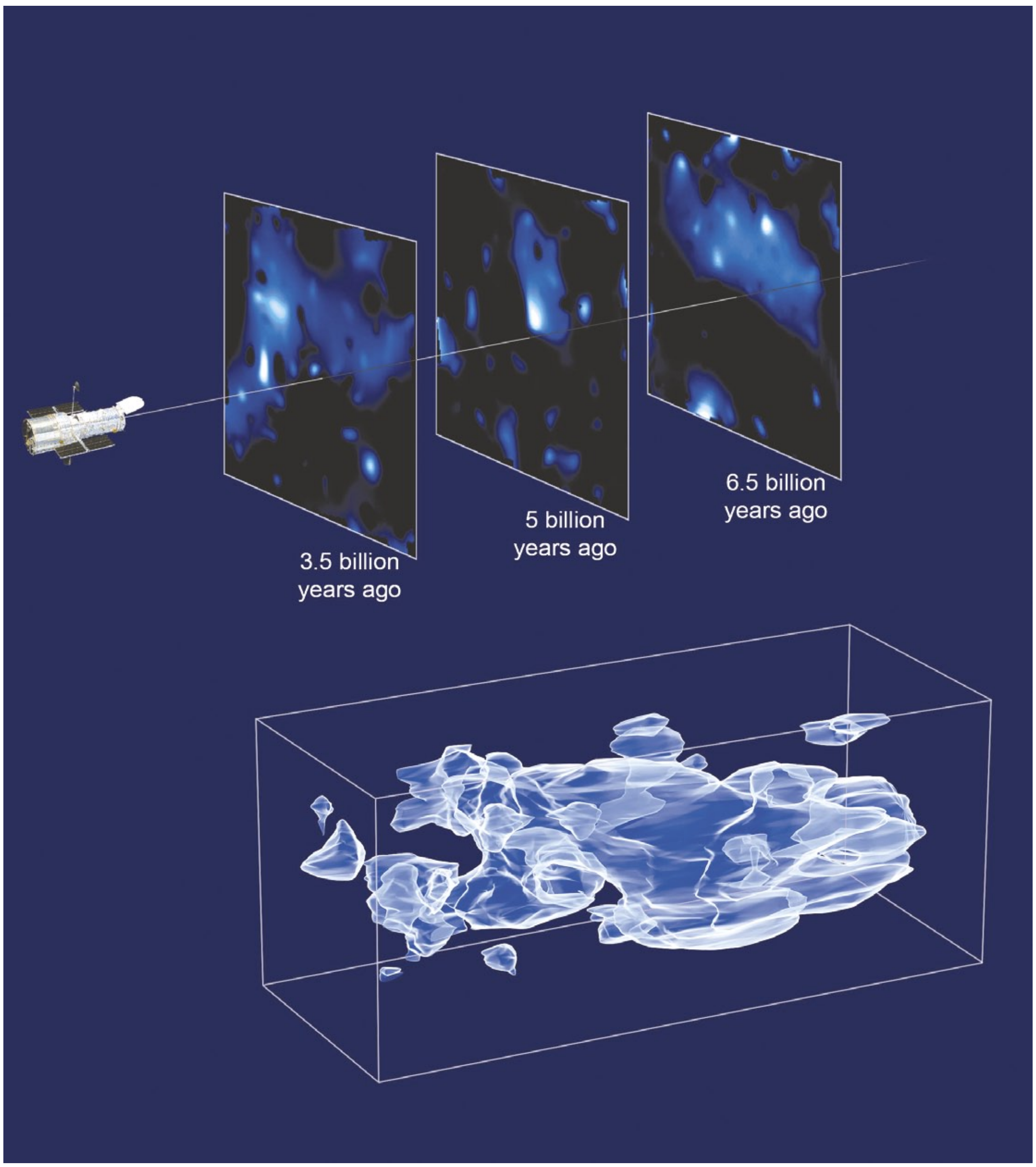
Dark Matter in 3-D

Below: Light travels at a finite speed, so looking out into the distance is equivalent to looking back through time. Combining a set of slices at fixed distances (top) gives a 3-D map (bottom) that is like a geological core sample of the universe. Evolving over time from right to left, the distribution of dark matter becomes increasingly clumpy.

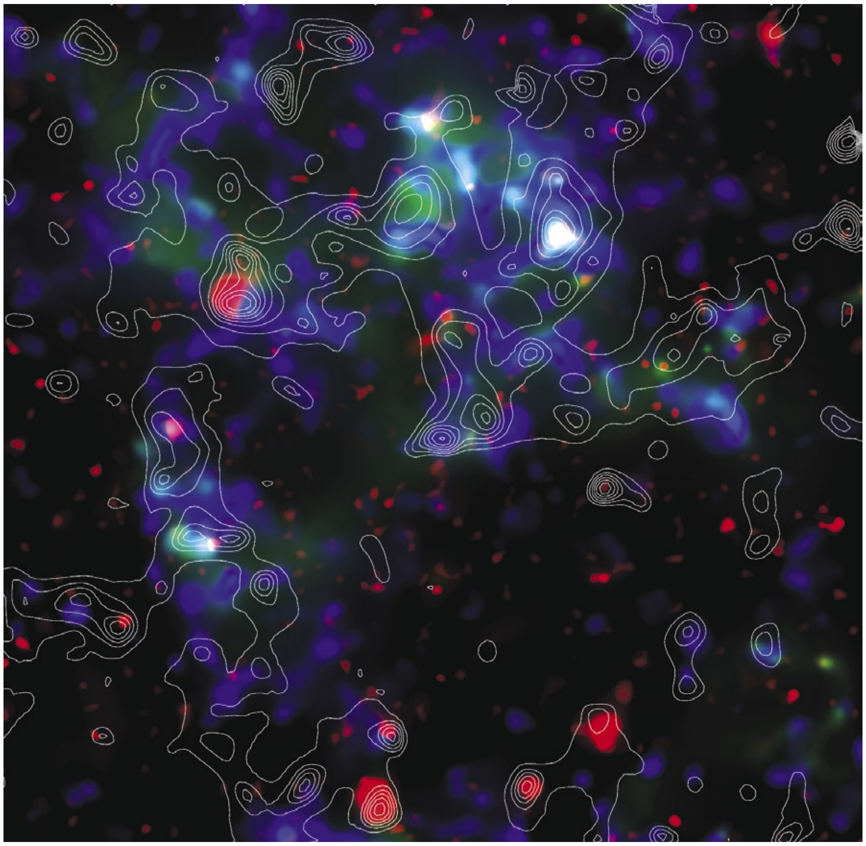


An international team led by Caltech scientists has made a three-dimensional map of dark matter that offers a first look at its distribution. Dark matter, which makes up most of the universe's mass but neither emits nor reflects light, has so far eluded direct detection or even a definitive explanation for its makeup. But a cosmic quirk called "gravitational lensing," first predicted by Einstein, allows the invisible stuff to be traced out.

The light rays from distant galaxies are deflected where space is curved by the gravitational influence of dark matter, making the shapes of background galaxies appear distorted. So postdoc Richard Massey and JPL scientist Jason Rhodes carefully measured those shapes to infer the distribution of foreground structures. Since gravitational lensing is sensitive to all mass, it reveals the location of otherwise invisible features—including one concentration of dark matter a trillion times more massive than the sun, around a previously unknown cluster of galaxies.

The 3-D map, which was unveiled at the January meeting of the American Astronomical Society and also appeared in the January 18 issue of *Nature*, reveals a gelatinous network of cosmological filaments that grew over time, intersecting to form massive structures containing clusters of galaxies. According to lead author Massey and coauthor Richard Ellis, the Steele Family Professor of Astronomy, this provides the best evidence yet that normal matter coalesces to form galaxies only inside the preexisting scaffolding of dark matter.

The map was derived from



Reprinted by permission from MacMillan Publishers Ltd: Massey, et al., *Nature*, vol. 445, pp. 286–290, January 18, 2007.

Above: In this rendering of the entire COSMOS field, the contours show the total mass of both visible and dark matter. Ordinary matter grows inside a dark matter scaffolding: the galaxy mass distribution is shown in blue and number density in yellow; the two combine to become green. Red shows X-ray emission from hot, dense gas in the centers of dense clusters of galaxies. This view covers nearly two square degrees of sky, or roughly nine times the area of the full moon.

the Hubble Space Telescope's widest survey of the universe, led by Nick Scoville, Caltech's Moseley Professor of Astronomy. The Cosmic Evolution Survey (COSMOS) consists of 575 slightly overlapping views of the universe requiring nearly 1,000 hours of observations—the largest project ever undertaken with the Hubble.

Scattered through the COSMOS images are some half-million distorted galaxies whose distances were measured to high accuracy—using color data from the Subaru telescope in Hawaii—as part of COSMOS's research on large-scale structures.

The resulting map stretches halfway back to the beginning of the universe, showing how dark matter started out smooth and grew increasingly clumpy as it continued to collapse. These observations will guide theorists grappling with how large cosmic structures evolved under the relentless pull of gravity, and may illuminate the role of "dark energy"—a sort of negative gravitational force that is believed to influence how dark matter clumps.

According to Scoville, stars in the galaxies in the densest cosmic structures of the early universe are generally found to be older than those in galaxies in more rarified environments, indicating that the galaxies in the denser regions formed first and that the mass accumulated in a bottom-up fashion. By contrast, those galaxies with ongoing star formation today dwell in less populated cosmic filaments and voids.

"Both the maturity of the stellar populations and the 'downsizing' of star formation in galaxies vary strongly with the epoch when the galaxies were born, as well as their dark-matter environment," says Scoville. His team's findings will appear in a future issue of *The Astrophysical Journal*. Other Caltech participants in this COSMOS research on large-scale structures include postdocs Peter Capak and Mara Salvato, Member of the Professional Staff Patrick Shopbell, and Kartik Sheth of the Infrared Processing and Analysis Center. □—*RT*

Delbrück Centennial

A day of science, remembrances, and partying marked the 100th anniversary of the birth of Nobel laureate, molecular biology pioneer, and Caltech professor Max Delbrück. The party, at the Delbrück home one block east of campus, was in keeping with the biologist's penchant for high-spirited shenanigans—until his retirement in 1977, he was known as quite the campus prankster.

"That home became a second home to many of us," recalled Seymour Benzer, the Boswell Professor of Neuroscience, Emeritus, who showed footage of a hike to the bottom of the Grand Canyon in 1949, hosted by Delbrück and his wife Manny. "I had never climbed more than two staircases in my life," Benzer joked. "After 18 miles, I became a unit of tiredness."

Former postdoc Gunther Stent, who went on to establish both the department of virology and the department of molecular biology at UC Berkeley, from where he retired in 1992, recounted Delbrück's early scientific career. Delbrück trained as a theoretical physicist in Göttingen, Germany, but the discipline never fully captured his interest. Just before he came to Caltech in 1937 for a yearlong Rockefeller Fellowship, he was inspired by physicist Niels Bohr to explore the relation of atomic physics and biology, and thus began his foray into the biological realm. Delbrück commenced genetic work on *Drosophila*, a genus of fruit fly that was already becoming a workhorse of molecular genetics, but the forbidding-looking papers categorizing every one of the fly's genotypes turned him off.

By the time he returned to the Institute as a biology professor in 1947, he was fascinated by the question of how viruses infect bacteria, and founded the freewheeling "phage lab," which essentially pioneered the field of bacterial genetics. This work led to a Nobel Prize in Physiology or Medicine in 1969, but according to Stent, accepting it was difficult for Delbrück. He felt the prize contradicted the "Copenhagen Spirit"—an ideal that stressed self-criticism and an egalitarian regard for scientific findings.

Remembrances of Delbrück's early years gave way to today's frontiers of biophysical research. After jokingly referring to himself as an "extinguished" fellow of the Salk Institute, molecular biologist and Nobel laureate Sydney Brenner, an occasional visitor to Caltech since 1960, challenged the audience to tackle biological complexity by returning to phage biology. "The best thing we can do in biology is what we're damned good at: the forward problem. We can't do the inverse problem—I call that the 'low-input, high-throughput, no-output problem,'" he said. Howard Berg (BS '56), now a professor of both physics and molecular and cellular biology at Harvard University, recalled how Delbrück's influence led him to study *E. coli*. Delbrück once told Berg that if he had to do it over again he'd work with bacteria, but he didn't know how to tame them. The word "tame" caught Berg's interest, and the rest, as they say, is history. Berg gave a nod to the Caltech team that took 3-D pictures of a bacterium's flagellar motor (see *E&S*, 2006, No. 3, p. 6); he himself studies the rotary motor of *E. coli's* flagella. Max Delbrück's son Tobi Delbrück (PhD '93) came from Zurich, where he teaches neuroinformatics at the Eidgenössische Technische Hochschule (ETH), and showed off his new toy—a retina built like the human eye's, but in the form of a silicon chip. He had been inspired to his current pursuits during his graduate work with the senior Delbrück's colleague Carver Mead (BS '56, MS '57, PhD '60), the Moore Professor of Engineering and Applied Science, Emeritus.

The celebration resonated even for those who had never met the legend. Rob Phillips, professor of applied physics and mechanical engineering, credited Delbrück for influencing his own career path, which has led to insights into how DNA is packed into viruses—like balls filling a bathtub and locking together to form hexagons. "He's an abstraction, a myth, and a legacy in the same way Feynman or Gibbs might be," Phillips said.

The centennial ended as one imagines it would have in Delbrück's day, with movies and jokes. Professor emeritus and former chair of the biology division Ray Owen recalled the party that marked his last day of chairmanship in 1968. Delbrück presented to Owen an accurate metal sundial fabricated in the astrophysics shop, and then began scribbling on the board a lengthy equation of time demonstrating how it worked.

Finally, under Benzer's direction, the audience joined in with recordings of Delbrück himself, singing a parody by former biology student Sandra Winicur (PhD '71) of *The First Lord's Song* from Gilbert and Sullivan's *HMS Pinafore.* Imagining a Nobel laureate belting out this first verse might amuse many a Caltech grad:

When I was a youth, I wanted to be
A full Professor in Biology.
How I could become one was hard to see
Since my IQ was only ninety-three. □—*EN*

Just Breathe

580 million years ago, the ocean that once covered the present-day Sultanate of Oman was flooded with enough oxygen that the way in which life was constructed was completely changed. This moment, the birth of multicellular organisms, shortly preceded the burst of biological diversification called the Cambrian explosion. Recent evidence indicates that this was the last in a series of similar increases in oxygen availability.

"The presence of oxygen on Earth is the best indicator of life," says John Grotzinger, the Jones Professor of Geology at Caltech who coauthored a recent paper on the subject in *Nature*. "But it wasn't always that way," he adds. "The history of oxygen begins about two and a half billion years ago and occurs in a series of steps. The last step is the subject of this paper."

The study was led by Dave Fike, an MIT grad student who made the move to Caltech in 2006 to stay with his advisor, Grotzinger. Fike uncovered evidence for this final stage in oxygenation at three kilometers' depth in the oil fields of Oman, where the oldest commercially viable oil on the planet is found. He analyzed carbon and sulfur isotope ratios from core samples and drillings to determine the oceanic conditions under which the deposits were originally laid down.

At the time, the ocean covering Oman resembled the modern-day Black Sea, which has a thin oxygen-rich layer on top underlain by an oxygen-starved (what chemists would call a "reduced") environment. "The ocean today is pretty well mixed and thus oxidized at all layers, but the ocean before the Cambrian period must have been very different," says Grotzinger. Different enough to be hostile to complex life—a deep ocean devoid of sufficient oxygen can't sustain multicellular life forms. For this reason, life continued in its single-celled form from its first days, more than three and a half billion years ago, until just before the Cambrian explosion. At that time, according to the team's geologic evidence, deep water began mixing with the shallow ocean, and the result was the first fully oxidized deep ocean. With enough oxygen in the deep ocean came the successful establishment of Earth's first multicellular community, the Ediacara fauna, some of which looked a lot like upright leaves waving on the ocean floor.

Grotzinger says the clarity of the new evidence is persuasive. Geologists have long believed that the rise of oxygen was a key element of the Cambrian explosion, and this discovery certainly seems to confirm it.

The other authors of the paper, which appeared in the December 7, 2006, issue of *Nature*, are Lisa Pratt of Indiana University and Roger Summons of MIT. □—*RT*

Caltech Cops Crack Crooks' Covey

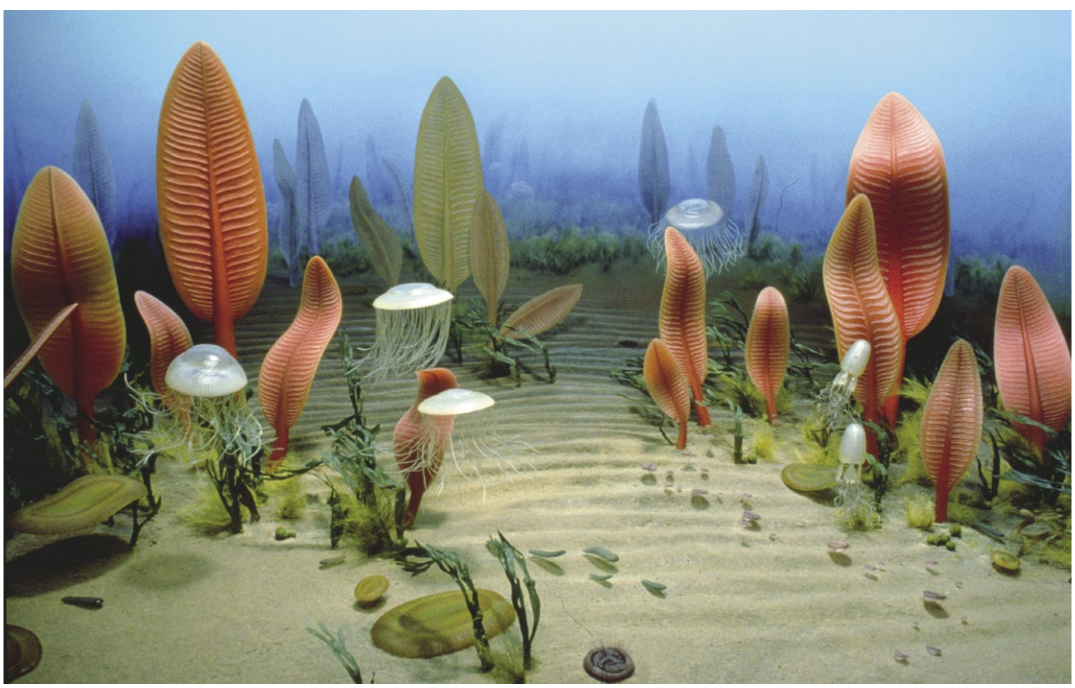
When three unarmed Caltech security officers approached a couple of guys trying to force their way into a campus building, they had no idea that they were helping to crack a Southland burglary ring. For their efforts, Doni Harrelson, Agustin Valadez, and Ivan Gaor will receive the annual Award of Merit from the California College and University Police Chiefs Association at an April 13 ceremony in South Lake Tahoe.

"I'm extremely proud of the entire organization and their commitment to making Caltech a safe place," says Gregg Henderson, head of Caltech Security. "What these three did exemplifies what the entire force does."

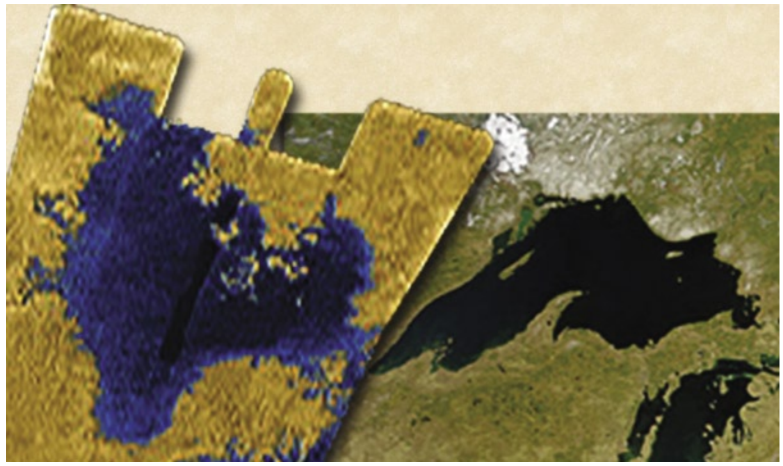
The incident unfolded one day last fall when Harrelson spotted two men wandering the campus. Several campus buildings had been burgled recently, some several times, and all officers were on high alert, so she tailed the men and contacted her partner Gaor and Valadez. Minutes later, the three confronted the two suspects as they tried to jimmy open the basement door of the Parsons–Gates building (which had never been hit before), and asked to see their Caltech identification. One of the suspects ran—to be arrested the next day off campus—but the officers caught and held the second until Pasadena police arrived. His parole information linked him to other burglaries around the neighborhood. The police later linked the two suspects, along with a third, to at least 30 burglaries in Monrovia, Arcadia, Pasadena, and possibly as far away as the state of Colorado. □—*RT*

We're Online!

And have been since 1997, but the *E&S* website is pretty deeply buried. The URL (which also appears on our table of contents page) is **http://EandS.caltech.edu**. If you're looking for Feynman's greatest hits, fear not—*E&S* and the staff of the Sherman Fairchild Library have created an online archive starting with Volume One, Number One back in 1937 (yes, we just turned 70) and running up through Volume 36, Number 7, published in June 1973. Feynman articles after that date are also in the archive; the remaining issues will be filled in as budgets and summer interns permit. The simplest way to find anything in either archive is to type the subject or author's name and perhaps a keyword into the search box in the upper right corner of the Caltech home page—the article you're looking for will usually be the fourth hit or above. □—*DS*



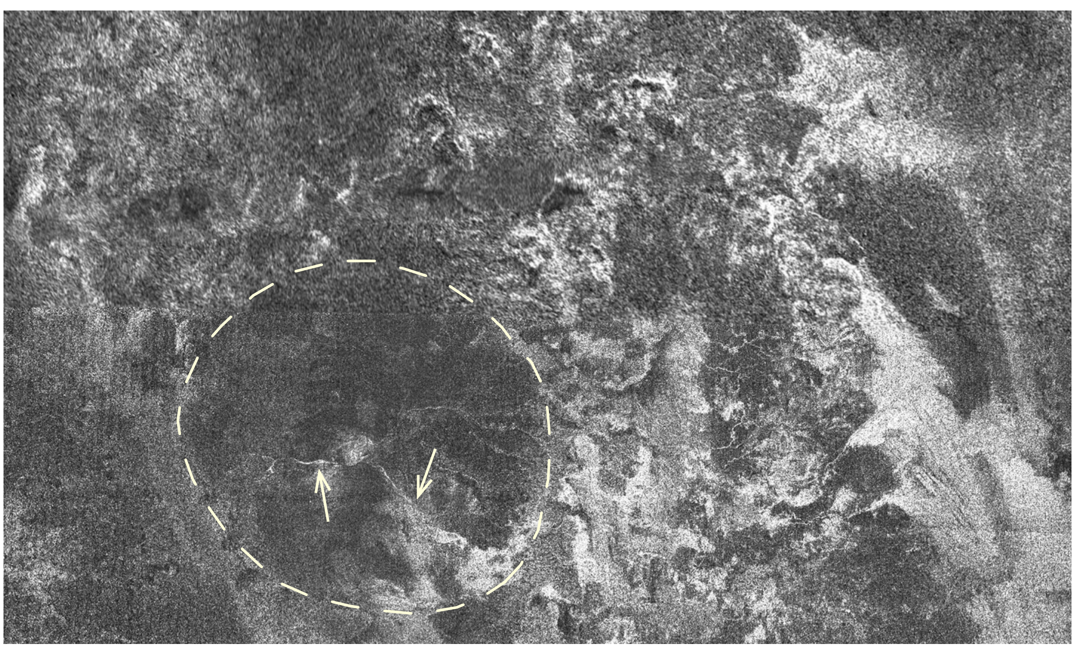
Some of the earliest known multicellular animals, members of the Ediacaran fauna, from about 570 million years ago: *Charnodiscus* (large, orange sea pen); *Ediacaria* (three jellyfish on left), *Kimberella* (tall, skinny jellyfish on right); *Dickensonia* (large, flat, segmented worm), *Spriggina* (small, slender, green segmented worm); *Tribrachidium* (pinwheel-shaped, possibly echinoderm); and *Parvancorina* (lavender arthropod). Image of a diorama from the National Museum of Natural History, courtesy of the Smithsonian Institution.



Rosaly's Volcano

The notoriously foggy city of San Francisco was an appropriate venue for the unveiling of the latest pictures of methane-haze-clouded Titan, shown by JPL's Rosaly Lopes at the annual meeting of the American Association for the Advancement of Science (AAAS). Every February, scientists, journalists, and policymakers from around the world gather to showcase and ogle the year's top science stories. The session devoted to Cassini–Huygens, the JPL–European Space Agency–Italian Space Agency mission that has been exploring Saturn and its moons since 2004, emphasized how closely Titan's surface geologic processes resemble Earth's. According to Lopes, the investigation scientist on Cassini's RADAR team, "Titan is the Earth of the outer solar system."

Indeed, recent views of Titan's northern latitudes reveal the full extent of a volcano that Lopes thinks could be a lot like one of our own. The 180-kilometer-wide Ganesa Macula, endearingly dubbed "Rosaly's volcano" by some of Lopes's colleagues and members of the press, is a large, conical volcano that could resemble either the "pancake domes" of Venus or shield-shaped volcanoes like Hawaii's Mauna Loa. But unlike terrestrial volcanoes, from which molten rock gurgles, Ganesa spews thick slurries of a "cryolava" that had been thought to be made of water mixed with ammonia.



Recent radar images of a region of Titan, the largest of Saturn's moons, reveal a fuller extent of a province riddled with volcanic activity. At 180 kilometers across, Ganesa Macula (shown with base outlined) is so far the largest cryovolcanic feature seen. In this region, bright areas are cryolava. On the volcano, the left arrow points to one of several thin cryolava channels and the right arrow points to where such a channel spills out into a flow. All flows seem directed toward the right (east), suggesting an overall eastward slope to the region.

In other radar-mapping news, the Cassini orbiter has discovered a sea of liquid methane or ethane near Titan's north pole. Since this first-of-its-kind feature extends beyond the mapping swath, its exact extent is unknown, but it is at least 100,000 square kilometers in size—bigger than Lake Superior, which is shown on the right for comparison. And as it is bigger in proportion to Titan's total surface area than the Black Sea, our largest inland sea, is to Earth (at least 0.12 percent versus 0.085 percent), it is, indeed, a sea. The comparison image is from NASA's SeaWiFS, or Sea-viewing Wide Field-of-view Sensor project.

Although Titan's opaque atmosphere hinders spectroscopic analysis of its surface, some clues about the composition of its cryomagma can be gleaned from radar images of individual flows, whose lobate margins are clearly defined. A thick, viscous fluid, like hot tar, would be required to make such lobes—a thinner liquid would simply run off. An isolated flow in another region, around 2,200 kilometers away from Ganesa, is estimated at 300 meters thick, suggesting that the material moves with some difficulty. A water-ammonia slurry would not move that way, Lopes and colleagues argue in a paper in the February 2007 issue of *Icarus*, but adding a dash of methanol to the mix would thicken the cryolava up just fine.

Some individual flows are huge—the newly named Winia Fluctus extends at least 23,700 square kilometers, an area slightly smaller than the state of Vermont.

Despite the multitude of volcanic landforms recently found on Titan's surface, no eruptions in progress have been spied. But this could be because only around 15 percent of the surface has been radar imaged so far, with very little of the overlap needed to show surface changes.

Lopes also thinks that many of Titan's methane or ethane lakes, which so far have been seen only at latitudes north of about 70°, could be housed in volcanic craters, or calderas. Alternatively, she suggests that they could be like karstic lakes on Earth, in which water fills sinkholes formed over pockets of dissolved rock. But it is clear that the Ganesa region, near latitude 50° north, houses an unusually high concentration of recently active volcanoes.

The *Icarus* paper points out that the volcanic provinces on Mars and Venus are associated with large bulges in the crust, presumably caused by the upwelling of magma from below. Whether a similar bulge will be found on Titan remains to be seen. So stay tuned—future flybys could also pick up surface changes from recent eruptions.

The AAAS meeting was especially meaningful for Lopes, as she was the only JPL scientist among the 449 new members elected to the status of Fellow by their peers. At the meeting's close, David Baltimore, professor of biology, Nobel laureate, and former Caltech president, stepped into the AAAS presidency for the coming year. □—*EN*

Surf's Up

If you could not even conceive of a way to answer the question "Is every finite group realizable as a Galois group over the rational numbers?"—if you don't even know what it means—then you might find the odds of someone winning a speaking competition on that topic pretty slim. Yet, at the 2006 Doris Perpall Summer Undergraduate Research Fellowship (SURF) Speaking Competition, sophomore Po-Ling Loh, a math major from Madison, Wisconsin, bagged her second first prize in a row for a math talk. It was a banner year for the subject, in fact: one of the two third-prize winners also talked about math, and this is only the second year since the competition began in 1993 that mathematics speakers have won prizes.

The details of Loh's project, in an obscure but important field of math called Galois theory, seemed to sail above the heads of the audience members. But Loh kept them enchanted with stories, such as how legendary mathematician Evariste Galois died in 1832 at age 20 in a duel with an artillery officer over a woman—but not before recording his ideas the night before. Loh's public-speaking skills are so strong that she needs no show-and-tell props to win over her audience, but she brought some anyway, demonstrating how origami folding can successfully trisect an angle where a simple compass and straightedge fail at the task. (See *E&S*, 2004, No. 1, p. 10 for how to do this at home.)

Mercilessly titled *Q-Admissibility of PSL(2,q)*, the algebraic abstraction that was Loh's project required constructing a polynomial equation with many variables in just such a way that they would factor in a specified pattern. The pattern forms the so-called "Galois group" of the polynomial, and it's part of a fundamental problem that has perplexed mathematicians since long before Galois murkily drafted his thoughts on the matter. Bandying about terms like "Sylow p-subgroup" and "maximal subfield of a Q-division algebra," it was hard to believe Loh's claim that a lack of higher math skills prevented her from solving the challenge. But she will keep plugging away, taking more math classes and attacking another SURF challenge, on a related math topic, this summer. "For now, I'm just focusing on the theory of my research, rather than its applications," she says.

The second prize went to Alex Huth, a senior in computation and neural systems who hopes to pursue further studies in Sweden. His research, which used functional Magnetic Resonance Imaging (fMRI) to mark contrasts in the responses of the visual cortex in the brains of blind and sighted people, was easier to grasp. One subject, a blind man who employs bat-style echolocation to ride a bicycle, also had quite a sense of humor, Huth recalls. "We asked how the train ride to Pasadena had been, to which he replied, 'The view was horrible.'"

Huth's seven sighted subjects responded as one might expect—their visual cortexes lit up when they looked at moving objects. Surprisingly, though, the visual cortexes of the five blind subjects lit up in response to moving sounds, suggesting that this area of the brain keeps working even though its manner of use changes. Huth was lucky enough to work with an additional two subjects who were blind most of their lives but gained vision in their fifties. These fMRI scans seem to have captured brain reorganization in progress—their subjects' visual cortexes responded to both visual and auditory signals. Huth will continue to work on the subject with mentors Melissa Saenz (BS '98), a postdoc in biology, and Christof Koch, the Troendle Professor of Cognitive and Behavioral Biology and professor of computation and neural systems. "In the coming era of sensory rehabilitation—retinal implants for the blind are gaining some traction, and cochlear implants for the deaf are already very advanced—it's becoming increasingly important to study how the brain adapts to such major changes," Huth says.

Tied for third place were freshman Evan Gawlik and senior Arturo Pizano. Gawlik tackled the three-body problem—an infamous conundrum dealing with the motions of three masses in space subject to mutual gravitational attraction—by comparing the accuracy of different numerical methods that try to predict them. In a configuration in which one mass dominates, like the sun in the sun–Earth–moon system, it's relatively straightforward to predict orbits. But when the three masses closely match, their movements are somewhat chaotic and much harder to predict—even when the problem is simplified by considering one mass to be negligible, as Gawlik did.

Pizano studied folding in cytochromes, which are a large family of proteins that, even though their amino acid sequences are similar, all fold their own way. This is a great mystery, as it is the attractions between the amino acids that make proteins fold, so proteins with similar sequences should fold into similar shapes. Within this greater problem lies the subplot of Cytochrome c–b_{562}, the particular class that Pizano studied. While these proteins do have similar folded structures, each accomplishes the task in a different manner. Pizano will continue to pursue the dilemma until he graduates this June.

The runners-up were Matthew Lew, who devised a device for the study of optics, Diana Lin, who tested a model of a signaling pathway in cells, and Andrew Kositsky, who mathematically reconstructed the 20th-century record of slip distribution along the Sumatra fault. □—*EN*

LIGO's Wave Wall Wins Design Award

The Laser Interferometer Gravitational-Wave Observatory (LIGO) Science Education Center in Livingston, Louisiana, has won a 2007 New Orleans Design Award from the New Orleans chapter of the American Institute of Architects.

The Science Education Center was one of 12 winners chosen from over 70 submissions, which is more entries than the chapter has received in any previous year. The award, in the category of "Divine Detail," cited "form and function coming together in an exciting and unexpected way" in the design of the building and its dynamic exterior *Wave Wall*.

Visitors walk into the center under the wall, which is a kinetic wind sculpture consisting of 120 27-foot-long pendulums strung across the entire 85-foot length of the building's façade. *Wave Wall* is activated either by wind or by energetic LIGO guests, who can initiate the wave's motion and propagation via ropes and pulleys. In response, the massive aluminum masts swinging just overhead may trace graceful undulating patterns, or they may break into a chaotic dance with a gust of wind.

Nationally renowned architects Eskew + Dumez + Ripple of New Orleans designed the LIGO Science Education Center, which officially opened in November 2006. *Wave Wall*, commissioned by the U.S. National Science Foundation, was designed by a team of artists that included Shawn Lani, Charles Sowers, and Peter Richards, along with Thomas Humphrey and Susan Schwartzenberg of the San Francisco Exploratorium. They collaborated with scientists and engineers from the LIGO Laboratory, Caltech, High Precision Devices of Boulder, Colorado, and Superior Steel of Baton Rouge.

Fully operational since 2001, LIGO is a scientific facility designed and managed by Caltech and MIT for detecting astrophysical gravitational waves. To visit the LIGO Science Education Center online, go to http://www.ligo-la.caltech.edu/contents/sechome.htm. *Wave Wall* is even on YouTube—check out http://www.youtube.com/watch?v=mIA9zq80hx4. □—*DW-H*

PICTURE CREDITS: 2—NASA/ESA/Richard Massey; 6—NASA/JPL, NASA/JPL/GSFC

Wave Wall **is a linked set of 120 hanging aluminum beams 27 feet long. When set in motion by a visitor or the wind, the interplay of light and shadow, resonance and gravity, makes a hypnotic and ever-changing series of undulations. Photo courtesy of the Exploratorium, San Francisco.**