California Institute of Technology

# E&S
ENGINEERING AND SCIENCE

*Volume LXXI, Number 1,* 2008


IN THIS ISSUE

**On March 11, 2008, space shuttle *Endeavor* carried not one, but two Caltech alums to the International Space Station. Here, astronauts Garrett Reisman (MS '92, PhD '97), left, and Robert Behnken (MS '93, PhD '97) posed for the camera before Behnken embarked on the mission's fourth spacewalk. After the successful mission, which included installation of a module of the Japanese laboratory, Kibo, on the ISS, *Endeavor* touched down on the night of March 26 at Cape Canaveral—but without Reisman. He will remain on the ISS as the flight engineer, not returning until space shuttle *Discovery*, scheduled for launch on May 25, comes to pick him up. Reisman also took some special cargo on behalf of his former advisor, Hayman Professor of Mechanical Engineering Chris Brennen, whose wife suddenly died of cancer in August 2007. Accompanying Reisman on his cosmic journey are the Brennens' wedding rings, fused together.**

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**On the cover: Mission specialist Robert Behnken (MS '93, PhD '97) seen during a six-hour, 53-minute spacewalk, his first, outside the International Space Station. Behnken and fellow mission specialist Rick Linnehan were installing parts for a two-armed Canadian servicing robot named Dextre.**

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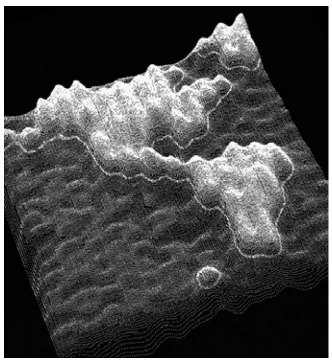
## From the Lab to the Gallery



Right: Rothemund's DNA origami of North and South America rendered as a three-dimensional glass etching.

Below: Lang's *Snack Time* depicts the wedding feast of a female praying mantis on her unfortunate male partner. And yes, this was folded from a single uncut square of paper.

Matisse, Picasso—and now, DNA and computational origami. Science, art, technology, and design come together in a new exhibit at the Museum of Modern Art in New York. The show, entitled Design and the Elastic Mind, includes work by two Caltech alums—origamist Robert Lang (BS '82, PhD '86) and Paul Rothemund (BS '94), a senior research associate in computation and neural systems and computer science.

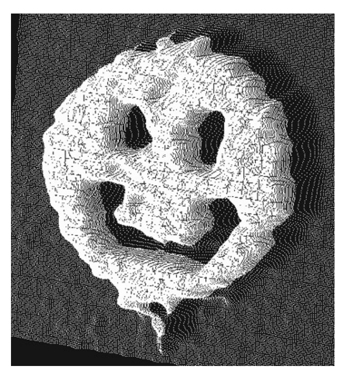
Rothemund, one of Caltech's two 2007 MacArthur "genius" grant winners, invented "DNA origami," in which he turns strands of DNA into any desired flat shape, from a smiley face to the outline of a contient. He took DNA from a harmless virus and developed a method to fold and pinch strands together. The result is a powerful way to build nanoscale structures out of DNA. The shapes measure about 100 nanometers, or 100 billionths of a meter, across—about one thousandth of a hair's breadth.

In addition to atomic-force micrograph (AFM) prints of Rothemund's creations, the exhibit includes representations of the AFM scans etched into glass blocks, using the same techniques used to make laser-etched glass paperweights.

Lang has combined his love of mathematics and paperfolding, becoming one of the pioneers in computational origami—the art and science of designing origami with mathematical techniques. The exhibit showcases some of his intricate creations, as well as the TreeMaker software he wrote to make his increasingly complex designs.

Both types of origami are displayed alongside a myriad of provocative exhibits, including a honeycomb vase, pig bone tissue grown into the shape of wings, and furniture modeled after human bones. The show runs through May 12. □—*MW*

Right: Have a nano day!



**On March 6, the post office issued its second series of four American Scientists stamps. This set includes Caltech Nobelist Linus Pauling (PhD '25). The background art refers to his discovery that sickle-cell anemia is a molecular disease—the first to be recognized as such. Caltech is two-for-two in this series of stamps: the first set, issued in 2004, included fellow laureate Richard Feynman.**


## Getting Nanowired

One day, they could be everywhere, powering your computer and keeping its microprocessor cool at the same time. They're silicon nanowires, narrow devices hundreds to thousands of times thinner than this piece of paper. Two groups of Caltech researchers are discovering the remarkable properties of silicon nanowires, enabling the wires to harness solar power and to act as refrigerators by converting heat to electricity, and vice versa.

The latter group, led by James Heath, the Gilloon Professor and professor of chemistry, found that silicon could be an efficient thermoelectric material when made into wires only 10 nanometers (10 billionths of a meter) wide. "At these tiny dimensions, nature is doing things that were previously not thought possible," he says.

In a thermoelectric material, a difference in temperature sends electrons scurrying to the cooler end, creating a current. To be efficient, the material must conduct electricity well; but to maintain a temperature difference, it must conduct heat poorly. Most thermoelectric materials efficient enough to be useful are expensive and hard to make, restricting them to niche applications. Silicon, on the other hand, is one of the most abundant elements in the universe. The microprocessor industry has also made processing silicon inexpensive and easy. But because silicon is also an excellent conductor of heat, it didn't seem promising as a thermoelectric material—until now.

By growing silicon into nanowires, researchers in Heath's lab improved silicon's thermoelectric efficiency by a factor of 100. One of the reasons for the enhanced performance might be a phenomenon called phonon drag, according to the team. Phonons are heat-carrying vibrations that travel across the material. Constricted by the small size of the nanowire, the phonons don't scatter off the sidewalls in the nanowire. Instead, they travel unimpeded down the wire and drag electrons with them, which improves thermoelectric performance.

Although the silicon nanowires are still only about half as efficient as state-of-the-art thermoelectric materials, further improvements—as well as lower manufacturing costs—could make these tiny devices useful in a host of applications. They can make microprocessor chips more efficient by recovering leaked heat. Eventually, they may be able to recover heat from larger systems like car engines, and may also be used in refrigeration devices. The researchers, who include William Goddard (PhD '65), the Ferkel Professor of Chemistry, Materials Science, and Applied Physics; Jamil Tahir-Kheli (MS '86, PhD '92), a senior staff scientist with the Materials and Process Simulation Center; and graduate students Akram Boukai (PhD '08), Yuri Bunimovich (PhD '07), and Jen-Kan Yu, reported their findings in the January 10 issue of *Nature*.

Silicon nanowires may also help solve the energy crisis. Researchers in the labs of Nate Lewis (BS, MS '77), the Argyros Professor and professor of chemistry, and Harry Atwater, the Hughes Professor and professor of applied physics and materials science, are using the wires to build a new kind of photovoltaic cell.

Most conventional cells are made from silicon wafers. Incoming photons from the sun are absorbed by the silicon and dislodge electrons from their atoms. The electrons are then free to move, producing enough current to power calculators, light bulbs, and even entire homes. The drawback is that these solar cells must use pure, top-quality silicon, which is expensive to process.

Growing silicon nanowires is not only cheaper, but can also be done with lower-quality silicon. The trick to turning nanowires into solar cells is a unique geometry, an idea first developed by graduate student Brendan Kayes (MS '04) in 2005. Regular solar cells are flat, and absorb photons face-on. The newly freed electrons then move along the same direction, parallel to the incoming photons. They're collected at the surface of the silicon slab, where they then join the electrical current. Additionally, the cells have to be thick enough to capture all of the photons.

In the new photovoltaic cells, silicon nanowires sit alongside one another like blades of grass. Light is absorbed along the length of the wires, which, at tens of microns, are still long enough to snatch all the photons. The advantage of this configuration, however, is that the electrons move widthwise—perpendicular to the photons' paths. The nanowires are only several microns in width, so the electrons don't have to travel as far, allowing them to produce electricity more easily. Once the electrons are collected in the outer shell of the wire, they quickly travel to the top of the wire and enter the current.

The team has made nanowire arrays one square centimeter in area—orders of magnitude larger than any made before. The researchers have also been able to embed the nanowires in a flexible membrane for added versatility. The membrane is excellent at absorbing light, as is evident from its near-black color.

The best conventional silicon solar cells are about 25 percent efficient at converting sunlight to energy, says postdoc Michael Filler. The researchers' nanowire cells are just over one percent electrically efficient. But Filler says they are making rapid progress, and are aiming for 20 percent efficiency. "Our group has been pushing the forefront of the field right now," he says. Other members include postdocs Stephen Maldonado and Kate Plass, and graduate students Michael Kelzenberg (MS '06), James Maiolo, Leslie O'Leary, Morgan Putnam, and Josh Spurgeon (MS '06). Once the researchers achieve higher efficiencies, Filler hopes industry will jump in and push the design toward commercial use within the next decade. □—*KS/MW*

## Dances with DNA

Nature is a software engineer par excellence. By rearranging protein and RNA building blocks, nature programs myriad molecules to synthesize, haul, detect, and regulate one another. Now scientists are trying their hands at it, and in the January 17 issue of *Nature*, a group of Caltech researchers published examples of their own molecular programs. Associate Professor of Applied and Computational Mathematics and Bioengineering Niles Pierce, senior postdoctoral scholar Peng Yin, grad student Harry Choi, and research technician Colby Calvert showed how molecules of DNA only ten nanometers in length could be directed to perform specific tasks unaided—without external energy sources, temperature changes, or enzymes.

Biomolecular engineers have assembled DNA molecules into stable patterns, like planar crystals, wireframe cages, tubes, smiley faces, and maps of North America. Pierce and his colleagues concentrate on the motion of the interacting DNA molecules. To see the distinction between these approaches, consider the difference between a choreographer (Pierce) and a cheerleading coach. The coach primarily cares where the cheerleaders end up in a human pyramid: stronger, heavier people go on the bottom, while more agile, lighter people are at the top. He doesn't care how they get there: all's well that ends well. By contrast, when directing dancers, the choreographer cares most about how the dancers move across the floor and who they partner with. Where they end up is of less importance. "The trajectory the molecules take is actually the goal of our programs, and the destination is just the by-product: it's what you get when the function is complete," says Pierce.

The dancers are short "hairpins" of DNA that fold back onto themselves. Each hairpin has three domains—one input and two output—that can interact with domains in other hairpins by matching the "letters" in one strand with the letters in another. In the alphabet of DNA, A pairs with T and G matches C; the hairpins contain between 50 and 100 letters. The hairpin's input domain is initially available to pair up with other DNA molecules, while its output domains are inaccessible. Once a matching piece of DNA binds to the input domain, the hairpin pops open and the output domains are exposed. Output domains of open hairpins can then seek out the input domains of closed hairpins and open those molecules. The ensuing cycle becomes a molecular square dance with hairpins exchanging partners according to the design of the bioengineers.

All of these exchanges occur without Pierce having to add energy to the system. So what makes them go? "The basic feature of the hairpin is that it's initially trapped in a high-energy state," says Pierce. This state is similar to a mousetrap that has been set and baited. Until a mouse trips the trigger, the trap is stable and doesn't move. But within the spring of the trap, there is energy waiting to be released when the unsuspecting mouse goes for the cheese. A piece of DNA binding to the input domain triggers the hairpin to release the stored energy locked up in the inaccessible output domains—when the output domain pairs up with still other pieces of DNA, the entire system goes to a lower-energy state.

By designing how each hairpin domain pairs with its fellows, the Caltech team can harness this energy to make the molecules perform the specific task they want. This part of the design process is the most difficult, and requires the team to model the physics of the hairpins. Using algorithms developed by Pierce's group, the researchers ensure that when the hairpins are mixed together, they interact appropriately so that no hairpin runs off with another hairpin's dance partner.

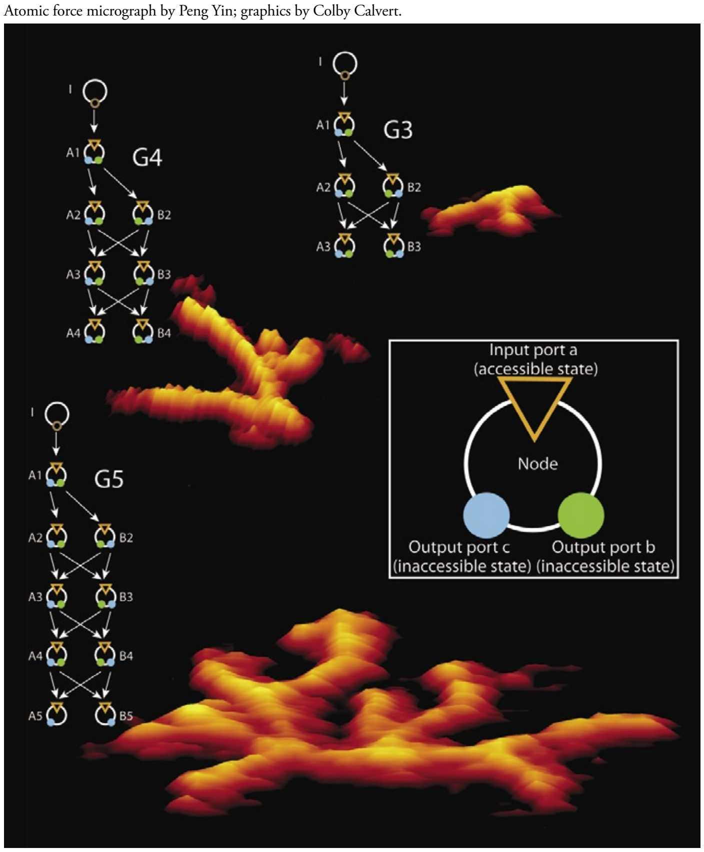
To showcase the hairpins' capabilities, Pierce and his colleagues "wrote" four different programs. In each case, the hairpins were designed not to interact until an initiator molecule was introduced to the system. For the first program, the initiator triggered the hairpins to self-assemble via a specified sequence of "handshakes" into branched structures with multiple arms shooting out from a central point, like three- and four-armed starfish. Upon completing this assembly process, the initiator then disassembled from the structure to catalyze the formation of more starfish. In the second program, the hairpins assembled into a tree-like pattern called a dendrimer, growing from the root of the tree to the leaves. Another program demonstrated a phenomenon called autocatalysis, in which a chemical reaction—in this case, the production of fluorescent pairs of hairpins—feeds on itself. After the initiator was added to the solution, the test tube would begin to glow, getting brighter and brighter exponentially. The most dramatic example was a DNA "walker" that used its DNA "legs" to lurch along a DNA track one step at a time. The walker was inspired by the protein kinesin, which glides along protein microtubules in cells to move molecular freight. "Years ago, I was amazed when introduced to the programmable chemistry of kinesin. I decided then and there that I wanted to be able to engineer that kind of molecular complexity. We still have a long way to go," says Pierce.

Pierce foresees these hairpins being put to use as molecular sensors or nanomechanical drugs. Molecular instrumentation could detect small changes within cells, like the switching on of a gene within a developing embryo, producing a fluorescent signal for scientists to read and analyze. He hopes that programs like the exponentially glowing one could develop into cheap technologies that would amplify the presence of a miniscule amount of an interesting molecule into a detectable signal. "Instead of thinking of instrumentation as something expensive that your experiment resides within, we want to design exquisite instruments that you embed within your system of study," says Pierce. Programmable molecules may also eventually lead to dynamic drugs that use one input domain to pinpoint cancer cells, triggering an output domain to kill them.

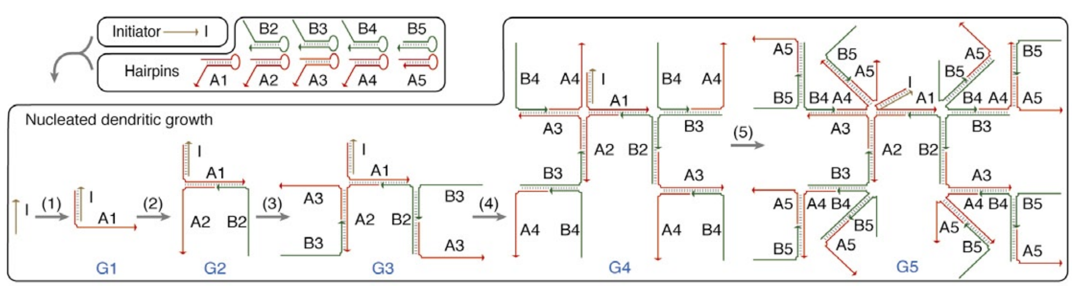
For Pierce, the work represents a step toward the long-term goal of developing a compiler for biomolecular functions that would allow bioengineers to write molecular programs the way that computer scientists write electronic ones. A compiler is the software that translates high-level programs written in a language like C++ into the binary instructions the machine actually executes. As a first step, the team has developed graphical representations of their hairpins that are used in schematics, called reaction graphs, to describe each step in a program—for example, an output domain on strand C binding to an input domain on strand D in step four, only to unbind again later in preparation for the next cycle. These reaction graphs are not unlike the flow charts beloved of computer programmers. As a software package, the molecular compiler would translate an engineer's design ideas into reaction graphs and then translate those graphs into a specific set of DNA hairpin sequences to be synthesized. "We want to liberate the molecular engineer from having to think about the detailed structural features of the molecules and instead focus on the functional behavior of the system," says Pierce.

"In designing a compiler, there's work for many different fields: computer science, applied mathematics, control and dynamical systems, chem-

Atomic force micrograph by Peng Yin; graphics by Colby Calvert.




**Left: How to grow a ninja-star dendrimer. The *Matrix*-esque glyph to the left of each stage is the reaction graph, or programming instructions, for making it. Left, inset: The key to the reaction graphs. Each circular "node" represents a DNA hairpin. Input domains are triangles; output domains are circles. Inaccessible domains are filled with solid colors. Binding to an accessible domain will open the inaccessible ones. Arrows between the nodes indicate what binds to what. Below: The dendrimer is built from five kinds of A hairpins and four kinds of B hairpins that assemble themselves in sequence according to the reaction graphs.**




Inset and bottom figure reprinted by permission from Macmillan Publishers Ltd. from Yin, et al., *Nature*, vol. 451, January 17, 2008, pp. 318–323. Copyright 2008.

istry, and physics," says Pierce, who is teaming up with other researchers at Caltech and elsewhere on the project. "Building a molecular compiler is a very daunting challenge, but progress in the field has been pretty dramatic in the last five years, so a primitive first-generation compiler is probably now within reach," says Pierce. Even so, the day when dancing molecules detect and kill cancer cells in humans is probably still far in the future. □—*MT*

## How Do You Get to Carnegie Hall?

Practice! And that's exactly what everyone in the Caltech-Occidental Concert Band has been doing. On Saturday, May 24, about 60 musicians, including Caltech and Occidental College students, Caltech faculty and staff, JPL employees, and members of the local community, will perform at Carnegie Hall. "We are extremely excited about this," says senior physics major and clarinetist Lauren Porter, who has been integral to organizing the trip. "It's a huge opportunity for us, and the culmination of a lot of hard work."

Band director and artist-in-residence William Bing, a professional trumpet player, has performed at such venues as Lincoln Center, the Kennedy Center, and Disney Concert Hall, but this will be his first apperance at Carnegie Hall. He handpicked the concert's pieces to fit the venue. For instance, "Chorale and Alleluia," by Howard Hanson, was chosen because it suits the renowned acoustics of the hall. "A Prairie Hymn," by Joseph Curiale, on the other hand, was chosen for its "meditative quality, and it's a contrast to the other pieces, which are much louder," according to Bing.

Paul Asimow, associate professor of geology and geochemistry at Caltech, will be conducting "Be Glad Then, America," by William Schuman, which Asimow has known since playing as a student at Harvard. Asimow says the piece treats the timpani as melody makers, not rhythm instruments. "Our timpanist, Scott Babcock, is one of the few professional members of the band, and I am happy to give him this opportunity."

Also featured is vocal soloist Kjerstin Williams (BS '00, MS '02, PhD '06), on George and Ira Gershwins' "Someone to Watch Over Me." Williams has been a trombonist with the Caltech jazz and concert bands since her freshman year, but singing brings her an indescribable thrill. "To sing with a wall of music behind you, there's nothing quite like it," she says. "Karaoke doesn't even begin to touch it."

If you live near the Big Apple and would like to catch the show, visit http://www.carnegiehall.org or call 212-247-7800 for tickets. □—*JS*

## Caltech Connects with Local Classrooms

As a Caltech grad student, I *never* get to work at a quarter after 7 a.m., but when I join science teacher Tobias Jacoby in his classroom at Blair High School in Pasadena, this is when my day begins. Mr. Jacoby and I have been paired up through the Caltech Classroom Connection (CCC), an outreach program that brings together Caltech graduate students, postdocs, faculty, and staff with Pasadena teachers. The hope is that putting people who practice and love science into the classroom might inspire students to take it more seriously—in their course work, and maybe also in their career plans.

The guidelines for interaction within teacher-Techer pairings are pretty loose; each pair decides how to spend their time together. For some teachers, science is a little outside their comfort zone, and they enjoy the confidence boost of having an expert volunteer on hand to field difficult questions. "It's so great to have someone with me who I don't have to explain everything to, because he just knows," gushed one teacher, describing her volunteer at a recent CCC dinner. Other teachers—like Jacoby, who is perfectly at ease explaining torque, momentum, and kinetic energy—can really use an extra set of hands, as well as someone to bounce

**Thalia Reyes (left) and Maria Murillo, physics students at Pasadena's John Muir High School, try to turn on a light-emitting diode (LED) with a battery made from a potato, a zinc nail, and a penny during a CCC-assisted lab session. Photo by their physics teacher, Dave Herman.**

ideas off of for new labs and activities.

During my classroom visits, I have mostly been helping out with labs and problem-solving sessions. Today I am helping out with a physics lab on collisions, and before the students arrive we set up five-foot-long, low-friction tracks on tables around the classroom. We place two brick-like carts with magnetic front bumpers on each track. The students will roll one cart into the other, stationary cart to observe how momentum is conserved in elastic and inelastic collisions. In an elastic collision, the magnets repel each other, and the carts rebound. In an inelastic collision, the bumperless ends collide with a satisfying "thunk," and the moving cart comes to rest, sending the stationary cart rolling down the track. A motion detector positioned at one end of each track records the positions and velocities of the carts over time.

There are 45 students in this class, one of two large classes Jacoby teaches in addition to a smaller IB (international baccalaureate) group. At first glance they seem to be masterfully combining high social energy with academic lethargy: friends giggle and chat and seem to pay no mind to the assignment at hand. They make the people I interact with in an average day at Caltech seem awfully sedate.

I circulate among the groups. There are some questions about the instructions. I demonstrate the use of the motion tracker for one group, sliding the cart slowly along the track as the position and velocity are plotted on a laptop screen. "Wow," said one girl. "I actually understood that because someone actually explained it to me." She just made my day.

It's a challenge to come up with activities aligned with the state's science standards, using inexpensive and readily available materials. CCC volunteers are succeeding admirably and having fun in the process. One volunteer used Kool-Aid to demonstrate the concept of molarity to a chemistry class. The students made several batches of Kool-Aid with different proportions of powder and water, and then calculated the concentration—or molarity—of sugar in each, by assuming that Kool-Aid is 100 percent glucose. They then related how the drinks tasted to their sugar concentrations. Another volunteer demonstrated that energy could take on different forms by powering an LED with a battery made by sticking a zinc nail and a copper penny into a potato. Volunteers are endowed with a small budget for supplies; after purchasing a graphing calculator for his class, a volunteer demonstrated for his group how optimization can be used to figure out the most efficient combination of ingredients to make Cheez Whiz.

As I relive the high-school physics curriculum, it strikes me, as it has many, that science as taught in schools doesn't really tell kids anything about how scientists do their jobs. In my class, I hope to use some of the time devoted to magnetism to tell students about one of the tools I use in my own neuroscience research: magnetic resonance imaging. Maybe with the help of some cool pictures, showing detailed brain structures and specific regions that light up when people learn reward associations, I can impress upon them that physics is important for many fields of study: biology, psychology, medicine, and engineering.

The CCC works with the Pasadena Unified School District, which has seen its ups and downs through the years. As a district where a high proportion of parents send their kids to private schools, the public system is left to fend for itself. In my classroom, the diverse group of students is friendly and open with each other, and Blair strikes me as a safe and genial place to learn. That said, class sizes are large, resources are scarce, and state test scores are often below standard.

Founded in 2002 by Eddie Branchaud (MS, PhD '06), then a mechanical-engineering graduate student, the CCC has grown from just a few teacher-Techer pairings to 20 this year. This growth has been possible thanks to funding from the Howard Hughes Medical Institute, Caltech's Moore-Hufstedler Fund, the Mattel Children's Foundation, and the National Science Foundation, secured with the help of faculty director Christina Smolke, assistant professor of chemical engineering. This generous support has enabled the hiring of James Maloney (MS '06) as full-time codirector. He acts as an ambassador for the project, visiting local schools and sitting on education committees. His presence has helped secure an ample supply of teachers who are interested in participating in the program—what they need now is Caltech volunteers to match. (If you think you might be interested in participating, please visit http://www.classroomconnection.caltech.edu/ or email ccc@caltech.edu.)

Graduate students Tara Gomez and Jennifer Franck (MS '04) codirect with Maloney. The trio is extremely proactive about providing support to volunteers. "We want to make sure that grad students are getting some good teaching experience from the program, and we hope that this will help them decide if they want teaching to be a part of their future," says Franck.

It's really striking how much fun volunteers are having with students at all levels. As a scientist walking into a third-grade class, "you get treated like a rock star," says Maloney. Kids that age are so naturally curious that a simple, hands-on demonstration can be the basis for a great lesson.

My high-school group is a little more aloof, and at first I worried that they would just dismiss me as a hopeless nerd. They very well may, but I'm not in high school anymore—so who cares? My students always make me laugh, and if I can say or do some small thing to help them squeeze a passing grade out of the torture session that is high-school physics, then we will both be happy. ☐—*SB*

*Signe Bray is a graduate student in computational and neural systems who does brain imaging in the labs of Professor of Biology Shinsuke Shimojo and Assistant Professor of Psychology John O'Doherty.*

## Martian Avalanches

JPL's Mars Reconnaissance Orbiter has captured the first-ever picture of Martian avalanches in action. The dramatic image below, taken on February 19, shows billowing clouds marking the course of dust and ice spilling down a 700-meter-high cliff that slopes at more than 60 degrees.

The High Resolution Imaging Science Experiment (HiRISE) camera shot a swath of terrain some six kilometers wide by more than 60 long near the Martian north pole. The frame captured at least four avalanches—in this close-up of one of them, the dust cloud is 180 meters across. The white to the left in this false-color rendering is carbon-dioxide frost at the top of the cliff.

This action snapshot provides a rare glimpse of the Red Planet's geology in motion. Scientists will compare it with previous shots of the area, and more observations through the Martian summer might reveal details about how the ice erodes. ☐—*MW*

## Marketing Gets into Your Head

Do you often lust after the most expensive item on the shelf?

You're not alone. After all, expensive stuff is coveted—by definition. Otherwise, why would people pay exorbitant prices for things they really don't need?

Take wine, for example. On surveying a wine menu in a fancy bistro, you might be tempted to judge the quality of the wines by their price. And why not? The more expensive wines are probably better, and will likely be a tastier accompaniment to your tuna carpaccio.

Now suppose that your usually cheap date orders an expensive bottle before you sit down, but you take a sip assuming that she chose her usual house red. Would you enjoy it more had you known that she made an uncharacteristic splurge? A new study led by Caltech Associate Professor of Economics Antonio Rangel (BS '93) suggests that yes, the mere knowledge that a bottle is pricey can cause you to enjoy it more.

In a paper published in the January 2008 issue of the *Proceedings of the National Academy of Sciences*, Rangel, postdoc Hilke Plassmann, Associate Professor of Psychology John O'Doherty, and Stanford Professor of Marketing Baba Shiv describe performing a little bit of trickery on a batch of study participants recruited largely from the Caltech community. "We advertised we'd pay people money for tasting wine—everybody was willing," says Plassmann. During the study, participants were asked to sample five wines identified only by their price.

Unbeknownst to the eager tipplers, however, two of the wines were the same but labeled with two different prices, one markedly higher than the other. For example, a \$90 wine was presented sometimes as a \$10 wine and other times at its true retail price.

After tasting the wines, people were sometimes asked to evaluate either the intensity of the flavor or the pleasantness of the taste. It turns out that a \$90 wine doesn't taste nearly as good when you think that it costs \$10. Both wines that were presented at two different prices were rated as more pleasant when identified with the higher price tag. However, the flavor intensity ratings, which acted as a control question, were not affected by the labeled price. Follow-up questions showed that participants truly believed that they tasted five distinct wines.

Eight weeks after the initial study, participants were invited back to taste the wines again, this time without any price information. Not surprisingly, without the price tags, the difference between two samples taken from the same bottle disappeared. And this time, the wine people liked the most was actually the cheapest—a \$5 bottle.

"In marketing, people spend a lot of money to create brand associations in people's minds, and establish a price-quality relation," says Plassman, "and we know that it works. Marketing studies demonstrate that people perceive more expensive items as higher quality. But does it taste different, or do people rationalize? We didn't know."

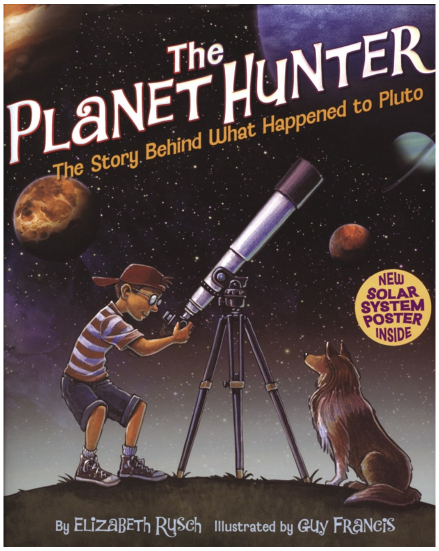
To answer this question, the researchers looked at what was going on in participants' brains while they sampled the wines. They used functional magnetic resonance imaging, a technique that takes a three-dimensional snapshot of activity throughout the brain at a rate of about once every two seconds. They compared brain responses to the wines presented as expensive to responses when the same wines were presented as less expensive, and found that the medial orbitofrontal cortex was more active when people tasted the more expensively labeled wine. This region is located above and between your eyeballs, and is involved in processing experiences we deem rewarding, like winning money and smelling food. Activity in this area was correlated with people's expressed enjoyment of the wine, which tended to be greater the more expensive the bottle.

This is not the first study to show that information culled from sources other than our noses and taste buds can influence our enjoyment of a smell or taste. An earlier study by an Oxford University research team led by Edmund Rolls tested the impact of labels on our perception of an odor. They gave participants a whiff of cheddar cheese while a computer monitor displayed either the words "body odor" or "cheddar cheese." Not surprisingly, people preferred the scent labeled as cheese. Activity in both the orbitofrontal cortex and another region involved in processing emotional information, the amygdala, mirrored this preference.

But this study is the first to show that marketing actions, in the form of hefty price tags, can have an effect on the brain. The authors propose that activity in the orbitofrontal cortex reflects a value that the brain assigns to the wine that combines information about its taste and its price. Activity levels are higher the more impressive the overall value, teaching the brain to make this excellent choice again.

The brain's propensity to integrate outside knowledge into what we think are internally generated opinions might make humans seem like dangerously manipulable creatures. But we evolved in social groups, so why not make use of the group's wisdom when making decisions? If you are unable to ascertain the value of an item for yourself, integrating other people's impressions into your judgment might not be a bad idea.

Unfortunately, the wisdom of the group is not going to help you pay for that expensive bottle, or prevent you from indulging in regrettable trends. If your brain can trick you into thinking something tastes better than it does, could this explain those terrible '50s food fads? Spam-and-fruit-cocktail gelatinized party loaf, anyone? □—*SB*




***The Planet Hunter: The Story Behind What Happened to Pluto***
**by Elizabeth Rusch**
**Illustrated by Guy Francis**
**Rising Moon, 2007**
**32 pages, $15.95**

High-achieving researchers often get their share of the spotlight. They win prestigious prizes, go on national television and radio, have books, and newspaper and magazine articles written about them and their discoveries. But rarely do you see a scientist featured in an illustrated children's book.

Professor of Planetary Astronomy Mike Brown now has that distinction. He is the hero of *The Planet Hunter: The Story Behind What Happened to Pluto* (Rising Moon, 2007), a children's book written by Elizabeth Rusch and illustrated by Guy Francis. Rusch tells the story of Brown's childhood, his discovery of Eris—briefly known as the 10th Planet—and the subsequent vote that demoted Pluto and made headlines around the world.

A perusal of children's books about scientists turns up stories about the likes of Albert Einstein, Galileo, and Leonardo da Vinci—subjects who tend to be old and dead. So if you're like Brown and don't fit either category, how do you get a children's book written about you?

In January 2005, Brown discovered an object in the Kuiper Belt, a population of at least 70,000 icy bodies beyond the orbit of Neptune. But this object, nicknamed Xena (as in the television series' Warrior Princess), was bigger and farther away than Pluto. Controversy swirled over whether the shiny sphere, now officially named Eris, was indeed the 10th planet. If it wasn't a planet, Pluto shouldn't be either, since both objects are markedly different in size, orbit, and location—among other characteristics—from the other eight planets.

Rusch had been engrossed in the debate since the beginning, she says. In August 2006, the controversy came to a head as the International Astronomical Union convened in Prague to vote on the definition of a planet. Rusch realized the implications of the vote were huge, regardless of the result. Every book, poster, and placemat adorned with the solar system loved by children everywhere would have to be changed. This dramatic revision would have to be explained to kids, says Rausch, who has written for both adults and children. "It wasn't so much that [Brown] discovered the 10th planet," she says, "but that our understanding of the solar system was going to change one way or another, and the story behind that had to be told." She wanted to show that science was about constant discovery involving real people, and not just facts to be memorized from a textbook.

She pitched the idea to her editor, got quick approval, and, just a week after Pluto got the boot, sent Brown an e-mail requesting an interview. Initially unsure about the request—admittedly an odd one for an academic—Brown agreed to talk and help with the book. Swamped with media requests and other distractions from the "crazy Pluto thing," as he calls it, Brown then forgot about the project. "The funniest part of this, at least to me, is that I have almost no memory of this," Brown says. "There were so many other things going on, this was just one of a million things that were happening." In fact, Brown neglected to tell his wife until the book came out in December 2007.

Since the topic was a timely one, the project had to move swiftly. The fact that it took just over a year from pitch to publication is an anomaly, Rusch says. Normally, children's books can take three years to publish. The editor found an illustrator, Guy Francis, who, as it turned out, illustrated the favorite book of Brown's two-year-old daughter, Lilah. Everything came together smoothly, as if, well, the eight planets were aligned.

For Rusch and Brown, the final product was a success. According to Brown, "The story is dead accurate," including such details as his failed childhood attempts at rocketry, illustrations of his childhood dog Roscoe and the green 1964 Volkswagen Beetle he drove in high school, and the discovery of Eris and the demotion of Pluto. He's not sure how successful it'll be in bookstores, but "it's fun to watch the Amazon rankings," he says. At the time of this writing, it's number 138,554, and at one point reached the top 25 in the category of science and technology biographies for children, joining Einstein, da Vinci, and others who are old and dead. *The Planet Hunter* has also been nominated for a 2008 Pacific Northwest Book Association Award.

The fact that Brown has a young daughter helps him understand the book's audience, he says. Lilah, who appears in the story, loves the book. "She thinks it's the book about her," he says.

The last illustration portrays Brown with Lilah a few years older, looking at the night sky with a telescope. "When I was flipping over the proofs, I saw that, and my heart just sort of melted," he says. "I have a soft spot for the book just for that." □—*MW*

## Annenberg Groundbreaking

Caltech will soon have a new home for its interdisciplinary program in information science. The first institution in the nation with such a program, Caltech broke ground for the Walter and Leonore Annenberg Center for Information Science and Technology on December 7.

The field of information science is as broad as it sounds, encompassing many areas of science and engineering from the theoretical foundations of information to how nature handles it in biological systems to how it shapes social systems.

"When you're crossing so many different disciplines, when you're reinventing the very boundaries of science and the way it can improve our lives, you deserve a research home, an intellectual crossroads that is as collaborative and inclusive and revolutionary as the work itself. This center will be that home," said Wallis Annenberg, vice president of the Annenberg Foundation, which donated $25 million to build the center. Stephen D. Bechtel Jr., a life trustee of Caltech, recently awarded $1 million to the project. Caltech hopes to raise a total of $31.5 million.

The 50,000-square-foot building will contain an 80-seat lecture hall, several small classrooms, an instructional computer lab, and studio and office space for faculty and students. The center will also feature atrium and lounge spaces to promote collaboration and interaction. The building's exterior is mostly glass, with a window in nearly every room, connecting the structure with the campus, said Frederick Fisher, the principal architect.

The center will also herald a new information-based curriculum at Caltech, and possibly beyond. "The dream is very vivid in my mind," said Jehoshua "Shuki" Bruck, the Gordon and Betty Moore Professor of Computation and Neural Systems and Electrical Engineering and founding director of the Information Science and Technology initiative. One day, he hopes, information will be taught in schools and universities alongside traditional subjects like history or physics.

The Annenberg Center aims for a Silver rating from the Leadership in Energy and Environmental Design (LEED) Green Building Rating System, developed by the U.S. Green Building Council. Slated for completion in the summer of 2009, it will be one of three new LEED-rated buildings on campus. □—*JP/MW*

PICTURE CREDITS: 2 — Paul Rothemund, Robert Lang; 3 — USPS; 8, 12 — NASA/JPL-Caltech/U. of Arizona; 11 — Audrey Wu, Dick Sneary Illustrations

## And Schlinger, too.

Chemists and chemical engineers at Caltech will soon have a new playground. Work on the Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering began on February 13.

The lab will form a new focal point for the Division of Chemistry and Chemical Engineering, said David Tirrell, the McCollum-Corcoran Professor and professor of chemistry and chemical engineering. The new lab will attract new faculty and spur research, said Tirrell, who also chairs the division.

Located near the western end of the San Pasqual walkway on campus, the four-story building will occupy 60,000 square feet and should be finished in 18 months. It will also likely merit a Silver rating under the Leadership in Energy and Environmental Design (LEED) Green Building Rating System for environmentally sustainable buildings.

The Schlinger Lab was named in recognition of a $20 million campaign donation from Warren and Katharine Schlinger. Warren (BS '44, MS '46, PhD '49) spent 12 years studying, researching, and teaching at Caltech. Katharine grew up in the Pasadena area and met her husband while working as a department secretary for Chemical Engineering.

In addition to the Schlinger and Moore Foundation contributions, gifts have come from an array of supporters, including the estate of former trustee Victor K. Atkins; trustee G. Patricia Beckman (daughter of Mabel and Arnold Beckman, PhD '28); Barbara J. Dickinson (widow of Richard Dickinson '52); the Ralph M. Parsons Foundation; the John Stauffer Charitable Trust; John W. Jones ('41); Helen and Will Webster ('49); Gregory P. Stone ('74); and others. Funds raised to date total $37 million; the building is anticipated to cost $45 million. □—*EN*

# Fifty Years in Space

By Douglas L. Smith

*An international Who's Who of aerospace luminaries packed Caltech's Beckman Auditorium last September to celebrate "50 Years in Space." The conference was organized by Ares Rosakis, the von Kármán Professor of Aeronautics and Mechanical Engineering and director of the Graduate Aeronautical Laboratories at the California Institute of Technology (GALCIT), and Dwight Streit, vice president, electronics technology, for Northrop Grumman Space Technology, which cosponsored the event with GALCIT and the Jet Propulsion Laboratory, which Caltech administers for NASA. The heavy hitters from all of Earth's spacefaring nations were invited, says Rosakis, but the representatives from China and Russia were no-shows. According to Rosakis, the conference's three chairs—Caltech president Jean-Lou Chameau, JPL director Charles Elachi (MS '69, PhD '71), and Northrop Grumman Space Technology president Alexis Livanos (BS '70, MS '73, PhD '75)—represented the triumvirate of academia, national laboratories, and industry that has woven the exploration and use of space into the fabric of our society. The speakers, who were drawn from all three branches of the triumvirate, celebrated past accomplishments, reflected on our current situation, and speculated on the future of humanity's endeavors in orbit and beyond. Herewith are some of their thoughts, culled from a day and a half of presentations and panel discussions and reassembled in narrative form. Streaming video of all the presentations, along with event photos and speaker biographies, can be found at* http://galcit.caltech.edu/space50.

## Where We've Been

The journey into space began humbly enough, as astronaut Ronald Sega, retired undersecretary of the U.S. Air Force, pointed out. The Wright brothers' first flight in 1903 was about 120 feet, roughly the length of the auditorium, and Robert Goddard's first rocket in 1926 reached about 41 feet, or approximately to the ceiling. It took another 30-plus years to reach orbit, with the Soviet Union's October 4, 1957, launch of Sputnik as Earth's first artificial satellite propelling the world into the Space Age and the United States into the Space Race.

Numerous speakers paid homage to the Cold War as a powerful motivator. Opening keynoter Ronald Sugar, chairman and CEO of Northrop Grumman, said that "an international space movement based on cooperation and the quest for knowledge emerged from one originally based on geopolitical struggle and military competition." Joanne Maguire, executive vice president of Lockheed Martin Space Systems, was blunter. "One wonders if the U.S. would have done anything in space in the 1960s if it were not for the Cold War."

DARPA, the Defense Advanced Research Projects Agency, was founded in 1958 along with NASA, both in response to Sputnik. That 84-kilogram sphere, clearly visible every 98 minutes as

Image credit: X-ray–NASA/CXC/SAO; Optical–NASA/STScI; Infrared–NASA/JPL-Caltech

**Supernova remnant Cassiopeia A through the eyes of three of NASA's Great Observatories. The outer shell of cold dust seen in the infrared by the Spitzer Space Telescope is colored red, the filaments of warm gas visible to the Hubble Space Telescope are yellow, and the superheated shock wave seen by the Chandra X-ray Observatory is green and blue.**

A false-color mosaic of Saturn's far side from the Cassini spacecraft. The rings are backlit, so the most opaque parts appear darkest. Thermal radiation from Saturn's interior lights up the night in red. Thick clouds deep in the atmosphere block some of it, appearing as dark streaks, spots, and globe-encircling bands. Saturn's sunlit side appears greenish-yellow.

it passed overhead, was a great shock to America's presumption of superiority in all things scientific and technical. David Whelan, chief scientist for Boeing Integrated Defense Systems and former director of DARPA's tactical technology office, said DARPA's charter was to "prevent technological surprise," and described how it functions as part think tank and part piggy bank. DARPA foresaw the military usefulness of space for photoreconnaissance, weather forecasting, telecommunications, and GPS. All of these, of course, have now found civilian uses as well, and the synergy between military and civilian space efforts was a constant theme of the conference. The agency started writing checks immediately, said Whelan, with ARPA (the word "Defense" wasn't added to its name until 1972) Order #1 going to Wernher von Braun to develop the first American spacecraft, the Explorer 1. Later ARPA funding orders were for the development of the Mercury and Gemini space capsules that took Americans into orbit, and the Saturn rocket motors that took us to the moon.

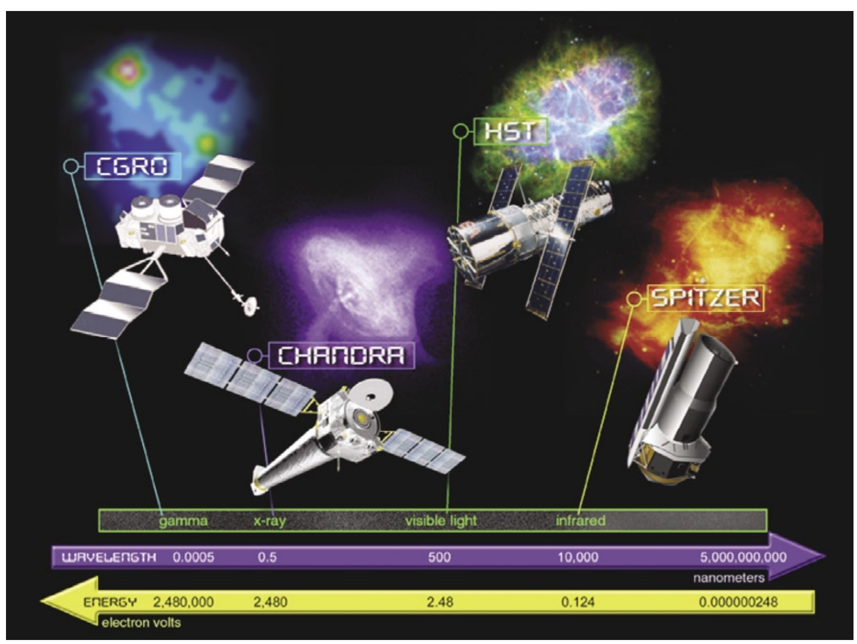
On May 25, 1961, President Kennedy addressed a joint session of Congress after the Russians had beaten the Americans once again by putting cosmonaut Yuri Gagarin in orbit on April 12. Kennedy challenged the nation to put a man on the moon by the end of the decade. NASA hopped to it, and in 1962, Eugene Shoemaker (BS '47, MS '48) of the U.S. Geological Survey helped NASA develop a plan for lunar exploration. In January 1963 he began field-training astronauts, leading the Gemini group—which included future moonwalkers Neil Armstrong, Pete Conrad, and John Young—on a two-day tour of Arizona's Meteor Crater and nearby volcanic features, said Apollo 17 astronaut Harrison "Jack" Schmitt (BS '57). "Shoemaker was one of the best and most infectious of teachers. I know that this trip impressed my future colleagues." By 1967, "science training reached a new level of sophistication," with spacesuited astronaut-geologists using the equipment they would actually be carrying, operating under realistic time constraints, and communicating their observations by radio to scientists at mission control. Shoemaker, USGS colleague Gordon Swann, and William Muehlberger (BS '49, PhD '54) of the University of Texas had become Apollo's field-geology principal investigators. They planned mission-specific training trips, scouted appropriate locations, and, perhaps most importantly, recruited mentors. These included, besides the three PIs, Caltech geology professors Lee Silver (PhD '55) and Robert Sharp (BS '34, MS '35), who "provided infectious emphasis on 'belly geology,'" and Richard Jahns (BS '35, PhD '43), a recent defector to Stanford from the Caltech geology faculty by way of Penn State.

Various speakers described the robotic post-Apollo exploration of the solar system and our growing understanding of the evolution of the cosmos and our place in it through a panoply of astronomical missions, including NASA's Great Observatories. This fleet of four space telescopes has covered the electromagnetic spectrum from ultra-energetic gamma rays down to the coldest of infrared radiation. (The Compton Gamma Ray Observatory was de-orbited in 2000; its successor, the Gamma-

Eugene Shoemaker points with his rock hammer as he describes the geology of Meteor Crater's rim ejecta to astronaut trainees during a field trip in May 1967.

NASA/Eugene Cernan

Harrison Schmitt, Apollo 17's lunar-module pilot and the second-to-last man to set foot on the moon, wields an adjustable sampling scoop. Apollo 17 brought back 109 kilograms of lunar material from the Taurus-Littrow region in December 1972.




Three of NASA's four Great Observatories are still in service.

ray Large Area Space Telescope, is slated for launch this May.) JPL's Michael Werner, the project scientist for the infrared Spitzer Space Telescope, called the ensemble "a programmatic stroke of genius," as they were built in sequence, maintaining a steady stream of funding from year to year and from mission to mission, as opposed to the more usual approach of starting with a clean slate annually and having to rejustify the budget.

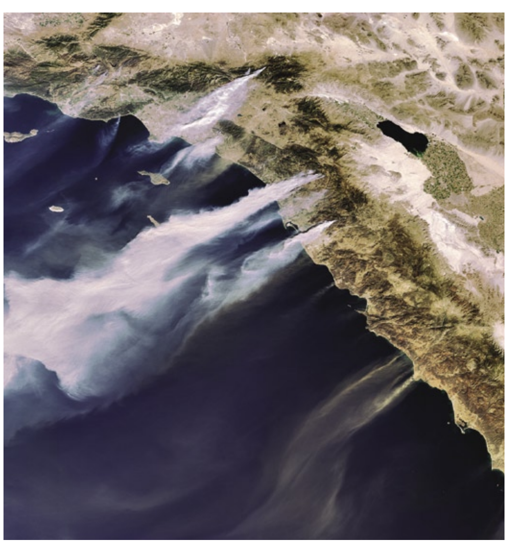
"The cost per year of Cassini, all of that three billion dollars amortized over the life of the mission, is about what Americans spend annually on lip balm."

This assortment of intellectual riches led Neil deGrasse Tyson, director of New York City's Hayden Planetarium, to comment that "the highest form of compliment is [that] people see NASA's achievements and they think it's 20 percent of the federal budget. They complain about how much we're spending on NASA to generate what they see, and they have no idea how little it is." For example, "the cost per year of Cassini, all of that three billion dollars amortized over the life of the mission, is about what Americans spend annually on lip balm."

## Where We Are Now

In some ways, NASA has been a victim of its own success—space is now such a part of our lives that we don't notice it. William Ballhaus Jr., then president of the Aerospace Corporation, told "two stories about whether people recognize the impact of space. . . . A CNN reporter asked a soldier in Iraq, 'You're in a net-centric environment, space has become an integral part of defense, how is space affecting you?' And he said, 'I don't need space. All I need is my rifle and my GPS.' Another good example is [that] when Dan Goldin was the NASA administrator, a congressman asked him what is a very legitimate question if you don't understand anything about space: 'Why do we need weather satellites when we have the Weather Channel?'" Ballhaus called space a utility. "It's just like power to your house. People don't understand how the power got there, but they sure notice if it doesn't get there. . . . Last week we completely changed the ground system on GPS, and you didn't read about it in the news, because it worked smoothly."

**Below right: The European Space Agency's Envisat dwarfs its handlers. Below left: An Envisat view of the smoke plumes from Southern California's wildfires on October 22, 2007.**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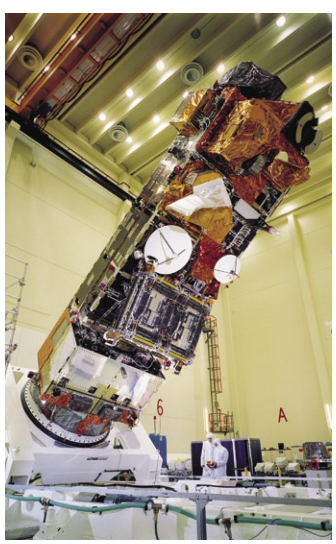
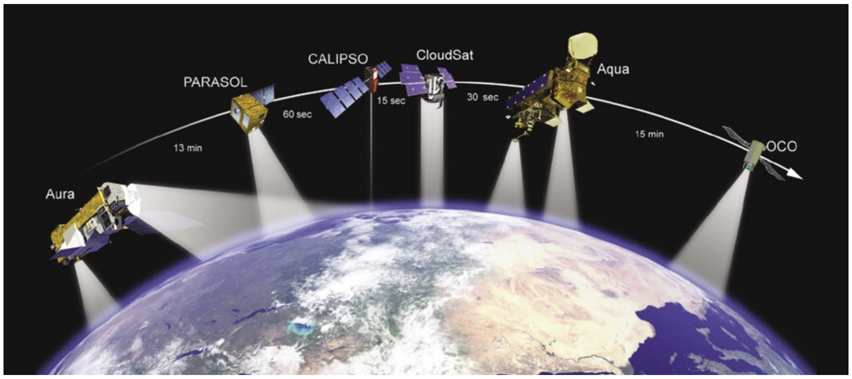

ESA/A. Van Der Geest

Just like the water and electric companies, space utilities turn a profit. According to Boeing's Whelan, "The U.S. government's cost to pay for and manage GPS for the country is actually offset by the profit to the tax base due to all the revenues from people buying cars with GPS units and so forth. So it's actually revenue-positive to the Treasury." To which Maguire replied, "Try explaining that to Congress."

Several speakers ticked off space's many uses: crop management, traffic management, disaster management, land-use planning, environmental monitoring, antiterrorism. A. P. J. Abdul Kalam, India's 11th president and the aeronautical engineer who founded that country's missile program, boasted that in India, tele-education (2,700 classrooms) and telemedicine (250 hospitals) are practiced routinely, and that the nation plans to link 100,000 villages by satellite in a "knowledge net."

The European Space Agency's director general, Jean-Jacques Dordain, proposed having a "Space Day" once a year on which all satellites are shut off for 24 hours so people can see how much they depend upon them, and suggested, tongue firmly in cheek, that the World Cup finals might be a good day for this.

Unfortunately, we will get an involuntary demonstration of this as America's aging fleet of climate-monitoring satellites starts to go off line. As CNN's chief technology and environment correspondent Miles O'Brien noted, "By the end of the next decade, the U.S. will have 40 percent fewer sensors in orbit because of flat or reduced budgets. Many programs have been canceled; many have been delayed," which will lead to gaps in the data sets required for climate modeling and prediction. Several speakers bemoaned this state of affairs, and hoped that future administrations would do better. Meanwhile, ESA is stepping up to the task, said Dordain, with Earth missions being its fastest-growing area of endeavor. ESA's seven-ton Envisat, launched in 2002, is the biggest Earth-observing spacecraft ever built, returning over 280 gigabytes of data per day. A fleet of much smaller craft of some 500 kilograms each will be launched every six months beginning this spring. But NASA's stumble will be felt—according to Yannick D'Escatha, president of France's Centre National d'Études Spatiales, "the overall European annual space-science budget is equal to the single Mars-exploration budget [line] in the U.S." Said Ballhaus, "The fact that weather mod-




NASA/Alex McClung

**Climate modeling requires lots of data about any given place at any given time. Hence the Afternoon Constellation, better known as the "A-Train" in homage to jazz great Duke Ellington. These satellites share a polar orbit, with very short time gaps between them.**

**There was plenty to see between sessions. Here Jean-Jacques Dordain, ESA's director general (with red folder); Caltech trustee Jon Kutler (with sunglasses), a member of the JPL oversight committee; and Yannick D'Escatha, president of France's Centre National d'Études Spatiales (CNES), check out a replica of one of JPL's current Mars rovers. JPL's first rover, Sojourner, also full-size, can be seen in the background, behind JPL director Charles Elachi (red tie) and Sylvie Callari, head of international affairs at CNES.**

eling is a utility and we can't afford to gap it is a national-security issue. It's fundamentally important that we plan the future so we don't have those gaps."

Frank Fernandez, DARPA's director emeritus, said that with the onset of global warming, "We're going to need, in a decade, the global observations to drive the models to make the predictions to tell people when to leave. Because the weather is going to get more *active*. As more energy is trapped in the atmosphere, we're going to have more chaotic weather." He added that "someone needs to make it clear to the policy makers that this is not a 'nice-to-have,' it's a 'gotta-have.' We're doing this amazing experiment. We're putting all of this stuff into the atmosphere, and there's a lot of controversy over what effect it will have, but we do know that it won't go away by itself for a couple of hundred to a thousand years. The only way we're going to be able to get the data to tell us what's going on and to refine the models to do the predictions is going to be global sensing. If we don't start now, in 10 or 20 years when somebody finally decides 'we have to solve this problem,' we won't have the capacity to do it."

This capacity is not just in space, but on the ground, in the form of a new generation of scientists and engineers. France Córdova (PhD '79), president of Purdue University and an astrophysicist with an instrument on ESA's XMM-Newton X-ray telescope, noted that Purdue's alumni include Gus Grissom, Neil Armstrong, Gene Cernan, Roger Chaffee, and 18 other astronauts. She recently had the opportunity to talk to the daughters of two of them, now Purdue undergraduates themselves, and "one was in our hospitality management program, and the other was an English major. Both fine majors, but where's the engineering spark?"

Burt Rutan, founder of Scaled Composites and designer of SpaceShipOne, the world's first privately built manned spacecraft, pointed out that "all of the billionaires now who are putting money into space—[Virgin's] Richard Branson, [Microsoft's] Paul Allen, [PayPal's Elon] Musk, [Amazon.com's Jeff] Bezos—were all little kids for Apollo. And that's where their inspiration came from. Right now, kids are inspired by the next iPhone, not by exploration or adventure or taking risks. And that's going to hurt us in future generations."

The average age of Apollo's mission controllers was 26, meaning that they were starting high school when Sputnik was launched, Córdova said. "Now at the dawn of a new century that should push the boundaries of knowledge far beyond 'the surly bonds of Earth,' the United States finds fewer students pursuing degrees in science, technology, engineering, and math." Citing various recent studies, she went on to say that the number of U.S. citizens getting science degrees fell from third in the world three decades ago to 17th in 2004. Forty percent of NASA staff are 50 and older; only 4 percent are younger than 30. Meanwhile, U.S. jobs requiring a science and technology background are growing at 5 percent per year.

America shouldn't look for the last couple of decades' influx of foreign students continuing to make up the difference, said Tyson, who worried that our "jingoistic" policies are making it harder for them to get into the country. American science has been so fertile because we have always welcomed the best from abroad, he said. The atomic bomb and the Apollo program are "American" achievements, but both relied on foreign-born brains, from Hans Bethe to Wernher von Braun.

Speakers proposed various remedies, including more industry-academia-government partnerships, mostly aimed at college students. Former Air Force honcho Sega spoke of the new National Defense Education Program, named by analogy to Eisenhower's National Defense Education Act of 1958, and modeled after it. The Act was designed to bring American students up to speed in science and math—as Northrop Grumman's Sugar observed, "It was not just that beeping metallic sphere that induced so much hysteria in the free world, it was the Russian rocket technology that put it there," and America needed to catch up. Córdova touted Purdue's Discovery Park—a 40-acre complex of labs for biotech, nanotech, and the like—as a model for a steady source of funding for high-risk, high-payoff research, which is what the Apollo program was. Caltech's own Ares Rosakis described the Institute's efforts in this field—see the article on page 34.

Meanwhile, space is getting crowded. There are

240 commercial communications satellites alone in geosynchronous orbit, said India's Kalam. Speakers from various space agencies reeled off head-spinning slates of missions to worlds beyond. The moon is a popular destination—Japan's Kaguya and China's Chang'e-1 are in lunar orbit right now, mapping away. India's Chandrayaan-1 will be launched to the moon later this year. Chinese and Indian rovers will follow, then humans. Lockheed Martin's Maguire quoted Michael Griffin, NASA's administrator, as saying, "I personally believe China will be back on the moon before we are," and added that the Russians plan a manned mission to the moon in 2025, and a permanent base there somewhere around 2030, despite having one-sixteenth NASA's budget.

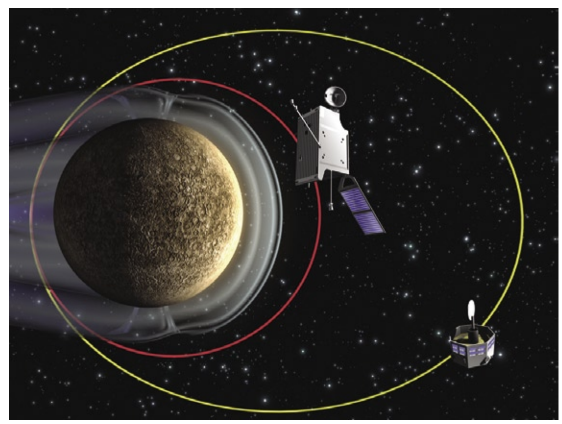
"There's been nothing much new in propulsion technologies in the last 50 years. But there must be some new discovery still around the corner. You young people at Caltech have a reputation for breakthroughs in propulsion technology—let that be your homework assignment for the next week."

Getting any big project off the ground, and especially out of Earth's gravitational well, requires international effort these days. As ESA's Dordain said, "It is always easier not to cooperate, but it is always more difficult to succeed alone." But cooperation won't happen unless every party's national interest is served. Even something as seemingly universally beneficial as free exchange of climate data has pitfalls, said Charles Kennel, former director of NASA's Mission to Planet Earth, the world's largest Earth-science program. "Different nations have different conceptions about the value of their environmental intellectual property." For example, "countries in the Middle East would regard information on the water flows for the next season to be a matter of national security."

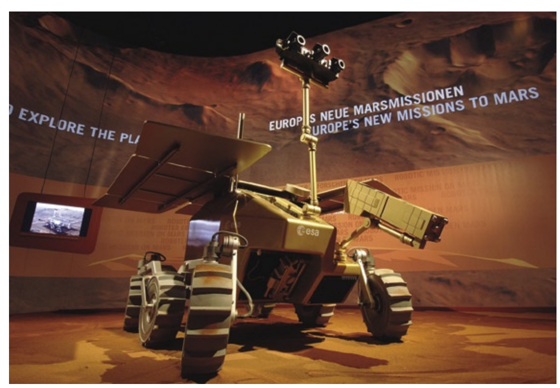
The biggest obstacle to the high frontier is the price of liftoff. It costs $20,000 per kilogram to put a payload in orbit, says Kalam; he'd like to see that figure go down to $2,000 and eventually $200. The problem is the oxidizer, which allows fuel to burn once the air gets thin. Liquefied oxygen takes up nearly 70 percent of the launch weight of a liquid-fueled rocket. Kalam said studies in India show that a reusable single-stage-to-orbit vehicle of some 25–30 tons launch weight is feasible. Such a craft would, once up to speed, scoop up air, liquefy it, and extract the oxygen on board, accumulating enough to reach orbit. He foresees scaling these designs up to 270-ton vehicles with a 15 percent payload fraction. "If you had 20 percent payload fraction—10 times current—and reused it 100 times, you'd get about $200 per kilogram launch cost." He said that India is working on such systems, and called for international cooperation to develop the technologies needed.

Boeing's Whelan proposed a tiered pricing system instead of the current one-cost-fits-all approach. Manned missions need the highest reliability factor—three nines, or 0.999 out of 1.0—and so one might be willing to pay $20,000 per pound. But for satellites, 0.99 reliability would suffice, and the cost should drop to $3,000 to reflect that. And for low-value launches of items like water, fuel, and toilet paper needed for life in low Earth orbit or on the moon, one could opt for 0.9 reliability and pay $200. "It's a commodity—I don't care if you lose it. And in fact, on a strictly economic basis, you only need 0.5 reliability."

Rutan opined that "lift capacity started out being so expensive because there was so little of it. That's true of every new technology—you do it in onesies, twosies. But now, 25, 50 years down the road, it hasn't changed much. I think the problem is the folks . . . don't care that it costs $100 million to buy a booster, because their satellite costs $500 million." The only solution is to drive down manufacturing costs by making it up in volume, he said, and the only way to generate sufficient demand is "if we go through a time period where

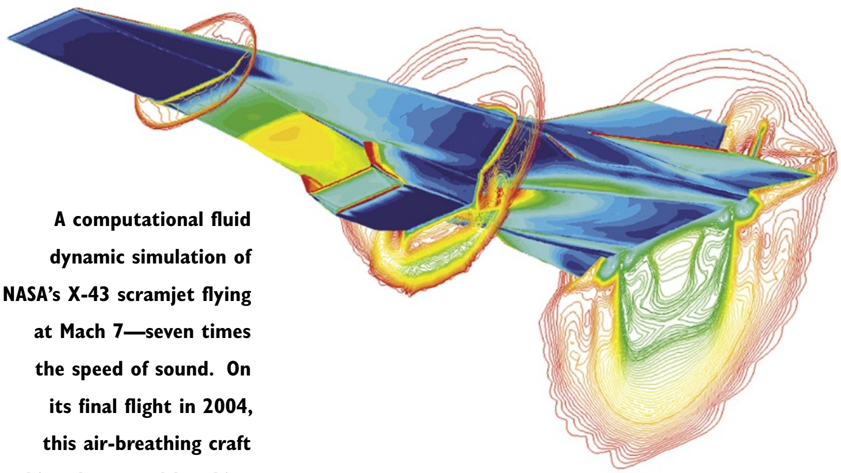


ESA/C. Carreau



ESA/M. Pedoussaut

**In space, international cooperation is the norm. The BepiColombo mission to Mercury (top) consists of two spacecraft, ESA's Mercury Planetary Orbiter and the Japanese space agencies' Mercury Magnetospheric Orbiter. And ESA's ExoMars rover will include Russian and American collaborators. Both missions have 2013 launch dates.**



A computational fluid dynamic simulation of NASA's X-43 scramjet flying at Mach 7—seven times the speed of sound. On its final flight in 2004, this air-breathing craft achieved a record-breaking Mach 9.6—nearly one-third the velocity needed to reach orbit.

the focus is on flying the consumer. [Humans] don't cost anything—in fact, they pay to fly. And these payloads can be easily reproduced in huge number with unskilled labor, with tools you already have around the house."

"You can now fly nonstop to London for $500 round trip," Elon Musk, founder of SpaceX, which is developing the Falcon reusable rocket, pointed out. But "the only reason that round-trip flight from L.A. to London is $500 is because that 747 can be reused thousands of times."

Maguire hoped for an outside-the-box solution. "There's been nothing much new in propulsion technologies in the last 50 years. But there must be some new discovery still around the corner. You young people at Caltech have a reputation for breakthroughs in propulsion technology—let that be your homework assignment for the next week."

### Where Are We Going?

Developing cheap orbital access will cost quite a lot of money. The feeling among the speakers seemed to be that the cash should come from the private sector as a corollary to the continued commercialization of space. The always-outspoken Rutan led the charge. "NASA should only fund research, not development. When you're spending hundreds of millions of dollars to put people into space using pieces of the shuttle, and pieces of Apollo, you're dumbing down a whole generation of new, young engineers who are told, 'No, you can't take any risks, you've got to do it the way we know will work.' . . . Having the government repeat Apollo 50 years later is just silly." Musk felt that the potential was indeed there. "If we have a base somewhere, on the moon or Mars, hopefully a tiny growing civilization, the transport back and forth will be a multitrillion-dollar industry."

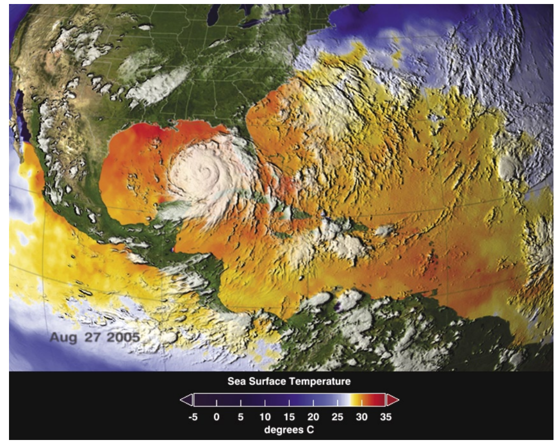
David Thompson (MS '78), chairman and CEO of Orbital Sciences Corporation, which builds and

### A Tribute to Si Ramo

A special session of the conference honored Simon Ramo (PhD '36), a founding giant of the aerospace industry. Session chair Alexis Livanos (BS '70, MS '73, PhD '75), the president of Northrop Grumman Space Technology, called him an "entrepreneur, scientist, author, musician, philanthropist." At Caltech, Ramo got dual doctorates in physics and electrical engineering in just three years. "He had more requirements than he had time," which once led him to take a course and its prerequisite concurrently. (He passed both.)

Livanos described how Ramo and classmate Dean Wooldridge (PhD '36) founded the Ramo-Wooldridge Corporation, "the most successful electronics corporation in history." The duo made the cover of *Time* on April 29, 1957; by then Ramo was Chief Scientist of the Air Force's ballistic missile program, and Ramo-Wooldridge was overseeing the production of the Atlas and Titan ICBMs. (The firm's Pioneer 1, launched October 11, 1958, by the newly formed NASA, became the first privately built object in space.) In *Time*'s description, Ramo "'lets his thoughts bounce around like an errant light beam,'" Livanos quoted. "That brilliant light beam has shone brightly at TRW, Northrop Grumman [both Ramo-Wooldridge's successors], and nationally for more than five decades. Si has counseled industry leaders. . . . He was awarded the National Medal of Science by Jimmy Carter, and he was awarded the Presidential Medal of Freedom by Ronald Reagan." Livanos and several other conference participants spoke of how Ramo had mentored them personally—often through one-on-one lunch conversations over simple cheese sandwiches.

Ramo, who was in the front row with his wife, Virginia, did not take the mike, but reflected on his career in a recorded interview with former JPL director Ed Stone. After talking about Sputnik, systems engineering, the proper role of humans in space, and the future of society, the conversation turned personal. When asked what career advice he would give the next generation, Ramo replied, "If something will interest you and be right for you, my advice is do what comes naturally. . . . When I got to Caltech, I found it was a science school. It didn't really teach engineering, it taught the science underlying engineering . . . at a period of time where engineering was about to be changed greatly, because of the scientific breakthroughs taking place." He got a job at General Electric upon graduation, and "the older engineers . . . did not know the new physics. So I had opportunities right off the bat to do some things. . . . It was an acccident. I was just lucky." □—*DS*




**These three views of Hurricane Katrina give an inkling of the wealth of data that needs to be integrated into climate-prediction models. From left: NASA's Aqua satellite recorded sea surface temperatures on a three-day average. The Tropical Rainfall Measuring Mission, a joint project of NASA and the Japan Aerospace Exploration Agency, tracked rain-cell intensity in three dimensions. And NASA's QuikSCAT satellite depicted wind speeds in color and wind directions with small barbs.**

launches satellites, charted the vital signs of a large and thriving space industry—$82 billion in commercial satellites and ancillary services worldwide in 2007, versus $42 billion in defense and $27 billion in all other areas, including manned spaceflight. Satellite TV revenues are now double the total U.S. national security space budget—$52 billion versus about $25 billion—"not bad for a business that didn't even exist 15 years ago." GPS equipment revenue, "the success story of the next decade," is bigger than our missile-defense budget ($10 billion versus $9 billion). And commercial remote sensing (think Google Earth, through which, as Rutan remarked, "in the last few years, with free downloadable software, you've been able to do what only a few analysts at the CIA used to do.") is approaching a billion dollars a year.

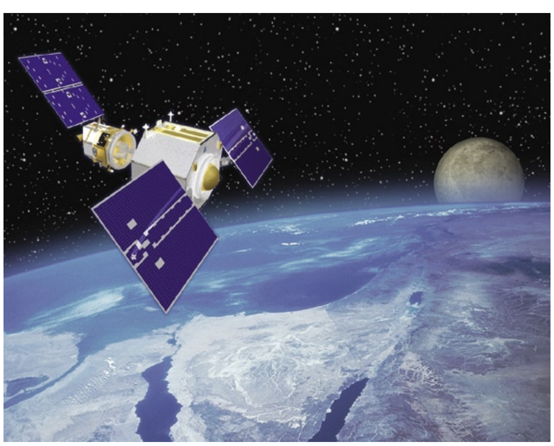
"While Apollo and its predecessors drove the technology development that launched the first generation of space businesses, now technology development often flows in the other direction," Thompson concluded. "It is time for the private space sector to repay the debt to NASA that got it started in the 1960s."

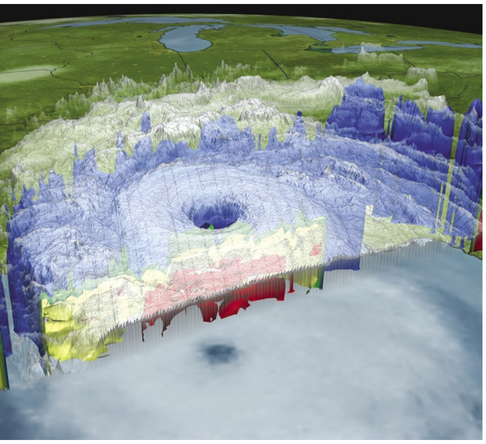
Several speakers speculated about the Next Big Thing. Would it be tourist hotels in low Earth orbit? Mining helium-3 on the moon and exporting it to Earth to produce clean energy by nuclear fusion? Orbiting arrays of solar panels that would beam their harvested power down? But all agreed that an airtight business plan would be required to start such a venture, and none were in the offing.

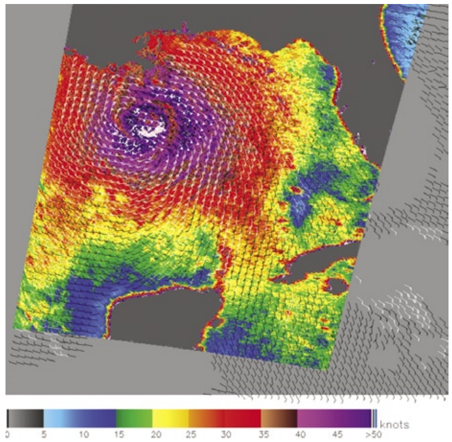
Boeing's Whelan sketched out an infrastructure for space, using DARPA's Orbital Express as the exemplar. A collaboration with NASA, the Air Force, Boeing, and other firms, Orbital Express consisted of two vehicles, Boeing's Autonomous Space Transport Robotic Operations, or ASTRO (the servicer, named in homage to the family dog in the 1960s prime-time animated TV series, *The Jetsons*) and Ball Aerospace's NextSat (the client). For four months in 2007, the two spacecraft demonstrated that they could perform such feats as rendezvousing with each other, docking themselves, and executing service missions such as refueling and component swap-outs—all using only their onboard computers and navigation systems, with no human intervention. Whelan proposed that fleets of unmanned transports carrying fuel and spare parts would one day rendezvous with automated service vehicles. These sophisticated robots would do whatever maintenance was needed on clients near their orbits, and even assemble large structures like space stations, or spacecraft destined for Mars and beyond. NASA is already planning to use a similar approach for moon base construction, launching the lunar lander with just crew and cargo and then fueling it aloft, allowing it to ferry a lot more weight per trip. Said Whelan, "I may not be able to reduce gravity, but I can improve the productivity of every pound I send into space."

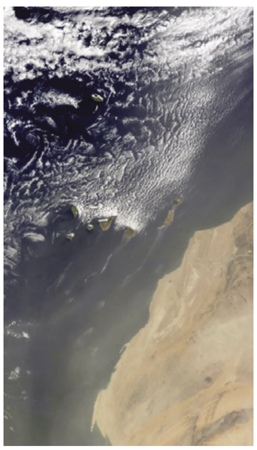
Not surprisingly, the future of space science was a hot topic. Our own planet will continue to get close scrutiny, although Berrien Moore III, then director of the University of New Hampshire's Institute for the Study of Earth, Oceans, and Space, remarked that global warming in and of itself is "not what the body politic is interested in. After all, if we double the amount of $CO_2$ in the atmosphere, it will lead to a three-degree, on average, temperature rise. Many people move from New Hampshire to Arizona for that three-degree global warming. What people are interested in are changes in severe events or extreme events." With advances in computing, "we are learning to put the pieces together—we can link wind fields with rainfall fields and sea-surface temperatures to understand the mechanisms of hurricanes." He pointed out that even though atmospheric $CO_2$ levels do not cause Earth's glacial cycle—that's an orbital thing—they have closely tracked the temperature records for the last 400,000 years. Earth is now in an interglacial period, which means that $CO_2$ levels should be about 350 parts per million by volume. Instead, "we're now at 450, 100 over

**Had there been a third spacecraft watching, Orbital Express's ASTRO (two solar panels) and NextSat (one solar panel) might have looked like this while docked.**







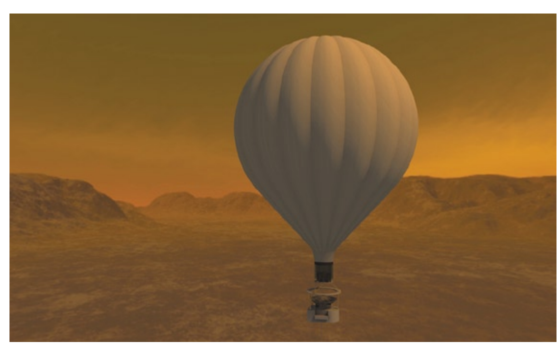



Saharan dust storms like this one have been revealed to deliver trace nutrients, including iron, to vast areas of the ocean that would otherwise be much less fertile. Through global satellite monitoring, "we're beginning to understand couplings that we didn't expect," said Moore. This shot of northwest Africa and the Canary Islands was caught on July 24, 2003, by NASA's Terra satellite.

the recorded high, and if we convert to a clean energy system the IPCC [Intergovernmental Panel on Climate Change] thinks we can stabilize it at 550. Business as usual puts us over 1,000. Even if $CO_2$ were not a greenhouse gas, this would be a major disruption in the carbon cycle, and it would be worth studying very carefully." Several missions, including JPL's Orbiting Carbon Observatory and Japan's GOSAT (Greenhouse Gases Observing Satellite) will track carbon's sources and sinks, and the decadal plan is to "orchestrate that with other missions that look at changes in vegetation, changes in radiation balance, changes in aerosols, changes in ozone to begin to get a handle on changes in climate." The radiation balance—how much heat we get from the sun versus how much we lose back to space—is critical, Moore said, because climate change is altering the rate at which the planet soaks up heat. Bright, reflective ice and snow is becoming dark, absorbent open water and exposed soil, for example. "We see that in the Arctic sea ice. Envisat in 2007 showed us that the long-searched-for Northwest Passage has finally appeared."

As for other worlds, Jonathan Lunine (MS '83, PhD '85), professor of planetary science and physics at the University of Arizona and an interdisciplinary scientist on NASA/ESA's Cassini/Huygens mission, talked about its exploration of Saturn's moon Titan as a paradigm, both as a model of international cooperation and an intrinsically interesting destination. He called Titan a "Once and Future Earth" because its atmospheric chemistry—hydrocarbons and nitrogen, but no oxygen—resembles prebiotic Earth's, and at the same time Titan may presage Earth's eventual fate long after humans have died off or moved on. "As the sun's luminosity grows [Earth's] temperatures will rise, the oceans will evaporate into the stratosphere, and the water will be photolyzed, just as methane is on Titan." He described a JPL proposal to explore Titan "in a leisurely way, with imaging that covers hundreds of thousands of square kilometers, rather

**Moore quoted what poet Archibald MacLeish wrote in *The New York Times* on Christmas Day, 1968, upon seeing the first photo of our home planet ever taken from deep space: "To see the earth as it truly is, small and blue and beautiful in that eternal silence where it floats, is to see ourselves as riders on the earth together, brothers on that bright loveliness in the eternal cold." The picture had been taken on December 22 by Apollo 8 astronauts Frank Borman, James Lovell, and William Anders as they rounded the far side of the moon.**



**A balloon-borne survey of Titan could send back data for months instead of hours.**

Backdropped by Earth's horizon and the blackness of space, the International Space Station is seen from space shuttle ***Atlantis*** as the latter departed on February 18, 2008.

than just 150," riding the gentle winds in a hot-air balloon lifted by the waste heat from the radioisotope power source that would provide the electricity for the instruments in the gondola.

Looking beyond our solar system, JPL's Michael Werner of the infrared Spitzer Space Telescope noted that the visible-light follow-on to NASA's Great Observatories program, the James Webb Space Telescope, is slated for launch in 2013 and will have 50 times the light-collecting area of the Hubble. With this and other missions, we will one day answer the Big Questions: Where do we come from? Are we alone? Some of the answers are already coming in, he said. "How prevalent are planetary systems around other stars? We can say with confidence that they are either prevalent or very, very prevalent."

The running controversy in the academic community over the merit of manned versus unmanned missions was explored. NASA administrator Michael Griffin debunked the widely held notion that NASA's budget peaked during the Apollo years, and has been in steady decline ever since. Although it is true that NASA spent more money in the few years when it was buying large pieces of expensive hardware like Saturn Vs, he said, if the budget is averaged over the length of time it takes to see a big project like Apollo or Cassini through to its end—say a 10-year running average—the flow of money has been remarkably steady.

Over 1,000 people in more than 17 countries are developing the James Webb Space Telescope. Some team members pose with a full-scale model at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

Griffin sees NASA's funding as remaining constant at about 0.6 percent of the federal budget, or "about 15 cents per American per day" for the foreseeable future. "In Washington, it's very difficult to get programs started, but it's even more difficult to get them stopped." Given that, he said, "the president's goal, return to the moon by 2020, is a rational goal in constant dollars." The Hayden's Tyson agreed that more could be done with the manned program's share of the money than what we have to show for it recently. "We designed Mercury, Gemini, Apollo, and Skylab on that budget. We got out of low Earth orbit on that budget. And ever since, we've been driving around the block on the Shuttle, boldly going where hundreds have gone before."

Griffin said that even Mars is reachable on that budget. Assuming that the manned portion ($9 billion of NASA's $14 billion per year) continues to go to the International Space Station until around 2020, and then gets rolled over into developing a lunar base—which would cost a few billion dollars a year to sustain—there would be five or six billion a year left over to begin working on Mars. At that rate, we could get to Mars in about 15 years, because most of the heavy lifting—literally, the development of the Ares V booster—will have been borne by the moon program. "We could be launching in 2035 and landing in 2037. And so by the time we are celebrating the 100th anniversary of Sputnik, we can be celebrating the 20th anniversary of landing on Mars."

In a rousing closing keynote speech, Tyson stated that manned space flight was NASA's top priority. "We in the academic community have this delusion that NASA is our own private science funding agency. But it has never been that." In fact, he said, NASA's science budget began at around 10 percent in the '60s and has grown to about 30 percent today. "But most of the money was *never* directed at science." He pointed out that the manned program is spread out across the country, where the representatives who vote NASA's budget live, and that the citizens who elect those representatives are interested in people. "I don't think anybody is ever going to name a high school after a robot. Yes, people love the rovers. I'm told the number of hits to the JPL website monitoring the rovers in the two weeks after they landed exceeded the total world traffic in Internet pornography." But, he said, "I would bet you that if humans were on their way to Mars at the same time, the rover site would go unremarked-upon." In the early days of manned flights, "every mission was an advancement on the previous one, which gave the media something to talk about. . . . That is a truth that's never recognized by the naysayers of the manned program—science is piggybacking on the manned program, and always has been. And I have not been given reason to presume that that will ever change. So if you have a healthy manned program, science will be riding on its back. Maybe not as much as we academics would like, but *it's there*."

While agreeing that sending mankind to Mars *could* be done, Tyson wondered if it *would* be done. He summed up our species' other great cultural investments of human and financial capital, and stated that there were only three drivers powerful enough to motivate them. "War. That is the biggest driver there ever was. There is always money for war." In this category he put the Great Wall of China, the Manhattan project, and the interstate highway system. (It, like Apollo, was a product of the Cold War—highway construction began in earnest in 1956 to move troops and tanks around the nation in the event of a Soviet invasion.) "The Promise of Economic Return." Here he listed the voyages of Columbus and Magellan, and the Tennessee Valley Authority. "Praise of Power." This could be civil or religious, he said: pyramids, cathedrals, or castles. "If you're a wealthy nation, you can do a billion-dollar mission. But can you do a 10-billion-dollar mission? I don't know. There's a threshold. Did we build the Superconducting Supercollider? No. Because there wasn't a weapon at the end of the supercollider. There weren't diamond mines at the end of the supercollider. We didn't see the face of Jesus at the end of the supercollider." To sustain a project with a Mars-sized price tag, he argued, only one of the Big Three will do. "All it would take would be one message from Beijing: 'We're going to put military bases on Mars.' Badda-bing; we'd be on Mars in nine months."

**Spacecraft old and new: Up front is a mockup of the Phoenix Lander, slated to touch down in the north polar region of Mars on May 25. In the background is Explorer I atop its second-stage Jupiter-C rocket.**

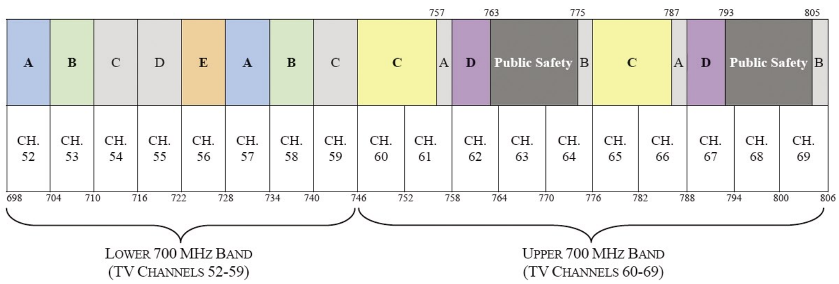
**Clockwise from the top: 1. Conference co-organizer Dwight Streit, vice president, Northrop Grumman Space Technology. 2. Conference cochair Alexis Livanos, president, Northrop Grumman Space Technology. 3. (from right to left) Conference co-organizer Ares Rosakis, director of the Graduate Aeronautical Laboratories at the California Institute of Technology; A. P. J. Abdul Kalam, the 11th president of India; and Kent Kresa, chairman emeritus of Northrop Grumman and chairman of Caltech's board of trustees. 4. Ronald Sugar, chairman of Northrop Grumman.**

Tyson ended the conference with slides of various technologies at infancy and maturity: Karl Benz's first motorcar and a high-end Mercedes, a Wright Flyer and an Airbus A380, and so on. "The first one looks quaint and should go in a museum. . . . But the Saturn V, 36 stories tall, does not look quaint. You have the urge to genuflect when you walk by it and ask, 'How the hell did we achieve this thing?' . . . The challenge today is to work at something that will make the Saturn V look quaint. That's what's going to have to happen to enable the next generation of space exploration." Whether the means to get us into orbit will undergo the same rapid technological evolution as the telephone, the mouse, the PC, and other workaday devices, ushering in a bright new era in space, only the next 50 years will tell. □

PICTURE CREDITS: 13, 17, 19, 20— NASA; 12 — NASA/JPL-Caltech/U. of Arizona; 13 — USGS, NASA; 18 — Boeing, NASA/SVS; 19 — NASA/JAXA, NASA/JPL; 20 — NASA/GSFC; 15, 21— Bob Paz

# Auctioning off the FCC's Crown Jewels

By Elisabeth Nadin




| Block | Frequencies (MHz) | Bandwidth | Pairing | Area Type | Licenses |
|---|---|---|---|---|---|
| **A** | 698-704, 728-734 | 12 MHz | 2 x 6 MHz | EA | 176 |
| **B** | 704-710, 734-740 | 12 MHz | 2 x 6 MHz | CMA | 734 |
| C | 710-716, 740-746 | 12 MHz | 2 x 6 MHz | CMA | 734 |
| D | 716-722 | 6 MHz | unpaired | EAG | 6 |
| **E** | 722-728 | 6 MHz | unpaired | EA | 176 |
| **C** | 746-757, 776-787 | 22 MHz | 2 x 11 MHz | REAG | 12 |
| A | 757-758, 787-788 | 2 MHz | 2 x 1 MHz | MEA | 52 |
| **D** | 758-763, 788-793 | 10 MHz | 2 x 5 MHz | Nationwide | 1 * |
| B | 775-776, 805-806 | 2 MHz | 2 x 1 MHz | MEA | 52 |

**The 700 MHz spectrum consists of several blocks dispersed across abandoned analog television channels. Hierarchical Package Bidding (HPB) was tested on the C block, which offered a total of 22 MHz in 12 Regional Economic Area Groupings (REAGs) that together would span the nation. (Blocks in gray were auctioned before Auction 73; the D block was set aside for public safety announcements but failed to meet the FCC minimum reserve price.)**

It's been called beachfront property . . . the last big slice of the spectrum pie . . . the crown jewels of the Federal Communications Commission (FCC). It is the 700 megahertz (MHz) frequency band, which actually runs from 698–806 MHz and until now has been the exclusive domain of broadcast television. On January 24, as a step on the road toward ubiquitous digital television, the FCC began auctioning off licenses for other uses of swaths of this band in what was called the most significant airwave auction in U.S. history.

The 700 MHz band is a hot commodity, especially for wireless companies, because the signal penetrates walls. Each tower broadcasting in this range can cover at least four times as many square miles as conventional cell-phone towers, which means fewer towers and therefore less expense to the winning bidders. To cell-phone users, it may also mean goodbye to roaming charges. Auction 73, as the 700 MHz auction is officially known, was the first chance for newbies like Google and Cox Cable, who each fronted the money the FCC required to enter the auction, to break into the wireless scene. They would bid alongside entrenched giants like Verizon and AT&T.

Caltech professor of economics Jacob Goeree monitored the auction closely, focusing particularly on one segment of the spectrum called the C block. The auction action was centered here because the C block—two bands totaling 22 MHz of the spectrum—would be sold under a new scheme: companies could bid either for any of 12 large-region licenses or for a package deal to win coast-to-coast coverage. By the end of the auction, which dragged on for 261 rounds spanning 38 weekdays as bidders haggled over tiny portions of the 700 MHz offerings, the C block had generated about a quarter of the $19.6 billion total that the FCC reaped in Auction 73—the most money the federal treasury has ever earned in a single auction. All the bids had been placed anonymously, but before the FCC finally announced the winners on March 20, those who had followed the daily action speculated that Verizon and AT&T were locked in a bidding war with

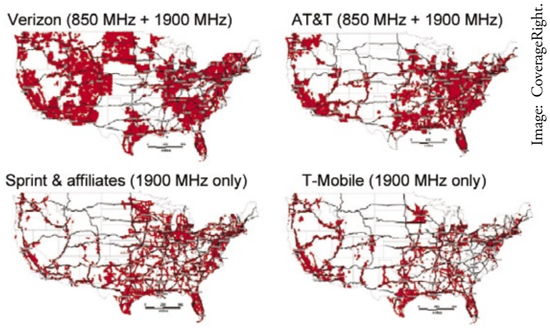
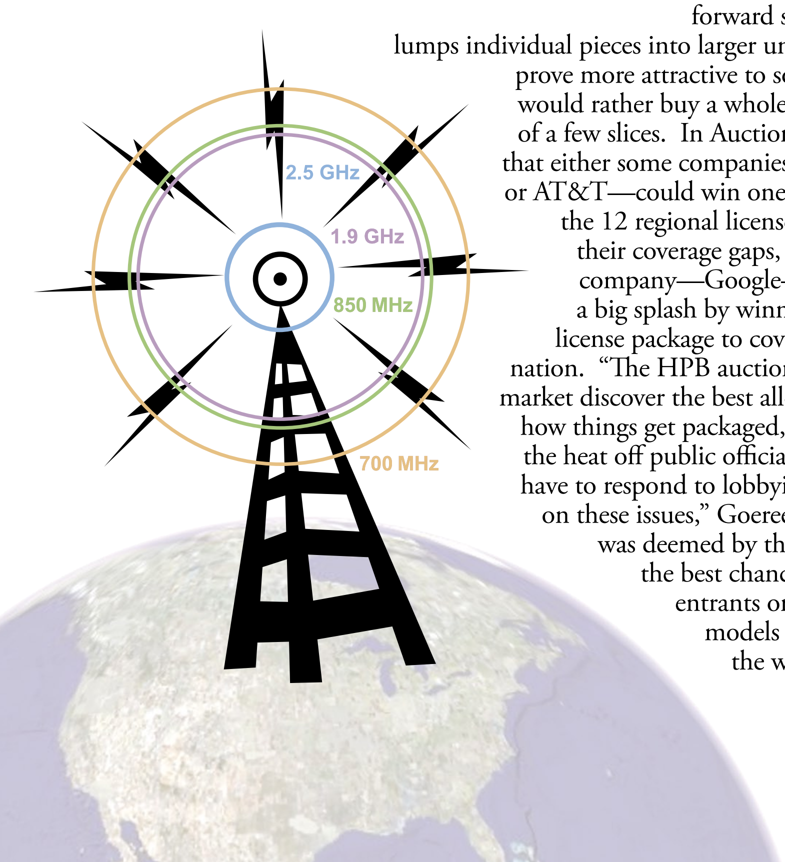



Image: CoverageRight.

**Above: Current coverage at the 850 MHz and 1900 MHz frequencies—the primary mobile communications bands in North America—leaves much of the country with no signal. Below: The 700 MHz signal propagates much further, necessitating fewer cell-phone towers.**




Google for nationwide coverage, driving prices up. All that had been known for sure was that someone was casting bids that topped $2 billion for the nationwide package as early as the fifth round.

Goeree was personally invested in the action around the C block, as he had designed the bidding mechanism that was used. Called Hierarchical Package Bidding (HPB), it's a relatively straightforward system that lumps individual pieces into larger units that might prove more attractive to someone who would rather buy a whole pie instead of a few slices. In Auction 73, it meant that either some companies—Verizon or AT&T—could win one or more of the 12 regional licenses and fill in their coverage gaps, or another company—Google—could make a big splash by winning the 12-license package to cover the whole nation. "The HPB auction rules let the market discover the best allocation, and how things get packaged, which takes the heat off public officials who would have to respond to lobbying pressures on these issues," Goeree says. HPB was deemed by the FCC to offer the best chance for new entrants or new business models to penetrate the wireless grid.

### Crunching Numbers

During the two years preceding that FCC auction, you would find students sitting at computers in the Social Science Experimental Laboratory (SSEL), in Baxter Hall's basement, weighing their options, placing their bids, and waiting for the next round. SSEL director Goeree would stride around the room watching the students in action, or bend his tall Dutch frame over his own computer screen, tracking each bidder's move. He had outlined the stakes—how much money each student stood to make if their bid won—and exhorted them to keep their profit margins as high as possible. Goeree wanted to know, could the bidder who stood to profit most actually win the auction? Time and again the answer was yes.

Goeree had no problem attracting students to run his experiments. "I heard about it from other students," says physics major Justin Chen, who earned enough in the FCC experiments to buy his longboard, on which he's often spotted rolling through the campus. (Chen is no stranger to strategic decision-making: he and a friend at Harvard concocted an equation to help them decide whether it's better to just wait for a bus or to start walking. Their answer, which made worldwide news, showed it's almost always better to wait.)

"It's generally straightforward," remarks Chen. "The experiments are designed assuming that all the players want to make as much money as they can." Before each round, each student bidder read from their screen what licenses they were interested in and how much winning them would be worth: Their earnings from the auction were proportional to the difference between those values and their bids, if their bids won. The better the bidder, the more he won, and in this manner Chen scored his greatest win of $140. A friend once made $303. Not bad for two hours.

Even though the students didn't actually know what they were supposedly buying, they competed with each other so realistically, says Goeree, that their bidding mimicked professional auction behavior. Their motivation, after all, was the same. "You start thinking about your strategies in the game—how you're going to bid to make more money," Chen says. He discovered that the main problem with auctions is that "you can't really lose money, but you can pay too much for something." Auctions are supposed to run such that the winning bid goes to the person who values the prize most. But in an ordinary auction format, the FCC would have no way of making sure that happened, even though they are charged with awarding licenses in an efficient manner that serves the public interest.

### Auctioning the Airwaves

Back in 1927, the Federal Radio Commission faced a straightforward task in granting airwave access—the demand was low enough that every applicant got a license. By the time the FCC took over seven years later, television was on its way. Several parties competed for each license, and the FCC had to weigh which one had the public's interest best in mind. The winner often sold its license for a profit, and losers appealed and won, and the FCC found itself mired in lawsuits. It took a lot of time and tax dollars to grant a license. License fees were fixed at a low rate, and the FCC sure wasn't pulling in any money for all its work.

"The experiments are designed assuming that all the players want to make as much money as they can."—student volunteer Justin Chen

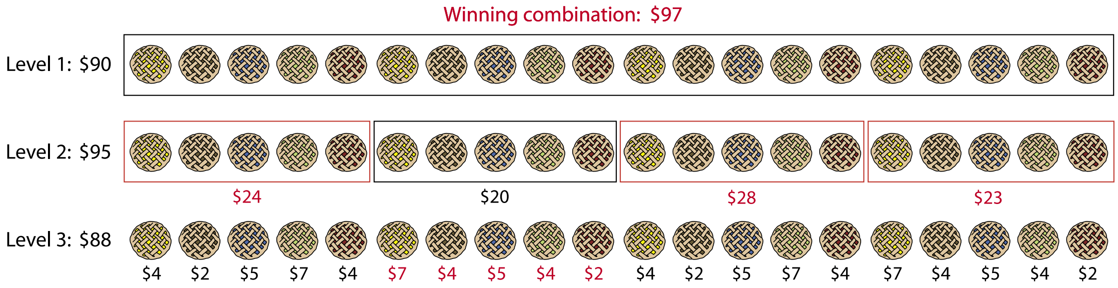
Imagine what happened as the telecommunications industry grew. The FCC now regulates interstate and international communications by radio, television, wire, satellite, and cable. In 1982, the agency switched to a semiregulated but arbitrary license-granting system: a lottery, allowing the FCC to award one applicant and avoid litigation from the losers. But then came a flood that would have made Noah blanch: applicants filed under multiple names to increase their chances, and opportunists realized they stood to make a killing if they happened to win—they could sell the license at a vastly inflated price to someone else who really wanted it. This was especially true for cellular communications, and wireless lottery schemes were called "the number one investor fraud in the country." The FCC seemed like the biggest loser under the lottery system.

A little over a decade later, the FCC switched to a competitive bidding system. The system makes sense to economists, says Goeree, because it gets licenses into the hands of those who value them most. And the FCC came out ahead, too—it no longer had to figure out which applicants qualified; each could bid as high as they decided a license was worth to them, and the FCC would reap the profits. These auctions employed simultaneous multiple bidding for individual licenses—all the companies interested in a license would bid on every license they were interested in, and then stay in the bidding as long as they had the money.

The first FCC auction back in 1994 was considered a great success—the *New York Times* termed it the "Greatest Auction Ever"—and even then Caltech researchers played a pivotal role. Caltech's Johnson Professor of Business Economics and Management, Preston McAfee, helped design the auction together with Stanford University professors Paul Milgrom and Robert Wilson. Another Caltech scientist, Charles Plott, the Harkness Professor of Economics and Political Science, had been testing the FCC's system and discovered that the bidding software was flawed shortly before the auction was supposed to start. Plott impressed the FCC, and the industry, by providing the FCC with a manual backup system he created with Antonio Rangel (BS '93), then an undergraduate student and now an economics professor at Caltech.

Another snafu the FCC faced in the auctions was bidding collusion. Companies weren't allowed to communicate directly but they could signal through the bidding process how to divide the market. With bids that reached over $100 million, bidders could use the many zeros in the bid amounts to signal information that might help in an attempt to keep prices down. The FCC tried to fix this by imposing predetermined bid increments, but the suspicion of bidder collusion continued to overshadow later auctions. The problem was finally resolved in Auction 73, when the FCC decided to use an anonymous bidding procedure. Until the close of the auction, no one but the bidder knew who had placed the highest bid in a round.

The FCC's simultaneous bidding mechanism, used for over a decade and copied around the world, is generally considered a great success. But even prior to that first auction in 1994, some economists saw room for improvement. They worried that companies interested in winning certain combinations of licenses, like a package that might serve the entire East Coast or establish nationwide coverage, might be hurt in the license-by-license competition the FCC was organizing. Several Caltech professors, including John Ledyard, the Davis Professor of Economics and Social Sciences, pioneered a different approach, one in which bidders could place bids on individual licenses as well as combinations of licenses. Their research had convincingly shown that efficiencies and revenues of the FCC auctions were reduced because bidders hesitated to incorporate synergistic values into their bids for fear they would end up being in a bad spot financially when competing fiercely for a desired




**In this HPB scheme involving pies, bidders competed on three levels. The winning bids, in red, maximized profits by combining winners in levels two and three. The level-one bidder, who stood to take home 20 pies, couldn't outcompete bidders on level two, who wanted packages of five pies. Likewise, the level-two bidder for the second "block" of five pies lost to those on level three, who bid on the individual pies of that package.**

package but winning only part of it. Their findings formed the impetus for the FCC to build a new system that incorporated combinatorial bids.

## Building a Better Airplane

When the FCC approached Goeree and his colleague Charles Holt at the University of Virginia in 2004, it asked them to test the combinatorial auction the FCC had already built. Goeree recalls, "It was as if they were saying, 'Before we bring people on board, please fly our plane around.'" Like testing a scale model of an airplane in a wind tunnel, experimental auctions allow economists to control all the variables. "We know everything because we induce it ourselves," Goeree remarks.

The FCC wanted a method in which all buyers could compete equally and the commission would make the most money in the process. It turned out the combinatorial auction the FCC had devised for the 700 MHz auction was too complex. "In computer science it's known as the knapsack problem," says Goeree. "When you have a knapsack of finite volume and you can choose among objects of different sizes and values, how do you pack it to maximize its value?" Or, in mathematical parlance, the problem was "NP-hard"—it exploded exponentially because there were far too many potential combinations on which to bid, in this case too many bandwidth licenses spread over too many geographic regions. "We tested the plane the FCC built and it didn't fly that well," says Goeree. It didn't maximize profits for the FCC or potential wins for the bidders. Most of all, it alienated bidders with its intricacies.

**Caltech students compete in earnest in HPB trials.**

Goeree and Holt tested related auction designs, but these didn't fly well either and were still too complex. Goeree recalls thinking that after having discussed the possibility of combinatorial auctions for over a decade, the FCC might opt out altogether. So he decided to create a new method. "We had a very simple idea for how to do it," he says. "First, imagine you construct a hierarchy of packages by dividing a large nationwide package into two pieces, dividing each of those into two pieces, and on and on, all the way down to the smallest geographic regions that could not be divided further." Unlike previous combinatorial auctions that were considered NP-hard, such a hierarchy makes it trivial to find the best allocation: simply compare the revenues that result from selling in one hierarchy level to the next, starting at the bottom and recursively solving to the top. The challenge Goeree and Holt faced was determining appropriate prices given that package bids would be placed on many different levels. After they solved how to "trickle down" the excess amount of a winning package bid at a higher level by imposing "taxes" on lower-level licenses, Goeree decided to call the FCC and present HPB as a viable alternative.

In his initial tests of the HPB auction, Goeree grouped the available licenses into packages in a three-tiered hierarchy, as shown at the top of this page. Say the HPB is auctioning off pies. On the top level, level one, you stand to win all 20 assorted pies in one fell swoop. On level two, there are four packages, each consisting of five different flavors. On level three, you can bid on the 20 pies separately. Now say you're throwing a party for 200 people—well, you might as well go for the gusto on level one. But if you merely want one pie to take home for dessert, your choice is equally clear: bid on level three. There could be 19 more people like you who also want only one pie, and all your bids together might just win out over the level-one bidder. The intermediate level, level two, may appeal if you own a small diner and want to serve a few different options. And if you wanted a package of five from level two and one more apple pie from level three, well, you could even bid on both levels.

As the bids roll in, the party-throwing bidder on level one might find he can't afford to outbid the personal pie eaters on level three. He might revise his strategy and start bidding on three packages on level two and two more pies on level one. The HPB format not only allows bidders to decide what sort of bid suits their needs, it provides flexibility as the auction progresses.

In the view of student volunteer Chen, "HPB is better because you can win two licenses combined as a package for less than what you might bid on the two individually." So if you want an apple pie and you're clearly winning it, and you also want a pecan pie for which there's a lot of competition that you can't afford to outbid, you could lump your resources together for a stronger bid on a package that includes both.


**REAGs for the C block split the country into 12 regions. In the two-level HPB format that the FCC chose, bidders could win all 12 regions in one fell swoop or bid on them individually.**

Although the FCC ultimately chose to use a two-tiered system, Goeree says his testing showed that even this was more efficient than the previous format. At the bottom level, 12 individual licenses corresponds to 12 geographic regions that the FCC designated—Region 1 is the Northeast, for example; Region 4 is the Mississippi Valley; Region 12 is the Gulf of Mexico. The top level, level one, was forged into a three-package deal: a 50-state grouping of eight of the 12 licenses, another package of two covering Pacific island territories, and a two-license Atlantic package combining the U.S. Virgin Islands, the Gulf of Mexico, and Puerto Rico.

The bidding kicked off on January 24, with one round per day. (On day 10, the FCC accelerated the bidding to five rounds per day to speed up results.) At the close of every round, Goeree's software totaled up the money bid at each level. In a two-level system, let's say the bids at level two totaled $0.8 billion after day one, and at level one the top bid was $1.2 billion. The software then advised bidders on what their next move should be if they wanted to stay in the game. Thus, if there were 12 bidders on level two, they would each be alerted to increase their bid by a little over $33 million to make up the $0.4 billion difference, and the bidders on level one would be told they could sit tight until the next round. There is no need to do your own calculations; the bidders just check if they can afford the suggested bid. "It solves the complexity for them," says Goeree. It also meant that if each bidder at level two followed the advice in unison, they would all move on to the next round. Of course, whoever couldn't fork over the dough would get shut out.

Although the opportunity to win it all in one fell swoop is a strong appeal of Goeree's packages, the FCC saw HPB as an opportunity for smaller players to merge forces at a lower level and overtake one giant bidder at the top. In an October 2007 public notice, the FCC declared, "The HPB auction format was chosen in part because it mitigates issues inherent in some other package bidding formats that give bidders interested in large packages an advantage over bidders interested in individual licenses."

The FCC also liked Goeree's calculation tool and the way the software seemed to prohibit collusion. "In fact, we will use HPB in part because the mechanism for calculating [prices] is significantly simpler than other package bidding pricing mechanisms," it stated. "In addition, we find that . . . HPB procedures in general strike a careful balance between permitting bidders adequate bidding flexibility and discouraging insincere and anticompetitive bidding behavior."

## HPB in Action

It became immediately clear that the option to buy the C block in its entirety was extremely valuable. In July 2007, Google chairman and CEO Eric Schmidt had written an open letter to the FCC chairman offering a deal: the promise of a minimum $4.6 billion bid on the national package in exchange for open access to the wireless network that would be set up on the C block, regardless of who won it. Open access means any wireless customer can download any software and use it on the device of their choice, and the service provider would have to abide. This doesn't just mean ring tones, it applies to anything you might use your cell phone for: image-processing software for camera phones, e-mail software for Blackberries, maybe an iTunes knockoff for your Kyocera phone. In the recent past, a closed market meant that AT&T could connive with Apple for exclusive rights to providing iPhone service, and Apple could void the phone's guarantee if users hacked their gadget by installing non-Apple software.

It was also well known that Google was developing its first cell phone. If Verizon Wireless ended up a big winner in Auction 73, Google's open-access bid assured that Verizon would have to provide service to anyone who wanted its plan on a Google phone. Indeed, Google's demand prompted Verizon, months before the start of the auction, to grudgingly commit to open its network to wireless devices, software, and applications that the company did not offer. This would happen even if Verizon did not win the national package—because of the way the auction is structured, as long as C-block bids topped $4.6 billion, the winner(s) would be obliged to allow their customers to use any mobile phone they wanted and allow outside applications to run on their network.

On day six of the auction, electronics bloggers across the world celebrated. "There was a brief, tense pause in the bidding this morning, but some anonymous giant telecom company (Google, perhaps?) has just pushed the price of the 700 MHz C block over the FCC's reserve price of $4.6B—and the rest of us straight into the promised land of open access," one wrote. "Yep, January 31, 2008, Round 17 will be the day to remember."

The technorati were abuzz, issuing daily progress reports on Auction 73. As it turned out, bidding on the C block at level one ceased shortly after the open-access benchmark was passed. The bids on level two rose to nearly $5 billion as bidders ended up duking it out over licenses for the 12 individual regions.

The auction as a whole drew to a close on March 19, and the FCC waited one day to announce the winners. The leading bid for the C block had shifted back and forth only twice between the cumulative prices for the individual licenses and bids for the national package, demonstrating, according to Goeree, that the market was determining how the spectrum would be most valued. As Goeree's colleague Holt put it, "The lead switched about the same number of times as in the final quarter of the Super Bowl."


**Goeree, pictured here, hopes that the HPB design will transform wireless markets in other countries as well. He recently visited Taipei, where he presented the details of the mechanism to a group of scholars involved with designing Taiwan's own 700 MHz auction.**

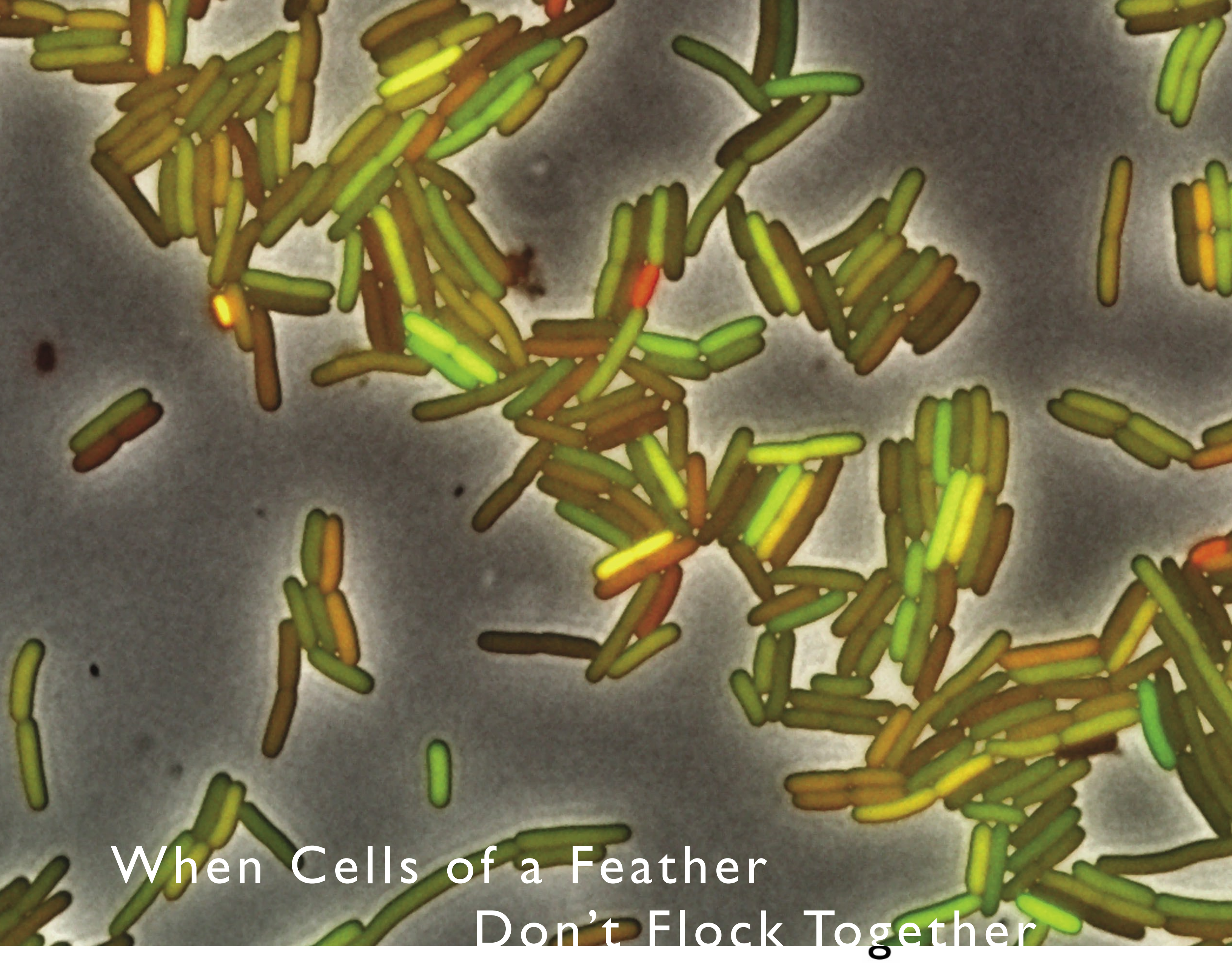
As it turned out, Verizon and AT&T spent the lion's share—$16 billion—of the FCC's total earnings. Verizon won C-block coverage of the continental U.S. and Hawaii, while AT&T swept up most of the 12 MHz sold as the B block. It seems likely that Google never really wanted to run a national cellular network, and was happy to call it quits as soon as it secured what it had entered the game to get. And apparently no one else wanted or needed nationwide coverage once open access was guaranteed. But even though HPB did not bring a new entrant to the wireless market, Goeree says, "this auction is a winner because of the open access. It never would have been possible without the 50-state package."

Goeree sees room for improvement, however. The auction was implemented with a mix of hierarchical package bidding for the C block and the FCC simultaneous single-license bidding for other blocks, which were offered in a wide dispersion of license sizes. This dispersion, together with FCC "activity rules," made it difficult for firms to reenter the bidding on the C block after they had started bidding on other licenses, which may have created some inefficiencies.

Overall, the auction is evaluated to be a success. The main outcomes of the 700 MHz auction, entry and open access, would have been virtually impossible in the license-by-license competitions the FCC has organized so far. "Competing for open access by pushing prices over a $4.6-billion hurdle is simply too risky when bidding on individual licenses," Goeree says. "You may end up paying high prices for a subset of licenses that can't guarantee a profitable business plan."

The current chairman of the FCC, Kevin Martin, called the auction the FCC's "transformative auction." When asked about his legacy at the FCC after the Bush administration leaves, Martin responded, "I certainly think that the success of this auction, the success of raising more money than the commission ever raised before in any auction, the success of moving forward with a more open platform that will transform the entire wireless industry, is going to be a significant accomplishment." □

PICTURE CREDITS: 22, 26 — FCC; 25 — Jacob Goeree; 23, 25 — Doug Cummings



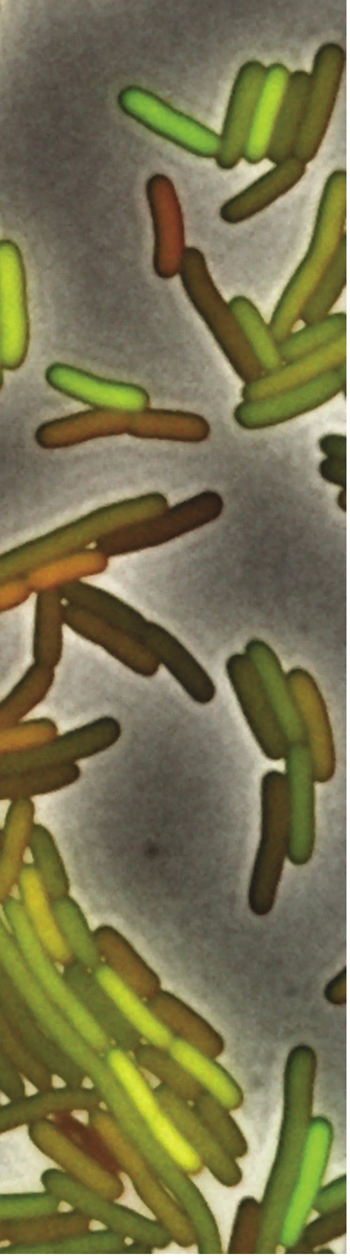
# When Cells of a Feather Don't Flock Together

By Marcus Woo

In a scene worthy of a horror movie, pill-shaped bacteria cells glow green in the darkness. The ghostly cells squirm, grow, and divide, expanding their reach across the screen. Some shorten and turn into white spores, entering a dormant state from which they can come back to life decades—even centuries—later. Others temporarily glow red when they choose yet a different fate. But not all of the cells become spores, and only a few percent ever turn red at a given time. Michael Elowitz, assistant professor of biology and applied physics and Bren Scholar, and colleagues created these cells to explore the fundamental questions of how and when they decide to change. Applying the innovative approaches that won him a 2007 MacArthur Fellowship, the so-called genius grant, Elowitz wants to understand how a cell's genes work to make these decisions.

Even for simple organisms like *Bacillus subtilis*, this transformation process, called differentiation, remains a mystery. Cells choose different fates, even when they're genetically identical and grown in the same environment. As creatures become more complex, so do the choices. In mammals, for example, the power of embryonic stem cells lies in their ability to turn into anything, from blood to muscle to skin. Understanding the diversity of cell behavior could lead to new ways to attack cancer or develop new drugs, Elowitz says. If you want a drug to affect a cell a certain way, it helps to know how it behaves.

Elowitz's lab is peeking under the hood of the molecular interactions within the cell, where networks of genes, proteins, and other molecules work in concert to ensure the cell does what it's supposed to do. Called genetic circuits, these networks "form the foundation of all biology," says Gürol Süel, a former postdoc in Elowitz's lab and now an assistant professor at University of Texas Southwestern Medical Center. "Any biological



**The colors of *B. subtilis* demonstrate variations in cell behavior from random fluctuations in the cells. Researchers engineered cells to glow green and red depending on which of two nearly identical genes were expressed. Fluctuations in gene expression, called intrinsic noise, cause the two genes to be expressed differently. Instead of a uniform yellow from equal parts green and red, the cells glow in shades of yellow, green, and orange.**

process you can think of occurs as a result of interactions between biological molecules. There's no gene or protein that acts on its own—everything is interacting."

## A Noisy Clock

Elowitz is part of a burgeoning field called systems biology, an outgrowth of molecular biology, which has mainly focused on the roles of individual molecules and their structures. Systems biologists, however, seek a broader understanding of how these parts underlie the mechanics of life. Traditionally, research papers would propose a series of interactions to explain a particular phenomenon, according to Elowitz. But this frustrated him, he says, because papers stopped short of quantifying the important components. Imagine someone giving you a cake recipe that told you to use flour, eggs, milk, and butter, but didn't tell you how much of each you needed. Given the inherent complexities of genetic circuits and biological systems in general, studying them in detail is a challenge. While a graduate student at Princeton, Elowitz decided to approach the problem from another direction—he set out to make his own simple circuit. After all, what better way to learn how to bake a cake than to try your own recipe?

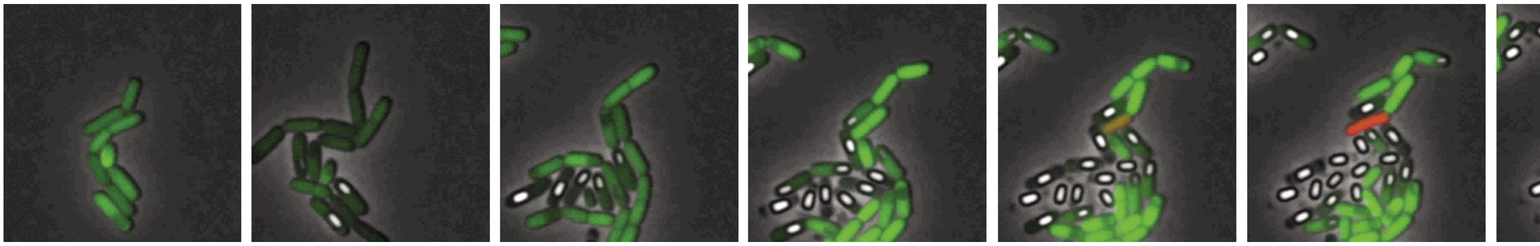
In 2000, Elowitz and his thesis advisor, Stanislas Leibler, designed and built a simple biological clock based on proteins called repressors, which turn off specific genes. As with all proteins, repressors are made when their genes are turned on, so the researchers engineered a set of three genes that turned each other on and off, like a three-way rock-paper-scissors game. In such a loop, rock turns off scissors. But scissors turns off paper, so if scissors is off, paper remains on. Paper, on the other hand, turns off rock, so if paper is on, rock turns off. This then causes scissors to turn back on, and the entire sequence cycles through as each gene switches on and off. One of the genes was engineered to light up when on, so that, when the researchers inserted their homemade circuit into a bacterium called *Escherichia coli*, the cells pulsed. Elowitz and Leibler called their circuit the repressilator, a combination of the words "repressor" and "oscillator."

The repressilator was an exciting proof-of-principle experiment, showing that the genetic circuits underlying cellular behavior can ultimately be understood and manipulated. Researchers had tinkered with genetic circuits before, but this was the first made entirely from scratch that also had a dynamic function. "We were very happy at first—wow, we were able to create this oscillator," Elowitz recalls. But they soon noticed something odd.

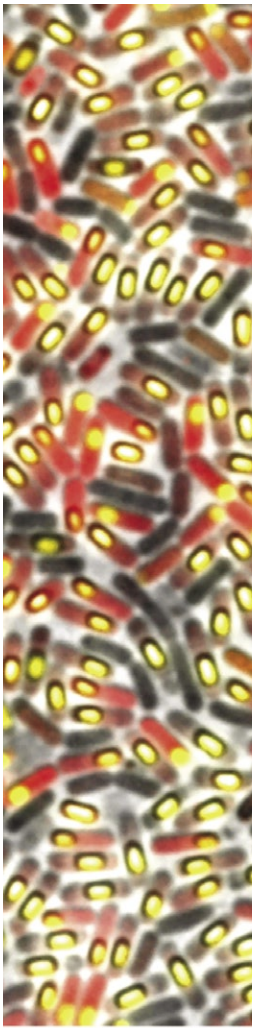
To study the repressilator in detail, they had made black and white movies of the *E. coli* cells. Each film began with a single cell, dark and faintly visible, at the center. The cell began to divide, and its offspring pulsed, casting an eerie glow on their neighbors. But none of the cells pulsed in sync with the other—even though all of the cells had identical genes. "If the oscillator were behaving exactly the same in all the cells, they would all remain in perfect synchrony," Elowitz says. "But they clearly don't—they get out of synchrony really fast."

Perhaps this shouldn't have come as a surprise, since biology—and the life of a cell—is known to be complicated and messy. Gene expression—the process by which a gene turns on to make a protein—is itself a muddled affair. Consisting of many biochemical reactions, gene expression is, in essence, a mechanical dance. Although choreographed well, it may be ungainly and missteps are inevitable. Molecules called transcription factors bind to specific DNA sequences and help genes get made into proteins. But they may not bind properly, or they may fall off the strand before their job is done. Some of the molecules involved may number fewer than 100—or even 10—making these missteps even more pronounced. As a result, a genetic circuit doesn't work the exact same way every time. There's a certain amount of inherent noise. Like the random variations that cause static in your AM radio signal, this noise was likely the culprit that knocked the represillators out of sync.

Biologists have long suspected that cells and their internal biochemistry might be inherently noisy. But in a 2002 paper, Elowitz, then at Rockefeller University, and colleagues were able not only to identify and quantify noise in cells, but to separate it into two components they called intrinsic and extrinsic noise. Extrinsic noise is due to fluctuations throughout an individual cell—differing concentrations of the transcription factor, for instance. Intrinsic noise comes from the process of gene expression itself. To isolate these two kinds of noise, the researchers put two nearly identical genes into the same cell. The researchers engineered each gene to make a different color-coded



**This series of time-lapse frames shows the dynamics of cell behavior over the course of nearly two-and-a-half days. The cells that are expressing ComS glow green, and the white shapes are spores. After the cells have divided some, one cell begins to glow red, indicating competence. During competence, the cell can't divide, although it still grows. Only when the cell leaves its competent state is it able to divide again.**



**The fluorescent proteins in this image track sporulation in *B. subtilis*. Cells about to sporulate turn red, while the part that's about to become the spore turns yellow.**

fluorescent protein, so that they could track the gene's expression. This powerful technique, now commonplace, was only made possible when biologists cloned fluorescent protein genes from jellyfish off the west coast of North America more than a decade ago. Although many scientists have used fluorescent proteins and movies to study cells, the Elowitz Lab is among the first to use them in a highly quantitative fashion. Much like how oscilloscopes allow electrical engineers to measure an electrical circuit, these movies allow biologists to measure a genetic circuit, Elowitz says.

If the noise were mainly extrinsic, it would affect the genes in the same way, and the researchers would see equal amounts of each color in any particular cell. For example, if the two colors were red and green, then every *E. coli* cell would appear a uniform yellow. Alternatively, if the noise were mainly intrinsic, then each gene would behave differently. You would now expect intermediate shades such as orange-yellow and goldenrod as well as red and green cells. The cells behaved as the team had hoped. The researchers engineered a strain dominated by intrinsic noise, and the cells glowed a whole spectrum from red to green. Likewise, for colonies with minimal noise, the cells were all yellow. The researchers also found that cells were more susceptible to intrinsic noise when genes were expressed at low levels. "Noise is not just some mysterious fluctuation that causes cells to be different from each other," Elowitz says. "We can understand why cells are different from each other, and we can break [noise] into these different components."

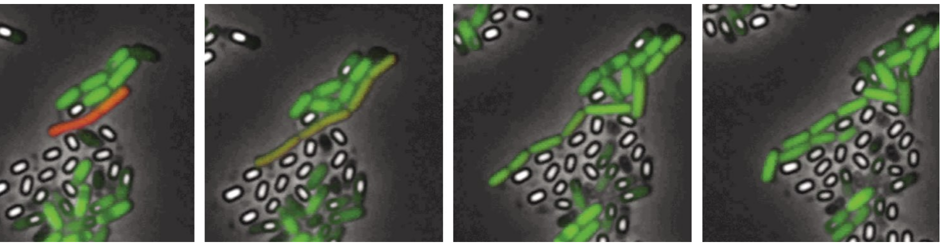
These direct measurements of noise demonstrated its importance, but what wasn't clear was how noise influenced a genetic circuit and, subsequently, cellular behavior. The question was twofold: how does a cell suppress fluctuation when it wants to do something accurately, and how can a cell use the noise to its advantage? The answer to the latter, at least, lay in another bacterium: *B. subtilis*.

## It's Just Like Flushing a Toilet

Commonly found in soil, *B. subtilis* is sometimes used to make a type of fermented soybean eaten in Korea and Japan. But Elowitz and his colleagues were interested in what *B. subtilis* did when there were no soybeans to ferment. When faced with stress—such as a lack of nutrients—*B. subtilis* sometimes assumes a state called competence. In its competent state, *B. subtilis* can take in stray strands of DNA that happen to be floating around. Many scientists say competence is bacterial sex, a means for it to exchange genetic material. Others contend that it allows *B. subtilis* to eat the DNA as food.

But what interested Elowitz was that competence, like many other types of cellular differentiation, is not a predetermined fate. Instead, each cell has a certain probability of becoming competent or not. Even when they have the same genes and are put in the same environment, only a few percent of the cells ever become competent at a given time. This is good for the bacteria, because *B. subtilis* can't divide when competent. If all became competent at once, then none could divide, spelling doom for the colony. The researchers also discovered that the competent state is temporary. After less than a day, a competent cell returns to normal. But how do these cells, which are genetically identical, know which ones should become competent, and how do they know when to turn back? "It's very mysterious," Elowitz says. "All the cells are supposed to be the same, but they all do something different, even when you control the system as carefully as possible."

The key player is a transcription factor called ComK. ComK activates the genes needed for competence as well as the gene that makes ComK itself, which is written as *comK*, forming a positive feedback loop. A second player is a protein called ComS, made when one cell sends another a chemical signal; the reception of that signal activates



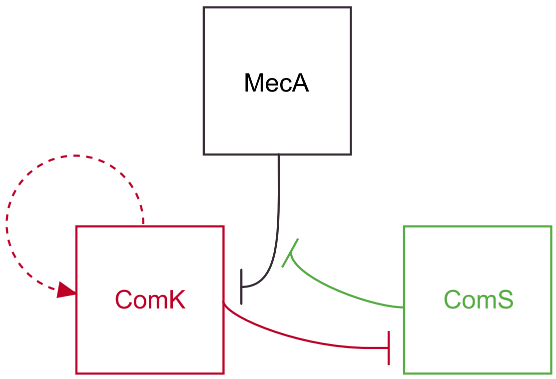



**Diagram of the basic competence circuit. The key player is ComK, the protein that triggers competence. ComK, which also promotes itself, as indicated by the dotted arrow, blocks the expression of ComS, as indicated by the T-shaped arrow. The third player is called the MecA complex, an enzyme that destroys both ComK and ComS. When enough ComS is produced, MecA goes after ComS instead of ComK, allowing enough expression of ComK to start competence. In this way, ComS prevents MecA from blocking ComK.**

the gene—known as *comS*—that makes ComS. Finally, a third party called the MecA complex joins the dance. MecA causes a protease, an enzyme that destroys proteins, to target both ComK and ComS.

Similar to the repressilator, the three proteins work together in a network of negative and positive feedback loops. By destroying ComK, MecA blocks competence. But when enough ComS is expressed, MecA becomes occupied zapping ComS instead of ComK. The production of ComS, then, indirectly supports competence by acting as a decoy for MecA. It also turns out that, through a series of intermediate interactions, ComK blocks the expression of ComS, which prevents any more decoys from distracting MecA. MecA then can attack ComK, eventually shutting down competence.

Although past research had unearthed this batch of interactions, no one had been able to explain the subtle interplay between each step. Here was another case of a cake recipe consisting only of a list of ingredients. In 2006, however, then-postdoc Süel, along with Elowitz, graduate student Louisa Liberman, and Jordi Garcia-Ojalvo from the Technical University of Catalonia in Spain, were able to mathematically model the competence dance. The model didn't get bogged down in every single biochemical reaction, but captured the essence of the genetic circuit. It showed that the cell's decision to differentiate relied on random noise—the same kind of fluctuations that prevented the repressilator from pulsing in sync among all the cells. In other words, to determine which cell would become competent, *B. subtilis* drew straws.

"What's great about this," Elowitz says, "is that we went from the repressilator, where noise was an annoyance—we found it wasn't working precisely because of the noise—to a natural differentiation circuit where the cell has actually taken advantage of this seeming annoyance to produce a system that can control the probability of whether something happens."

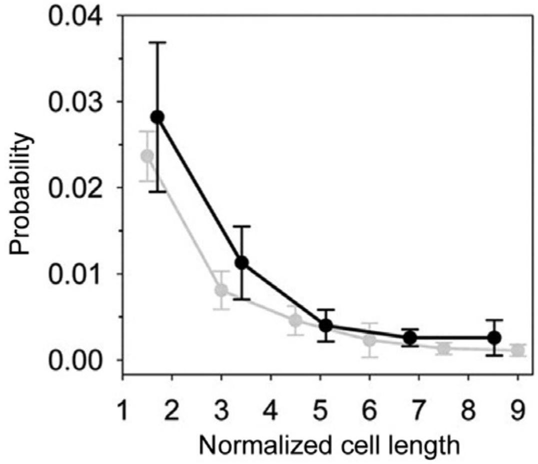
To develop their model, the researchers used fluorescent proteins that glowed different colors when ComK and ComS were expressed. The brightness of each color corresponded to how much ComK and ComS was being made, with the glow of ComK heralding competence. They then took snapshots of the bacteria colonies every 20 minutes or so, allowing them to track each cell.

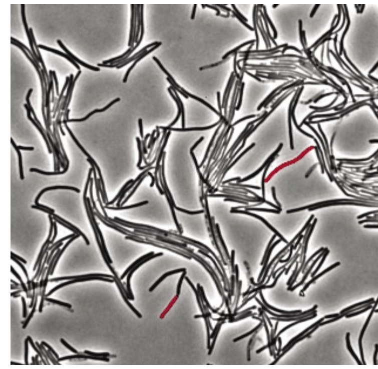
Their analysis showed that the competence circuit was an "excitable system," in which random fluctuations trigger some process after crossing a particular threshold. A simple example of an excitable system is jiggling the handle of a toilet. "Once in a while, you're going to jiggle a little too hard, and it'll just cross the threshold, and it'll flush," Elowitz explains. Another characteristic of an excitable system is that the strength of the trigger doesn't affect the system. Pushing the toilet handle harder doesn't make the flush more powerful or last longer. In the competence circuit, the expression of ComK is inherently noisy—like jiggling a toilet handle—and once in a while, enough will be expressed to trigger competence. But more ComK doesn't cause the cell to become competent more often or for a longer time.

The competence circuit is a self-controlling one. Once the system turns on, it sets up a chain of events that eventually turns itself back off. "The system can spontaneously flick on, but when it's on, it starts to activate something that will build up and build up," Elowitz explains. "When it goes to a high enough level, it'll shut the whole thing down." The competent state happens while MecA is busy gobbling up ComS, and additional ComS isn't being made because ComK is repressing it. Over time, ComS dwindles—in this case, what's "building up" is the depletion of ComS. Once MecA runs out of ComS to destroy, it goes after ComK. Since ComK is the trigger for competence, repressing ComK returns the cell to its normal state.

This work is among the first to show how cells can use noise to their advantage. Evolution has created an excitable system that allows just the right fraction of *B. subtilis* cells to become competent. But even though the model is consistent with what *B. subtilis* does, how do you know for sure that noise is indeed the driving force behind differentiation? Elowitz points out that the decision making could be hiding in an unknown interaction. The researchers continued tweaking and tuning the genetic circuit, and in an elegant experiment showed that without noise, competence was not possible, Elowitz says. "This was kind of the proof that noise was necessary."

**Left: As the size of the cells increase, the probability of their becoming competent decreases, as predicted by the model. The experimental results (black line) are consistent with computer simulations (gray line).**
**Far right: An image of the extra-long *B. subtilis*. The red cells are competent.**



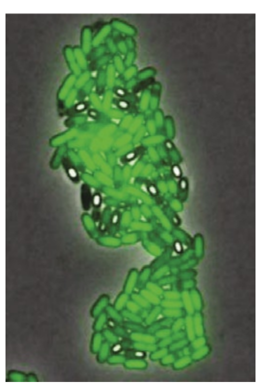



From Süel et al., *Science*, vol. 315, p. 1718, March 23, 2007.

## Tuning Out the Noise

Noise is all about numbers. If you want to know America's favorite ice cream flavors, but only ask 10 people, you probably won't have much confidence that your results are representative of the general population. But if you ask 100,000 people, the results will surely be more accurate. With more numbers, the uncertainty—i.e., the noise—goes down. Noise is prevalent in the cell because cells are tiny, and molecules like ComK number in only the tens or hundreds. To boost the numbers, Süel, graduate student Rajan Kulkarni (PhD '06) , Jonathan Dworkin of Columbia University, Garcia-Ojalvo, and Elowitz reduced noise by engineering versions of *B. subtilis* that were up to nine times their original lengths, and thus contained nine times as many molecules like ComK.

To make the extra-long bacteria, the researchers introduced a mutation that prevented the cells from fully dividing. Now, during division, each cell would double in size, but not split off. Since the molecular concentrations remained the same throughout, with bigger cells came more molecules and therefore less noise. The researchers' model predicted that with reduced noise, the cells would not become competent. Fewer fluctuations meant a smaller chance that enough ComK would be expressed to trigger differentiation. To return to the toilet analogy, you probably won't flush the toilet if you barely jiggle the handle. In fact, the probability of a cell becoming competent went from about 3 percent to less than a half percent as the cell lengthened.



**A group of green-glowing *B. subtilis*, signifying that ComS is being expressed. A few cells have become white spores.**

The team also discovered that the minimum, or basal, expression level of the *comK* gene controls the frequency of competence, and the basal expression level of the *comS* gene independently controls the duration of competence. In the context of the model, this makes sense, since the amount of the ComS protein acts like a timer in the circuit; the cell is competent until MecA finishes off ComS and turns to ComK. Likewise, ComK controls the decision to enter competence in the first place.

By tweaking the two basal expression levels, the researchers tuned *B. subtilis* to become competent more often or for a longer time. Increasing the basal expression level for ComK by about 20 times its normal amount caused all cells to become competent. By increasing the basal expression level for ComS, the team was able to make most of the cells remain competent for about 40 hours, compared with a normal duration of about 20 hours.

This finding is more than a bioengineering novelty, however. The fact that competence frequency and duration can be tuned independently may be critical for a bacterial species' evolutionary survival. Scientists still don't fully understand the reasons behind competence, but if the reasons were to enhance genetic diversity, then competence would allow *B. subtilis* to evolve a response against a stressful environment. Say that the time the organism spends in competence is already evolutionarily fine-tuned. If a more stressful environment favors more *B. subtilis* to become competent, then the organism can evolve in that direction without affecting the optimized duration. According to Süel, it's like designing a race car: "Maybe you want to improve the braking performance but don't want to sacrifice the steering."

The team then wanted to see what would happen if they added another feedback loop to the competence circuit. They inserted a protein called Rok that represses the expression of ComK. They anticipated that the addition would spur the cells to leave competence faster, and indeed that's what happened. Instead of 20 hours, most of the cells were competent for only about 14 hours. But then the modified circuit offered a surprise: there was less variability among the cells than in the normal circuit. Remember that since every system has a certain amount of noise, every measurement features an inherent variability. Even though most of the normal cells were competent for about 20 hours, a few would remain in that state for 10 or 30 hours. In the new circuit, more cells stayed competent for similar amounts of time.

> "What's important is the creativity of the experiment. Can we make simple, beautiful, and elegant experiments that push this field into new directions, or allow us to see things in a simpler, clearer way?"

The researchers were able to explain this enhanced precision with their model. Normally, when a competent cell returns to its normal state, there are few ComS molecules, since its depletion is what allows MecA to gobble up ComK and send the cell back to normal. But with the addition of Rok to help block ComK, the cell returns to its normal state earlier, while there are still many ComS molecules left. Since ComS governs competence duration, and the reengineered circuit has left a higher number of ComS molecules, there is less noise in the distribution of duration times. "This is weird for biological circuits," Elowitz says. "Normally, when you mess around with these genetic circuits, you're going to screw them up in some way."

### Toward Something Crazier?

The ability to understand a genetic circuit at such a deep level is an accomplishment in and of itself, but this work has broader implications. Many other single-celled organisms, not to mention cells in multicellular organisms, differentiate on a probabilistic basis. Additionally, being an excitable system is not unique to the competence circuit. Biological systems at scales other than the gene level are also excitable—the firing of neurons in the brain, for example.

"You have a tree, a rat, or a human—they're all governed by proteins, DNA, and RNA," Süel says. "The rules for how these molecules work together and give physiological behavior at the cellular level seem to be conserved among all organisms. Maybe the details are different: the organism has more genes or different interactions. But the approach, the thinking, and the tools we're using are not limited to this one particular bacteria."

In the past, biologists were primarily interested in looking at whether specific genes are expressed or not, the researchers say. Now, scientists want to learn about the dynamics of gene expression—how fast does the gene express itself, and at what level? How does it change over time?

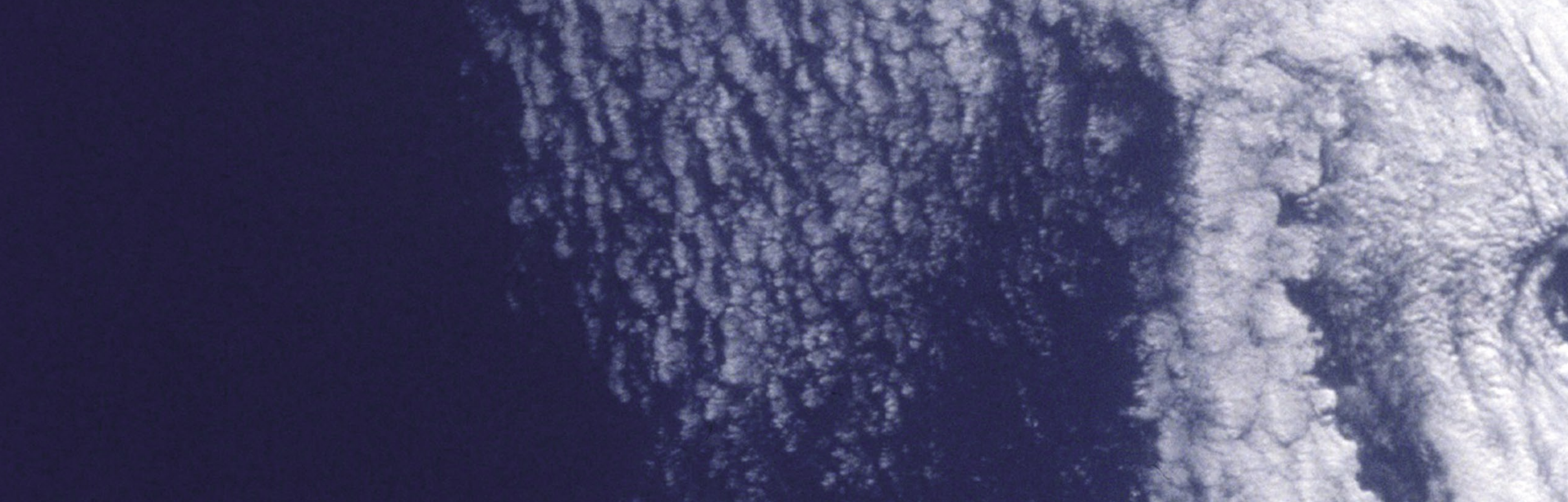
According to Elowitz, researchers now have enough biochemical data about genetic interactions to develop mathematical models that can make quantitative predictions. Elowitz, trained in physics, winnows complexity into simplicity. A complicated network of interactions, the competence circuit, has been distilled into two equations describing the dynamics of ComK and ComS. "Sometimes a physics point of view lets you ask questions you otherwise wouldn't ask," says Elowitz.

Perhaps it was this kind of interdisciplinary thinking that earned him a MacArthur Fellowship, which, as its website says, is given to "talented individuals who have shown extraordinary originality and dedication in their creative pursuits and a marked capacity for self-direction." The distinction includes $500,000, given over five years, for the individual to do with as he or she pleases.

The recognition, he says, was a nice pat on the back. "It's encouraging," he says. "It makes you stop and think about what's important, and what's important is the creativity of the experiment. Can we make simple, beautiful, and elegant experiments that push this field into new directions, or allow us to see things in a simpler, clearer way? It makes you ask yourself, are we doing enough? Are we doing the right things? Are we doing things that are too easy?" He says he hasn't decided what to do with the money yet, but the fellowship nevertheless propels him forward. "People think what we did so far is good," he says. "We have to do something crazier now." □


**From left to right: Gürol Süel, Michael Elowitz, and Jordi Garcia-Ojalvo.**

PICTURE CREDITS: 28-33 — Elowitz lab; 31 — Doug Cummings



# Ad Astra per GALCIT

By Douglas L. Smith

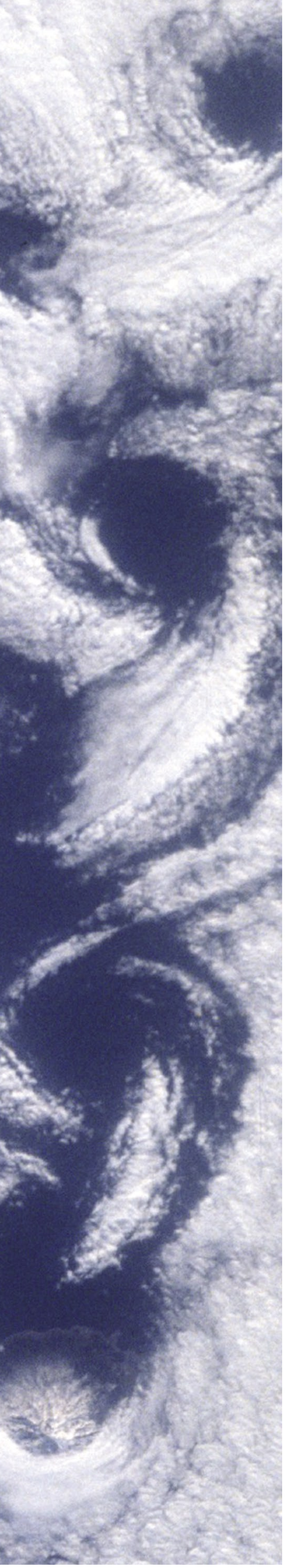
Rendering courtesy of John Friedman Alice Kimm Architects.

**Air flowing over and around objects in its path can create trains of spiraling eddies known as von Kármán vortices, as seen (top and right) over the island of Rishiri in the northern Sea of Japan. In Caltech's remodeled Guggenheim Aeronautical Laboratory (above), swirling shapes resembling von Kármán vortices will decorate the ceiling of the conference room named for the man who first described them—aeronautics professor and GALCIT founding director Theodore von Kármán.**

Just about every kid wants to be an astronaut at some point. The *Star Wars* and *Star Trek* franchises are still going strong 30 and 40 years after their inception, and the commercial satellite business brought in some $82 billion dollars last year worldwide. Amazing pictures, from Mars to distant galaxies, are only a few mouse clicks away. Yet U.S. aerospace firms can't fill some 10 percent of their MS- and PhD-level engineering jobs, according to industry insiders. The problem will just get worse as the rest of the bright young minds who came of age in the years of the Apollo program retire—28 percent of them will have called it a career by the end of this year, says the National Science Board, which is the governing body of the National Science Foundation.

It's not that kids get bored with space, says Ares Rosakis, the von Kármán Professor of Aeronautics and Mechanical Engineering and director of the Graduate Aeronautical Laboratories at the California Institute of Technology (GALCIT). "Space is actually the easiest way to start teaching science in ages below 16." The problem, he says, comes when those 16-year-olds start thinking like grownups—when they start worrying about a career. "I see it in my own children. They have been indoctrinated since they were young about how fantastic science is, but their classmates tell them it's not cool to become an engineer—not only because it's difficult, but because my father makes much more money than yours." College graduates with engineering degrees tend to go into information technology, biotech, or some other -tech, or even farther afield to business, law, or investment careers that seduce them with promises of millions before they're 30.

If there's any place that can make space engineering cool again, it's got to be Caltech. After all, the Institute founded and still administers NASA's Jet Propulsion Laboratory, which got America into the Space Race and is now exploring our solar system and beyond. Since 2004, Rosakis has been spearheading an initiative to launch a master's



degree program at GALCIT that would go beyond the traditional MS in aeronautics, which keeps one safely within Earth's atmosphere. The new MS in aerospace engineering "reconnects to JPL in a major way," says Rosakis. "It engages JPL, Caltech's seventh division, in curriculum design and classroom teaching. I don't think I would dare do a space-engineering master's program anywhere else that didn't have JPL next to it. This program is illuminated by JPL's existence." In the program, students work on a real spacecraft, solving real engineering problems. "We are not designing entire missions. You could imagine us trying to launch a Mickey Mouse GALCIT experiment. It's much better to isolate a small part of a real mission." Rosakis credits JPL director Charles Elachi (MS '69, PhD '71) for this approach. "His philosophy is to expose the students to something of real importance to JPL that would allow JPL instructors to be enthusiastic because they are working, through teaching, on an actual JPL mission." But although the JPL instructors are working in their areas of expertise, they are paid by Caltech, not JPL. "This is very important," Rosakis emphasizes. "The JPLers are employed as consultants, as instructors separately from their JPL duties. It's against NASA rules to use government contracts for teaching."

The one-year aerospace program, now in its second year, is just as big as the aeronautics program—nine students each per year—and, like the traditional degree, is designed to be a stepping-stone to a PhD. Eight of the students from the inaugural class have, in fact, gone on to Caltech PhD programs in space-related fields. Because the program is not intended to lead to a terminal master's, it focuses on the science behind space engineering rather than on job-specific training. "It's not an applications-based program," says Rosakis. "That's a very big difference from the rest of the space graduate programs you see around the country." Another big difference is the overkill factor. Four GALCIT members—fully one-third of the aeronautics faculty—and six JPLers teach the nine students. The basics of fluid mechanics, solid mechanics, and structural mechanics are addressed in all their gory detail in a set of core courses common to both the aeronautics and the aerospace option. The math is just as strong as it would be for a PhD, "and so of course our students have suffered," laughs Rosakis. "But that's life." But the pain pays off when a prepared mind finds the right situation, as Simon Ramo (PhD '36) did when he went to work for General Electric armed with all the latest physics that was about to revolutionize electrical engineering—see the sidebar on page 17.

The program's elective courses are taught by JPL staff members. This is overseen by JPL's chief technologist, Paul Dimotakis (BS '68, MS '69, PhD '73), who is also Caltech's Northrop Professor of Aeronautics and professor of applied physics. The exact slate varies from year to year, but the current lineup includes four offerings:

Ae 115, Spacecraft Navigation, covers astrodynamics, orbital calculations, and precision tracking systems. The class is being taught by Michael Watkins, who often draws examples from his work as the mission manager for the Mars Science Laboratory (MSL), the "super rover" set to launch in 2009, and as the project scientist for the Gravity Recovery and Climate Experiment (GRACE), launched in 2002. MSL requires ultra-precise navigation to enter the Martian atmosphere at exactly the right time and place for a safe landing. GRACE consists of two satellites orbiting Earth in tandem about 220 kilometers apart, with their relative positions determined to an accuracy of less than one micron—akin to measuring the distance between JPL and San Diego to within the thickness of a red blood cell. That knowledge allows the mapping of minute changes in Earth's gravitational field due to climate-related effects. "We even weigh Earth's ice sheets," says Watkins.

Ae 121, Space Propulsion, looks at solid- and liquid-fueled rockets and their control, plus such exotica as electrical and even nuclear thrusters. This course features James Polk, principal investigator for the NEXIS (Nuclear Electric Xenon Ion System) engine, a high-power electric thruster designed to propel a nuclear-powered spacecraft to the icy moons of Jupiter. NEXIS was an advanced version of the ion drive demonstrated on JPL's Deep Space 1, which flew by comet Borrelly in September 2001 and took the best-ever pictures of a comet's nucleus.

Ae 159, Space Optical System Engineering, includes not just sensors, lenses, and mirrors but all the other considerations needed to bring the universe into focus: the thermal properties of materials, the design of servomechanisms, and the subtleties of image processing. The instructor is James Breckinridge, JPL's Origins theme technologist, which is a fancy way of saying he oversees telescope technology at the Lab. Breckinridge headed the nationwide team that gave an eye exam to the flawed mirror on the Hubble Space Telescope. He also led the JPL team that built the Wide-Field and Planetary Camera 2 to prescription to compensate.

And EE/Ge157, Introduction to the Physics of Remote Sensing, covers devices across the electromagnetic spectrum, from microwave radars that look beneath the sands of the Sahara to infrared spectrometers that take the temperatures of distant planet-forming systems. This very popular class, originated and taught by synthetic-aperture radar scientist Charles Elachi long before he became JPL's director, is now led by Jakob van Zyl (MS '83, PhD '86), an Elachi protégé who started off flying Earth-mapping radar missions on the Space Shuttle and now leads JPL's Astronomy and Physics Directorate.

But the plum course is a required one—Ae 105, Aerospace Engineering, co-taught by Dimotakis, Gregory Davis, and Marco Quadrelli. Dimotakis is an expert in turbulent flows in general and propulsion systems in particular. Davis is the chief technologist for JPL's Mechanical Systems Division; before that he built the advanced deployable structures group, and before that he was a mechanical-systems engineer on the Mars Exploration Rovers, Spirit and Opportunity, and a dynamicist for the original Sojourner rover. Quadrelli is a senior dynamics and control analyst in JPL's guidance,

"One cannot change the world with nine students, but perhaps one can. I would be very happy if one of them became a future director of JPL. . . and maybe in 10 years one will become another von Kármán."

navigation, and control section who has been an entry, descent, and landing dynamics analyst for the Huygens probe to Saturn's moon Titan and the Mars Exploration Rover and MSL missions, and has developed control algorithms for multivehicle and tethered spacecraft. Ae 105's fall term covers launch vehicles, fundamental structural and thermal systems, and introductory orbital mechanics. The winter quarter looks at advanced orbital mechanics, spacecraft dynamics, and planetary reentry—taking the students from the ground to space and back again in two terms. Occasional guest lecturers from JPL provide additional spice to this challenging stew.

In the spring term, the Ae 105 students reach the promised land of flight hardware. The class is doing a theoretical analysis of the telescoping mast for the Nuclear Spectroscopic Telescope Array, or NuSTAR, slated to launch in 2011. A partnership between Caltech, JPL, and 10 other organizations and headed by principal investigator Fiona Harrison, professor of physics and astronomy, NuSTAR is an X-ray telescope. Since X rays go through pretty much everything, you have to place any optics intended to focus them at a very shallow angle. This means they have to be quite some distance from the detector, which is a problem if you're designing a compact spacecraft that's relatively inexpensive to launch. Hence the deployable mast—essentially a set of collapsible cubes stacked one atop another—which, when fully extended, will hold the mirrors 10 meters away from the spacecraft.

This summer, some of the Ae 105 students and some JPL new hires assigned to the mission will begin actual deployment experiments with real prototypes. In the fall, the 2008–09 academic year will mark the start of a four-year program of collaboration with the NuSTAR team as the mission develops. That first year, students will be doing mission planning. The second year, 2009–10, will see the hardware design and procurement. The third year, 2010–11, will be NuSTAR's assembly, test, and launch. And the final year, 2011–12, will monitor the hardware's performance in orbit. "We will repeat this cycle every four years with a new JPL mission," Rosakis says.

Next year, Ae 105 will be overseen by Professor of Aeronautics and Civil Engineering Sergio Pellegrino, just recruited from the University of Cambridge, England, where he founded the university's Deployable Structures Laboratory in 1990. (He is also teaching Ae 221, Space Structures.) "There are many joint Caltech-JPL appointments," says Rosakis, "but they took the joint appointment after being hired by Caltech. This is our first professor to be hired by a joint Caltech-JPL committee." This arrangement will give JPL access to a large chunk of Pellegrino's time, and allow him unfettered access to JPL.

Pellegrino is no stranger to expandable structures. His office is crammed—or will be, when he finishes unpacking—with models that would make excellent toys, should someone care to mass-produce and market them. Some of them are solid shapes, like the circular plate that expands into a lacy circle about twice its original size. Others look like bundles of sticks, joined by hinges on their ends. Shake out the bundle, and four sticks become a square, six a hexagon, and so on. Put a wire mesh on that framework, says Pellegrino, and voilà! You have a radar array. Pellegrino and his collaborators have worked out general mathematical techniques for dealing with both classes of objects, so that "when people have a particular problem, they can go to the general theory and pull out the specific geometry they need. I don't like to work on problems no one could make use of."

In the years to come, Pellegrino and Harrison will be co-teaching a course devoted to NuSTAR. It's not yet in the catalog, and so doesn't have an

**Pellegrino holds an expandable sphere—a 3-D version of the expandable circle mentioned above—that might make a dandy space habitat as a hollowed-out shell.**

**GALCIT-JPL connections then and now. Right: Allen Puckett (PhD '49), a grad student of von Kármán's, designed several supersonic wind tunnels for the then-Army laboratory. In the front row at the January 1947 groundbreaking for one of them are, from left, Clark Millikan (PhD '28), professor of aeronautics and future GALCIT director; Puckett; Louis Dunn (BS '36, MS '37, MS '38, PhD '40), JPL director and associate professor of aeronautics; Caltech president Lee DuBridge; Major General Everett S. Hughes; von Kármán; and Robert A. Millikan, professor of physics and Caltech president emeritus. Far right: Two of the aerospace master's degree program's prime movers—Rosakis (at far right) and Dimotakis (at far left)—are alumni of Athens College, a Greek-American high school in Athens, Greece . . . as are (middle left) Sterge Demetriades (Eng '58), retired from a long aerospace career, and Alexis Livanos (BS '70, MS '73, PhD '75), president of Northrop Grumman Space Technology and chair of the GALCIT advisory council. This picture was taken at the 50 Years in Space conference.**

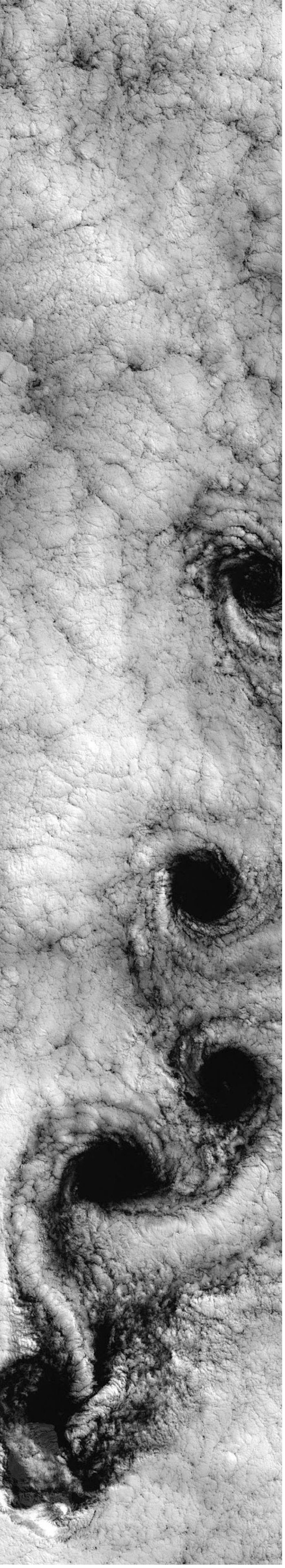
official number, but it will be called On-Orbit Performance of Large Deployable Space Structures. "As the design and construction of the mission continues, the students will be doing hands-on work with the flight hardware," says Pellegrino. They'll be creating a diagnostic package that will use cameras and other techniques to watch the boom as it deploys. Rosakis says the package will "look at the mechanics of the expanding boom, and make sure that it goes where it has to go and how it vibrates in the process. That has nothing to do with the science mission of NuSTAR directly. It has to do indirectly, because it helps in the positioning of the instrument, but it is a mechanics and an optics problem."

The grad students won't have all the fun—there will also be Summer Undergraduate Research Fellowships (SURF) available. "Fiona was very inspired by President Chameau's call for new opportunities for the students to learn," Pellegrino says.

The new program is housed in a completely remodeled Guggenheim Aeronautical Laboratory. Built in the late 1920s as a shell wrapped around a wind tunnel with a 10-foot-diameter working section—the biggest and fastest wind tunnel on the West Coast, capable of generating sustained flows of up to 200 miles per hour—much of the cavernous space has been underutilized since the wind tunnel was decommissioned in 1997. The new interior, designed by John Friedman Alice Kimm Architects, has already won a 2007 American Institute of Architects, Los Angeles Chapter, Next L.A. Merit Award—one of 10 among a couple of hundred submissions. "This project allowed us to do a little more experimentation than usual in terms of design," says Kimm, the lead architect. "It was a really exciting project, with lots of digital modeling techniques. The design committee [Rosakis; Guruswami Ravichandran, the Goode Professor of Aeronautics and Mechanical Engineering; Morteza Gharib (PhD '83), the Liepmann Professor of Aeronautics and professor of bioengineering; Assistant Professor of Aeronautics Beverley McKeon; and option administrator Dimity Nelson] was very forward-looking." The interior's organic forms "were based on turbulent flow diagrams from the aerospace faculty," says Friedman. "Now you don't send mechanical drawings to the shop any more, you send digital files to a CNC [computer numerical controlled] machine."

All the corridor walls follow graceful curves rather than straight lines. "There are no oblongs here. No circles, either. It's all about the flow," says Rosakis proudly. The lobby features a translucent, undulating ceiling with large, shallow, backlit dimples that produce moiré-like patterns. The lantern, as Kimm calls it, is reminiscent of the dimpled wing surfaces that McKeon studies. Decorative elements throughout the building reflect other researchers' work, and a number of artifacts from the old building have been incorporated as well, including a control panel from the old 10-foot wind tunnel that has been mounted into a wall on a third-floor corridor.

The centerpiece of the new Guggenheim—the Laboratory for Large Space Structures—is Pellegrino's province. The lab occupies much of the ground floor and includes a two-story-tall "high bay," an open space big enough to accommodate an Apollo moon lander. Windows look into the high bay from the second floor outside, making it part lab and part interactive display. The high bay's first occupant will be NuSTAR's truss—a perfectly rigid structure in the microgravity of space, but incapable of supporting its own weight when extended to full length parallel to the ground. In order to test such ultralightweight—one could even call them flimsy, but in a good way—structures here on Earth, they need to be "gravity compensated," which essentially involves suspending them from wires like X-wing fighters hanging from the ceiling of a 14-year-old's bedroom. The suspension systems may include pulleys, counterweights, and



Von Kármán vortices off the Chilean coast near the Juan Fernández Islands.

servomotors to balance the changing forces. "As the structure deploys, the suspension has to move with it," Pellegrino explains. "And so a high ceiling is good, because the angles of the wires change less." Mounting the pulleys on tracks doesn't help, says Pellegrino. "Fixed wires are better than tracks, because the structure would only be able to go in a straight line to follow the track. And tracks have friction, so they'll drag. So wires are actually better, not to mention cheaper!" Pellegrino also works with inflatable structures—if you've ever blown up an air mattress straight out of the box, you know that it doesn't always unfold precisely as planned—and with composite materials that can be formed into thin, stiff things like antenna dishes. Equipment for making and testing these kinds of structures will be housed in the lab as well.

Wrapped around the second floor of the high bay is the Gordon Cann Laboratory of Experimental Innovation. This lab will house Ae/APh 104, Experimental Methods, which, says Rosakis, "is a signature course. No other university has a required full-year graduate-level experimental course. They are all simulations and numerics." The class teaches solid- and fluid-mechanics methods of all sorts in one dedicated lab space. The facility includes clean rooms, a transmission electron microscope, materials testing equipment such as a coherent gradient sensing (CGS) laser-interferometry system for measuring how materials and structures deform under stress, and particle-velocimetry equipment to see how fluid flows behave, and even small wind tunnels. "Students used to have to go from lab to lab and from professor to professor for all these different things," Rosakis says. Down the hall will be the new von Kármán Conference and GALCIT Archives room, underwritten by Bob Herzog. The third floor will include two new labs for student experiments, and the Allen Puckett Laboratory of Computational Fluid Mechanics, which includes a seminar room and open-plan computer-lab area, plus open spaces designed to hang out in.

The renovations have even spilled over into the second floor of the adjoining Karman Laboratory of Fluid Mechanics and Jet Propulsion, where the Joe Charyk Biomechanics Laboratory has been located. This facility will house work being done by Gharib and by John Dabiri (MS '03, PhD '05), assistant professor of aeronautics and bioengineering, on bioinspired designs of such things as low-power propulsion systems for exploring worlds with dense atmospheres—picture a robotic jellyfish pulsating its way through Jupiter's clouds, for example. (For more on Dabiri's work, see his 2007 *Caltech News* profile, in Volume 41, Number 1.)

Cann (MS '56, PhD '61), Herzog (BS '56, MS '63, Eng '64), Puckett (PhD '49), and Charyk (MS '43, PhD '46) are all GALCIT alumni. Two of them have left quite a mark on aerospace themselves. Puckett, now retired as chairman of Hughes Aircraft, designed and built the United States' first supersonic wind tunnel while still a grad student. And Charyk, a former undersecretary of the Air Force, was the founding president of the Communications Satellite Corporation, or COMSAT, which in 1965 launched the world's first geosynchronous communications satellite to beam TV broadcasts and telephone conversations between Europe and North America.

Even though the new labs will have been in use over the summer, they will officially open on September 26, when President Chameau cuts the ribbon as part of the celebration of the 80th anniversary of Guggenheim's completion and the birth of GALCIT. But the highlight of this two-day party will probably have been the previous evening, when astronaut Gregory Chamitoff (MS '85) addresses the banquet attendees from aboard the International Space Station just before GALCIT's Aerospace Historical Society awards the 23rd Annual International Wings of von Kármán Award to Alexis Livanos (BS '70, MS '73, PhD '75), president of Northrop Grumman Space Technology and a 2008 Caltech Distinguished Alumnus. Incidentally, that afternoon's keynote speaker, David Thompson (MS '78), chairman and CEO of Orbital Sciences Corporation, once said, according to Rosakis, that "the reason he left GALCIT, as did Chamitoff—they did not get PhDs with us—is that we did not have a concentration in space. This shows the need. Thompson actually said that that was one of his biggest disappointments, because he really wanted to work in space."

And work in space these new degree holders will. Virendra Sarohia (MS '71, PhD '75), who works in the chief technologist's office at JPL as liaison to Caltech, is in charge of making that happen. He's on the Caltech-JPL committee that recruits JPLers to teach in the program, but his broader role, says Rosakis, is to facilitate the research connections between Caltech professors and JPL scientists in a way that will lead to thesis topics for the students. "So that's why it's important that he is a GALCIT graduate who is intimately familiar with JPL research and Caltech research." Besides brokering these "arranged marriages," Sarohia oversees the JPL summer fellowship program that lets program graduates work full-time in space before going on to a PhD and, Rosakis hopes, a career in the space business. "One cannot change the world with nine students, but perhaps one can. I would be very happy if one of them became a future director of JPL, and a few others become CEOs of major aerospace companies in Southern California, and maybe in 10 years one will become another von Kármán." □

PICTURE CREDITS: 36, 37 — Bob Paz; 34–35 — NASA Landsat; 37 — Caltech Archives

Thank you for the special issue of *E&S* on JPL. It read like a very good novel. Even though I was familiar with all of the missions that you described, the details of the problems that had been addressed were fascinating. My familiarity with JPL as a Caltech student, having classmates on the staff, working with them in setting up Seminar Day talks, and following the adventures in the news media gave particular significance to your story. As I followed the pictures I recognized many as persons that I had met or worked with in industry.

My one compelling thought was that it would be great if some sort of recognition could be afforded to JPL itself. I doubt that the ground rules for the Nobel Prize could be stretched far enough to permit their inclusion in such an award, but I do feel that their contribution to the exploration of the Solar System should receive some sort of international recognition.

Thanks again for your work.

Alfred W. Thiele (BS '51)

I thoroughly enjoyed your "50 Years of Caltech and JPL" issue. Very well written. An excellent selection of material. As an alumnus who closely followed the many spectacular events chronicled, it was great to get such a well-done compilation. I enjoy every issue of *E&S*, but this one was special.

Walter V. Goeddel (MS '51)

The article by Erik Conway, arriving shortly after my 90th birthday, really stirred memories.

I would have been the class of '39, but took a year off to work for the New York World's Fair of 1939, followed by returning for my senior year with my new bride, a Hungarian girl who's fluent in about five languages. This put me in with a group of postgraduates, all delightfully somewhat weird, including Frank Malina.

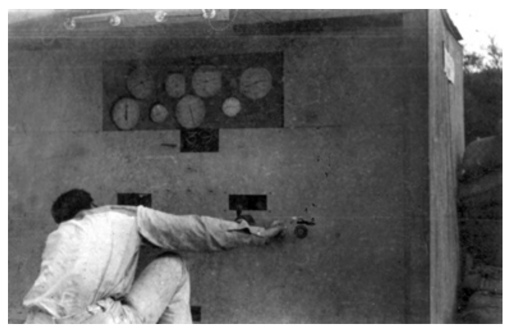
Part of our association was because I was a good mechanic and there were things to be performed on rocket motors, and mostly because my wife was good at translating various technical papers for this group and some other postgraduates.

Your article led me to dig out my scrapbook, made from 35-mm film that has long since deteriorated, but I enclose not only the original prints but some enlargements from my office copier that show one of the firings, sandbags and all.

The group played when they weren't rocketing, and I have other photographs showing us camping on the Mojave and trying to shoot jackrabbits with a .45.

I graduated and went to work for Menasco airplane engines, and all of a sudden JATO came along and the weird but wonderful group all became VIPs.

Robert O. Cox (BS '40)



**According to Cox, these old scrapbook photos show Frank Malina testing rockets—apparently in someone's backyard. If anybody knows where these photographs were taken (Cox doesn't remember), we'd love to hear from you!**

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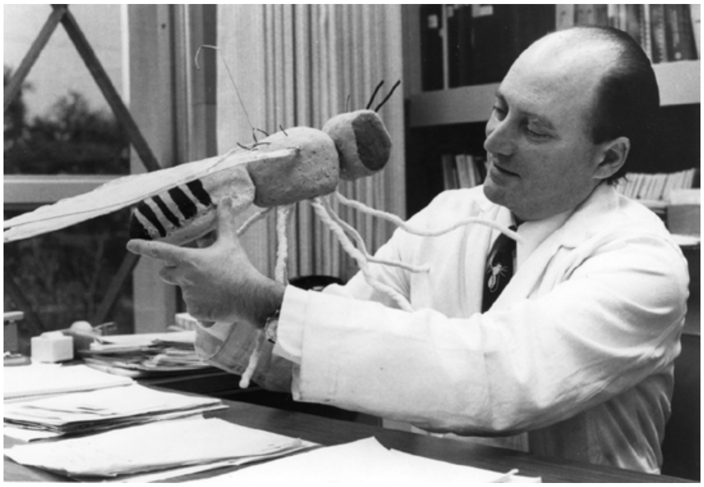
## Seymour Benzer
## 1921 – 2007



Seymour Benzer, the Boswell Professor of Neuroscience, Emeritus, a founder of modern genetics, and one of the giants of 20th-century science, died from a stroke on November 30, 2007, in Pasadena. He was 86.

In a series of elegant experiments, Benzer made groundbreaking discoveries about the structure of genes, finding that they were not indivisible units of inheritance, as many scientists had believed. He also pioneered the field of behavioral genetics, in which he probed the connection between genes and behavior.

Benzer was born to Polish immigrants in New York City, growing up on a street nestled between Jewish and Italian neighborhoods in Brooklyn. During the Depression, his parents, who worked in the garment district, managed to shield him and his three sisters from most of the era's hardships. To make ends meet, Benzer's parents brought clothes home to work on late into the night.

Benzer had an interest in science from an early age. During summer trips to the Catskill Mountains in upstate New York, he caught and dissected frogs. A whole new world opened up when his brother-in-law bought him a microscope for his 13th birthday, he said in his oral history. He looked at everything he could find, and did experiments in his basement laboratory—such as making frog legs twitch with electric wires. Although never a religious person, Benzer said he respected his parents' faith, and followed his father to synagogue on holy days. There, he would slip a physics book on top of the Torah; his father looked the other way while he read.

Benzer was the first in his family to go to college, enrolling in Brooklyn College in 1938. Although he was interested in biology, he eschewed the introductory classes and instead graduated with a physics degree in 1942. He went on to earn his PhD at Purdue University, developing a special type of germanium crystal for a secret military project. His work led to the first transistor and a Nobel Prize for William Shockley (BS '32), John Bardeen, and Walter Brattain in 1956. The researchers who developed the transistor came to him and told him, "You should have done this," he recalled. He said, "It escaped me, and it was under my nose."

By then, however, he was an assistant professor in physics at Purdue with a renewed interest in biology. Inspired by Erwin Schrödinger's book *What is Life?*, Benzer attended a summer course in 1948 on bacteriophages, viruses that attack bacteria, at Cold Spring Harbor—organized by Caltech biology professor Max Delbrück. "Three weeks of that, and I was converted," Benzer said. He continued studying bacteriophages during a year at Oak Ridge National Laboratory in Tennessee before joining Delbrück's lab at Caltech for two years as a postdoc. He then went to the Pasteur Institute in Paris for a year, before returning to Purdue. Back in Indiana, he started what would become some of his most well-known work on the structure of the gene.

At the time, molecular biology was in its embryonic stage. James Watson and Francis Crick had just discovered the double-helix structure of DNA in 1953. But until Benzer's experiments, the physical nature of the gene was a mystery.

He worked with mutant strains of a bacteriophage that infected *Escherichia coli*. When two strains of the virus infected *E. coli*, their offspring contained new genes that combined elements of the same gene from both progenitors. Benzer analyzed tens of thousands of these so-called recombination events, in which portions of the gene called *rII* swapped places. By comparing the length of these portions, he mapped *rII*'s fine structure, showing that it was not an indivisible unit of heredity, but many smaller units strung together. His map was on a scale large enough, in fact, to see changes the size of a single nucleotide—the letters that make up the DNA code and formed the double helix. This work bridged the gap between classical genetics and molecular biology.

As molecular biology exploded in popularity, Benzer went in a different direction. In the 1960s, partly inspired by the divergent personalities of his daughters, he became interested in behavior and the "nature-versus-nurture" debate. He began experiments with the fruit fly *Drosophila melanogaster* while on sabbatical from 1965 to 1966 in the lab of Roger Sperry, Caltech's Hixon Professor of Psychobiology, and stayed on to become a professor of biology in 1967. At Caltech, Benzer developed a novel device that allowed him to separate flies according to behavior and isolate mutant strains. Benzer treated the flies as if they were particles, bits of statistical data from hundreds of individuals that he could collect in minutes, rather than taking weeks to prepare a handful of rats.

His lab first studied the flies' response to light, creating strains that failed to go toward a light, as normal flies do. Benzer, his students, and his postdocs also developed strains that slept and woke at random intervals, flies that died early, and mutant females that brushed away males. By finding these kinds of mutants, they identified the genes responsible for the flies' circadian rhythms—the natural biological clocks of organisms—and other genes responsible for courtship, memory, and learning.

His research was controversial at the time, as many scientists were skeptical as to whether the small and simple fruit fly could be used to dissect the complexities of behavior. His first seminar in Sperry's lab outlining some of his initial fly research was met with a divided reaction. "They were pretty much split down the middle between those who thought that this was great stuff and others who thought this was pure crap," he recalled. "They were really screaming at each other."

Nevertheless, Benzer was highly respected, and he pursued his interests with freedom. His work with fruit flies grew into the new field of neurogenetics, showing that much of behavior is hardwired and not the result of one's environment.

He became Caltech's Boswell Professor in 1975 and officially retired in 1992, although he remained an active researcher afterward. In the late 1990s, Benzer and colleagues identified the famous "Methuselah" gene in fruit flies. Named after the Biblical character who supposedly lived 969 years, the gene is key to longevity. The mutants lived 35 percent longer, tolerated higher temperatures, survived longer without food, and were more resistant to poison than normal flies.

Over his career, Benzer accumulated more than 40 honors, including membership in the National Academy of Sciences, the Royal Society, and the American Academy of Arts and Sciences. He won the National Medal of Science, the Wolf Prize in Medicine from Israel, the Crafoord Prize of the Royal Swedish Academy of Sciences, the International Prize for Biology from Japan, the Albert Lasker Award for Basic Medical Research, and the Albany Medical Center Prize. He also won the Gairdner International Award twice. In 2000 he became the subject of the book *Time, Love, Memory: A Great Biologist and His Quest for the Origins of Behavior*, by Jonathan Weiner. Although many colleagues said his work deserved a Nobel Prize, the award eluded him. "My mother always regarded me as a failure because I didn't get the Nobel Prize," he remarked.

Benzer savored gastronomical experiences, whether it was discovering sushi in Japan or, upon encountering a dearth of good restaurants in Cambridge, England, forming a gourmet club with friends to prepare their own meals. Colleagues in his lab recalled him offering them bizarre food such as rotten fish or chocolate-coated grubs.

His enthusiasm for trying diverse cuisine paralleled his passion for reaching across scientific disciplines, having gone from physics to molecular biology to neurogenetics. Colleagues remembered him as a visionary and scientific maverick, following wherever his curiosity took him. But his science was more than mere interest—it was an extension of who he was. Often waking up just before noon, he would work deep into the early morning hours, prompting colleagues to wonder if his own biological clock was the inspiration behind his research on circadian rhythms. He relished starting afresh in a new field in which he was ignorant and could ask basic questions. "Ask stupid questions," he said, "and you often get amazing answers."

Benzer is survived by his wife, Carol Miller; two daughters, Barbara Freidin and Martha Goldberg; a son, Alexander Benzer; two stepsons, Renny and Douglas Feldman; and four grandchildren. His first wife, Dorothy Vlosky, died in 1978. □—*MW*

## David C. Elliot
## 1917 – 2007

David C. Elliot, professor of history, emeritus, died on November 21. He was 90.

Born in Larkhall, Scotland, Elliot was the son of a minister. He attended the University of St. Andrews, where in 1938 he met Nancy Haskins, an exchange student from Chattanooga, Tennessee. The next year, they decided to get married.

India was then under British colonial rule. Elliot joined the Indian Civil Service, of which only about 1,000 members governed the country at a given time. In 1940, he was sent to the Punjab region at what today is the northern border of India and Pakistan. At 23, he governed an area larger than Scotland, and he spent much of his time traveling the countryside on horseback. He would return to India in 1997 for the 50th anniversary of the nation's independence.

In order for Haskins to join Elliot in India, she had to be a British citizen—or at least married to one. She went to South Carolina, which recognized common law marriage, and married Elliot by proxy.

She spent the next six years trying to join him in India, finally succeeding in 1945. They had a second wedding in Lahore.

The couple left India in 1947 and went to the United States, where Elliot studied history at Harvard. He earned a master's degree in 1948 and his PhD in 1951. He later earned a second master's from Oxford in 1956. Immediately after Harvard, he ventured out west to Caltech, became an assistant professor, and was appointed a full professor in 1960. He served as secretary of the faculty from 1973 to 1985, before retiring in 1986.

Elliot's research interests included the Liberal Party in Scotland, the English Restoration, arms control, and national defense. A consultant for RAND, NASA, and the Ford Foundation, he served as a trustee and honorary trustee of the Institute of Current World Affairs, and he spent 30 years on the board of trustees of Westridge School in Pasadena. He was chairman of Caltech's 75th anniversary celebration and, in 1977, Caltech students voted him the most popular professor. On his own time, Elliot was an avid golfer and bridge player.

Predeceased by his son, John, in 1991 and his wife in 1994, he is survived by his daughters, Nan Elliot Hale and Enid Elliot, a son-in-law, Richard Kool; and four grandchildren and two great-grandchildren. □—*MW*

## Herbert B. Keller
## 1925 – 2008

Herbert B. Keller, professor of applied mathematics, emeritus, and a leader in numerical analysis and scientific computing, died in his Pasadena home on January 26, after his routine morning bicycle ride. He was 82.

The son of a bartender who loved numbers and puzzles, Keller was born in Paterson, New Jersey. He studied electronics at Georgia Tech and joined the Naval Reserve Officers Training Corps. During World War II, he became a fire-control officer in charge of the guns on the USS *Mississippi*, where he trained future president Jimmy Carter to be a gunnery officer.

Keller later went to New York University and received his PhD in mathematics in 1954. He eventually became a professor of applied mathematics at the Courant Institute of Mathematical Sciences at NYU. In 1965, he came to Caltech as a visiting professor and returned as a full professor two years later, joining the newly formed applied-mathematics group. He later became the executive officer for applied mathematics and director of Caltech's branch of the Center for Research on Parallel Computation.

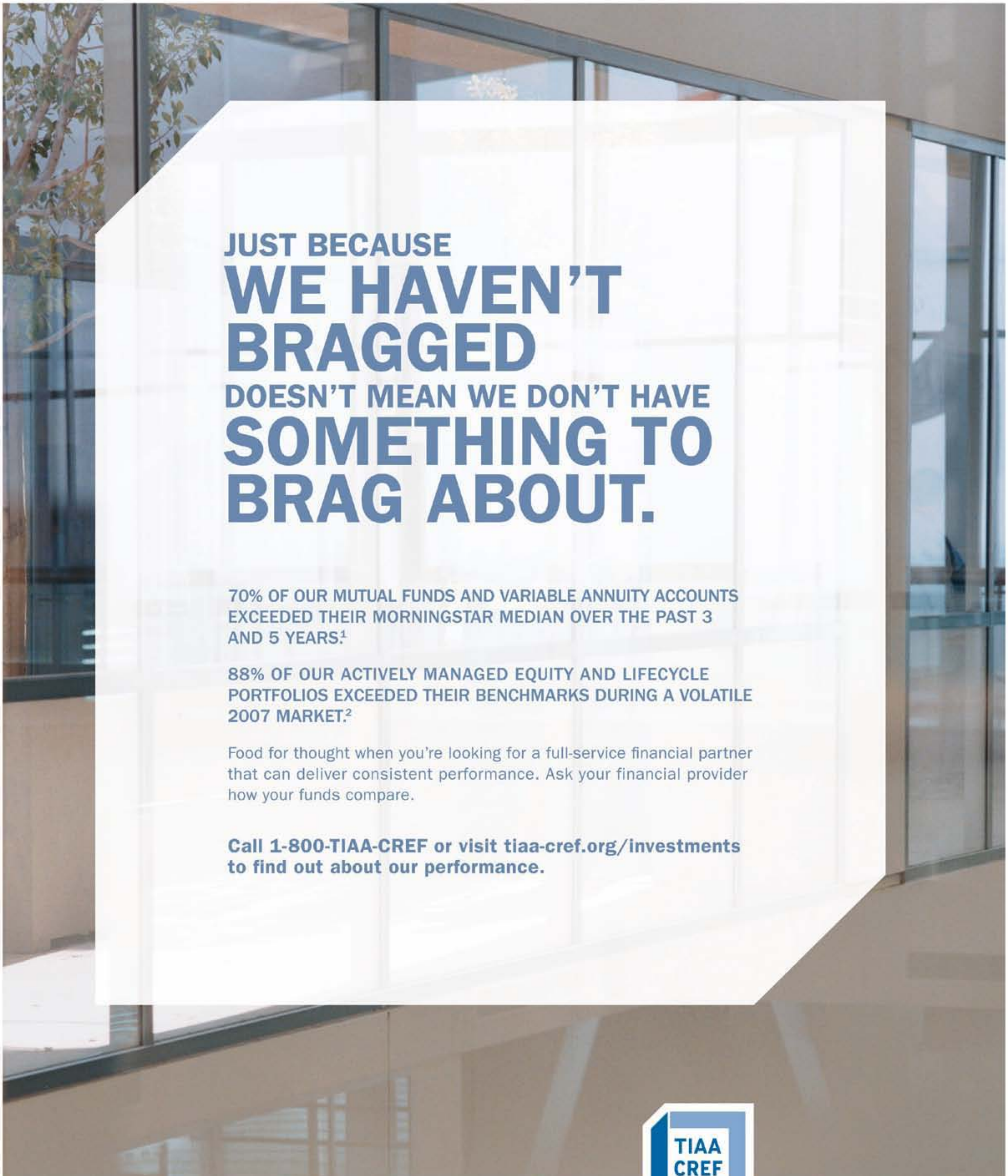
Keller made significant contributions toward techniques for solving complex problems with a computer. He was known for developing methods to solve two-point boundary-value problems, which arise in many areas of physics and engineering, from fluid flow to stellar structure. He also made strides in bifurcation theory, which looks at how changes in parameter values influence a system. One simple example is the problem of how changing the number of fishing licenses given out each year affects fish population dynamics. He remained an active researcher even after his retirement in 2000.

Colleagues described him as a mathematician with chutzpah, unafraid to speak his mind and to go after whatever problem interested him—advice that he doled out through the years as an influential mentor to dozens of students and postdocs. His fearless approach to research mirrored his other passion in life: cycling.

His brother recalled a cycling trip they took in the south of France in 1948, when they inadvertently joined the Tour de France after riding through roads lined with cheering spectators. Keller rediscovered the sport in the early 1980s, and despite suffering countless accidents—many with serious injuries—never stopped riding. In one of his most oft-told stories, he said a collision he had with a pile of lumber in Germany fixed his nearsightedness. Typically biking 100 to 150 miles a week, Keller didn't allow age to slow him down—he finished a 1,250-mile European tour when he was 68. He completed several centuries and double centuries, which are rides stretching 100 or 200 miles; he said he rode his last double century when he was 72.

In addition to serving on numerous committees and councils, he was a fellow of the American Academy of Arts and Sciences, the American Association for the Advancement of Science, and the Guggenheim Foundation. He was the president of the Society of Industrial and Applied Mathematics, and later won their von Kármán Prize. With Eugene Isaacson, he coauthored a textbook that became a classic in numerical analysis.

His brother, Joseph, a retired professor of mathematics and mechanical engineering at Stanford University; his son, Steve; his daughter, Debra; and four grandchildren survive him. □—*MW*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