrington, saxophonist Andrew Pask, drummer Jimmy Branly, and guitarist / synthesizer programmer Bob Rice. Sound engineer (and holder of a double fistful of Grammys) Rich Breen handled the mix, and the music was backed by a wall-sized mash-up of live camera feeds, assorted Feynmanalia, and trippy video effects created in real time by digital artist Jon 9.

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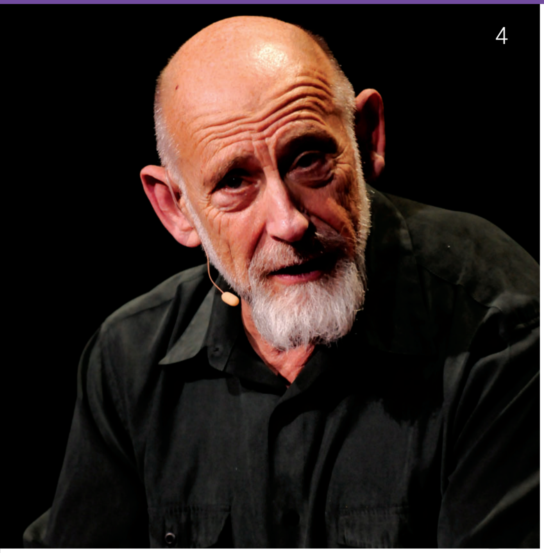

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1. The multimedia jam session before the lunch break explored the connections between nonlinear dynamics, jazz, and visual perception in a full-on sound and light show that evoked the sixties on steroids.

2. The line to get in stretched past Beckman Behavioral Biology and all the way out San Pasqual Walk almost to Wilson Avenue.

3. Feynman was fascinated by the central Asian nation of Tannu Tuva, whose distinctive triangular postage stamps he'd collected as a child. While he never made it there, his interest has allowed several Tuvans to visit here, including throat singer Kongar-Ol Ondar. Throat singing is a folk art in which the singer produces two or more pitches simultaneously to create strange, mesmerizing harmonics.

4. Stanford physicist Leonard Susskind told stories about Feynman the showman and Feynman the gamesman. "He had a kind of macho one-upsmanship. He loved intellectual battle. . . . And he loved to win. But when he lost, he laughed and seemed to have just as much fun as if he had won." On one occasion, Susskind actually got the last word: Feynman loved to tell the story of a bunch of undergrads taking him to a local eatery featuring sandwiches named for celebrities. By arrangement, all the students went off-menu, ordering "Feynman sandwiches." Susskind wondered what a Susskind sandwich might be like, and Feynman cracked that it would be about the same as a Feynman sandwich, but with "'a lot more ham,' as in a bad actor. Well, I happened to have been very quick that day, and I said, 'Yeah, but a lot less baloney.' The truth of the matter is that a Feynman sandwich had a *load* of ham, but absolutely no baloney. What Feynman hated worse than anything else was intellectual pretense."

5. Saying, "Feynman didn't just dress differently; he thought differently," Microsoft's Tony Hey showed this 1969 photo of, from left, Carl Anderson (a 1936 Nobelist), Murray Gell-Mann (1969), Max Delbrück (1969), Feynman (1965), and George Beadle (1958), which he said the *California Tech* once ran under the headline "Four Kings and a Joker."

6. The game show *Finding Things Out—Ordinary Genius Edition* featured (at left) Kid Throne (Kip Thorne, BS '62, the Feynman Professor of Theoretical Physics, Emeritus) and (center) Jot Pretzel (John Preskill, the Feynman Professor of Theoretical Physics) answering Feynman trivia questions to win an answering-machine greeting recorded by Stephen Hawking: "Nobody's home . . . dude." Hawking himself made a surprise appearance, rolling into the auditorium in response to the "Phone a Friend" lifeline.

Session Three: Nanoscience and Future Biology

There's still plenty of room at the bottom, but the real estate is getting parceled out. Don Eigler of the Almaden Research Center was among the first to plant a flag there, using a scanning tunneling microscope back in 1989 to push xenon atoms around on a nickel surface to form the letters *IBM*. Afterward, he said, he was rereading Feynman's "Plenty of Room" late one night, "and the hair on the back of my neck went up. . . this is the ghost of Feynman! And if he's here, what would he say? 'What took you so long, kid?'" Harvard's Charlie Marcus and UC Santa Barbara's David Awschalom continued to carry the torch for quantum computation. Steve Quake, now at Stanford, talked about the microfluidic circuits he began developing here at Caltech. (See "Rubber Layered Micropumpers," *E&S* 2003, No. 2.) These circuits essentially shunt cells or even proteins around a silicon chip as if they were electrons, using tiny fluid-filled channels in lieu of wires. Beyond making an entire set of blood tests as disposable as the syringe that draws the sample, this technology opens up what conference co-organizer Michael Roukes called "plenty of room in the middle"—fluid-based integrated circuits whose performance will be measured in "GBOPS: billions of biological operations per second."

The day's final speaker, Danny Hillis, made it all personal. Hillis, cofounder of Thinking Machines and a longtime friend of Feynman's, recalled a walk in the San Gabriels in the summer of 1987, when the toll the cancer had taken suddenly became obvious. Feynman was philosophical, saying, "By the time you get to be my age, a lot of what's good about you has rubbed off on other people."


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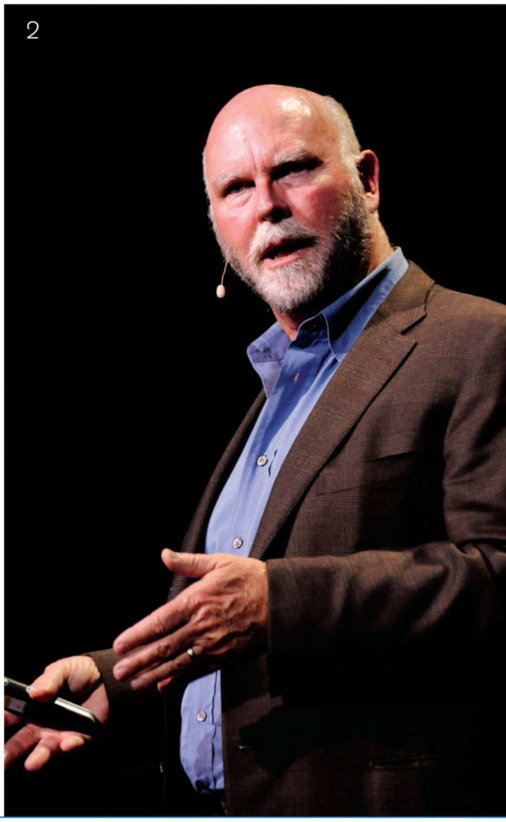
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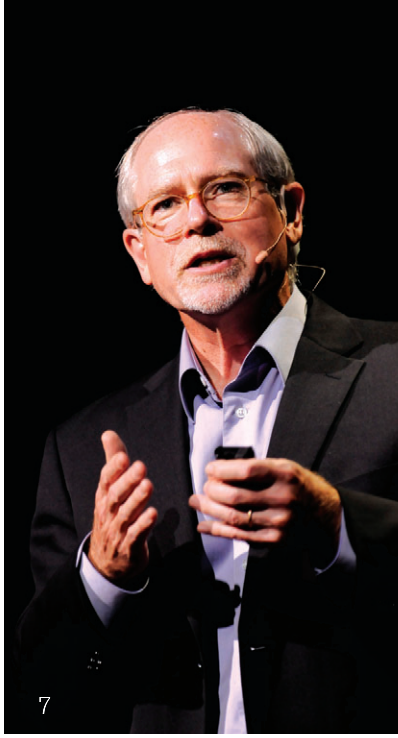
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1. Rives (right) wrapped it up by rapping with Ondar and the band before calling TEDx co-organizer Roukes to the stage to thank the folks who made it happen. Rives's riffs were "curated" from the speakers' words, ending with the thrice-repeated tag "People lose a lot of pleasure / Who find science dull." Nobody found this day dull.
2. Biologist J. Craig Venter's eponymous Institute recently assembled the first "synthetic" organism by inserting cobbled-together bits of bacterial DNA into an enucleated cell, which happily "booted up" and reproduced itself. When the news broke, "We got an immediate response from both the pope and the president—a first. And I was not invited to a barbecue, so I was very happy about that."
3. At the dinner that evening, Caltech president Jean-Lou Chameau (at right) presented Fred Kavli of the Kavli Foundation and Caltech's Kavli Nanoscience Institute with a facsimile of Feynman's notes for a lecture—jotted on a place mat from Gianonni's, a topless restaurant near Feynman's house where he sketched the girls and doodled about physics.
4. Caltech grad student Nadine Dabby showed off a nanorobot made from DNA. A collaborative project with researchers at Arizona State, the University of Michigan, and Columbia, the 'bot crawls along a sinuous strand of DNA bewhiskered with little wisps of DNA that it grabs and releases—"a robotic lawnmower propelled by uncut grass."
5. And grad student Pete Trautman showed off his somewhat larger robot, which is capable of threading its way through crowds of people. (See "Automata In Our Midst," page 7.)
6. Junior chemistry major Jordan Theriot wowed the crowd with "The Pleasure of Finding Things Out"—an enthusiastic recounting of her 2010 Summer Undergraduate Research Fellowship (underwritten by Caltech's Office of Development and Institute Relations, of which *E&S* is a part), which has inspired her to pursue a career in academia after graduation.
7. Caltech chemist Mark Davis updated the audience on his cancer-fighting nanoparticles (see "Sweet Revenge," *E&S* 2007, No. 1), which are now in Phase II clinical trials. In the last year, Davis has adapted the particles to carry interfering RNA molecules, which will in principle allow the selective shutdown of any specified gene in the cancer cell.
8. MacArthur "genius" Angela Belcher, a materials chemist and bioengineer, has programmed a brace of viruses to assemble carbon-nanotube electrodes into a high-output lithium-ion battery in a Petri dish. "My dream is to drive a virus-powered car." More broadly, she noted that biomaterials contain exquisitely designed nanostructures, but only make use of a few elements, such as iron and calcium. "I would like to convince biology to work with the rest of the periodic table. . . . What if we could convince [viruses] to build a solar cell for us?" In her freshman classes every year she passes out laminated, wallet-sized periodic tables that say, "Welcome to MIT, now you're in your element." When President Obama toured her lab last summer, she offered him one. He replied, "Thank you. I'll look at it periodically." Which he did, pulling it out later during a speech on clean energy.

ROUGHING IT

By Lori Oliwenstein

Beverley McKeon has made a career of creating turbulence—and that's a good thing, at least when it comes to golf balls and insect-sized aircraft.

Television and print journalists listen intently as Beverley McKeon explains the aerodynamics of an older, conventional soccer ball.

It was June 23, 2010. World Cup fever was, appropriately, at a fever pitch. So was the controversy over the reportedly odd behavior of the event's brand-new Jabulani ball—manufactured by Adidas, reviled by almost every goalie to touch it (or not), and half-jokingly rumored to have played a role in the recent, unexpected tie game between the U.S. and England, during which a relatively routine shot on goal got past England's keeper.

Deep within Caltech's Guggenheim Aeronautical Laboratory, at least a dozen cameramen, photographers, and reporters—and a dozen more onlookers—were crammed into the cramped spaces surrounding the Lucas Wind Tunnel, or peering down from wooden viewing platforms overhead.

They were all intently watching one woman: assistant professor of aeronautics—and fervent soccer fan—Beverley McKeon.

She, in turn, was focused on the tunnel's viewport, wherein smoke could be seen swirling over, under, and around a Jabulani that had been mounted on a support rod. After a short while and a few technical glitches—and after having already seen how the smoke flowed around an iconic black-and-white ball—she was ready to talk about her observations.

A soccer ball, McKeon explained to the gathered onlookers, is in no way a perfect sphere. It is a collection of stitched-together panels: 32 for the backyard-scrimmage ball used by most of us, but only eight for the Jabulani. Furthermore, the grooves between the Jabulani's panels are not nearly as deep as the ones on its predecessors.

Put all of that together, McKeon continued, and you get a ball that can behave unexpectedly—its interactions with the air through which it hurtles increase the drag and alter the lateral forces that act on the ball, slowing it down and curving its flight path in an unexpected way.

"So as the goalkeeper sees the ball coming, it suddenly seems to change its trajectory," McKeon told the reporters as they studied the Jabulani's shallow-grooved profile. "It's like putting the brakes on, but putting them on unevenly." And that, she added, was as good an explanation as any for England's near-loss.

"I'm sure it's entirely down to the ball and had nothing to do with our goalkeeper," the British-born scientist concluded, with only a hint of a grin.

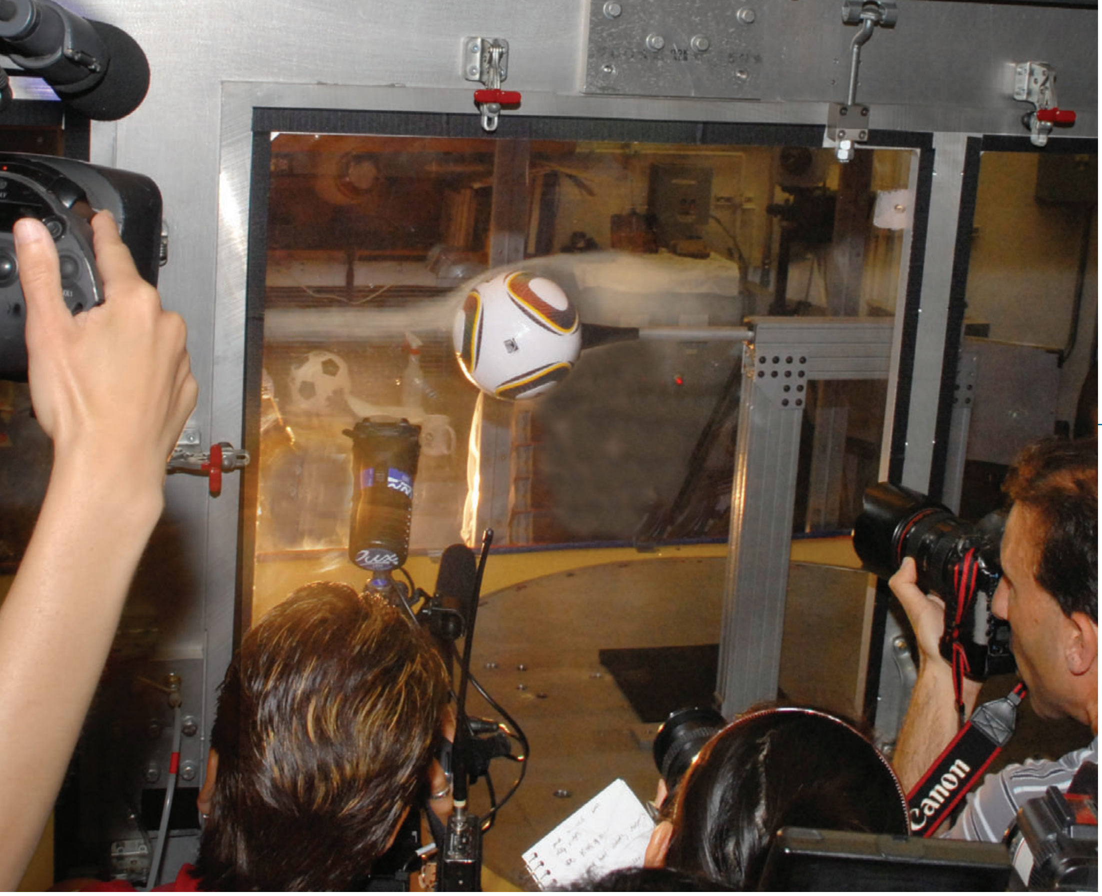
EMBRACING TURBULENCE

National pride aside, McKeon was a natural choice for the spotlight during this classically Caltech amalgamation of science and soccer. Besides being a self-proclaimed "huge sports fan," she studies wall-bounded flow: the way air behaves as it glides over—or, at times, twirls above, swirls around, or snags on—the surface of an object, its molecules either forming into layers or mixing things up as they go.

Of course, as she quickly pointed out, the Jabulani test was far from conclusive, and it would have been so even if the smoke machine hadn't benched itself early in the experiment. On a soccer field, a ball spins and changes speed as it flies, and it has to deal with changing winds, humidity, and the occasional errant insect. McKeon's test, on the other hand, involved a stock-still ball in a steady, 30-meter-per-second wind—a speed based on the average velocity of a ball kicked by a professional soccer player.

Still, even in McKeon's idealized scenario, the Jabulani followed the rules of fluid mechanics, which say that there are two main ways in which air can flow over pretty much any surface, including a soccer ball. The air can move in two dimensions, its particles sliding effortlessly over one another and the ball in smooth, parallel layers; this is called laminar flow. Or it can move more erratically, its individual particles tumbling about in three dimensions and resembling nothing so much as roaches skittering across the kitchen floor when a light goes on. This is turbulent flow.

We tend to think of turbulence as something to be avoided at all costs. And, in a pipeline transporting water or oil from one place to another, that is the case. When things get turbulent inside a pipe, the energy needed to pump the pipe's contents from point A to point B kicks up dramatically. Not good. But when it comes to soccer balls and their ilk, turbulence can have its benefits.



When a laminar flow in the boundary layer—the area closest to the ball's surface—hits the ball's equator, the smooth-gliding layers of air immediately peel apart from one another and away from the skin of the ball; the air molecules just keep traveling straight ahead, creating a wake that is, essentially, the width of the ball itself. And, in turn, that wake drags on the ball, slowing it down.

A turbulent flow in that same boundary layer, on the other hand, hugs the ball's surface for as long as it can, its air particles energized by all their jitterbugging. "A turbulent flow travels a little farther into the pressure gradient that pushes the laminar flow away from the ball, so it separates from the surface *past* the ball's equator," McKeon explains. "This creates a smaller, narrower wake. And because the wake is smaller, the drag on the sphere is lessened, as well."

Laminar flows tend to be slower, and they do best when traveling over smooth surfaces, whereas turbulence comes from rougher surfaces and higher flow speeds. Things get interesting—and confusing—in the middle ground, where the flow can go either way, and where just the slightest push can more quickly and easily turn a laminar flow turbulent.

McKeon and her colleagues have staked their claim to that middle ground. Their research into the effects of roughness on turbulent flow—done at GALCIT, the Graduate Aerospace Laboratories of the California Institute of Technology—is performed in tunnels of wind and water, into which they inject smoke or dye to see what the fluids they're studying are up to. And yes, to McKeon, air is a fluid, albeit a very runny one. "When we say fluid, we mean any liquid or gas," she notes. The mathematics shaping the flow are exactly the same whether you are watching wind or water pass over the surface. Which medium you use, says McKeon, depends chiefly on your experimental needs: Swirls and eddies can best be seen in flowing water with a shot of dye. But if you want to examine a high-speed flow, water may be too sluggish; in that case, air and smoke may be your best bet.

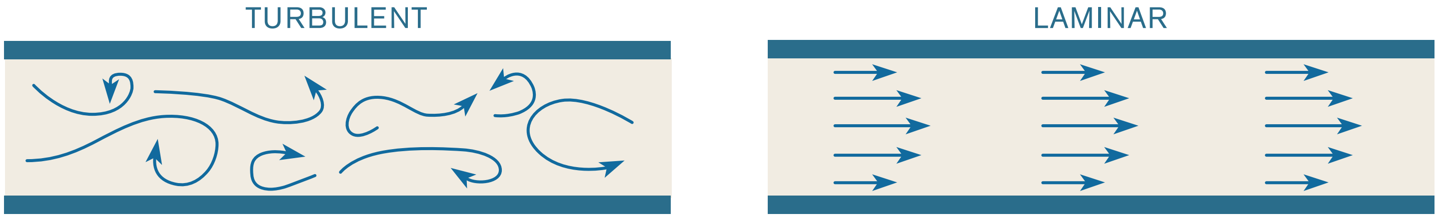
Swirl by complex swirl, layer by minuscule layer, McKeon is trying to understand just why the smooth, parallel lines of a laminar flow take on the helter-skelter unpredictability of a turbulent flow—and how we can make those flows behave the way we want them to, when we want them to. For her efforts, which range from building a better golf ball to reducing drag on a Boeing 747, McKeon was given the Presidential Early Career Award for Scientists and Engineers in 2009.

A DIMPLE DILEMMA

You might think that fussing around with the likes of golf balls and soccer balls is more child's play than serious science. You'd be wrong. These things are, certainly, "great teaching tools," says McKeon. But they are anything but simple.

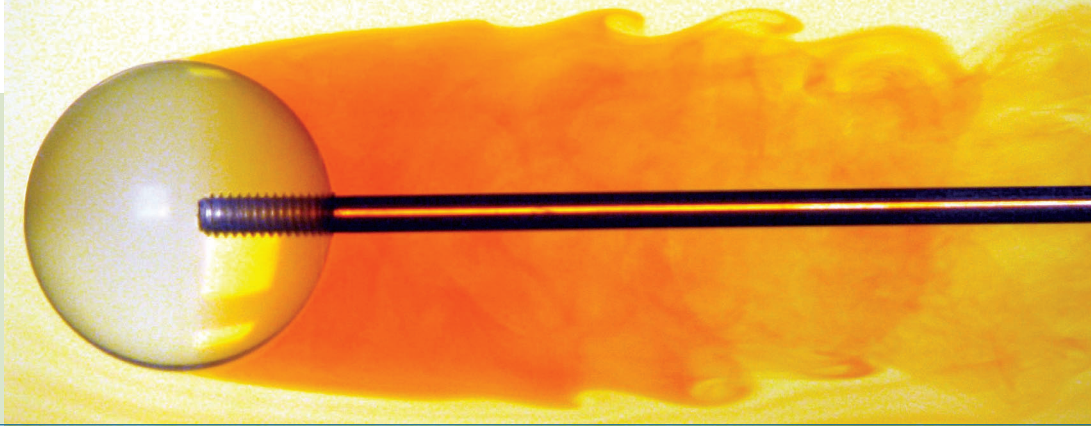
"The irony is, although spheres are used in sports all over the place, they present a very difficult problem from a fluid-dynamics perspective," she says.

Laminar Versus Turbulent Flow



Left: The Jabulani soccer ball is ready for its close-up in the Lucas Wind Tunnel.

Right: Dye-laden water, flowing past what is known as a "bluff body," allows scientists to really see the way the fluid interacts with the surface of the sphere.



"You have a tiny layer of fluid very close to the ball with a big wake behind it governing the forces that are generated; it's hard to investigate the flow experimentally or numerically, and it's very sensitive to surface conditions."

A golf ball, for instance, exploits a complex combination of aerodynamic forces to make its way from tee to green. But it wasn't always that way. In fact, the golf ball began its illustrious career as more of a runtish, rigid racquetball, picking up its distinctive dimples only after players began noticing that balls nicked during use, or pockmarked with clumps of mud and grass, flew farther and straighter than clean balls.

"The Scots learned about fluid dynamics the hard way," McKeon quips.

It turns out that the mud (or the dimples) bump the boundary layer—the zone of air hugging the ball's surface—from laminar to turbulent flow as early in the ball's flight as possible. This leads to a wake that is as thin as possible, which in turn leads to a dramatic reduction in drag.

How dramatic? "If you hit a golf ball without dimples, it will go less than half the distance of a ball with dimples," says McKeon.

As impressive as that is, McKeon and her team—including graduate students Ian Jacobi (MS '08), Jean-Loup Bourguignon (MS '08), Jeff LeHew (MS '07), and Rebecca Rought (MS '09), who work on turbulent flow and surface design—are trying to do the Scots one better. Their goal: a dynamic golf ball, one whose dimples change depth asymmetrically in response to changing conditions during flight.

This mighty morphin' golf ball would start on the tee looking much like a regular ball, with uniformly distributed dimples, McKeon explains. But, once hit, "if the ball were to begin to veer off target, you might trigger one side to be more rough than another. That would lead to more turbulence on that side, creating a lateral force that would steer the ball back on track."

Her team has found that it doesn't take much to give the ball a sideways push. "We can get a very large lateral control of the ball's trajectory with only a very small asymmetrical change to the ball itself," McKeon notes.

And when McKeon says small, she means *small*. In a recent study published in the *Journal of Fluid Mechanics*, a McKeon lab team that included graduate student Adam Norman (MS '06, PhD '10) added a single bump to an otherwise smooth sphere—a bump that took up all of two thousandths of a percent of the sphere's surface area and had a diameter and height equal to just one percent of the sphere's diameter.

But that bump—a metal stud held in place by a magnet inside the sphere—had a huge impact. The team used the magnet to drag the stud around the sphere, just upstream of the equator. The projecting stud created localized regions of turbulence in the boundary layer around the sphere. As the stud moved, the turbulence moved with it, altering the lateral forces and drag the sphere experienced. "Adam's work showed that it was possible to use a true morphing surface to control the forces acting on an object," says McKeon.

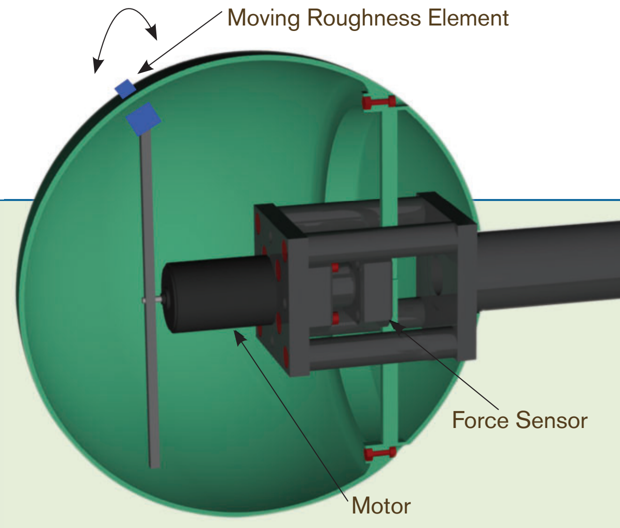
But don't head to your local sporting goods store quite yet, Tiger. It's one thing to mess with the dimples on a golf ball. It's another thing entirely to create a ball whose surface literally shape-shifts over time, and does so asymmetrically. A ball like that needs to be responsive to the conditions around it. A ball like that needs more than the brute-force mechanical maneuverings of magnets and studs. A ball like that needs to be smart.

Enter Caltech materials scientists Kaushik Bhattacharya and Michael Ortiz. McKeon challenged them to create "smart" materials that can rapidly change the flow around themselves in response to changing environments or changing needs—not just on a golf ball, but as part of any number of potential applications.

In yet-to-be-published research, the members of this multidisciplinary team have shown they can do just that. With the help of visiting student Andre Bauknecht from the University of Stuttgart, Germany, they've created inch-sized swatches of material that can respond to a stimulus—such as heating, stretching or contracting, or perhaps the application of an electrical field—by changing its surface roughness. "We've shown that when this morphing material is activated, the lift and drag on the object change," says McKeon.

But taking this breakthrough and turning it into a golf ball that knows when and where to change its surface roughness is a long way off, and no easy task.

To examine the effect of a small, dynamic change in a sphere's roughness, McKeon's group attaches a metal stud—the "moving roughness element"—to the surface with a magnet inside the sphere, then moves the stud using an internal motor.



So why pursue it so doggedly? Because, McKeon says with a wry grin, "it's the only way I'll ever be able to beat my husband at golf."

EGG CARTONS AND AIRPLANES

She kids, mostly. What she finds out about controllable changes in roughness, she explains, will in the end likely be of more use to the aerospace industry than to the PGA. Which is just fine with McKeon—airplanes are the reason why she's at Caltech in the first place.

McKeon has been interested in aerodynamics since her childhood in Surrey, England, much of which she spent flying with her father, a flight engineer for British Airways. "I used to wonder how it was that I got to 30,000 feet in the air," she recalls, "as well as how it was that I stayed there."

In high school, she decided that she, too, wanted to fly jets—fast ones. "But at that time in the U.K.," she says, "women couldn't fly anything fast enough or exciting enough. So I decided to do the next best thing and design them." Learning to design airplanes, however, required a serious foray into the worlds of physics and engineering, of ailerons and flaps, of airfoils and fluid flow.

"I got sidetracked," she admits. "And I've never looked back."

Ironically, McKeon can't fly many of the vehicles her work impacts today, either. Not because they're off-limits to women, but because they're unmanned air vehicles, or UAVs—drones intended to fly into places too small or too hazardous for larger, manned vehicles. They're the sorts of vehicles used today, for instance, in Middle East war zones. "Our goal is to make them more agile and more maneuverable, and to design new means of controlling them that allow them to be lighter and more efficient," McKeon says.

These UAVs obey the same principles of aerodynamics as commercial aircraft, increasing lift by increasing the angle of attack—tilting their wings (or flaps) to create the needed pressure differential between the wing's top and bottom.

"Of course, if you tilt too far, the air can't follow the wing any more, and the layers separate," McKeon explains. "You lose lift and you get more drag, which can be a problem when you're trying to take off. In addition, these things—loss of lift, increase in drag—can lead to stalling in midair when you're trying to maneuver in the sky."

The solution? You could make sure not to overrotate the wing, for one thing. But in UAVs that travel at speeds much lower than those of their bigger commercial brethren, restricting rotation can significantly reduce maneuverability.

Instead, McKeon suggests changing the interaction between wing and air. "Low-speed UAVs operate at conditions very similar to where a golf ball's dimples have their biggest effect," she notes. In other words, the vehicles fall right in the sweet spot where you can push a flow to either stay laminar or become turbulent. The best way to give a UAV such a push, McKeon adds, would be with a wing material that can go from smooth to rough as needed during flight. Smart materials: they're not just for golf balls any more.

But how rough is rough enough—and how rough is too rough? After all, rough-

Right: A U.S. Air Force Global Hawk unmanned reconnaissance aircraft. Photo reproduced with permission of the Air Force.

Far Right: Decomposing an irregularly rough surface into a series of regular egg-carton shapes like this allows McKeon's group to find the optimum surface for a given application.

McKeon has been interested in aerodynamics since her childhood in Surrey, England, much of which she spent flying with her father, a flight engineer for British Airways. “I used to wonder how it was that I got to 30,000 feet in the air,” she recalls, “as well as how it was that I stayed there.”

ness can foul things up as easily as it can make them better. Just ask the U.S. Navy: a guided-missile frigate with a hull befouled by barnacles and marine slime can burn an extra three-quarters of a million dollars’ worth of fuel a year.

Understanding the ways in which roughness affects turbulent flow is one of the things McKeon and her colleagues have been grappling with in the lab. And the best way to get a handle on roughness, they’ve found, is to turn sandpaper into egg cartons.

Sandpaper, the classic rough surface, has a wide, uneven range of peaks and troughs. Blow air over sandpaper and you’ll get lots of disturbances in the flow—but it’s nearly impossible to determine which peak is creating which disturbance, much less tease out whether that contribution is useful or detrimental.

Nearly. The way to make the impossible possible, McKeon says, is to simplify it—specifically, by turning it into a series of egg cartons. That’s because egg cartons, with their characteristic uniform peaks and troughs, have easily measurable effects on any fluid flowing over them—effects that can be analyzed in great detail.

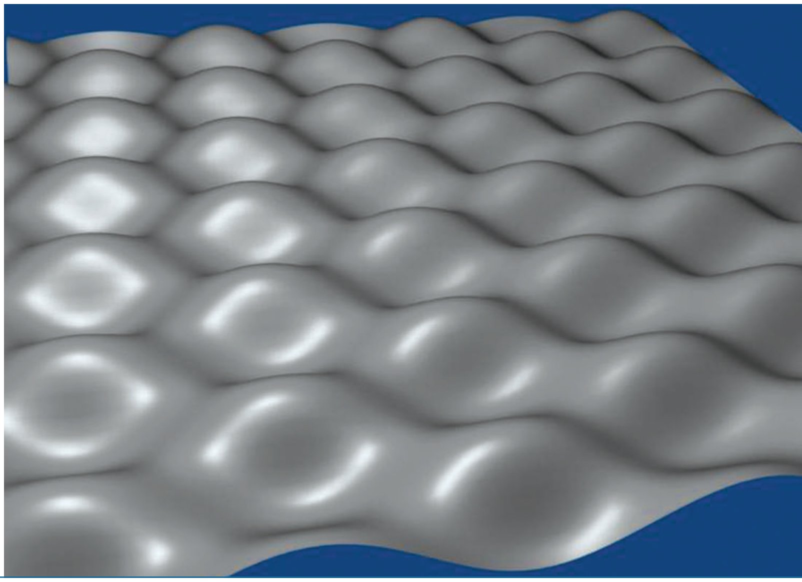
“Sandpaper is irregular,” she explains, “but we can decompose it into linear combinations of simple, characteristic streamwise and spanwise wavelengths that, like egg cartons, are all very regular.”

McKeon and crew have created a computer model of a dynamically morphing surface. The model can not only decompose a swatch of sandpaper into egg cartons, as she describes, but can pick out the carton that creates the biggest wavelike disturbance in the fluid’s flow. And from knowledge springs control: “If we want to mitigate the effect of the sandpaper, we know we need to get rid of this particular wavelength,” says McKeon. “If we want to enhance the sandpaper’s effects, then that’s the wavelength to use. We can predict which egg carton will give us our best response, and what that response will be.”

And soon, perhaps, they can begin to slap those egg cartons—or, rather, the real-world versions of those egg cartons—onto the wings of a type of UAV known as a micro air vehicle, or MAV, to see if they’re capable of replacing the flaps and ailerons of commercial aircraft.

“Because MAVs are tiny, insect-sized craft, it’s not clear that it’s best to use the same types of heavy mechanisms as in larger planes,” McKeon notes. “Instead, you could imagine that if you had this sort of dynamic roughness on both wings, you could make one wing rough relative to the other. Instead of flaps and ailerons, you could use patches of roughness to tickle the flow over the wings, maneuvering the vehicles while keeping them light.”

So this is where the flow of her still-early scientific career has carried Beverley McKeon: to huge, wind-and-water-blown tunnels; to collaborative treasure hunts for materials smarter than any created before; to palm-sized aircraft with the potential to dart and dash in ways previously thought impossible.



And to a vision of a golf ball that will let her best her husband in golf.

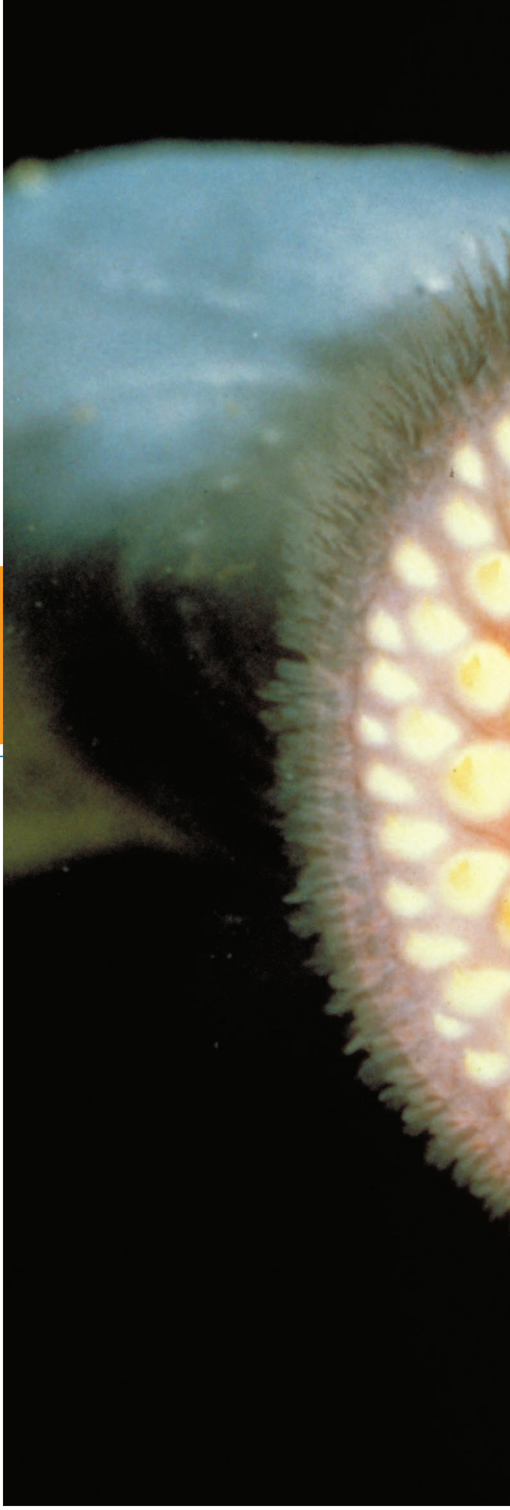
In the end, sometimes it really is the little, dimpled things that matter most.

Beverley McKeon is assistant professor of aeronautics at Caltech. She did her undergraduate work at the University of Cambridge, where she also received a Master of Engineering degree. She got her PhD from Princeton University in 2003 for work on pipe flow, and after a Royal Society postdoctoral fellowship at Imperial College, London, she arrived at Caltech in 2006. At Caltech, she works at GALCIT as well as with the flow-control group in the newly created Center for Bioinspired Engineering.

This work was funded by the National Science Foundation and the Air Force Office of Scientific Research.

Kaushik Bhattacharya is the Tyson Professor of Mechanics and professor of materials science, as well as executive officer for mechanical and civil engineering.

Michael Ortiz is the Hayman Professor of Aeronautics and Mechanical Engineering.



Jaws ‘R’ Us

By Kathy Svitil

You’d be hard pressed to find an organism that’s as unpleasant as *Petromyzon marinus*, the sea lamprey. Its looks alone are sure to turn heads . . . *away* . . . with its suction-cup-like, jawless mouth and concentric rings of sharp, curved teeth. And this three-foot-long, eellike creature’s behavior is even worse. A parasite, the lamprey latches onto its prey, rasps away scales, skin, and other tissue, and slurps out the meat and blood. Nasty.

And yet, this uncongenial life-sucking horror is turning heads among biologists. It may offer insight into some of life’s biggest mysteries—the origin of backbones, the development of jaws, and even how we higher vertebrates might have evolved the large brains that let us dominate our world. (A lot to lay at the feet of an animal that doesn’t actually *have* feet.)

Every summer, researchers from around the world flock to the laboratory of Caltech biologist Marianne Bronner to study lamprey embryos. Like salmon, lampreys are born in inland rivers and eventually migrate to the sea (and in the United States, to the Great Lakes, where they’re a scourge to native fish populations—and the rare unlucky swimmer). When they reach sexual maturity, around age seven, lampreys return to freshwater rivers and streams to breed. They essentially turn themselves, Bronner says, into “giant bags of gametes,” or eggs and sperm, which are released into the water. Then the lampreys—deflated—digest themselves from the inside out, and die.

Although the parasitic animals are, by definition, pests, “their embryos are really interesting,” Bronner says.

Her esteem for the lamprey comes in large part from the window this creature opens into her true research passion: the neural crest. In the embryos of lampreys and other vertebrates—animals with backbones—neural crest cells appear very early on in the budding nervous system’s development, then migrate away and transform into a host of other structures, including the skeleton of the face, many types of nerve cells, adrenal glands, and pigment cells in the skin. In contrast, these cells don’t exist in animals without backbones.

“Why do vertebrates have these neural crest cells? How was this cell type invented? And why would cells that come out of the central nervous system give rise to all these different non-nerve-cell types?” Bronner asks. To help answer those questions, she and her colleagues have tracked developing neural crest cells in the embryos of a variety of different vertebrates—including lampreys—and pinpointed a number of critical genes.

One gene, dubbed *AP2*, is crucial to the formation of your facial bones and nerves, both of which are derived from the neural crest. However, Bronner and her colleague Daniel Meulemans (PhD ’04) have found that *AP2* also shows up in the neural crest-less amphioxus, an invertebrate relative. Amphioxus, or lancelets, are also eellike, but they’re only about two inches long and can be found buried in the sand in shallow tropical seas. Though they are boneless, their embryos have a nerve cord that resembles our developing spinal cord, making them our nonvertebrate cousins on the chordate family

Meet *Petromyzon marinus*, the sea lamprey, in all its faceless glory. Instead of a mouth, the head end of a lamprey sports a wide, flat sucker equipped with rows of tiny teeth.

tree. In amphioxus, as in vertebrates, *AP2* is turned on very early in development, in the epidermal cells that eventually become skin. But then the gene turns off for a time, and when it comes back on, it behaves very differently. Instead of being active in neural crest cells, as it is in vertebrates, it turns up in an organ called the cerebral vesicle, which is amphioxus's primitive excuse for a brain. That suggests, Bronner says, that although the early job of *AP2* is similar in all chordates, "the gene gets turned on in a new place in the vertebrates, later in development."

The neural crest genes play different roles even among vertebrates themselves. For example, Bronner and her colleague Tatjana Sauka-Spengler have found that although almost all of the genes usually activated in the neural crest cells are turned on in lampreys, they are not always expressed at the same *time*.

"That's one of the reasons we want to look at the jaw," Bronner says. The lamprey's head contains neural-crest-derived cartilage that becomes facial structures in other vertebrates, but the faceless lamprey has no jaw. "We're trying to find out why, during vertebrate evolution, another derivative of neural crest cells was invented that gave rise to jaws."

Lampreys have been on the scene for 550 million years, so being jawless clearly hasn't hurt them much. But when jaws did appear, vertebrates really took off. It's hard to know what sparked the explosion of new species, Bronner says, "but you have to eat a lot less if you eat meat instead of plankton. Jaws are important because they allowed predation to occur, and there's some speculation that *that* allowed the brain to grow, and made vertebrates evolve even faster.

"These lampreys have really nice migrating neural crest cells that come out of the nervous system, and they go to the same places that neural crest cells would in us," Bronner says, "except they are not remodeled into the bones of the jaw." Furthermore, lampreys aren't *just* missing a jaw—they lack other common crest-cell derivatives such as sympathetic ganglia, which are clusters of neurons that prepare your body to fight or flee by doing such things as controlling the blood supply to your muscles.

Determining where these features come from requires decoding the genetic playbook that directs the differentiation of cells derived from the neural crest. "We want to see what is different in the lampreys' instructions compared to other organisms," Bronner says. To do that, she and her colleagues have recently turned to yet another organism: the tiny, tropical, transparent zebrafish. Zebrafish are used by many developmental biologists because they grow rapidly in the lab—and because you can peer into their see-through bodies.

"How that work began is one of those 'only at Caltech' stories," explains Bronner. At the time, about six years ago, the National Institutes of Health was creating so-called Centers for Excellence in Genomic Science. "These grants were tailored for projects that were considered very risky but potentially had very high yield," she recalls. "I thought, Who would be fun to work with, and what kind of project could we come up with that was really outside of the box—and outside of anything that I had been doing before? We ended up looking at performing a screen for novel genes in zebrafish and found many interesting ones involved in craniofacial development."

Bronner recruited postdoc Sean Megason, biologist Scott Fraser, and bioengineer Niles Pierce, and they pooled their disparate talents to create a new center for mapping vertebrate development—with Bronner bringing the developmental biology know-how, Megason and Fraser the tagging and imaging tools, and Pierce the molecular-detection methods he'd created in his lab. The ultimate goal? To create a "digital fish" to model the genetic orchestra that transforms an egg into an embryo.

The project was inspired by landmark studies on fruit flies conducted in the late 1970s and early 1980s by biologists Christiane Nüsslein-Volhard and Eric Wieschaus. Nüsslein-Volhard's and Wieschaus's research, which

A THREE-WAY SPLIT

Nüsslein-Volhard and Wieschaus shared their 1995 Nobel with Caltech's Ed Lewis. The Morgan Professor of Biology, Emeritus, at the time of his death in 2004, Lewis had been at Caltech as a student (PhD '42) and faculty member since 1939. Lewis, Nüsslein-Volhard, and Wieschaus all induced genetic mutations into the common fruit fly, *Drosophila melanogaster*, to determine the affected genes' roles in the insects' development.

Nüsslein-Volhard and Wieschaus discovered a handful of master genes that control which end of the fly egg becomes the embryo's head and that lay out the basic body plan. Meanwhile, Lewis found a second group of master genes that orchestrate the development of the body's parts: eyes, antennae, wings, legs, what have you. In work that united genetics, developmental embryology, and evolution, Lewis showed that these genes are strung along the chromosome in the same order, from head to tail, as the parts they control—a basic organizational scheme since found in all other animals. These homeotic or HOX genes, as they're called, are very, very old, containing almost identical DNA sequences in flies and in humans.

Tatjana Sauka-Spengler (left) and Marcos Simoes-Costa prepare the reagents for a study of facial defects in zebrafish.

Tatiana Hochgreb (left) and Bronner at the centrifuge used for protein separations.

earned them a share of the Nobel Prize in Physiology or Medicine in 1995, was deceptively simple in plan: douse flies with chemical mutagens to muck up every developmentally interesting gene, and then see what happens.

"When they did this, they were considered sort of crazy, but it ended up being incredibly important and drove the entire field of *Drosophila* developmental biology for years," Bronner says. "So we thought we could do something similar in vertebrates, using zebrafish. Our plan was to do a screen to identify lots of developmentally important genes, and perhaps understand their function."

Instead of mutating genes, however, they decided to randomly tag proteins with green fluorescent protein—a common molecular marker that glows green under ultraviolet light and allows the tagged proteins to be spotted within specific cells, or even particular parts of cells.

To date, Bronner and her colleagues have produced some 260 green fluorescent zebrafish lines, which are housed in more than 800 clear acrylic tanks in a basement lab. Using those fish, she and her team have discovered several proteins that are crucial to fashioning a proper face.

For example, postdoc Tatiana Hochgreb has found a protein that seems to be involved in the transition from cartilage to bone in the jaw. In normal jaw development, cartilage cells build a scaffolding and then die, paving the way for bone-forming osteoblast cells to climb into the scaffolding and convert it to bone. The protein Hochgreb found, a DNA-binding protein, is made by a gene that turns on for only 24 hours or so between days three and four of embryonic development. But during that short interval, it tells the cartilage cells exactly when to die. That timing is critical: the cells *have* to die at a particular time, when the scaffolding is the right size. If not, the bone doesn't form correctly.

Moreover, Bronner says, "if you knock out this protein, you end up with extremely malformed jaws"—a fish "face" that is squished flat. The defects only affect the cranial bones, she says, "so some of the bones of the neck are still okay, and the trunk forms normally."

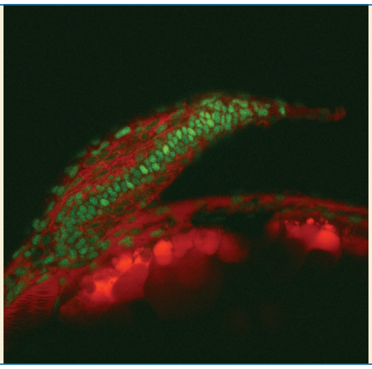
Intriguingly, many of these same proteins crop up in higher vertebrates, including us. Some may be associated with human craniofacial defects, like cleft palate. Tracing these proteins back to the network of genes that builds our faces could lead to new genetic screens, Bronner says, "so you'd know in advance that something is happening with a particular child." Not a bad day's work for a motley group of giant bloodsuckers and inoffensive, two-inch-long fish. e&s

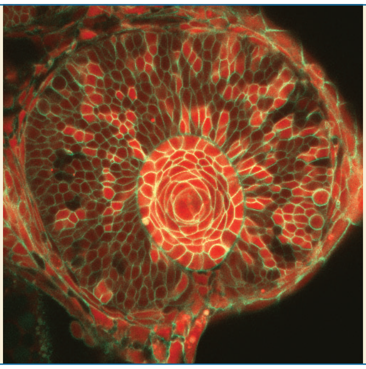
Ruddock Professor of Biology Marianne Bronner has been at Caltech since 1996. She got her BS from Brown in 1975 and her PhD from Johns Hopkins in 1979; both degrees are in biophysics.

Scott Fraser is the Rosen Professor of Biology and professor of bioengineering.

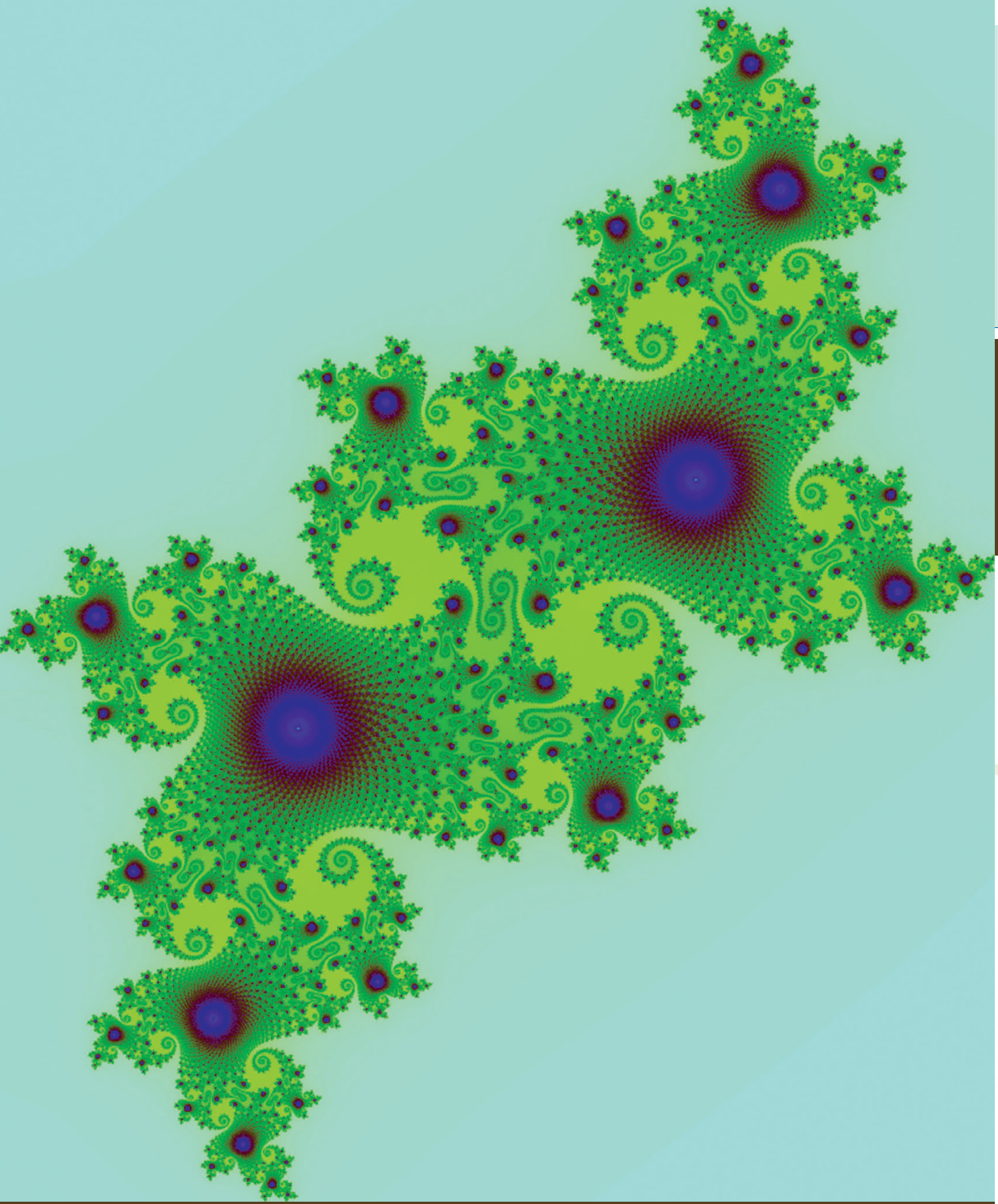
Niles Pierce is a professor of applied and computational mathematics and bioengineering, as well as executive officer for bioengineering.

This work was supported by the National Institutes of Health.





Fluorescently tagged proteins in a zebrafish's fin (far left) and eye (left). The tagging technique used in these pictures is the same as that used to identify proteins important for jaw formation.



The Julia set at left is a fractal pattern. Because of their irregularity, fractals are what mathematicians call noncommutative spaces, which could be important to understanding the universe.

Unexpe

For Matilde Marcolli, physics and mathematics don't intersect so much as form a two-way street—which she travels in both directions, exploring the abstract world of math and pondering the nature of the cosmos.

The joke goes something like this: a physicist and a mathematician are staying at a hotel when, in the middle of the night, small fires break out in their rooms. The physicist wakes up and surveys the scene. She grabs the hotel note pad and pen and does some quick calculations. After determining exactly how much water is needed to extinguish the fire, she fills up the ice bucket with water and pours it over the flames. In the other room, the mathematician wakes up and sees the fire. She gets up and looks over at the faucet and notices the ice bucket. "Ah ha! There's a solution to the problem!" she says. Satisfied, she climbs back into bed.

There are many versions of this joke, all of which seem to come at the expense of the mathematician, and it illustrates a certain divide that has plagued the two professions. Although they both work with complicated equations and share areas of research, mathematicians and physicists are seen as different breeds with different passions. For a pure mathematician, the beauty of a theorem is an end in itself, a greater truth that transcends physical reality. The fact that it is possible to extinguish the fire is enough to fulfill the mathematician's desires—any relevance to the real world is incidental. "Mathematics possesses not only truth, but supreme beauty," Bertrand Russell said. But for a physicist, math is the language of nature, a mere tool for understanding how the universe works. Richard Feynman, embodying the brash physicist, said, "I love only nature, and I hate mathematicians."

cted Connections

By Marcus Y. Woo

But math and mathematicians have always been inextricably tied to physics and physicists. Isaac Newton invented calculus to describe the laws of motion. Albert Einstein used a branch of pure mathematics called differential geometry to formulate his theory of gravity as warped space and time. You can't do physics without math, and regardless of cultural and intellectual differences—real, perceived, or manufactured—the two are committed to each other, in sickness and in health, till death do them part.

Matilde Marcolli is well versed in the relationship between math and physics. She studied physics at the University of Milan before going to the University of Chicago for a PhD in mathematics, and is now a professor of mathematics at Caltech. She thrives on taking seemingly unrelated ideas from physics and applying them to solve math problems—and vice versa. As a theoretical physicist, she develops new models of the universe and possible theories of quantum gravity, the so-called theory of everything. For Marcolli, math and physics don't intersect as much as form a two-way street—and she goes in both directions.

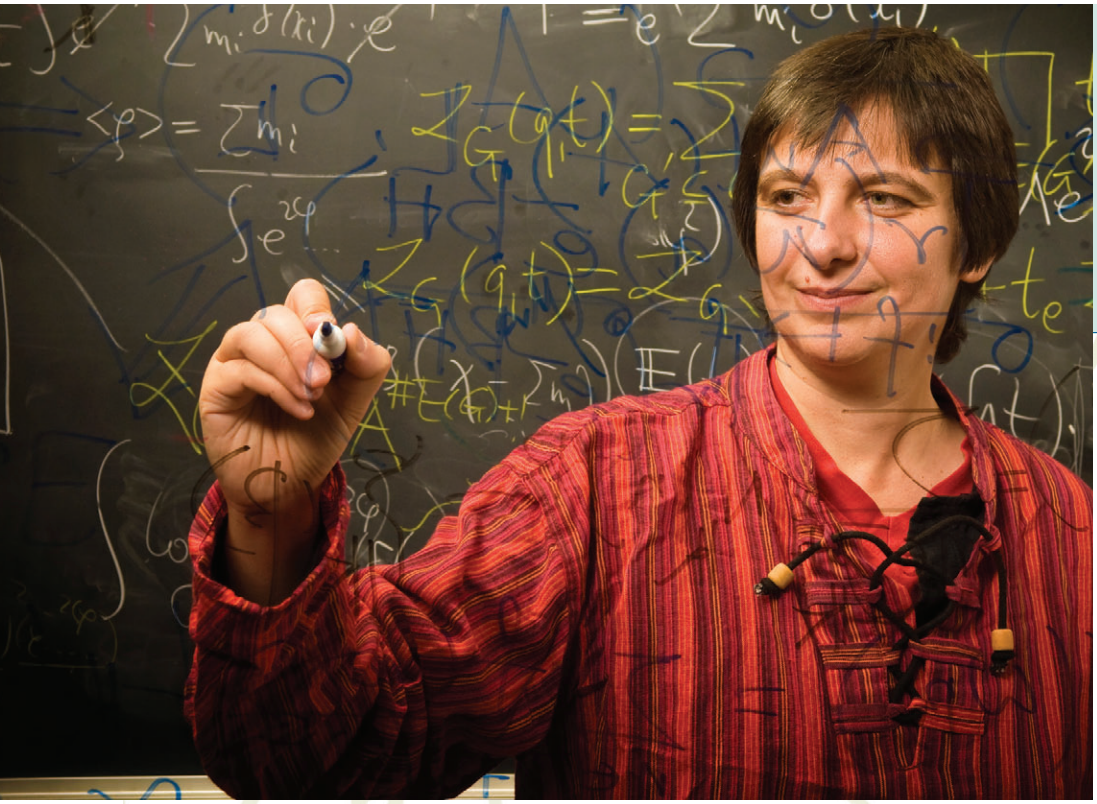
"One of the most exciting things in science is seeing unexpected connections between different things," she says. "At any given time, you're just looking at a very small detail of this great big picture, and you try to connect as many dots as you can." So does she consider herself a physicist or a mathematician? "Depends on the day," she quips.

On the days when Marcolli is mulling mathematics, she works on problems in areas such as number theory, which is the study of numbers and their properties. Although number theory has some emerging applications—in cryptography, for instance—it's about as pure as math can get. But with Gunther Cornelissen from the University of Utrecht in the Netherlands, Marcolli has recently applied ideas grounded in the physical world—albeit in quantum physics—to solve a problem in the even more abstract world of numbers, involving objects called number fields.

NUMBER FIELDS FOREVER

Most of us think of numbers as mere quantities, a way to represent how many apples you have in your bag.

One place number theory meets the real world is in the Fibonacci series (0, 1, 1, 2, 3, 5, 8, 13, 21, 34 . . .) where every number is the sum of the two that preceded it. The number of florets in each spiral on this head of Romanesco broccoli is a member of the series. The resulting pattern forms a fractal.



Regardless of whether she's a physicist or a mathematician, Matilde Marcolli immerses herself in a sea of equations.

But for a mathematician, they're like organisms with their own behaviors and characteristics, and, like organisms, numbers can be classified according to their properties and the operations one can perform with them. One way to classify numbers is by constructing a field, a set of numbers that satisfy certain rules. An example is the field of rational numbers—numbers that can always be written as a ratio of two integers and that obey rules like addition, subtraction, division, and multiplication.

You can generate a *number* field by extending the field of the rational numbers. To extend the field, you can include certain kinds of irrational numbers, such as $\sqrt{2}$. (For the mathematically inclined, these numbers must be solutions of polynomial equations with integer coefficients.) The extended field still contains all rational numbers, but also $\sqrt{2}$, and any combination thereof, such as $\sqrt{2} + 1$.

It turns out that you can use the numbers in a field to define various functions. As you might recall from high-school math, some simple functions include sine and cosine, where you put in one number and out comes another. One famous function is the Riemann zeta function, which is closely associated with prime numbers—integers that are only divisible by one or themselves. Each number field has its own prime numbers and a corresponding generalization of the Riemann zeta function, called the Dedekind zeta function.

Number fields and functions come from two completely different areas of mathematics, Marcolli explains, since number fields are discrete quantities while functions are continuous objects. The fact that the two have anything to do with each other is just another instance of connecting bits and pieces to make sense of the larger mathematical picture.

Marcolli and Cornelissen looked at a set of functions that includes the Dedekind zeta function, trying to understand how well these functions reveal the properties of the corresponding number fields. Although you can start with a number field and build functions from it, it's not obvious that you can go the other way and determine the corresponding number field solely from a set of functions. In other words, it's easy to take two-by-fours, nails, Sheetrock, and paint and build a wall. But if you just look at a finished wall, you can't really tell what components were used to construct it.

Mathematicians have long known that the Dedekind zeta function by itself was not enough to determine the field. But to their surprise, Marcolli and Cornelissen discovered that when you have the Dedekind zeta function *and* these other functions, you actually could characterize the corresponding number field. "These functions know everything there is to know about the field," Marcolli says.

And here's where the physics comes in: these functions describe the so-called equilibrium states of a quantum system, which consists of a collection of particles, such as a bunch of electrons. This type of system behaves like a collection of tiny magnets, Marcolli explains. At low temperatures, their poles align and point north. But if you turn up the heat, they become more energetic and their orientations mix, putting them in a new state. Likewise, a quantum system has different states depending on its energy levels.

Marcolli and Cornelissen realized that the set of functions that describe these equilibrium states could also be used to characterize their number fields. Such unexpected connections fascinate Marcolli. Who would have thought that some aspect of number theory, so far removed from the real world, would somehow be related to the quantum states of particles?

"This is an example of using ideas and methods from physics to answer a question that is purely mathematical," she says. "When you formulate the question, there's no physics in it. But the way that you think about it, and how you prove it, uses a lot of physics. It's an interaction between mathematics and physics that is less intuitive than the traditional way we use mathematics in physics problems. This is using physics for problems in mathematics."

SOME SPECTRAL ACTION

When Marcolli is driving in the more traditional direction on the physics-math highway, using mathematics for problems in physics, she's developing new mathematical models for gravity and elementary particles, with the goal of introducing new ideas for a possible theory of quantum gravity. This is the type of theory that has been touted as a potential theory of everything, combining gravity with the other fundamental forces of nature. A viable theory of quantum gravity has been elusive because it tries to blend two divergent yet wildly successful theories. At one end, there's quantum mechanics, which deals with subatomic particles and tiny scales. At the other end, there's general relativity, which describes gravity and the nature of the universe at cosmic scales. According to general relativity, space is smooth. But when you zoom in to the minuscule scales of quantum gravity—a hundred billion billion times smaller than an electron—space is intrinsically not smooth, with particles popping in and out of existence in what's been dubbed quantum foam. "These two things seem at odds with each other," says graduate student Kevin Teh, who works with Marcolli on new mathematical models for cosmological theories.

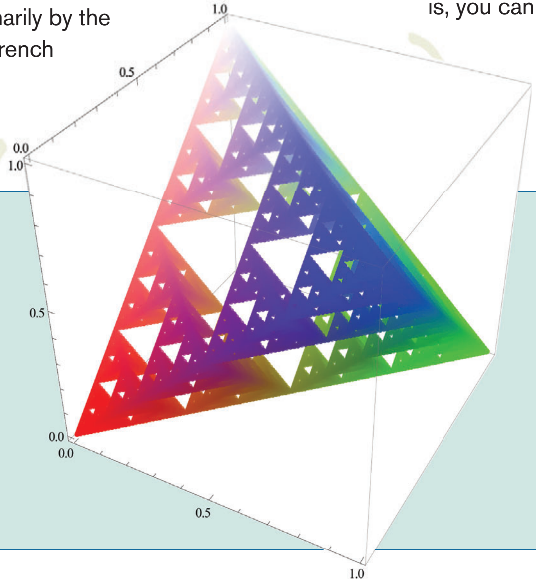
Mathematically, this "nonsmoothness" manifests itself in a property called noncommutativity. The normal, everyday rules of math are commutative—that is, A × B = B × A. But quantum mechanics isn't exactly normal, and because of the Heisenberg uncertainty principle, which says you can't precisely measure a particle's velocity and position at the same time, the simple commutativity rule breaks down. Incorporating these messy, unsmooth spaces—called noncommutative spaces—with the smooth spaces of general relativity, requires different mathematical techniques. Perhaps not surprisingly, one such approach is called noncommutative geometry.

Developed primarily by the French mathematician Alain Connes in the 1980s, noncommutative geometry tries to make sense of these weird spaces, which, in the broader mathematical context, are abstract spaces—not necessarily the space of the universe. "The thing is, you can't visualize noncommutative spaces—you fundamentally cannot," Teh says. But we can come close—the jagged, rough edges of the Mandelbrot set that's popular in calendars and posters are also examples of noncommutative spaces. Or, in a metaphor that gives a better sense of how bizarre these spaces are, Marcolli compares them to the seemingly haphazard arrangement of colors, splotches, and squiggles in a Jackson Pollock painting.

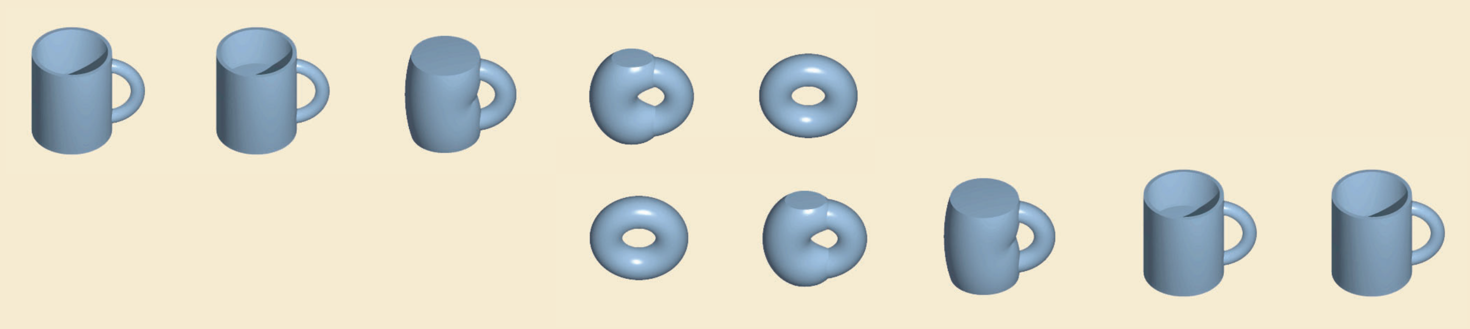
Using noncommutative geometry, Marcolli, Teh, and Elena Pierpaoli at the University of Southern California have

> "The thing is, you can't visualize noncommutative spaces—you fundamentally cannot."

Above: Marcolli and grad student Kevin Teh talk cosmology outside the Red Door Café on campus.



Left: This three-dimensional representation of the solids and voids in a type of fractal called the Sierpinski triangle was calculated by sophomore Christopher Perez, who worked with Marcolli on a Summer Undergraduate Research Fellowships (SURF) project.



recently come up with a model that makes a new prediction about cosmology. This model is derived from something called a spectral action. Generally speaking, an action is a quantity that captures all the relevant physics of a theory into a single, neat mathematical term. The term can then be manipulated mathematically to unzip all the relevant equations.

To visualize a spectral action, Marcolli explains, imagine that the space of the universe is a flat drumhead. Every drum vibrates at certain frequencies depending on its material, size, and shape, giving each instrument a distinct sound. Likewise, the space of the universe has a spectrum of frequencies, and by adding them up in a certain way you generate a spectral action.

Models based on a spectral action are exciting because they're an all-inclusive packaged deal. They give Einstein's equations for general relativity as well as the equations of the Standard Model—the theory of how elementary particles interact—and, as a bonus, equations that describe other observable phenomena. Some versions contain more speculative theories like supersymmetry, which physicists hope to confirm with the Large Hadron Collider (LHC) in Switzerland. The spectral-action model that the researchers came up with provides a mechanism for one of the cornerstones of modern cosmology: inflation, the theory that the newborn universe underwent a rapid expansion in a fraction of a second.

Early theories of inflation have been qualitative, says Teh, describing this cosmic event in broad strokes. But in our era of precision cosmology, in which scientists are making increasingly detailed measurements of the universe, physicists need ever more exact models that make quantitative predictions. As it turns out, the researchers' model predicts that the details of inflation depend on the universe's topology.

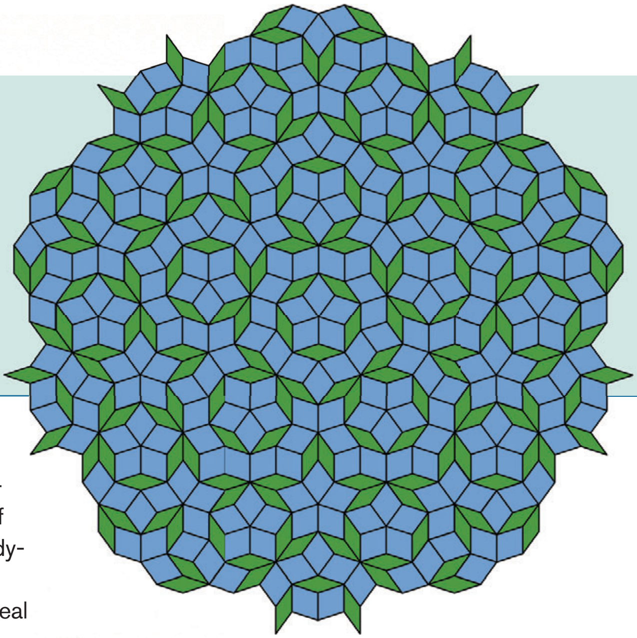
While geometry describes an object's specific size and shape, topology studies more general, fundamental features. The classic example involves a doughnut and a coffee mug: because both objects have a hole in the middle—the doughnut hole and the hole that's formed by the mug's handle—both have the same topology. If the doughnut were made out of clay, you could fashion it into a coffee mug while preserving the hole, thereby preserving its topology.

When physicists describe the universe as being flat or nearly flat, they're talking geometry: how space and time are warped according to general relativity. When they talk about whether the cosmos is closed or open, they're referring to its topology. The surface of a sphere, for example, is closed. If an ant walking on a billiard ball takes a straight path, it will eventually retrace its steps. Analogously, in a closed universe, you could shine a flashlight forward and, if you waited long enough, the light would strike you on the back of the head.

"Up to now, we couldn't say much about the topology of the universe," Teh says. But according to the researchers' model, different cosmic topologies would lead to different inflation scenarios, which in turn would leave different signatures on the cosmic microwave background—the pervasive radiation leftover from the Big Bang. This means that, in principle, careful measurements of the cosmic microwave background could reveal what the topology of the universe is like.

Above: Doughnuts and coffee mugs are topologically equivalent because both are pierced by exactly one hole each. In principle, the one could be transformed into the other, which is why one should never delegate a mathematician to make a Starbucks run.

Left: These swirling blots of paint could be seen as an abstract representation of a noncommutative space.



Right: Penrose tilings are also noncommutative spaces. Unlike the tiles on your bathroom floor, which repeat in a simple pattern over and over and over again, a Penrose tiling never completely repeats. You may be able to shift and rotate a Penrose tiling so that a small segment of the pattern overlaps itself, but the rest of it will not.

This is just one in a whole family of models based on the spectral action and noncommutative geometry—and there are many other models that use different mathematical approaches. But it's a good thing that theoretical physicists are rife with ideas, Marcolli notes. With a number of large experiments in cosmology and particle physics now under way—the Planck satellite and the LHC, for example—many of these theories will soon be tested. "It's an ideal time to try new mathematical techniques and see how far you can get by providing testable models," she says.

IT'S COMPLICATED

Noncommutative geometry is an example of pure mathematics having unexpected applications in physics. But whether a new mathematical idea is useful for physics shouldn't be the motivating force for a mathematician. "You cannot plan a priori what will be relevant," Marcolli says. "It's good to develop mathematics because new developments are interesting mathematics. It would be nice if they turn out to be interesting physics as well, but one cannot say whether it will take a few years, a hundred years, or several hundred years for people to discover that some types of mathematics lead to interesting physics." Teh, who considers himself a mathematician, agrees that math should be pursued for the thrill of discovering new ideas. "Mathematicians aren't interested in reworking old ideas," he says. "They're constantly expanding frontiers and finding new things."

On the flip side, Marcolli's work in number theory shows that you never know how physics will repay the favor and give back to math. "Physics is a never-ending source of inspiration for mathematics," Teh says. For example, in the 19th century, Joseph Fourier developed the Fourier series and Fourier transform—basic mathematical tools now used in all branches of physics and engineering—while studying heat flow.

For most of history, there was no real difference between theoretical physics and mathematics, Marcolli says. In the 19th century, as exemplified by the likes of Fourier, mathematicians and physicists were almost indistinguishable. But after the advent of general relativity and quantum mechanics in physics and of similar advances in pure mathematics in the early 20th century, both physics and mathematics became increasingly specialized, and it was then that the relationship status between physics and math became, well, complicated.

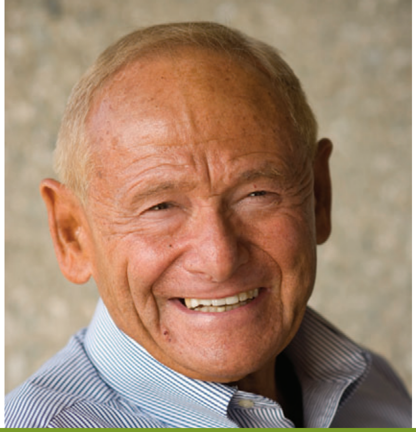
Physicists and mathematicians became so caught up in their own subfields that they stopped communicating. Even when they tried, their different languages made it hard for them to understand each other. According to mathematicians, physicists were sloppy, eschewing rigorous proofs for approximations while ignoring the real beauty and truth in pure mathematical ideas. And according to physicists, mathematicians were too enamored with their own thoughts and theorems, which distracted them from the beauty and truth of nature, of what's "real."

But this division was cultural and sociological and had nothing to do with research, Marcolli argues. "It's very artificial in some sense." She points out that even Feynman, for all his teasing of mathematicians, worked with highly sophisticated mathematics. It just became fashionable for both sides to look down on and disassociate from each other, she says. "I think this attitude is very damaging to both physics and math."

Recently, however, she has seen a shift. "The boundary between mathematics and theoretical physics has blurred over the years." Many areas of physics—not just the high-energy physics world of string theory, but also areas such as solid-state physics and quantum information science—have become more theoretical, requiring sophisticated new mathematical tools and forcing both sides to talk again. Marcolli, as someone who's right in the middle, personifies this remerging of the two disciplines. After all, physics and mathematics have the common goal of finding things out, whether it's learning about number fields or cosmic inflation—or just putting out a fire.

Matilde Marcolli received a laurea *in physics from the University of Milan in 1993 and her MS and PhD in mathematics from the University of Chicago in 1994 and 1997, respectively. After a stop at MIT as a C.L.E. Moore Instructor, she received a courtesy appointment at Florida State University, which she still holds today. She was an associate professor at the Max Planck Institute in Bonn, Germany, before becoming a professor of mathematics at Caltech in 2008. Since 2006, she has also held an honorary professorship at Bonn University.*

Her research is supported by the National Science Foundation and the Australian Research Council.



THOMAS J. AHRENS

1936–2010

Thomas J. Ahrens (MS ’58), the Jones Professor of Geophysics, Emeritus, died at his home in Pasadena on November 24. He was 74.

Ahrens, who worked in the U.S. Army’s Ballistics Research Laboratory from 1959 to 1960 en route to earning his doctorate, was among the first to take shock-compression techniques developed by government labs for testing nuclear weapons and apply them to the academic study of conditions deep within the earth. These methods subjected materials to extremely high temperatures and pressures by smashing two samples together at very high speeds—in other words, by loading one into a cannon and shooting it at the other. (Nowadays, researchers reach these conditions routinely by squeezing a sample between diamond anvils and heating it with a laser.)

Ahrens’s first “cannon” was a shotgun from Sears, but over the years larger and larger pieces of ordnance found their way into the subbasement of South Mudd—culminating in three 20-foot-long barrels cut from six-inch-caliber naval guns and joined end-to-end to form the pump section of a two-stage “light gas gun” that was in use until 1991. The first stage of such a gun uses a conventional smokeless-powder charge to fire a piston down the barrel, which is filled with highly compressible hydrogen. Halfway to the muzzle, the gun abruptly necks down into a second, smaller-diameter barrel containing the sample projectile and separated from the pump barrel by a thin metal plate. The supercompressed hydrogen bursts through the plate, gains additional velocity from being forced into the smaller second stage, and shoots the projectile at velocities of up to 7.5 kilometers per second—more than the minimum impact speed of a slow asteroid hitting Mars, and two-thirds the minimum impact velocity with Earth.

In the 1980s, Ahrens’s team used a single-stage, 40-millimeter gun capable of achieving pressures of 400,000 times Earth’s atmosphere—sufficient to melt an 80-gram iron projectile on impact—to estimate the temperature profile of Earth’s core. Other studies looked at the effects of meteor strikes. Ahrens concluded from these that our water (and much of our atmosphere) must have arrived from the outer reaches of our solar system via icy comets after the protoplanets that formed Earth had finished crashing into one another—otherwise, each fresh impact would have blasted such volatile substances into space.

In 1986, Ahrens and former postdoc Manfred Lange published a calculation of the amount of carbon dioxide that would have been released into the atmosphere when a 10-kilometer asteroid splashed into shallow seas just off the Yucatán peninsula 65 million years ago. Ahrens and Lange used bullets of steel and targets of limestone, a common sedimentary rock made of calcium carbonate, and concluded that enough of the greenhouse gas would have been generated to raise Earth’s average surface temperature between 5 and 20°C for up to 10,000 years. If this didn’t kill the dinosaurs, it would have made them mighty uncomfortable.

“Tom was a highly productive scientist and a dedicated mentor to dozens of students, postdocs, and visitors who now fill the ranks of mineral physicists at universities around the world,” says Professor of Geology and Geochemistry Paul Asimow (MS ’93, PhD ’97), an Ahrens protégé who now runs the Lindhurst Laboratory of Experimental Geophysics, as Ahrens’s gun collection is formally known.

Born in Frankfurt, Germany, on April 25, 1936, Ahrens received his BS from MIT in 1957 and his PhD from Rensselaer Polytechnic Institute in 1962. He headed the Poulter Laboratory’s geophysics section at the Stanford Research Institute from 1962 to 1967 before joining Caltech as an associate professor. He became professor of geophysics in 1976, and was the W. M. Keck Foundation Professor of Earth Sciences from 1996 to 2001; he was named Jones Professor in 2004, and went emeritus in 2005.

Ahrens published nearly 400 papers and held three U.S. patents. He was a member of the National Academy of Sciences and the American Academy of Arts and Sciences, and was a Foreign Associate of the Russian Academy of Sciences. His professional honors included the Geological Society of America’s Day Medal, the American Physical Society’s Duvall Award, the American Geophysical Union’s Hess Medal, and the Meteoritical Society’s Barringer Medal. The asteroid 4739 Tomahrens (1985 TH1) is named after him.

Ahrens is survived by his wife, Earleen; children Earl, Eric, and Dawn; and grandchildren Greta, Violet, Jacqueline, and Samuel.
—DS/MW e&s

Forty years ago, the estate of Margaret Ruddock endowed a professorship in honor of her husband.

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EUGENE W. COWAN
1920–2010

Eugene W. "Bud" Cowan (PhD '48), professor of physics, emeritus, passed away on November 4 in Menlo Park, California. He was 90.

Cowan's research included investigations of high-energy interactions of cosmic rays, air-pollution studies, and studies of the earth's magnetism.

An innovative instrument builder, Cowan was best known for his perfection, in 1950, of a cloud chamber capable of continuous operation. A cloud chamber makes the tracks of subatomic particles visible, allowing the particles themselves to be identified. The chamber works by causing droplets of vapor to condense along the trail of ions the particle leaves behind as it interacts with air molecules. Previous cloud chambers had required a sudden, large drop in chamber pressure in order for this condensation to occur, followed by a rest period during which no observations could be made. Cowan's innovation eliminated the need for the pressure decrease and thus eliminated the rest period.

Cowan was particularly proud of his work in the early 1950s on the Xi "cascade" particle, the first doubly strange baryon. His cloud-chamber image clearly confirmed the existence of the particle and provided important input that led to the subsequent development of the quark model. His later work focused on the dynamics of the mechanism that generates the earth's magnetic field.

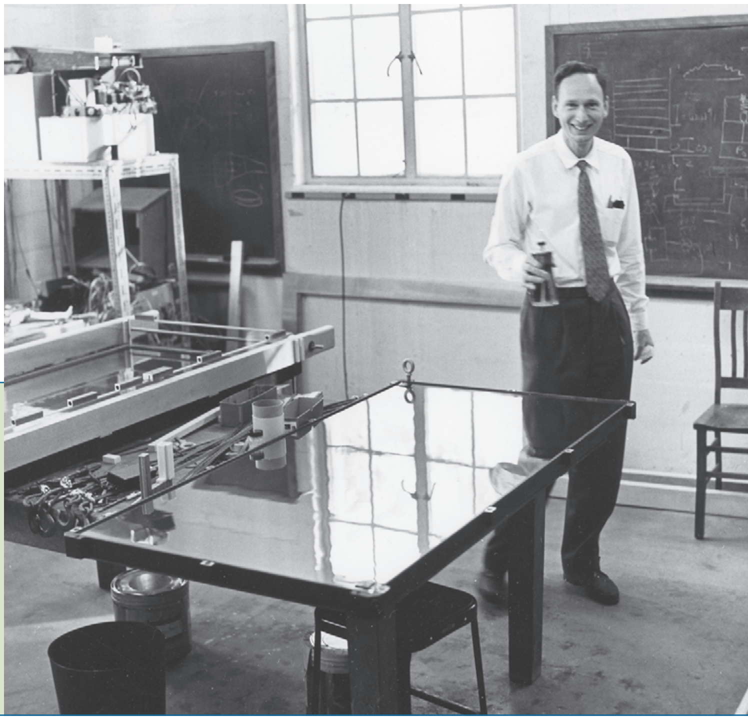
Cowan was born in 1920 in Ree Heights, South Dakota. After receiving his BS at the University of Missouri and his SM at MIT, where he was an instructor in the radar school and at the Radiation Laboratory, he came to Caltech in 1945. Cowan earned his doctorate under cosmic-ray researcher and Nobel laureate Carl Anderson (BS '27, PhD '30). He became a research fellow in 1948, an assistant professor in 1950, and an associate professor in 1954. In 1961 he was promoted to professor of physics, and he became an emeritus professor in 1986.

Cowan was awarded four patents, including one for his innovative cloud chamber. He was a fellow of the American Physical Society.

Long recognized for the quality of his teaching, Cowan received the 1986 Associated Students of the California Institute of Technology (ASCIT) award for teaching excellence for his course on classical electromagnetism.

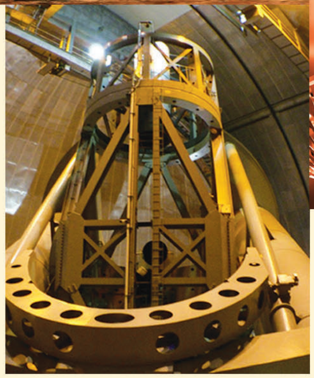
Says his son, Glen, a particle physicist at Royal Holloway, University of London, "My father truly enjoyed being part of the Caltech community. I believe he was there almost every day from 1945 to 2008. Maybe that's some kind of record." An avid hiker in the San Gabriel Mountains, he "walked the two and a half miles to and from work for probably more than 50 years, and for much of that time also went daily to the Caltech pool and gym." In 2008, Cowan and his wife, Thelma, moved from Pasadena to Menlo Park, California, to be near their daughter, Tina, a geneticist at Stanford University.

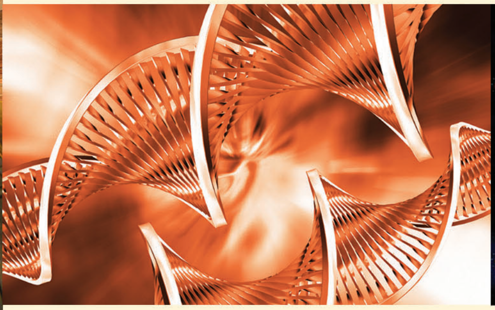
Cowan is survived by his wife of 54 years, Thelma Rasmussen Cowan; daughter Tina Cowan Hiltbrand and son Glen Cowan; and grandchildren David and Karin Hiltbrand. —*KS* e&s

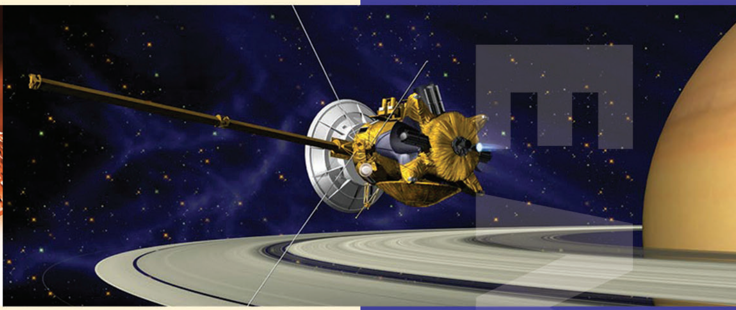


Bud Cowan with one of his cloud chambers—the flat panel that looks like a tabletop—circa 1959. Photo courtesy of Glen Cowan.

WHAT STELLAR ADVANTAGE DO 8 OUT OF 10 CALTECH EMPLOYEES SHARE?







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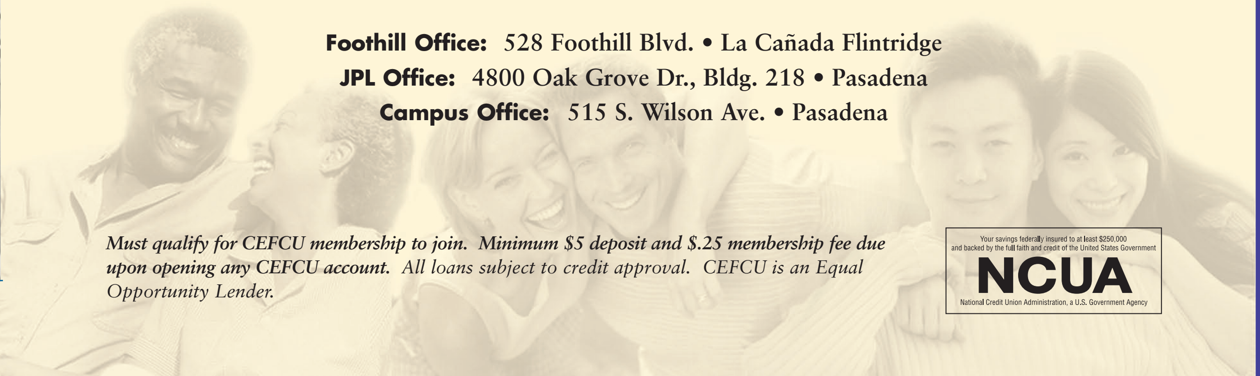

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We asked Caltech alums to tell us their favorite traditions. Here's what they had to say:

ENDNOTES

Ditch Day[1]

Millikan pumpkin drop[2]

INTERHOUSE[3]

Honor code[4]

Negative-time Tommy's run[5]

Midnight doughnuts[6]

BLACKER CHIMNEY STACK[7]

"The Ride of the Valkyries"[8]

FINALS WEEK SNAKE KITS[9]

Firing of the Fleming cannon[10]

1. The day when seniors ditch campus, leaving behind elaborate puzzles, or "stacks," for the rest of the undergrads to solve. The exact date of Ditch Day is a closely guarded secret; it's always "tomorrow." Until it's today.
2. The Dabney Hovse[a] interpretation of the Millikan Library's namesake's classic oil-drop experiment, performed at midnight on Hallowe'en. Pumpkins frozen in liquid nitrogen plummet 10 stories from the parapet to the pavement, a ritual begun in 1972 by a group of problem-set-avoiding sophomores to 1) test whether students could access the new library's reportedly inaccessible roof (success!) and 2) demonstrate triboluminescence, the emission of blue-green photons by compressed sugar molecules (not so much).
    a. The inscriptions on the lintels in the four original student residences read "Hovse" in the Latin style of carving; the residents have adopted the spelling.
3. Fall term's simultaneous and elaborately themed house (and hovse) parties. The tradition began in 1934 as the Interhouse Hallowe'en Dance.
4. "No member of the Caltech community shall take unfair advantage of any other member of the Caltech community."
5. A Caltech rite of passage possible only one night of the year: when daylight savings time returns to standard time. The object? Get to the original Tommy's burger joint (corner of Beverly and Rampart Boulevards, just off the Hollywood Freeway), order, eat, and get back to Tech before you left.
6. Offered by ASCIT (Associated Students of Caltech) on the Olive Walk during finals week.
7. Now-discontinued practice of stuffing wadded-up newspaper into the chimney flue in the Blacker Hovse lounge and lighting it on fire. Place the paper just so, and the roiling heat waves would hit a resonant frequency. The vibrations could be heard and felt.
8. The beginning of Act III of the second opera in Wagner's *Der Ring des Nibelungen*, blasted as loudly as possible at 7:00 a.m., every day of finals week—and *only* during finals week; play it at any other time and risk being tossed into the nearest shower. (An exemption is made if you play the entire four-opera ring cycle.) Why 7:00 a.m.? To wake up students in time to start their four-hour take-home finals and turn them in by noon.
9. Final-exam-week junk-food care packages, so named because of the snake printed on the back of the blue books in which many finals are submitted.
10. An 1857 artillery piece fired for important events, such as Ditch Day, the end of the term, graduation, and the president of Fleming Hovse's birthday.


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