California Institute of Technology

Engineering & Science

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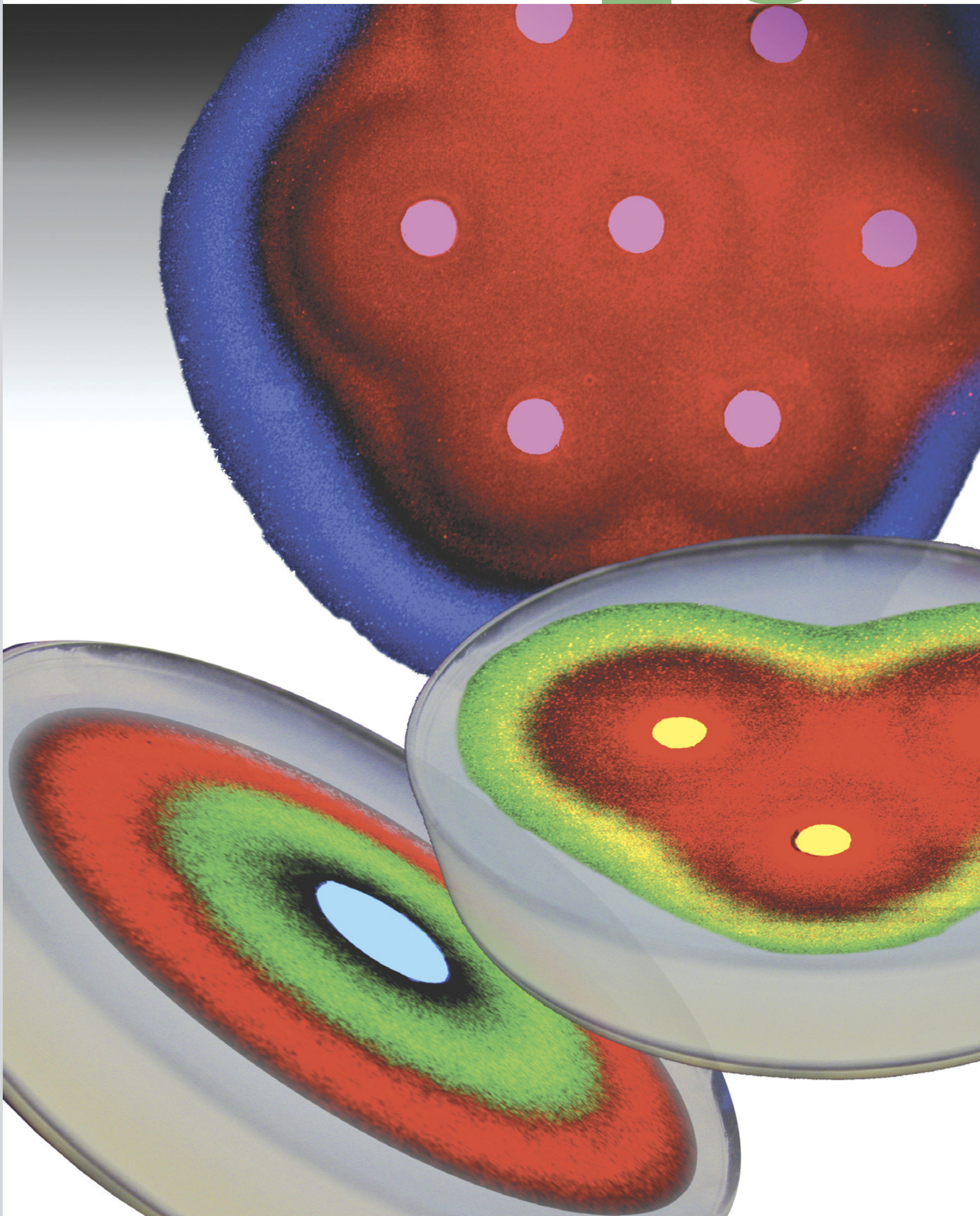

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Feynman's Vision

This slowly submerging grid of coconut palms stands on a promontory on the northwestern coast of the island of Nias. Nias sits on top of the rupture zone of the magnitude (M) 8.7 earthquake on March 28, which followed the great Sumatran earthquake on December 26 of last year. Caltech geologist Kerry Sieh has been doing fieldwork in Sumatra for more than a decade—to learn about his work, see the story beginning on page 24.

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On the cover: The interplay between genes and various chemical messengers controls how an embryo develops from a single cell into a complicated adult. Can the same principles be used to create patterns of any desired complexity to build, say, a biologically based computer? This is a first step in that direction—a collection of bacterial colonies that "light up" in response to chemical signals emitted by other bacteria. For more on where the information sciences are heading, see the story beginning on page 6.

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NuSTAR in the Sky with X Rays

If all goes well, an innovative telescope should be orbiting Earth by 2009 and taking the first well-focused, high-energy X-ray pictures of matter falling into black holes and shooting out of exploding stars. Not only will the telescope be 1,000 times more capable of finding black holes than anything previously launched into space, it will also give us an unprecedented look at the origins of the heavy elements we're all made of. Named the Nuclear Spectroscopic Telescope Array—or NuSTAR, for short—the project has been approved for detailed study as part of NASA's Small Explorer program (SMEX), which seeks out new technologies and new proposals for space missions that can be launched at low cost. NuSTAR will go through a confirmation review early next year to decide if it is ready to proceed.

A key high-altitude-balloon test on May 18 went well, says Fiona Harrison, an associate professor of physics at Caltech and NuSTAR's principal investigator. "We got lots of good data—images of the background and of cosmic sources—that demonstrate the NuSTAR concept." The balloon spent 20 hours in the stratosphere at 128,000 feet. The balloon's instrument, called HEFT (for High-Energy Focusing Telescope), returned sharp pictures at "hard X-ray" wavelengths—in this case, about 20 to 100 kilo electron volts—the first ever from high altitudes. In fact, the HEFT images are superior to existing satellite data at these energies. And NuSTAR will do even better, Harrison explains, because it will get above *all* of Earth's atmosphere. NuSTAR will observe at an altitude of about 550 kilometers for at least three years.

Hard X rays penetrate the gas and dust of galaxies much better than the "soft," lower-energy X rays observed by NuSTAR's forerunners. But hard X rays are very difficult to focus. They aren't bent by lenses, and they can only be efficiently reflected at very glancing angles. So HEFT and NuSTAR use specially coated surfaces placed nearly edge-on to the incoming X rays, which hit at a shallow angle and are gently deflected. The mirrors are nested like Russian dolls, increasing the number of photons focused. NuSTAR will have three sets of them, each composed of an amazing 150 nested paraboloids, called "shells," which are in turn made of 24 smaller pieces. (The coatings consist of hundreds of alternating layers of tungsten and silicon, each only a few atoms thick. Building these shells and the cadmium-zinc-telluride photon detectors has required groundbreaking work in a number of Caltech labs.) The X rays grazing off the mirrors come to a focus about 10 meters away, and the mirrors and detectors must be held rock-steady to prevent blurring. So NuSTAR's mirrors will be on the end of an accordion-like expandable mast that is only 45 centimeters long when

HEFT hangs from a crane while waiting for its balloon to go up at the National Scientific Balloon Facility at Ft. Sumner, New Mexico. The sphere over the crane's left wheel houses the detectors, while the mirror is at the top of the central tube pointing upward and to the right.

retracted.

NuSTAR has three main objectives. One is to count black holes of all sizes and measure the "accretion rate" at which material has fallen into them over time. The second is to trace how elements are formed in supernova explosions and then mixed in the interstellar medium, which is the space between stars. And finally, NuSTAR will study the highly energetic jets that stream out of certain black holes at nearly the speed of light—an enigmatic but powerful phenomenon.

The Jet Propulsion Laboratory (managed by Caltech for NASA), Columbia University, the Stanford Linear Accelerator (SLAC), the Lawrence Livermore National Laboratory, the University of California at Santa Cruz, and the Danish Space Research Institute are also participating in the project. The spacecraft will be built by General Dynamics C4 Systems. JPL is, among other things, managing the mission and overseeing the production of the mast, which is based on the design used in the Lab's hugely successful Shuttle Radar Topography mission. The Small Explorer program is designed to provide frequent access to space with small-to-midsized spacecraft for physics and astronomy. NASA has launched six SMEX missions since 1992, including the Galaxy Evolution Explorer, launched in April 2003 and led by Professor of Physics Chris Martin (see *E&S* 2004, No. 2). □

Hollywood Boulevard became the Scientists' Walk of Fame for a few hours on the morning of May 4, when more than 500 stars were relabeled as the class of '05's senior prank. Feynman got a star, of course, as did Galileo, Newton, Einstein, Stephen Hawking, Marie Curie, and a host of others who, alas, aren't quite such household names. Professor of Chemical Physics Aron Kuppermann, who does quantum-mechanical modeling of chemical reactions, got a choice spot across the street from Mann's (formerly Grauman's) Chinese Theater and its famed courtyard of footprints in cement.

WHO DO YOU TRUST?

The question may seem distinctly human—and limited only to "quality" humans, at that—but it turns out that we learn to trust in pretty much the same way that insects learn to expect food rewards. In other words, it's a lot more primitive than you might think. Furthermore, our biological roots make us reasonably trustworthy most of the time. In a neuroscientific milestone, experimenters at Caltech and the Baylor College of Medicine have, for the first time, simultaneously scanned the brains of subjects playing an economic game and building a trusting relationship.

The researchers placed volunteers in functional magnetic resonance imaging (fMRI) machines in Pasadena and Houston, respectively. Neither volunteer knew the other, and the two would play an economic game in which trustworthiness had to be balanced with the profit motive. Meanwhile, their brain activity was monitored through a new technique called "hyperscanning" brain imaging. The fMRI picks up evidence of a rush of blood to a specific part of the brain, which indicates that that region is more active.

According to Steve Quartz, associate professor of philosophy and director of the Social Cognitive Neuroscience Laboratory at Caltech, who led the Caltech effort, the results show that trust involves a region of the brain known as the head of the caudate nucleus. But the key finding was that trust tended to shift backward in time as the game progressed. In other words, the expectation of a reward was intimately involved in each subject's assessment of the other's trustworthiness, and that the recipient tended to become more trusting prior to the reward coming—provided, of course, that there was no backstabbing.

In the game, one player (the "investor") is given $20 and must choose to hold on to it or give some or all of it to the other player (the "trustee") 1,500 miles away. Any money the trustee receives is tripled, and the trustee can then give some or all of it back to the investor. In a perfect world, the investor would give the trustee the entire $20, which becomes $60, and the trustee would return $30 to the investor. But greed can make the trustee keep all the profit, or stinginess or lack of trust might persuade the investor to keep the original stake.

The researchers found that trust is delayed in the early rounds of the game (there are 10 in all), and that once the players begin determining the costs and benefits, the rewards get anticipated before they're bestowed. Players soon start showing activity in the head of the caudate nucleus that demonstrates an "intention to trust." Once the players know each other by reputation, they begin showing their intentions to trust about 14 seconds earlier than in the early rounds of the game.

"Neoclassical economics starts with the assumption that rational self-interest is the motivator of all our economic behavior," says Quartz. "The further assumption is that you can only get trust if you penalize people for non-cooperation, but these results show that you can build trust through social interaction, and question the traditional model of economic man." "They also show that you can trust people for a fair amount of time, which contradicts the assumptions of classical economics," adds Colin Camerer, the Axline Professor of Business Economics at Caltech and the other Caltech faculty author of the paper.

This is good news, Quartz explains, because trustworthiness decreases the incidental costs of doing business: a trusting society needs fewer laws to encumber it, fewer attorneys to ensure that documents are airtight, and so on. "It's like a deal on a handshake. You don't have to pay a bunch of lawyers to write up what you do at every step. Trust is of great economic importance, from everyday interpersonal interactions all the way up to the economic prosperity of a country, where trust is thought of in terms of social capital."

Behaviorally, the findings are similar to classical conditioning experiments. Just as a person is rewarded for trusting a trustworthy person—and begins trusting that person sooner—so, too, does a lab animal begin anticipating a reward for slobbering when a buzzer sounds, pecking a mirror, or extending the proboscis when a certain odor is smelled (see page 47). "This is another striking demonstration of the brain re-using ancient centers for new purposes. That trust rides on top of the basic reward centers of the brain is something we had never anticipated and demonstrates how surprising brain imaging can be," Quartz notes.

And, finally, the research could help understand the neurology of autism and schizophrenia. "The inability to predict others' behavior is a key facet of many mental disorders. These results may ultimately suggest new treatments," says Quartz.

The paper appeared in the April 1 issue of *Science*. The other authors are Brooks King-Casas, Damon Tomlin, and P. Read Montague (the lead author), all of the Baylor College of Medicine, and graduate student Cedric Anen of Caltech. □—*RT*

It's been a good season for pranks. A bunch of enterprising Techers flew east to attend That Other Institute of Technology's prefrosh weekend, where they distributed these shirts—packaged individually in plastic and neatly folded so that only the front logo was visible. The shirts are now on sale at the bookstore—go to www.bookstore.caltech.edu.

ERRATUM

The first paragraph of "The Caltech–Chile Connection" (*E&S*, 2004, No. 4) said that the cosmic microwave background radiation "was emitted just 400,000 years after the Big Bang (the equivalent of about 45 minutes after conception when compared to a human life)." A alert reader e-mailed:

> "I would expect more like 1,000 minutes (400,000/15 × 10^9 × no. of minutes for a 71-year-old).
> Yours truly, Rodger [Baier] (a 75-year-old chemist from the class of '52)"

To which Tony Readhead, the Rawn Professor of Astronomy and principal investigator for the Cosmic Background Imager, replies:

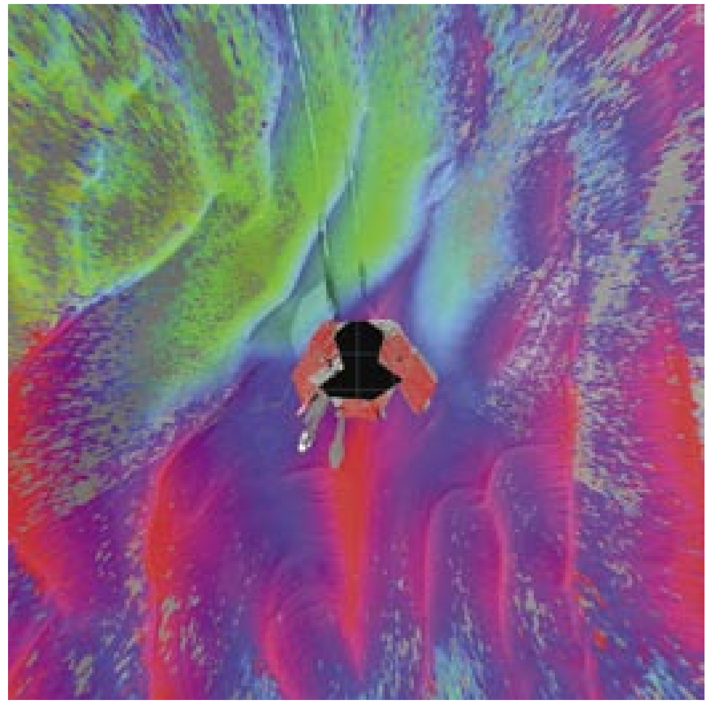
> "Sorry to say that I screwed up.
> The 3 hours was for a 14-year-old—and that was correct.
> I meant to change it to the relevant time for a 70-year-old—i.e. a change of × 5 instead of which I divided by 5."

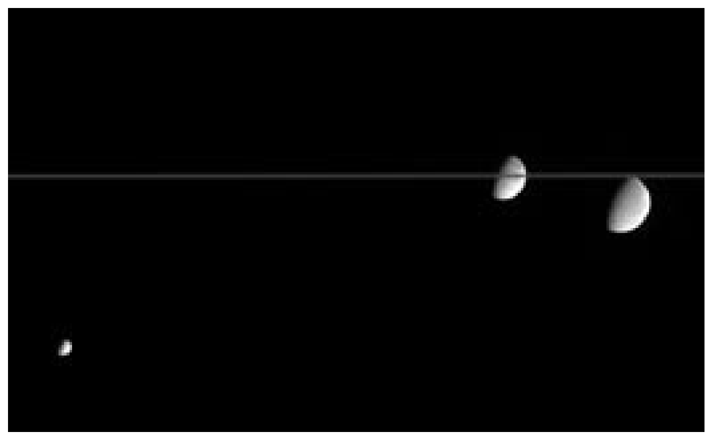
There may be hope for the rest of us yet! □—*DS*

E&S Editor Retires

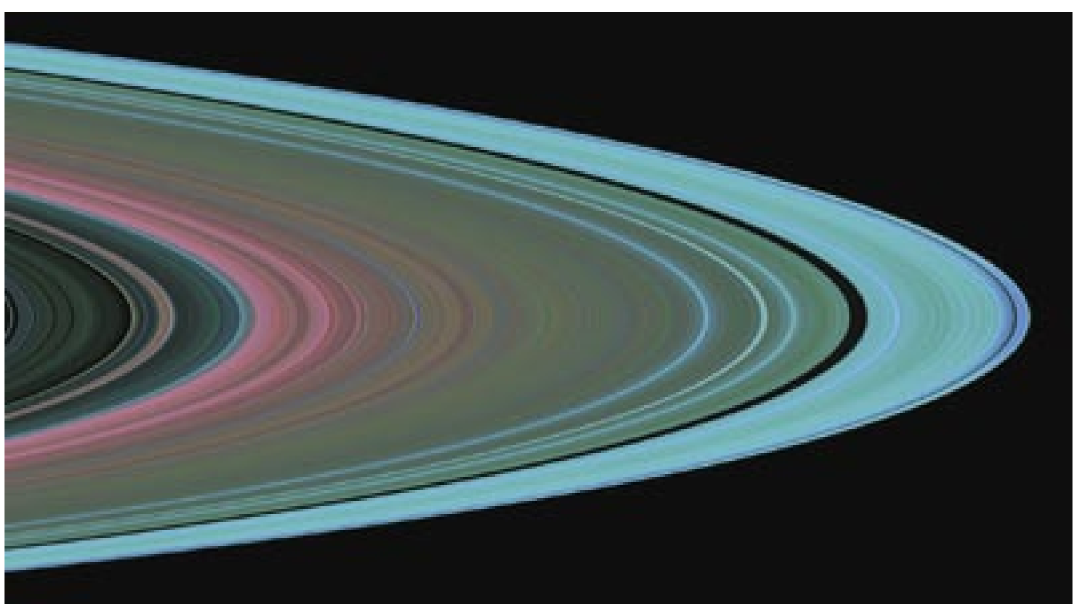
Jane Dietrich, editor of *Engineering & Science* since 1984, has called it a career. Dietrich joined Caltech as the writer for *E&S* in 1979, back when the magazine was produced using typewriters and paste-up boards, and color was a rare and expensive commodity seen only on the cover. As director of periodicals, she led *E&S*, *Caltech News*, and the staff newspaper, *On Campus*, into the age of desktop publishing—long before it was known by that name—and onto the Internet.

Doug Smith, her successor, has been with *E&S* for 18 years, the last 13 as managing editor. He expects that by the time he retires, *E&S* will be beamed directly into readers' heads via neural transceivers. □—*DS*

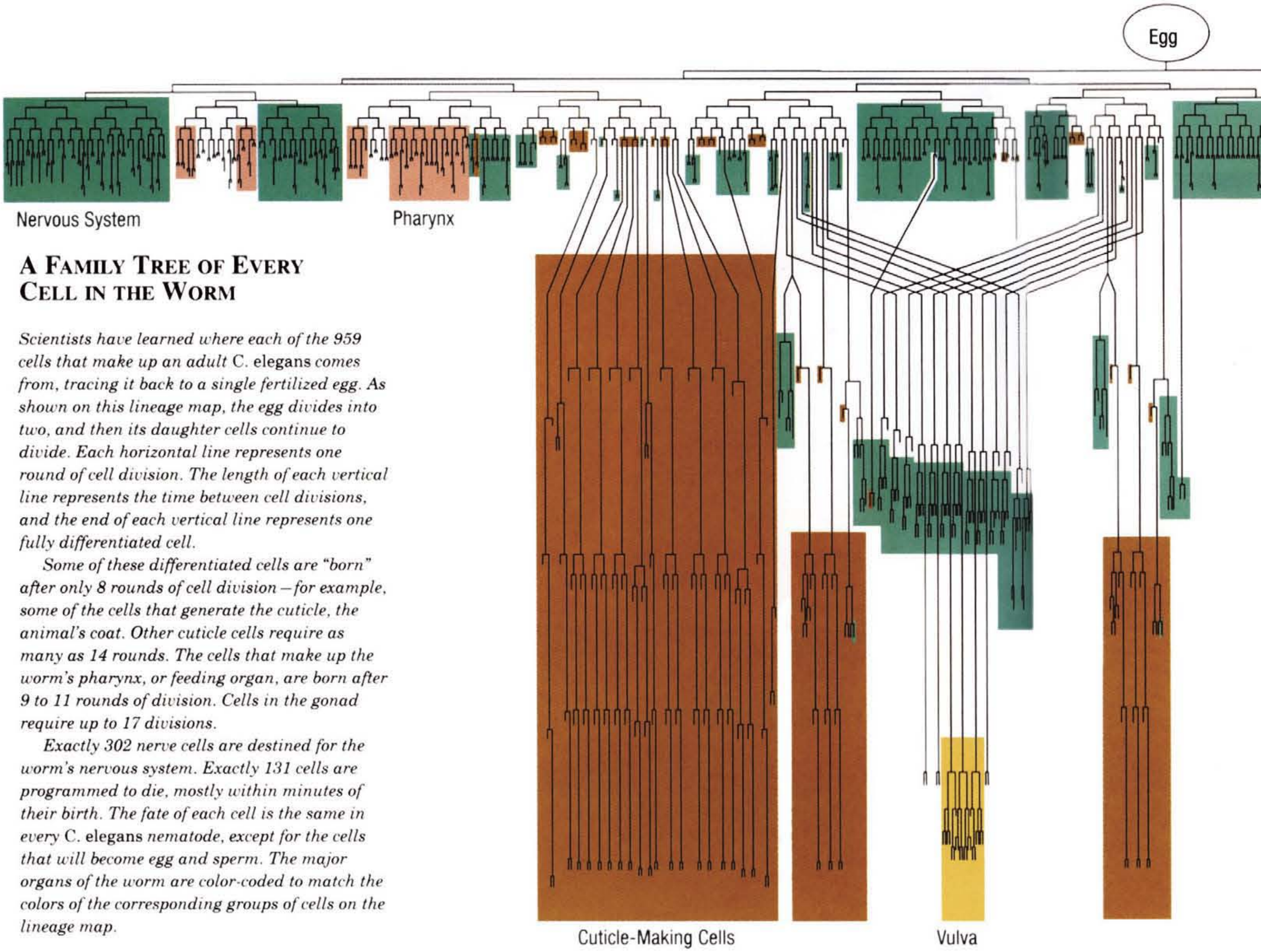




Above, right: Good news and bad news from Mars. The good news is that the winds have cleaned off the rovers' solar panels, restoring them to nearly full power. The bad news is that Opportunity is stuck hub-deep in a small dune on Meridiani Planum. JPL engineers working to free their robot made this plot of relative elevations, with green being the lowest and red being about 70 centimeters higher. Right: Cassini snapped this shot of, from left, Mimas, Dione, and Rhea as the spacecraft crossed the plane of Saturn's rings. The bright F ring can be seen above and below the darker A and B rings in front of it.



Right: Cassini's orbit was designed to allow radio signals to be sent back to Earth through the rings—a so-called occultation experiment—in order to measure the ring particles' size and distribution. In this rendering, red indicates regions where the particles are greater than five centimeters in diameter, and green and blue show where there are particles smaller than five centimeters and one centimeter, respectively.

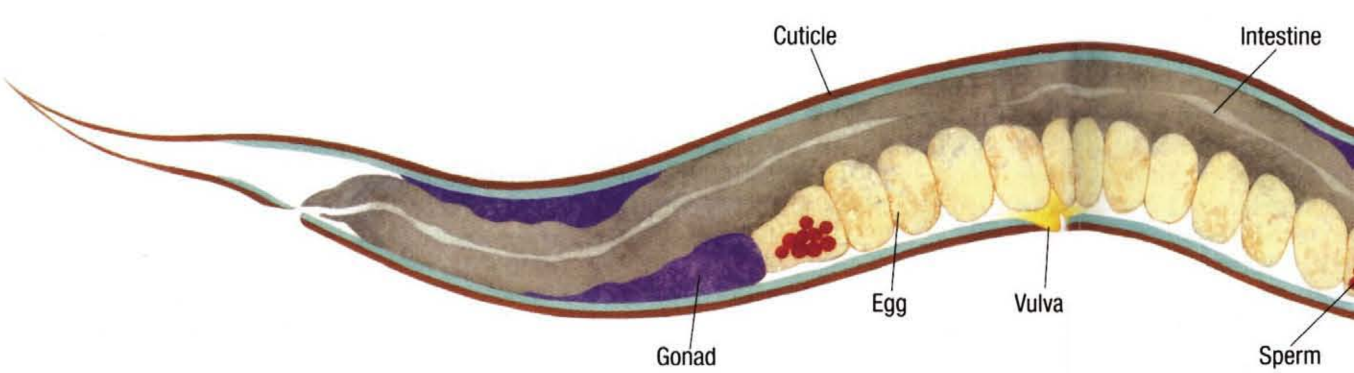


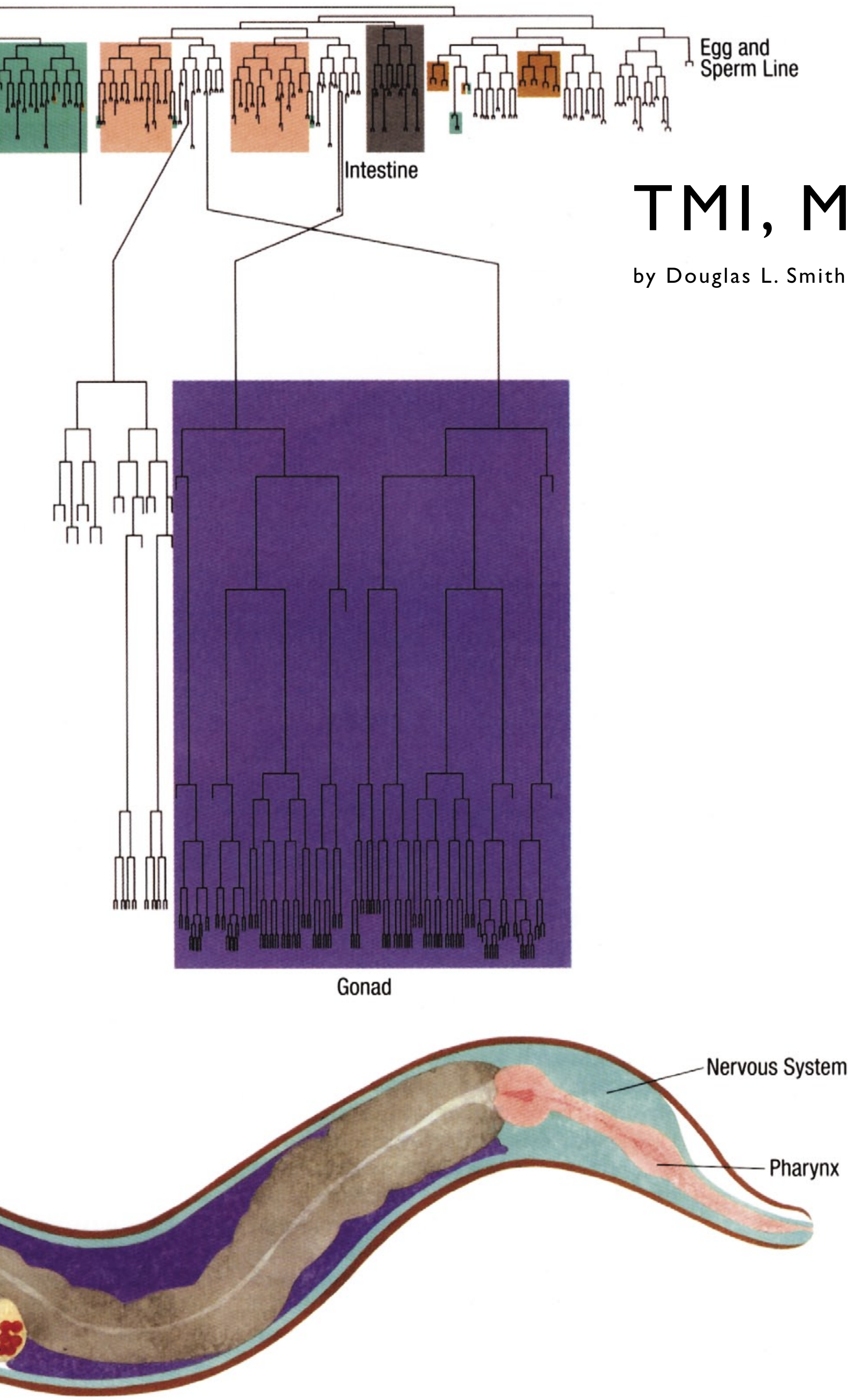
A Family Tree of Every Cell in the Worm

Scientists have learned where each of the 959 cells that make up an adult C. elegans *comes from, tracing it back to a single fertilized egg. As shown on this lineage map, the egg divides into two, and then its daughter cells continue to divide. Each horizontal line represents one round of cell division. The length of each vertical line represents the time between cell divisions, and the end of each vertical line represents one fully differentiated cell.*

Some of these differentiated cells are "born" after only 8 rounds of cell division—for example, some of the cells that generate the cuticle, the animal's coat. Other cuticle cells require as many as 14 rounds. The cells that make up the worm's pharynx, or feeding organ, are born after 9 to 11 rounds of division. Cells in the gonad require up to 17 divisions.

Exactly 302 nerve cells are destined for the worm's nervous system. Exactly 131 cells are programmed to die, mostly within minutes of their birth. The fate of each cell is the same in every C. elegans *nematode, except for the cells that will become egg and sperm. The major organs of the worm are color-coded to match the colors of the corresponding groups of cells on the lineage map.*





TMI, Meet IST

by Douglas L. Smith

In the old days, if your windshield wipers came on when you signaled for a left turn, it was probably a short in the steering column. But now, if your doors suddenly unlock as you punch the gas, it might be because the keyless entry system is getting cross talk from a defective accelerometer in the air bags. Today's cars have so many computer chips, says Jehoshua "Shuki" Bruck, the Moore Professor of Computational and Neural Systems and Electrical Engineering and director of Caltech's Information Science and Technology (IST) initiative, that nobody—not even their designers—has a complete understanding of them. The software in the average sedan can contain more than 35,000,000 lines of code—enough for maybe 100 copies of, say, *Grand Theft Auto*. Says Bruck, "The car industry is investing billions of dollars to figure out the interactions between the mechanical parts and the computers. Future development is actually getting stuck because they don't know how to manage the software."

But Nature controls far more complex mechanisms with ease: Consider the nematode *Caenorhabditis elegans*. A lowly roundworm about the size of this comma, it grows from a single-celled egg to an adult containing exactly 959 cells. The little fellas are clear as glass, and entire generations of grad students have spent countless hours hunched over microscopes tracking the career of each cell. The whole process takes 24 rounds of cell division—79 of the 959 cells line the guts from mouth to anus, 302 become nerve cells, and 131 die along the way. "Everything has been mapped precisely," says Bruck, who has a framed poster of this developmental tree on his wall. "But we, as engineers, don't understand how to handle all the information in that map. We don't understand what the principles are." But, somehow, the cells understand. The egg divides, and one cell has to call heads and the other, tails. The process involves the random diffusion of signaling molecules, but the result is very precise—you never end up with a two-headed worm. Then the other divisions have to follow in the correct order. "And even when every cell has a clock and the timetable," Bruck points out, "they still need to coordinate their actions. It's like driving on the freeway—sometimes you need to slow down and let another car pass." Organisms are just information made flesh.

A vast gulf yawns between our ability to describe and build complex systems and our ability to understand and manage them, says Bruck. "A Pentium chip has a hundred million transistors, but we cannot answer simple questions about *C. elegans* that has 959 cells. The bottleneck between what we see and what we understand is in our ability to abstract, and that's the power of IST." The calculus developed by Leibniz and Newton describes the physical world, at least on the human scale; Bruck hopes IST will develop a calculus for the realm of information in all its guises. We're drowning in data, from up-to-the-nanosecond stock quotes to blogs to digital sky catalogs and protein databases, but we can't read or think any faster than we could 100 years ago. We need a new way of dealing with it all—another technological revolution, if you will.

The computer revolution happened because there are explicit ways to translate a verbal concept—"let's add two numbers"—into a mathematical expression—"$x + y = z$"—that can then be turned into a series of logical operations by Boolean algebra. A mathematician and electrical engineer named Claude Shannon realized that any Boolean expression could be built as a set of wires and relays. From there to the Pentium is a bit of a technological leap, but today, with a few clicks of the mouse, you can specify what you want a chip to do and a computer will design it for you. "And that's why we can build things with a hundred million transistors," says Bruck. "What we are missing is the ability to go backward." Reverse-engineering things as diverse as nematodes and stock markets means bringing together people from many academic disciplines, which is a very Caltech thing to do. Bruck estimates that as many as one-quarter of the faculty will eventually participate in IST in some way.

A new building in which these folks can rub elbows will take shape soon. The international Office for Metropolitan Architecture (OMA), headed by Pritzker Prize–winner Rem Koolhaas of Seattle Public Library fame, has been chosen to design the Walter and Leonore Annenberg Center for Information Science and Technology, which will join the Gordon and Betty Moore Laboratory of Engineering on the south side of Avery Walk. Joshua Ramus, the partner in charge of the New York office, will direct the project. The building should be open for business in about three years.

To bring some structure to the initiative, it's organized into four new centers—the Center for the Mathematics of Information, the Center for the Physics of Information, the Center for Biological Circuit Design, and the Social and Information

IMAGE NOT LICENSED FOR WEB USE

George Boole
1815–1864

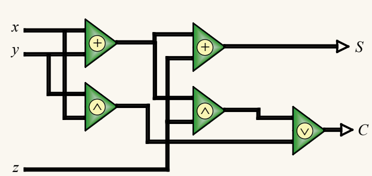
George Boole, professor of mathematics at Queen's College, Cork, Ireland, published his masterwork, *An Investigation of the Laws of Thought, on Which Are Founded the Mathematical Theories of Logic and Probabilities*, in 1854. He pointed out the analogy between algebraic equations and logical statements—for example, if x = *horned animals* and y = *sheep*, then $1 - x$ = *all things without horns* and $(1 - x)(1 - y)$ = *all things that are neither horned nor sheep*. This means that sets of logical statements can be manipulated using algebraic operations, in what is now known as Boolean algebra.

The next breakthrough happened almost a century later. In his master's thesis in electrical engineering, written at MIT in 1938, Claude Shannon showed how to build any Boolean expression as a circuit composed of relays, thus completing the set of rules for the explicit transformation from text to math to hardware. (Shannon, who had dual careers at Bell Labs and MIT, also established the fields of information theory and communication theory.) This work by Boole and Shannon led to the field of digital logic design, which is the theoretical foundation of the microprocessor revolution.

Courtesy of The History of Computing Project, www.thocp.net

Claude Shannon
1916–2001

Since any number can be rendered in binary form (ON or OFF, in electrical terms), this laid the groundwork for electronic math: The set of logical operations required to, for example, add two binary digits (0 + 0 = 0; 0 + 1 = 1; 1 + 1 = 10, send the 1 to the next adder to the left) could be encoded by a set of switches wired in the proper order. These logical operations are now commonly known as "gates"—the AND gate, the OR gate, the EXCLUSIVE OR or XOR gate (which outputs a 1 if either but not both of the two inputs are 1), and so on. The circuit for adding two one-digit binary numbers looks like this:



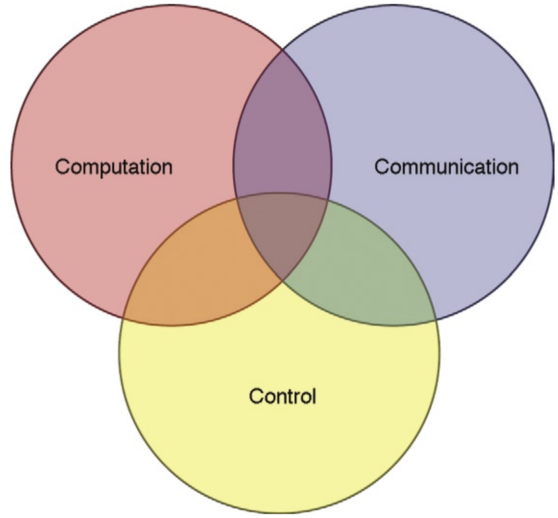
The green triangles are the logic gates—relays, transistors, or integrated circuitry; it doesn't matter. The + marks XOR gates, the Λ stands for AND gates, and the V is an OR gate. On the input side, x and y are the two numbers to be added, and z is the carry from the adder to the right. On the output side, S is the right-hand digit of the sum of $x + y$, and C is the carry to the next adder to the left.

The extrapolation to a Pentium is left to the reader as an exercise. □

Sciences Laboratory—and borrows from two existing ones: the Center for Neuromorphic Systems Engineering, and the Lee Center for Advanced Networking. Each new center attacks a basic question: Can we find an abstract mathematical description of information that applies across disciplines? What are the fundamental physical limits to information storage and processing? How does nature compute and communicate information? And how does information shape social systems?

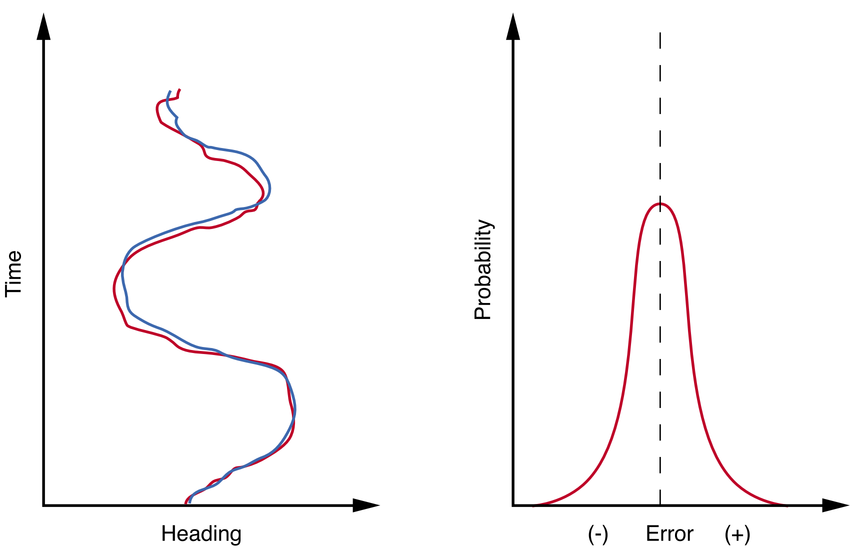
The Center for the Mathematics of Information (CMI) is trying to unify three branches of engineering: computation, communications, and control. Each field deals with a scarce resource. Communications theory tells you how much information can be reliably sent through a noisy channel of limited capacity, be it a fiber-optic data line, a radio signal from a distant spacecraft, or even a CD. "Storing stuff is a sort of communication from the present to the future," notes Leonard Schulman, associate professor of computer science and director of the center. The scarce resource here is bandwidth, or in the CD example, disk space. In control theory, the resource is real time—if your F-117 goes nose-down, a fly-by-wire system that takes five seconds to respond is going to leave a nice crater in the desert floor. And in computation, the resource is processing time: nobody likes to watch the waving Windows banner while a spreadsheet recalculates itself, and there are entire classes of useful problems that would take longer than the age of the universe for a computer to solve.

The CMI is charting the territory where these



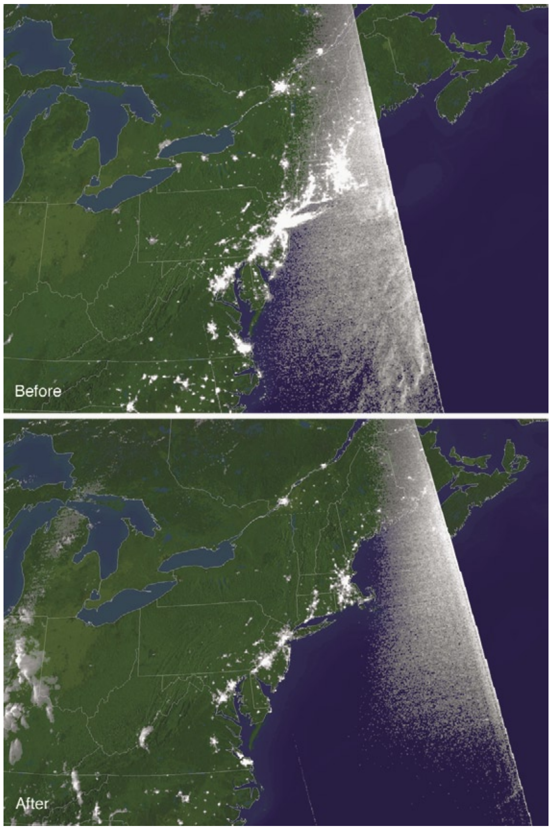
fields overlap. Take control and communication, for example. Says Schulman, "Suppose we're a couple of crazy teenagers. You're driving blindfolded on an abandoned road, and I'm sitting next to you giving instructions—'Less gas, turn right, turn *harder*.'" (Kids, don't try this at home! Leave it to the professional idiots on *Jackass*.) At five miles per hour, this works. But as the driver speeds up, "there's some maximum number of bits per second that we as humans are able to speak, and some minimum delay for us to comprehend what we've been told." The communication delay makes the control system unstable, crashing it literally as well as figuratively.

"That scenario was error-free," Schulman continues. "We're sitting two feet apart, and you can hear everything I say. But what if we've been drinking, which is why this probably seemed like a good idea, and the stereo is blasting heavy metal?" Now there'll be transmitter and receiver errors, and a noisy—in the engineering sense as well as the auditory one—channel between. The traditional communications-theory solution uses "block codes" or "convolutional codes" in which the accumulation of successive bits builds up a picture of what the original bit was supposed to be. But you can't retrieve that bit reliably until you've received a long block of code. That could take 20 or 30 rounds of communication, and by then, you'll be upside down in a ditch. What you'd like to do is abbreviate the messages—for example, instead of saying "change heading from 263 degrees to 262 degrees," which repeats a lot of information, just say, "-1." But that repetition helps suppress errors, and if you take it all out, errors accumulate and eventually you'll find that same ditch. So Schulman, Rafail Ostrovsky of UCLA, and Yuval Rabani of the Technion, the Israel Institute of Technology, devised a new class of error-correcting codes for control systems. "To do this, we needed error-correcting code theory, which everyone in electrical engineering knows, and something from combi-



When driving blindfolded with a buddy, the driver's course (red) will not follow the navigator's instructions (blue) with perfect accuracy, as shown above left. The trick is to keep the driver's tracking errors as small as possible, so that the probability of the error exceeding some acceptable limit is zero, as shown above right.

Top: This satellite image was taken at 9:21 p.m. EDT on August 13, 2003, the night before the blackout. Bottom: This one was shot at 9:03 p.m. during the outage. Local generators and other emergency systems kept the entire Northeast from plunging into total darkness, but cities including Cleveland, Detriot, New York, Ottawa, and Toronto were hard hit.



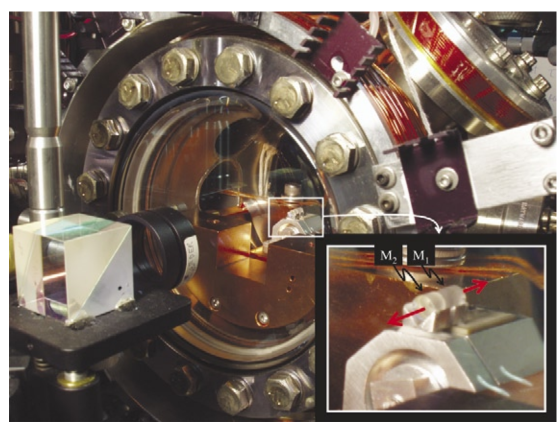
natorics called the Lovasz local lemma. It's a nice example of what can happen when you cross the lines between disciplines."

Similar gains can be made at the intersection of computation and control. The great blackout in the summer of 2003 was essentially a control breakdown, Schulman says. A relatively minor failure—one power line going out of service in Ohio—cascaded until 50,000,000 people in eight states and the province of Ontario were left in the dark. "It was a highly decentralized control system, and had they designed it properly, the outage would have been very localized. We are integrating systems that are much larger than used to be integrated, and we're pushing them much closer to their performance limits. That's what engineers do for a living, they try to get the most out of whatever hardware they've got. And in a system like that, the control mechanisms are gathering information—loads, temperatures, and such—from thousands and thousands of different sensors. Integrating all that data is a complicated computation."

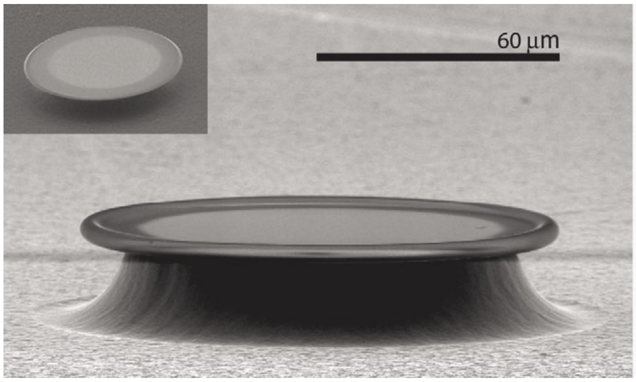
And in the intersection of computing and communication, you get problems such as how to keep the Internet from clogging up as more and more people use it. The way it works now, your files get sent through any available routers to their destination. It's like flying from Los Angeles to Portland, Maine—if you have to change planes in Philadelphia and the connection is tight, some of your bags may end up on other flights. But a new process called "joint coding" promises vastly increased network capacity at the expense of intensive computation at the routers. Essentially, everyone's luggage goes from curbside check-in to a wood chipper that purees it—socks, shampoo bottles, golf clubs, and all—and compacts the shredded material into space-saving bricks. Then, when the plane lands in Philly, all the baggage has to be reassembled (without mussing the neatly folded clothes!) so that the items actually bound for Pennsylvania can be fished out, and the rest goes into the chipper again.

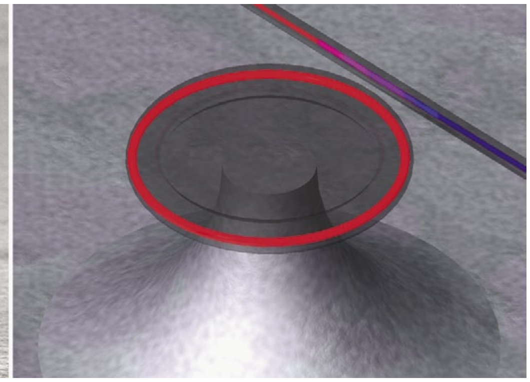
The CMI's eventual destination lies where all three fields converge and the really gnarly questions lurk, such as predicting how minor changes at individual computers will affect the global behavior of the Internet, and how to control that behavior if it's tending in the wrong direction. Says Schulman, "Engineering challenges of this magnitude can only be approached with good mathematical models. Until recently, models in computer science, electrical engineering, and control systems concentrated on the one constraint peculiar to their field. But integrating these enormous systems forces one to consider these problems as a whole. We are trying to develop the math to do that."

"Information" may be an abstract notion, says John Preskill, the MacArthur Professor of Theoretical Physics and director of the Center for the Physics of Information, "but in practice it always has some physical form. Whenever we strive to improve information technology, we are trying to find new physical processes." We'll need those processes pretty soon, because in the next few decades, our ability to miniaturize circuits in silicon will hit bottom. "Information technologies for the most part treat electrons and photons like they were basketballs," says Preskill. "You bat electrons around in a circuit, or send photons down a fiber and count them." But we're approaching the size where classical physics falters and quantum effects take over. This isn't necessarily bad—a lot of people have embraced quantum computing as the Next



The atom trap in Kimble's lab. The inset shows a close-up of the two mirrors (in the white box in the main photo), which are labeled M_1 and M_2. The red arrows show the path of the trapping laser.





Right: A scanning electron micrograph of one of Vahala's photon racetracks—the flared region around the rim of the mushroom's cap. Far right: An idealized representation of how a stored photon (red) could change the state of a passing photon (blue) in a fiber-optic line. In reality, the photon's color is one property that could NOT be changed, but it's easier to draw than, say, phase or polarization.

Big Thing, because by exploiting a system that is in all possible states at once until you measure it, "you can spectacularly accelerate the solution of a big class of problems."

But we're a long way from a quantum Pentium. People like postdocs Warwick Bowen and Tobias Kippenberg (MS '00, PhD '04) are still trying to build individual logic elements in which one photon changes the state of a second one—giving it a left-hand twist instead of a right-hand one, for example. The catch is that, unlike Jedi light sabers, photons pass through each other unhindered. They do interact weakly with atoms, however, providing a potential middleman, and Jeff Kimble, the Valentine Professor and professor of physics, greatly enhances this interaction by placing a single atom in the tiny void between near-perfect mirrors. A reverberating photon within this optical resonator smacks the levitated atom a million times or so, and, like a transistor, this turns a small signal into a big one. And Kerry Vahala (BS '80, MS '81, PhD '85), the Jenkins Professor of Information Science and Technology and professor of applied physics, builds ring-shaped silicon microstructures that store light—photon racetracks some 60 microns (millionths of a meter) in diameter and six microns thick—that sit on stalks like little silicon mushrooms. The cramped dimensions intensify the photon's electric field enormously, and Kimble's methods can be used to trap a single cesium atom within that field. The pumped-up field distorts the atom—enough, Bowen hopes, to some day affect passing photons one by one, providing a basic building block for the quantum Internet.

So much for quantum computing—what about computing quanta? "Information science is ripe to illuminate a lot of other fields," says Preskill. "What new insights can we get into physics? Information lost inside a black hole gets coughed up in the form of Hawking radiation, which is a quantum effect. I think the really juicy issues arise when we think about information confronting quantum physics."

Postdocs Frank Verstraete and Guifré Vidal have invented new methods for doing quantum many-body physics on classical, i.e., ordinary computers. This has been a burgeoning field for 30-some years as people try to simulate the behavior of materials that owe their properties to quantum effects—high-temperature superconductors, for example. Most simulations use the so-called Monte Carlo method, which generates random samples for statistical analysis. It's very straightforward—*if* you can ensure that the samples include a proportional representation of all the possible states of the system. A more sophisticated method called the Density Matrix Renormalization Group (don't ask) has been stalled since the early '90s, says Preskill. "People have had Moore's Law on their side, so there are bigger and bigger computers that can solve bigger and bigger problems, but the techniques have not advanced very much in 15 years. Verstraete and Vidal have made tremendous advances in six months, because they had a much deeper understanding of how information is carried by quantum systems."

Quantum entanglements affect all parts of a system at once, making them fiendishly difficult to simulate. There's no shorthand way to write down all the correlations and, says Verstraete, "Each particle doubles the size of the computation. So if 10 particles takes 10 minutes to run, 11 particles takes 20 minutes. The time increases exponentially." But there are degrees of entanglement, and most of the systems of real-world interest aren't Gordian knots. Says Verstraete, "Most of the correlations are redundant, so we found a way to compress the uninteresting ones and extract the very few numbers that tell you about the physical state of the system." "It's just an amazing achievement, and it's having a really big effect," says Preskill. Until now, people have mainly simulated ground states at zero temperature because modeling excited states—which is where all the action is—was just too difficult. But Verstraete and Vidal can track the dynamics of hundreds of atoms as an excited state is induced, peaks, and then decays.

Other center members are trying to figure out how to integrate photons into the silicon world, which won't fade away any time soon, and are looking at molecules, such as carbon nanotubes, that could be adapted for computing. But building complex machinery from molecule-sized parts is no cakewalk—how do you put all those tiny pieces in the right places? Nature uses a program encoded in the genes. Inspired by this, Senior Research Fellow Paul Rothemund (BS '94) and Assistant Professor of Computer Science and Computation and Neural Systems Erik Winfree (PhD '98) are making DNA "tiles" that spontaneously assemble into complex patterns based on information contained in the DNA. This raises some interesting questions about how information can be used to direct physical processes, Winfree says. "How can self-assembly be programmed to create a desired shape or pattern—such as a circuit layout for molecular electronics—and how can mistakes in self-assembly be controlled?" Like many faculty members, Winfree thus has a foot in two centers, the other one being the Center for Biological Circuit Design.

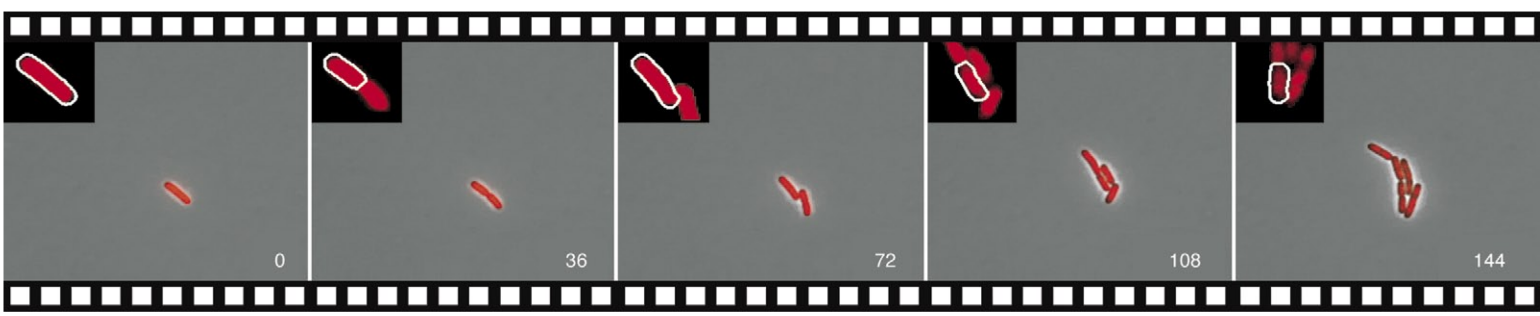
Cells do amazing things with seemingly slapdash components. The body heals broken bones and fights off diseases, and we walk around and we do crossword puzzles, all with flimsy, floppy protein molecules packed into cells that keep dying. There's nothing magical about the stuff we're made of, so clearly the miracles are in the circuits—broadly defined—that they're organized into. How do these circuits work? And what else can be done with the same components? Can we find Bruck's "calculus" for biology, and will it ultimately lead to a software package that will accept a high-level design and spit out the genes that will automatically grow that circuit?

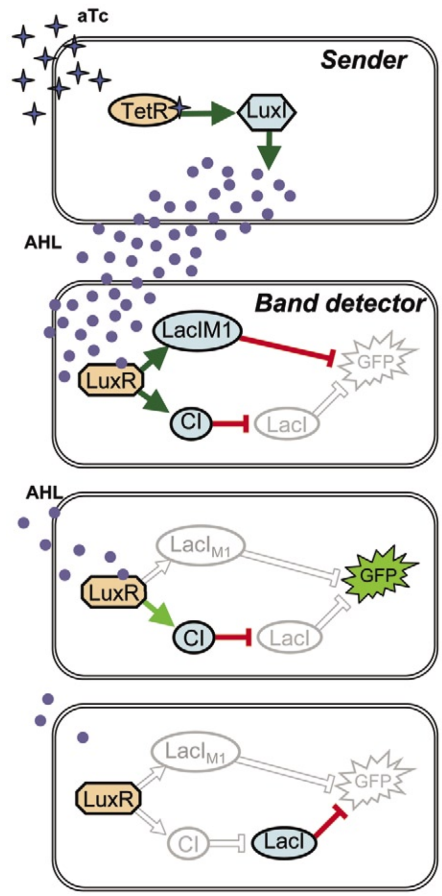
The goal of the Center for Biological Circuit Design (CBCD), says Paul Sternberg, Morgan Professor of Biology, investigator, Howard Hughes Medical Institute, and director of the center, "is to learn about biological circuits by trying to build them." Fortunately, a huge catalog of parts is available—every protein or regulatory network that has ever been published. There are actually three nested levels of circuitry, says Sternberg: networks of signaling molecules within a cell that handle such things as regulating metabolism or allowing an amoeba to find and engulf its prey; circuits consisting of several cells, such as the ones that coordinate our defense against infection; and the vast neuronal circuits that are responsible for, say, understanding speech. The CBCD will initially tackle the first two, leaving the brain to the ganglion of neuroscientists on campus. Says Sternberg, "The whole point of IST is to try to abstract what's general. And here, in terms of circuits, we believe that the general principles will apply across different levels." By biological standards, the human brain with its 20 to 50 billion cerebral-cortex neurons is only middlingly complex—a protein molecule can have 10 thousand atoms, a cell can contain a billion macromolecules, and the heftier *E&S* reader might consist of up to 100 trillion cells. That's 27 orders of magnitude of organization from an atom to a person, which is like going from the diameter of an atom to the distance to Sirius.

On the intracellular level, Assistant Professor of Biology and Applied Physics Michael Elowitz is examining "primitives"—basic functions that show up pretty much everywhere. One really basic function is gene regulation, in which turning on one gene produces a protein called a transcription factor that turns another gene on or off, stimulating or suppressing the production of *its* protein, which may in turn be another transcription factor, and so on. Elowitz, Caltech staff member Jonathan Young, Nitzan Rosenfeld and Uri Alon from the Weizmann Institute of Science in Rehovot, Israel, and Peter Swain from McGill University have been tracking the concentration of a specific transcription factor (fluorescently tagged to light up yellow) and the protein that it regulates (tagged to light up cyan) in a single *E. coli* bacterium through many cycles of cell division. The idea was to see how noise in the regulatory circuit—the randomness of biochemical reactions in the face of many competing processes, differences in the cell's environment, and the state of the cell itself—affected the circuit's performance. Elowitz calls it "popcorn biochemistry" because "we can determine how biochemical parameters vary from cell to cell, or in a single cell over time, just by watching movies of these cells." The study showed that gene regulation embodies a fundamental trade-off between speed and accuracy, Elowitz says. "If you want a cellular circuit to really accurately control the level of a transcription factor, it would take a very long time." In real life, speed is usually more important.

On the cellular level, Frances Arnold, the Dickinson Professor of Chemical Engineering and Biochemistry, grad student Cynthia Collins, and Ron Weiss, Subhayu Basu, and Yoram Gerchman at Princeton have developed circuits in which sender cells emit a tracer molecule called acyl-homoserine lactone, or AHL, which the surrounding bacteria detect. Each bacterium has been bred to respond

Below: A "movie" of one of Elowitz's fluorescent bacteria as it divides and becomes a colony. For greater contrast, the yellow-fluorescing cells have been colored red, and the cyan ones green. The insets show the original bacterium outlined in white. The numbers are elapsed time in minutes.





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A schematic of Arnold's cellular band-pass filter. The sender cell emits molecules of ALH (purple dots) that diffuse evenly out in all directions, so detector cells at greater distances get diminishing doses. At close range, the ALH receptor protein (LuxR) turns on both the $LacI_{MI}$ and the CI proteins (green arrows). The $LacI_{MI}$ protein inhibits (red T-bar) the production of Green Fluorescent Protein (GFP), trumping the CI protein that inhibits the production of another protein called LacI that in turn inhibits the production of GFP. At intermediate ALH concentrations, not enough Lac_{MI} is produced to shut down GFP production, but CI still inhibits the other inhibitor. This causes the cell to light up. At still lower ALH levels, CI turns off too, freeing the LacI protein to shut down GFP production. Got all that? And this is a very simple regulatory scheme, as these things go. . . .

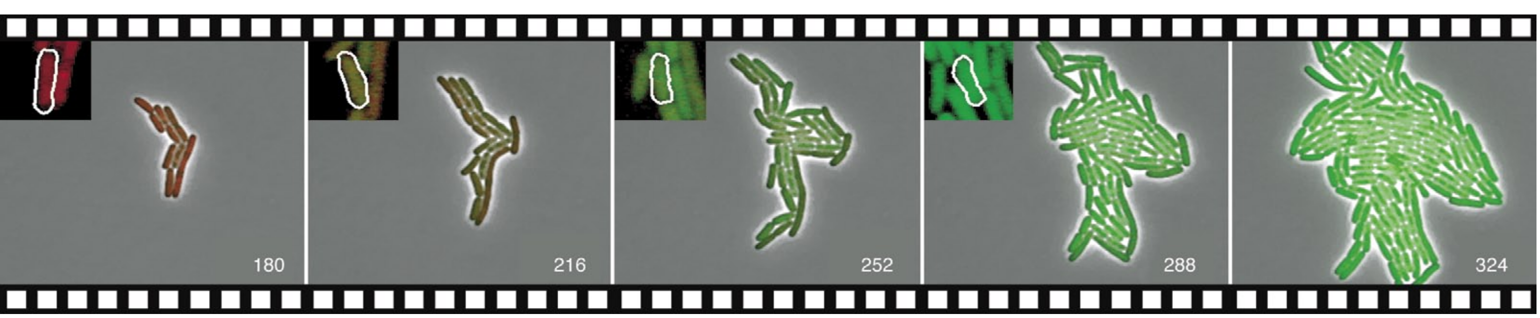
to AHL at a specific concentration—the cellular equivalent of a band-pass filter—and when it does, it turns on a fluorescent gene that makes it glow. "It's a little model of how organisms develop," says Arnold. "The cells communicate via AHL and turn on different genes. In this case, it creates a bull's-eye pattern in a homogeneous lawn of bacteria." Taken to its logical conclusion, this ability to lay down a gene-expression pattern of your choosing gives you a way to grow complex structures, maybe even molecular computers, automatically. Or the bacteria could be used as sensors by adapting them to recognize other substances—a whiff of TNT in a suitcase, perhaps. And since much of biology these days has to do with tracing signals carried by very rare proteins, a sensor with a big, easy-to-read signal could be a biotech bonanza. But more importantly, says Arnold, "we demonstrated that you can cobble together all these weird pieces from various organisms to make a human-designed system that does something nature doesn't do."

Sternberg sees biological computation not for general-purpose processors (at least, not any time soon!), but for embedded control "chips" to manage other microbes. "Even if they're slow, and don't do your taxes, they could run a little ecosystem on Mars that makes sugar. That's been in science fiction for decades." Assuming that we can fill a spaceship with modified pond scum from the lakes that lie beneath Antarctica's ice fields and send it to Mars, it could arrive months or years before the astronauts do, and a maintenance-free biological controller would be handy. Closer to home, one could foresee bioreactors—brewer's vats—in which kidneys, hearts, and other transplantable organs are grown. The biosensor cells would make sure that the right growth factors kick in at the proper times to form healthy organs. Or, to really get down to earth, these supervisory cells could run insulin-adjusting implants for diabetics.

Says Sternberg, "In 10 years, I think there will be a new technology of circuit design. There will be components, and circuits, and people will be using them. We're still in the days of making computers that fill a room and can add a couple of two-digit numbers—in fact, we're not quite even there yet. We're just trying to get *anything* to work." It helps that the CBCD houses people who are building artificial circuits and people who are reverse-engineering real ones. "Now we say, 'This cell has switchlike behavior—what mechanism is it using?' It would be nice if you could say, 'Well, there are four different ways that cells usually do that.' It would be even better if you could say, 'Well, there's one way that they usually do it, let's go test that one first.'"

The theoretical underpinnings will emerge naturally, Sternberg thinks. "The word on the street is that biology doesn't have that many abstractions. We want to generalize from special cases, lumping phenomena into mechanisms, and lumping mechanisms into variations of the same mechanism. And another good thing about IST is that our nonbiologist colleagues insist on abstractions. They're not going to listen to 20 hours of special cases. So they push us, push us, push us, and we'll get there faster."

Then there's the ultimate information-processing system—humanity en masse. Each of us as individuals holds little nuggets of information—some



of it incorrect, some of it opinion—that somehow produces a computational result, be it a stock price or a new president. The Social and Information Sciences Laboratory (SISL, pronounced "Sizzle"), directed by Matthew Jackson, the Wasserman Professor of Economics, looks at existing social and economic institutions to see how they work, and attempts to apply these insights to the design of new ones.

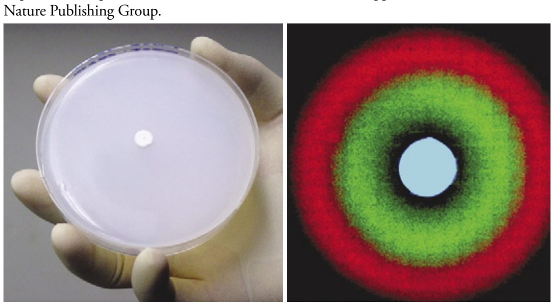
Some kinds of information flow are quite subtle. "Statistically, over a broad range of professions, more than 50 percent of people find jobs through social contacts," says Jackson. So forget the want ads and Monster.com—the more friends you have, and the better placed they are, the better your access to jobs. Conversely, if all your friends are unemployed, you're in a classic negative-feedback loop and you might as well stay in bed. "While labor economists have worked for a long time to explain why there are pockets of unemployment, there's a lot we don't know. Now we can begin to try to model these geographic patterns, and other socioeconomic patterns. Different social networks have different properties, and networks differ across societies and ethnic groups." Ultimately, Jackson hopes to be able to figure out what kinds of policies would help people trapped in the wrong sorts of networks.

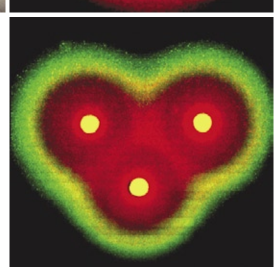
SISL melds engineering analyses and studies of human behavior, says Jackson. "For instance, in economics, we've always assumed that people can handle an auction protocol where you might have to bid on a large number of items at once. Say you're bidding on broadcast-frequency licenses for cell phones from the FCC, and you're thinking, 'Well, I really want the license in Los Angeles only if I can also get the license in Riverside, so if my Riverside bid isn't going well I want to drop out of the L.A. auction, but if I drop out there, do I want to get the San Francisco license instead?' Computing your optimum bid is a very complicated problem." So postdoc Ron Lavi has been using techniques from his computer-science background to develop multi-object auctions that people can actually use without their brains exploding. And economists traditionally deal with equilibria, that is, the final prices of things, says Jackson. "With all the information we have about markets, we still don't understand price formation. We know what equilibria look like, but how you get there, and *when* you get there, or *if* you get there, remains a mystery." But engineers are used to systems in motion, so postdocs Sean Crockett, an economist, and Tudor Stoenescu, an electrical engineer, are trying to apply engineering methods to track the forces at work in the marketplace.

In a similar vein, John Ledyard, the Davis Professor of Economics and Social Sciences; Richard Murray (BS '85), professor of mechanical engineering; and Mani Chandy, the Ramo Professor and professor of computer science are looking at electricity markets. Part of the project involves experiments in Caltech's Social Sciences Experimental Laboratory, in which subjects play the parts of the various utilities, consumers, network operators, and so on. The idea is to blend economics and engineering to design better distributed control systems without having to run a full-scale experiment on the state of California, as we did a few years ago. Says Ledyard, "Most analyses of power grids—both economic and engineering studies—rely on equilibria, which do not provide much insight into robust control."

These new centers join the Center for Neuromorphic Systems Engineering (CNSE) and the Lee Center for Advanced Networking, which served as a model for them. For years these two centers have been drawing faculty from across campus to work on problems that lie in the cracks between disciplines, and supporting studies that are hard to get funded through traditional means.

"Everything we do in CNSE is IST-related," says director Pietro Perona, professor of electrical engineering. "We take neurobiological principles and use them in engineered systems, and use engineering expertise to try to understand the brain." The center hopes to one day build autonomous intelligent machines. This may summon up visions of heroic robots rescuing little girls from burning buildings (or evil robots for global domination, depending on your predilections), but the reality is much more mundane. "Right now you have lots of machines around you—your car, your washing machine, your telephone. Many of them have microprocessors, and memory, and sensors, so they *could* figure stuff out about the world, but we don't know how to do it," Perona says. A high-end digital camera could learn to locate all the human faces in the viewfinder, for instance, and meter off of them instead of the bookshelves that hap-





Clockwise, from above: 1) A petri dish with the sender colony visible in the middle. 2) An experiment with two strains of sensor cells that have been tuned to different concentrations and fluoresce in different colors. 3) Additional sender colonies make more complex patterns possible.

Your cell phone is part of an electronic network, and the people in your cell phone's phone book are part of a social network. Are they governed by the same mathematics?

PICTURE CREDITS:
6-7 – Erik Jorgensen; 9, 15 – Doug Cummings; 10 – NOAA/DMSP, Jeff Kimble; 11 – Deniz Armani; 12-13 – Jonathan Young & Michael Elowitz

pen to be in the center of the frame. Then, if the camera were told by your computer that you tend to brighten your pictures in Photoshop, it could even learn your preferences. "Machines now are sitting lumps of matter, and we have to turn knobs, or read manuals that train us how to use menus. We work for the machine in some way, which is paradoxical since the machine should help us," he added as he fiddled with a webcam trained out his office window. Despite his ministrations, the cam resolutely adjusted its exposure to the shadows of the foreground arcade, washing out the vista beyond. "There is no reason why we cannot design docile behavior in machines."

And finally, the Lee Center was founded in 1999 by Caltech trustee David Lee (PhD '74) to create the technology needed for a global wireless and fiber-optic communication system that would be as ubiquitous and reliable as indoor plumbing. It was the first big center at Caltech to be privately funded, says director David Rutledge, the Tomiyasu Professor of Electrical Engineering and associate director of IST, and "it opened our eyes to a different kind of flexibility. David Lee wanted us to start a lot of small projects, so we fund 13 faculty members, and they decide what to do. When people follow what they are interested in, it often leads to quite new things." Indeed, the Lee Center has been a fruitful source of start-ups and spin-offs, which "suggested that we think about a bigger, much more ambitious project, which is IST." Lee also had the radical notion of funding the center for 10 years, period, on the logic that by then we'd either have solved the networking problems it was set up to address or we'd quit throwing good money after bad.

IST is taking a leaf from Lee's book—its four founding centers expire a decade from inception and new ones will take their places, ensuring a steady supply of fresh ideas. For the same reason, most of IST's seed money from the Gordon and Betty Moore Foundation is going into graduate students and postdocs. Says Preskill, "We're trying to attract exceptionally bright people at the peak of inventiveness in their careers, and see if something exciting will happen." Sternberg agrees, saying, "The postdocs are running around campus, coming up with ideas, and instigating things, and that's the glue that holds us together. Someone says, how about building this, and someone else says, you know, I've always wanted to try that. Now a lot of those projects will actually get implemented, which is the leverage that we really want." IST hired 23 postdocs last fall, and Bruck notes that a couple of them deferred faculty positions for a year in order to come. The initiative is also hiring several junior faculty members, the first of whom, Assistant Professor of Electrical Engineering and Computer Science Tracey Ho, will arrive this fall to work on joint network codes with Professor of Electrical Engineering Michelle Effros.

Setting up multidisciplinary research programs is the easy part. IST should also define a curriculum for this emerging discipline, says Bruck. Some of the core courses already exist—Boolean algebra, probability theory, and the like—but they haven't coalesced into a logical sequence, and new classes will be needed to fill in the gaps. "What should we teach? How do we integrate research into basic classes at the freshman level? That's still not clear. I wish we could have a Feynman's *Lectures on Physics* on information. Physics was the way to educate the generalists of the Industrial Age, and it was extremely successful. Electrical engineering and computer science emerged out of physics. But now we need to educate the generalists for the Information Age."

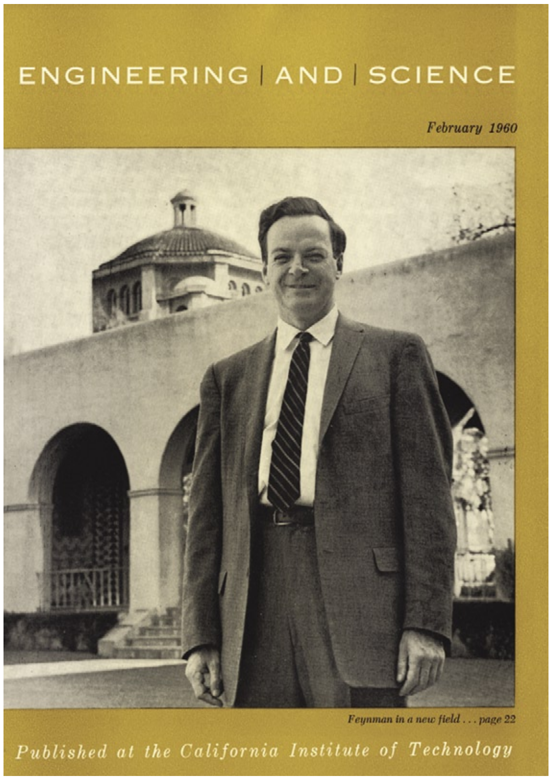
It's starting to happen. In 2002, Assistant Professor of Computer Science Andre DeHon and Winfree launched the Computing Beyond Silicon Summer School, which exposes a select group of undergrads from across the country to the emerging fields of bio-, molecular, and quantum computing. Last year Murray, Elowitz, and Assistant Professor of Chemical Engineering Christina Smolke did a SURF summer school on synthetic biology, which is what the art of growing logic elements and circuits in bacteria is called. And Chandy and Ledyard are teaching an upper-level undergrad course at the intersection of economics, game theory, and computer science. The class looks at "networks of systems that integrate markets with physical constraints," says Ledyard, who goes on to note that this includes health-care systems as well as power grids.

Says Bruck, "In time, I think 'information' will be a first-order concept. So in 20 years, if a high-school student asks her friend, 'Do you like information?' like, 'Do you like algebra?' the other girl will say 'Yes,' or 'No,' or 'Yes, but I hate the teacher.' But the other day I asked my daughter, a high-school junior, 'Do you like information?' and she said, '*What?!!*'" □

Does nanotechnology descend from Richard Feynman's 1959 talk?

Apostolic Succession

by Chris Toumey



Behind this cover lies "Plenty of Room at the Bottom," the article that launched nanotechnology—or did it?

As histories and mythologies of nanotechnology are created, and people try to establish which events and people were more important than others, one question arises repeatedly: how influential was Caltech physicist and Nobel Laureate Richard Feynman's 1959 talk, "There's Plenty of Room at the Bottom," which first appeared in print in the February 1960 issue of this very magazine? The article was, among other things, a vivid description of a precise science of manipulating matter at the molecular and atomic levels. It predates certain very important events like the invention of the scanning tunneling microscope, and it is frequently described as the text that instigated nanotechnology. In the words of noted futurist K. Eric Drexler, "The revolutionary Feynman vision . . . launched the global nanotechnology race." James Gleick, in his bestselling biography *Genius: The Life and Science of Richard Feynman*, says that "nanotechnologists . . . thought of Feynman as their spiritual father." The National Nanotechnology Initiative's glossy brochure reminds us that "one of the first to articulate a future rife with nanotechnology was Richard Feynman." His paper "has become one of 20th-century science's classic lectures. . . . It has also become part of the nanotechnology community's founding liturgy." And, in the January 2000 speech at Caltech that unveiled the initiative, President Clinton paid homage, saying "Caltech is no stranger to the idea of nanotechnology. . . . Over forty years ago, Caltech's own Richard Feynman asked, 'What would happen if we could arrange the atoms, one by one, the way we want them?'"

Actually, all of these statements except Drexler's are devilishly subtle. Careful reading shows that they do not claim unequivocally that "Plenty of Room" launched nanotechnology. Instead, they affirm that it is widely *believed* that Feynman's paper instigated nanotech, which then lets the reader infer that this was so. If a person thinks that nanotech began with "Plenty of Room," then later developments can be retroactively appreci-

President Clinton burnishes the Feynman mystique before a standing-room-only crowd in Caltech's Beckman Auditorium on January 21, 2000. Gordon Moore (PhD '54), chair of the Board of Trustees, and Caltech president David Baltimore look on.

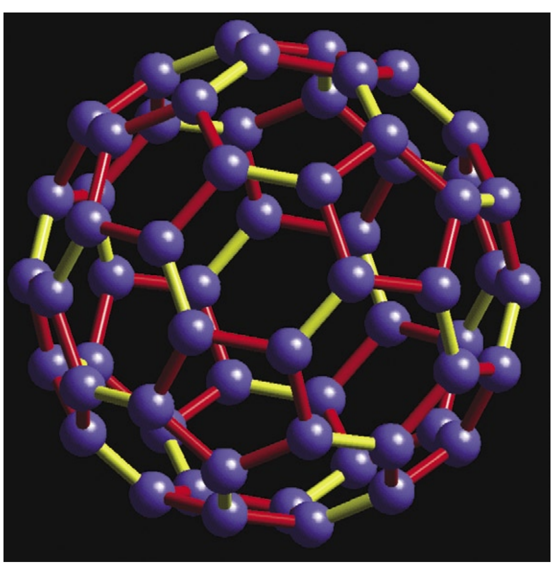
ated as fulfillments of Feynman's vision, which is to say that certain important people might *not* have thought what they thought, and might *not* have done what they did, if he had not bequeathed it to us. I think of this as a question of apostolic succession: did Feynman set the intellectual parameters of nanotechnology in "Plenty of Room" in such a way that those who came after him have traced their own legitimacy to that text by consciously and deliberately executing his vision? We can also ask about Feynman's follow-up talk, "Infinitesimal Machinery," published posthumously in the *Journal of Microelectromechanical Systems* in 1993. If "Plenty of Room" was the text that instigated nanotech, then "Infinitesimal Machinery" was a kind of Deuteronomy that restated the vision and elaborated it. But if "Plenty of Room" had little or no inspirational value, and if "Infinitesimal Machinery" had even less, then we are steered into a different history. Even though Feynman's 1959 talk *preceded* many important developments, it was irrelevant to them. Instead of an apostolic succession of nano-thought, we would see that important events and ideas arose independently of Feynman's vision.

This reminds me of the case of Gregor Mendel. No one denies that Mendel discovered the principles of genetics before anyone else, or that he published his findings in a scientific journal. But Caltech Nobelist Thomas Hunt Morgan and others later rediscovered those principles on their own, without being influenced by Mendel's work, or even being aware of him. Mendel deserves credit for priority, but that ought not to be overinterpreted as directly inspiring or influencing the later geneticists.

A related question concerns Drexler's legacy, particularly his 1981 paper, "Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation," in the *Proceedings of the National Academy of Sciences* (*PNAS*). Drexler has insisted that the core of Feynman's vision was the large-scale precision manipulation and combination of atoms and molecules (now called molecular manufacturing), and he adamantly suggests that he himself continues the rightful essence of that vision. Feynman said, "I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously, drilling holes, stamping parts, and so on." What could be more Drexlerian? In Drexler's view, the term "nanotechnology" has been debased by other, nonmanufacturing activities, and, consequently it is urgent to return to the essence of Feynman's vision. Or, if you like, Drexler's understanding of Feynman's vision.

Almost everyone would agree that Drexler's work as a popularizer, especially his 1986 book, *Engines of Creation*, has caused large numbers of people to become interested in nanotechnology. I have no reason to challenge this. Instead, I ask whether Feynman's influence had a secondary amplification through Drexler. After all, Drexler reminds audiences that his technical publications, beginning with "Molecular Manufacturing," demonstrate that he is more than a popularizer.

This question is interesting in light of the bitter exchange between Drexler and Richard Smalley in December 2003. In *Nano: The Emerging Science of Nanotechnology: Remaking the World—Molecule by Molecule*, Ed Regis writes that Smalley used to describe himself as "a fan of Eric" and that he distributed copies of Drexler's books to influential decision-makers at Rice University. In the special issue of *Chemical & Engineering News* that car-



Richard Smalley shared the chemistry Nobel for the 1985 discovery of fullerenes—more properly, "buckminsterfullerenes," for the inventor of the geodesic dome—a form of carbon in which the atoms form tiny spheres or ellipsoids. The C_{60} molecule shown here has the same symmetry as a soccer ball. Fullerenes can be built into bigger structures, doped with metals to become magnets or superconductors, and can do all kinds of things nanotechnologists might want to do.

ried the Drexler-Smalley debate, Smalley vehemently disagreed with Drexler and poured loads of contempt on him, but explicitly acknowledged that *Engines of Creation* had caused him to take an active interest in nanotechnology. This eventually resulted in Smalley's 1996 Nobel Prize in Chemistry (with Robert Curl and Harold Kroto) for the discovery of fullerenes. So if Drexler directly inspired one important scientist in nanotechnology, could he have also influenced others?

At this point we have a set of hypotheses:

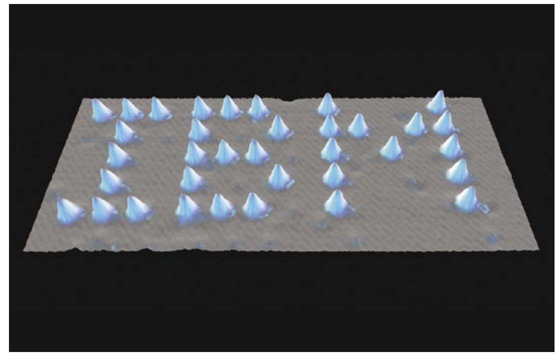
1. That "Plenty of Room" directly inspired important nanoscientists, and that this inspiration is evident in important scientific developments;
2. That "Infinitesimal Machinery" amplified the importance of that inspiration;
3. That "Molecular Engineering" directly inspired further important scientific developments, thereby continuing and multiplying Feynman's influence.

Popular Science ran a cute condensed version called "How to Make an Automobile Smaller Than This Dot" in November [1960] . . . "Plenty of Room" was also mentioned in *Science News* and *Life* in 1960.

Here I need to be more specific about "important scientific developments." There are thousands of scientific publications about nanotechnology, a large number of patents, and several Nobel Prizes. We could argue endlessly about which developments were most important. I've selected three: the invention of the scanning tunneling microscope (STM), the invention of the atomic force microscope (AFM), and the first manipulation of individual atoms using STM. These three events occurred well after the publication of "Plenty of Room." Gerd Binnig and Heinrich Rohrer (who shared the Nobel Prize in Physics in 1986) filed their STM patent in September 1980, but the other two events happened after the publication of "Molecular Engineering," in 1986 and 1990, respectively. Can we find evidence of either Feynman's or Drexler's influence in these developments? I have two principal sources of information for pursuing this question—a citation history from the *Science Citation Index* for "Plenty of Room," "Infinitesimal Machinery," and "Molecular Manufacturing;" and a series of comments I solicited from the scientists involved. I will start by examining Feynman's influence.

"Plenty Of Room," "Infinitesimal Machinery"

On December 29, 1959, Richard P. Feynman gave the talk at a meeting at Caltech of the American Physical Society. He presented a vision of the



precise manipulation of atoms and molecules so as to achieve amazing advances in information technology, mechanical devices, medical devices, and other areas. Attendee Paul Shlichta (PhD '56), then of Caltech's Jet Propulsion Laboratory, later said, "The general reaction was amusement. Most of the audience thought he was trying to be funny. . . . It simply took everybody completely by surprise." *Engineering & Science* printed a transcript in its February 1960 issue with the subtitle "An Invitation to Enter a New Field of Physics." *Saturday Review* ran a synopsis that April with the title "The Wonders That Await a Micro-Microscope," and *Popular Science* ran a cute condensed version called "How to Make an Automobile Smaller Than This Dot" in November. This article had a few comments that had not been in *E&S*, but it retained the heart of Feynman's argument. "Plenty of Room" was also mentioned in *Science News* and *Life* in 1960, and appeared in 1961 as the final essay, without the subtitle, in a volume titled *Miniaturization*, edited by Horace Gilbert.

Feynman spoke again on the topic of atomic-level miniaturization at the Jet Propulsion Lab on February 23, 1983. This talk was titled "Infinitesimal Machinery," and he explicitly described it as "There's Plenty of Room at the Bottom, Revisited." He reaffirmed his original views, and he elaborated on the methods and applications he had discussed 23 years earlier. Videotapes of this talk are available through the Caltech Archives.

Richard Feynman passed away in 1988. Subsequently, "Plenty of Room" began to reappear in books and journals. *Science* ran a one-page excerpt in its November 1991 special issue on nanotechnology, crediting *E&S* for permission to reprint. The next year, the *Journal of Microelectromechanical Systems* republished "Plenty of Room," with no subtitle, in its inaugural issue. It alluded to the *Miniaturization* volume as its source, but gave a date of December 26 for the original talk. (This is almost certainly a typographical error, since both the *E&S* and *Miniaturization* texts, and every other source I am aware of, had given the date as December 29.) Also in 1992, the proceedings of a Foresight Institute conference included "Plenty of Room" as an appendix, with the original subtitle, and derived the text from *E&S*. (Drexler founded the Foresight Institute, and remains chair

Opposite: Don Eigler and Erhard Schweizer of IBM's Almaden Research Center made nanotech history when they wrote their employer's name in xenon atoms on a nickel surface, using the weak attractive forces between the atoms in the STM needle's tip and the xenon atoms to nudge them into position. Their paper was published in *Nature* on April 5, 1990.

of its board of advisors.) In 1999, Jeffrey Robbins included "Plenty of Room" in his collection of Feynman's short papers, and Anthony J. G. Hey made it a part of his volume of Feynman's work on computation. It is also available at several websites at Caltech and elsewhere, including Zyvex and the National Nanotechnology Initiative.

"Infinitesimal Machinery" was published in the *Journal of Microelectromechanical Systems* in 1993, 10 years after Feynman delivered the talk. As best I can tell, this was the only hard-copy publication. It is not mentioned in the leading Feynman biographies by Gleick and Jagdish Mehra (*The Beat of a Different Drum: The Life and Science of Richard Feynman*), both of which have short chapters on "Plenty of Room." In fact, Gleick wrote that "Feynman . . . never returned to the subject," indicating that he was unaware of the 1983 talk. "Infinitesimal Machinery" is likewise invisible in the various collections of Feynman papers.

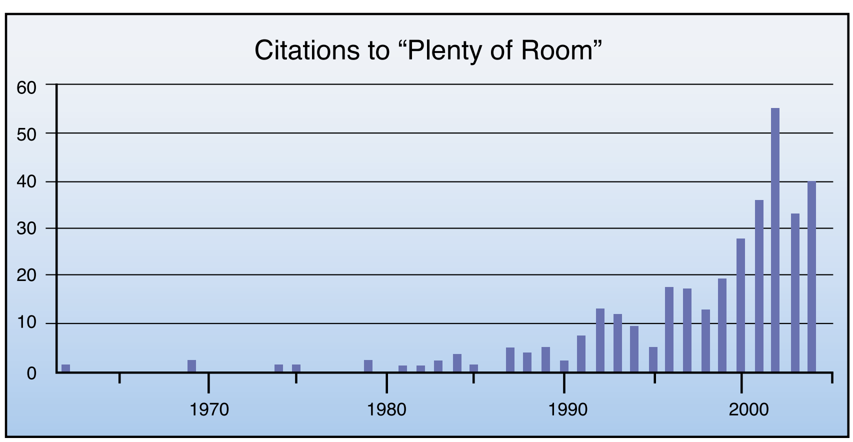
To assess the historical importance of "Plenty of Room" and "Infinitesimal Machinery," I did a citation search on each in ISI's *Science Citation Index*, with a supplemental search in *Dialog*, in November 2004. My assumption was that the frequency with which they were mentioned in scientific journals would give a measure of how influential they were. The period of 1980 through 1990 was especially important because this was when Binnig and Rohrer invented the STM, Binnig invented the AFM (with assistance from Calvin Quate and Christoph Gerber), and Don Eigler and Erhard Schweizer first manipulated individual atoms with an STM.

Citation tracing is an inexact science. In the hard copies of the *Science Citation Index*, from the days before electronic search engines became available, Feynman's name is sometimes spelled correctly, and sometimes not: Feynman, Feynmann, Feymnan, Feyman, and so on. There are also multiple ways to indicate his initials—R, RP, P, and no initials at all. Presumably these variations represent typographical errors in the citations, which the *Index* reproduced faithfully without editorial emendation. In the electronic version, the *E&S* text is listed four different ways, even though all four are obviously the same publication. (The *Dialog* search overlaps both the hard-copy and electronic versions of the *Science Citation Index*, but provides slightly different results.) A further complication is that the ISI database changes from time to time, as the editors add new journals and drop others. They follow a principle they call Bradford's law, which states that "the core literature of any given scientific discipline . . . [is] composed of fewer than 1000 journals." But this core shifts over time, so a search across four decades does not necessarily scan the same periodicals every year. The data are certainly incomplete to some degree, so we should consider them an approximation—expecting a perfect record is unrealistic.

My search began with the texts from *E&S* in 1960 and *Miniaturization* in 1961, since these were the only ones that preceded my "big three" developments in nanotech. I also searched for the two 1992 republications in the *Journal of Microelectromechanical Systems* and the Foresight volume. (The texts in the two 1999 collections edited by Robbins and Hey cannot be distinguished from the rest of the contents of those books in a citation search.) Later I discovered that some authors give a date of 1959 when they cite "Plenty of Room," thus referring to the original talk, not the initial publication.

I found a total of three citations in the 1960s, and four in the 1970s—a scant record in the two decades before the arrival of the STM and the AFM. These early citations present a variety of ways of reading Feynman. The first, in a 1962 *Science* article by John Platt, enthusiastically endorsed Feynman's point that "recent advances in physics and chemistry" make it possible to build better electron microscopes for biology. Platt then called for a national laboratory for biological instrumentation. Articles by Robert Keyes in 1969 and 1975 and Joseph Yater in 1979 and 1982 discussed ongoing work to make faster, better computers. Their references to Feynman amounted to brief, generic statements that improvements are possible. Marvin Freiser and Paul Marcus also addressed information technology in a 1969 piece,

Citations to "Plenty of Room" in scientific journals were pretty sparse in those years, however.



Bill Joy, in the April 2000 issue of *Wired*, raised the fear of self-replicating nanobots ("Why the Future Doesn't Need Us," which could also be called "There's Plenty of Gloom and Doom at the Bottom").

but were extremely skeptical of Feynman's suggestion of using individual atoms as storage units: "Such speculations appear to be completely vacuous so far as the real world is concerned."

Finally, in 1979, James Krumhansl and Yoh-Han Pao used "Plenty of Room" as a touchstone for evaluating and appreciating "microscience," as they called it: "In the past twenty years there has been an explosive growth in 'microscience,' in exploring that room at the bottom Feynman mentioned." As they took the reader through their article, which introduced a special issue of *Physics Today*, they occasionally pointed to passages from "Plenty of Room" that anticipated exciting developments, thereby using Feynman's paper as a loose frame of reference for understanding "microscience."

Eric Drexler told me by e-mail that "I [first] encountered a mention of 'There's Plenty of Room at the Bottom' in *Physics Today* while researching references for my 1981 *PNAS* ['Molecular Engineering'] article." Then, "We [Drexler and Feynman] met once, when his son, Carl, brought him to a party in my apartment in Cambridge in 1981. We discussed the implications of the paper, taking the soundness of the basic ideas for granted." Drexler cited the 1961 *Miniaturization* text in "Molecular Engineering" because that was the one Krumhansl and Pao had credited.

References to "Plenty of Room" did not get into double digits in any given year until 1992. From 1996 onward, the citations remain consistently in double digits, and they usually increase from year to year. The 1992 republications in the *Journal of Microelectromechanical Systems* and the Foresight volume increased access to "Plenty of Room." Citations to these two represent 16.1 percent of all citations from 1993 through November 2004, with the former accounting for most of the increase.

I found a total of two citations for "Infinitesimal Machinery"—one from 1997, and another from 1998.

I then asked the men behind my "big three" whether "Plenty of Room" had inspired or influenced their work, when they first heard of it, and some related questions. I received replies from Binnig, Rohrer, Quate, and Eigler. These nanoluminaries, as I call them, said uniformly that it had no influence.

Rohrer said, "Binnig and I neither heard of Feynman's paper until Scanning Tunneling Microscopy was widely accepted in the scientific community a couple of years after our first publication, nor did any referee of our papers ever refer to it. . . . It might have been even after the Nobel." Binnig stated that "I have not read [it] . . . I personally admire Feynman and his work but for other reasons than for his work on nanotechnology (which actually does not exist) [Binnig's parentheses]. I believe people who push too much his contribution to this field do harm to his reputation. His contribution to science is certainly not minor and he needs not to be lifted . . . [posthumously] onto the train of nanotechnology." They did briefly mention "Plenty of Room" at the end of a 1987 account of their work, but it is clear that they were speculating about the future, rather than crediting Feynman for influencing the process of invention. Feynman's paper is absent in the references in the U.S. patents for the STM and the AFM.

Quate wrote that "None of [AFM] derived from the publications of Feynman. I had not read the Feynman article and I don't think Binnig or Rohrer had read it. All they wanted was a better method for examining microdefects in oxides."

Eigler had a different experience. He had read Feynman's paper before his famous manipulation of xenon atoms: "I can not say for certain, but I believe I read, or came to be aware of 'There's Plenty of Room' in the late 1970's or early 1980's while I was a graduate student. I know for a fact that I had read it a long time before first manipulating atoms with the STM. The reason I say this is because, within weeks of manipulating atoms for the first time, I went back to dig up Feynman's paper. When I started reading the paper, I realized that I had read it a long time before." Nevertheless, he continued, "The technical aspects of my work have not been influenced by Feynman's paper." When he reread "Plenty of Room," he "found an extraordinary affinity between the written words of Feynman and my own thoughts . . . I was more than ever impressed with how prescient Feynman's thoughts were. I also clearly recall a profound sense of sadness that he had croaked just a tad too soon to see one of his provocative statements, i.e. 'all the way down . . .' realized in the lab." He concluded by saying that "Feynman's work would be on a dusty shelf without Binnig. It was Binnig who blew life into nano by creating the machine that fired our imaginations. Binnig created the tools that brought the nano world to our collective consciousness. . . . When it comes to nano, start looking at Binnig instead of Feynman."

I next wrote to several other nanonotables, and received replies from Chad Mirkin, James Tour, George Whitesides, and Stan Williams. Did Feynman's paper influence their work? "No," said Mirkin, who is the director of the Institute for Nanotechnology at Northwestern. "Not at all," according to Tour, a leader in molecular electronics at Rice. Whitesides (PhD '64), an organic chemist and materials scientist at Harvard, wrote that "it really had no influence." According to Williams, the director of the Quantum Science Research group at Hewlett-Packard, "my research has not been directly influenced by that talk or the ideas presented in it." Whitesides commented that Feynman's "enthusiasm for small science has certainly boosted [nanotechnology's] general attractiveness, and made it intellectually legitimate, especially in physics . . . I don't think that he was specifically important in the sense that Binnig/Rohrer/Quate were. My sense is that most people in nano became excited about it for their own reasons, and then . . . have leaned on Feynman as part of their justification for their interest." According to Williams, "I think he provided inspiration at the sociological level, but I don't think that he was a significant technical influence to the field. Scientists, including myself, would read his work after the fact and admire his prescience, but I don't think many people were inspired to go into the lab and perform a particular experiment by reading his work (other than his challenge to build a tiny motor)."

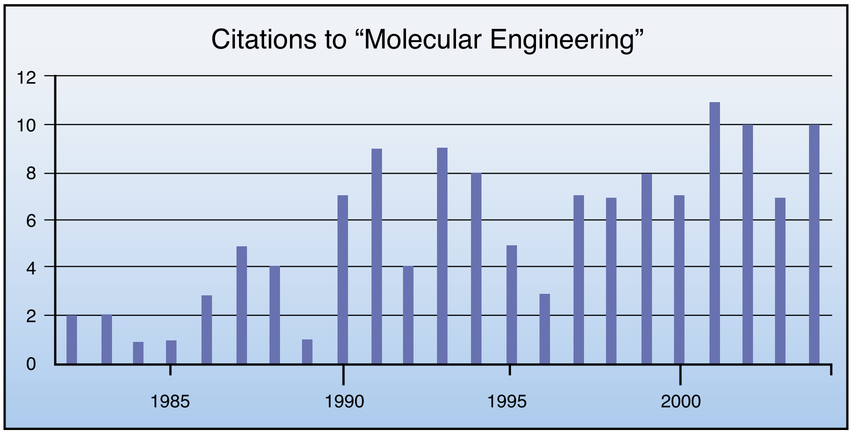
"Molecular Engineering"

There is a parallel story about Feynman's *in*direct influence. As mentioned before, Drexler began formulating his views on nanotechnology before knowing about Feynman's paper. Then he read Krumhansl and Pao's article in *Physics Today*. "Molecular Engineering," his first publication on nanotech, refers to "Plenty of Room" at the beginning of the very first sentence, and he invoked Feynman again in *Engines of Creation*.

Last year in "Nanotechnology: From Feynman to Funding," Drexler presented his views as the legitimate continuation of Feynman's, arguing that Feynman's bold vision instigated nanotechnology, and that the heart of that vision was atom-by-atom control of nanomachines to build things. "The Feynman vision," he wrote, "motivates research on assemblers and molecular manufacturing and has generated a substantial technical literature." He claimed that the term "nanotechnology" was abused by stretching it beyond the core vision so as to include much "unrelated research" and that "the excitement of the Feynman vision attached itself to the word, tempting specialists to relabel their nanoscale research as nanotechnology." (In an e-mail to me this April, he wrote, "I would, of course, never suggest that my studies of productive nanosystems inspired the bulk of what is now called 'nanotechnology.' This work continues laboratory research in chemistry, materials science, microscopy, and other areas, but under a new name. These fields long predate my contributions. Their chief connection is their adopted name and their inheritance of some of the excitement surrounding productive nanosystems.") And if it wasn't bad enough that the rightful vision was diluted, he continued, it was then purged from the definition entirely after Bill Joy, in the April 2000 issue of *Wired*, raised the fear of self-replicating nanobots ("Why the Future Doesn't Need Us," which could also be called "There's Plenty of Gloom and Doom at the Bottom"), thereby causing the leaders of the National Nanotechnology Initiative to worry that the public would fear nanotech. Those leaders, said Drexler, responded by trying to discredit Joy, telling the public that molecular manufacturing was not feasible. That tactic, he suggested, was tantamount to "attempts to suppress molecular manufacturing research."

If molecular manufacturing is the continuation of the essence of the vision, and if Drexler has been a faithful echo of Feynman, then has that echo inspired further work, the way Richard Smalley says Drexler motivated him? Regardless of the overall value or truth of Drexler's views, did the ideas in "Plenty of Room" receive further circulation within the scientific community because of "Molecular Engineering"?

Where might we find such a line of influence? "To see research that explicitly builds on my ideas," Drexler e-mailed me, "look at protein engineering." Noted protein designers William DeGrado and Carl Pabo have indeed cited Drexler in their work. Unlike DeGrado, who e-mailed me that "I actually only became aware of [Drexler's] paper after I had initiated my work in design, but I see it as an early statement of the objectives of protein design," Pabo's 1983 *Nature* article followed Drexler's suggestions in considerable detail in a passage about strategies for designing proteins. In a recent e-mail message to me, Pabo said Drexler "was a key source



of my motivation in first thinking about this problem. Eric's 1981 *PNAS* article clearly made the point that it might be possible to design new proteins reliably even before we could develop methods for reliably folding existing proteins."

"Molecular Engineering" appeared after the invention of the STM, but before the AFM and the manipulation of individual atoms. Again, if Drexler echoed Feynman, and if that echo influenced important scientific work in nanotech, then the citations of "Molecular Engineering" ought to complement Pabo's comments and give us a measure of that influence. Instead, references to it remained in the single digits until 2001. During the years of the invention of the AFM, and Eigler and Schweizer's feat of spelling out "IBM" with 35 xenon atoms, "Molecular Engineering" never received more than five citations in one year.

Thirty-one articles cited both Feynman's paper and Drexler's. This represents 9.2 percent of all the "Plenty of Room" citations and 24 percent of the references to "Molecular Engineering." I take this to mean that Drexler leads his readers to Feynman, which should not surprise anyone, but that those who start with Feynman are less likely to credit Drexler. (Incidentally, for the first 13 years that "Molecular Engineering" was out, it had almost as many citations as "Plenty of Room": 63 for Feynman, and 56 for Drexler.) Prior to the republications in 1992, a reference to the *E&S* text probably meant that the author had found it independently of Drexler. A citation of the 1961 *Miniaturization* text might be due to Drexler's advocacy, but not necessarily.

Some of the nanoluminaries who commented on Feynman's influence also had views about Drexler. Because of the way I framed my questions, their statements address his influence in general, and are not specific to "Molecular Engineering." Rohrer, who at one point had invited Drexler to the IBM Zurich Research Laboratory, wrote that Drexler had "no inspiration and no influence" on his work. "I am not aware," he continued, "of any influence which Drexler had on any scientific or technical development or on any scientist doing respectable work in nanoscience and -technology." Eigler seconded this view, explaining that, "To a person, everyone I know who is a practicing scientist thinks of Drexler's contributions as wrong at best, dangerous at worse. There may be scientists who feel otherwise, I just haven't run into them."

Similarly, Mirkin, Tour, Whitesides, and Williams stated clearly that Drexler's writings had *not* influenced their work, or that of other scientists they knew. Each of them saw Drexler as a popularizer, which they sharply distinguished from science. Mirkin's and Whitesides's comments were neutral, but Tour and Williams expressed hostility. In Williams's view, "The hype and the angst that have been a consequence of his claims provide the biggest obstacle I face when trying to present my work in public. I have had to spend a huge amount of my energy over the past 15 years or so putting distance between myself and Drexler so that what I do is not associated with him. In fact, when I founded my research group at Hewlett-Packard, we called it 'Quantum Science Research' to avoid any connection with the negative connotations of 'nanotechnology.' Eventually, because the word had found such widespread use in the public, we in the field essentially had to adopt it. Drexler has created unrealistic expectations that threaten the field more than aid it."

On the positive side, I identified Christof Niemeyer as the scientist who has cited "Molecular Engineering" most often—nine times in the past seven years. Niemeyer is a biochemist at Universität Dortmund who uses DNA as a platform for constructing nanoscale structures and systems. In his citations, "Molecular Engineering" is usually referenced on the first page of the article to support a statement like this: "The use of biomolecules for developing nanotechnology devices was already envisioned by early researchers, who suggested the use of biological macromolecules as components of nanostructured systems." He also cites Feynman in some of those articles. He draws no data, no case studies, and no quotations from Drexler's paper. The citations support the general point about assembling biological molecules into larger structures, but play no other role.

A Different Account Of Nanotech's Origins

There are surely some additional citations that I have not found, and there may be other scientists who have been directly influenced or inspired by Feynman or Drexler, paralleling the Feynman-Drexler-Smalley and Feynman-Drexler-Pabo lines of apostolic succession. Still, I conclude that much of the important scientific work that happened in the early years of nanotech, especially the big-three breakthroughs in instrumentation, owed little or nothing to either Feynman or Drexler.

I telephoned Feynman's son, Carl, on March 29, 2005, and presented my conclusion. He responded, "That seems completely true." I asked him about conversations about "Plenty of Room" with his father, and he said, "I heard about it from my dad," but "there was no interest in it" in the scientific community in the early years. He added that when he was a freshman at MIT in January 1980, he heard "Eric Drexler was aware of it, and I was stunned" that anyone had heard of it. He also told me of a time he went with his father to IBM's Watson Research Center in Yorktown Heights, New York, where scientists showed them an STM and said they could see atoms. His father corrected them, saying they were observing the tunneling of electrons. He also said that Richard Feynman "never talked about the STM in connection with ['Plenty of Room']." Were there any scientists who went into nanotech because of reading it? "I don't think so, except for Drexler," he answered.

We can speculate about why "Plenty of Room" was rediscovered. Perhaps it shows us that a new science needed an authoritative founding myth, and needed it quickly. If so, then pulling Feynman's talk off the shelf was a smart move.

That conclusion leads to some final thoughts:

First, we have an altered sequence of influence. The theory of apostolic succession posited that first there was "Plenty of Room"; then there was much interest in it; and finally that caused the birth of nanotechnology. My analysis suggests something different: first there was "Plenty of Room"; then there was very little interest in it; meanwhile, there was the birth of nanotechnology, independent of it; and finally there was a retroactive interest in it. I believe we can credit much of the rediscovery to Drexler, who has passionately championed Feynman's paper.

The second thing is to ask *why* "Plenty of Room" is retroactively important. One obvious possibility is that someone's scientific work will have its prestige enhanced if it is connected to the genius, the personality, and the eloquence of Richard P. Feynman. But is the Feynman cachet really transferable in this way? We can contrast that with a more modest style of alluding to Feynman. As we have seen, Binnig and Rohrer included a brief comment in their 1987 history of the invention of the STM, and so did Joseph Stroscio and Don Eigler in their 1991 description of atomic manipulation. But in both cases the references were cursory at best, and the authors did not cite Feynman until well after they had achieved notable success in instrumentation. They gave him a reflexive nod—an acknowledgement that he had had similar ideas—but none of the work was justified by connecting it to him, either while it was being done or afterward.

Third, how selective is the process of enhancing one's work by retroactively claiming the Feynman cachet? "Plenty of Room" describes many things, including the nano-etching of texts; the storing and retrieving of data in an atom-size code; the wonders of biological information systems; the miniaturization of computers; a mechanical surgeon that could be swallowed; a system of increasingly smaller master-slave hands (also known as Waldos); a system of "a billion tiny factories" working together; superconductivity; and simplified synthetic chemistry, to name only nine ideas in that paper. If someone borrows Feynman's prestige by citing some of these thoughts while disregarding others, is this a distortion of Feynman's views?

Fourth, why is "Infinitesimal Machinery" unknown to those who enthusiastically embrace "Plenty of Room," especially since Feynman described it as "Plenty of Room, Revisited"?

And finally, if we discount the usual Feynman-centered account of the origins of nanotechnology, does this enhance a different tale? The nanoluminaries point to an instrumentation-centered narrative. To repeat Eigler's comment, "When it comes to nano, start looking at Binnig instead of Feynman."

We can speculate about why "Plenty of Room" was rediscovered. Perhaps it shows us that a new science needed an authoritative founding myth, and needed it quickly. If so, then pulling Feynman's talk off the shelf was a smart move because it gave nanotech an early date of birth, it made nanotech coherent, and it connected nanotech to the Feynman cachet. But even as we speculate like this, we should not lose sight of a line of events that happened entirely independently. The invention of the scanning tunneling microscope made it possible to see atoms clearly and move them around, and then it enabled a great volume of additional scientific research. When we ask from whence nanotechnology descended, we ought to salute the STM as the founding ancestor. □

Christopher P. Toumey, Centenary Research Associate Professor of Anthropology at the University of South Carolina, Columbia, earned his PhD in anthropology from the University of North Carolina in 1987. He studies the cultural anthropology of science and of religion. His first book, God's Own Scientists: Creationists in a Secular World *(1994), looked at the process by which science is "interpreted" to promote ultra-conservative views. His second book,* Conjuring Science: Scientific Symbols and Cultural Meanings in American Life *(1996), explores the broader question of how these symbols convey not only well-defined scientific meanings but also moral and political ones. He now works full-time with an interdisciplinary team at the university's NanoCenter, studying society's interactions with nanotechnology and how nanotech policy is formed.*

This article is based on a paper presented at the March 2005 Cain Conference on the history of nanotechnology at the Chemical Heritage Foundation in Philadelphia, Pennsylvania. The work was supported by a grant from the National Science Foundation.

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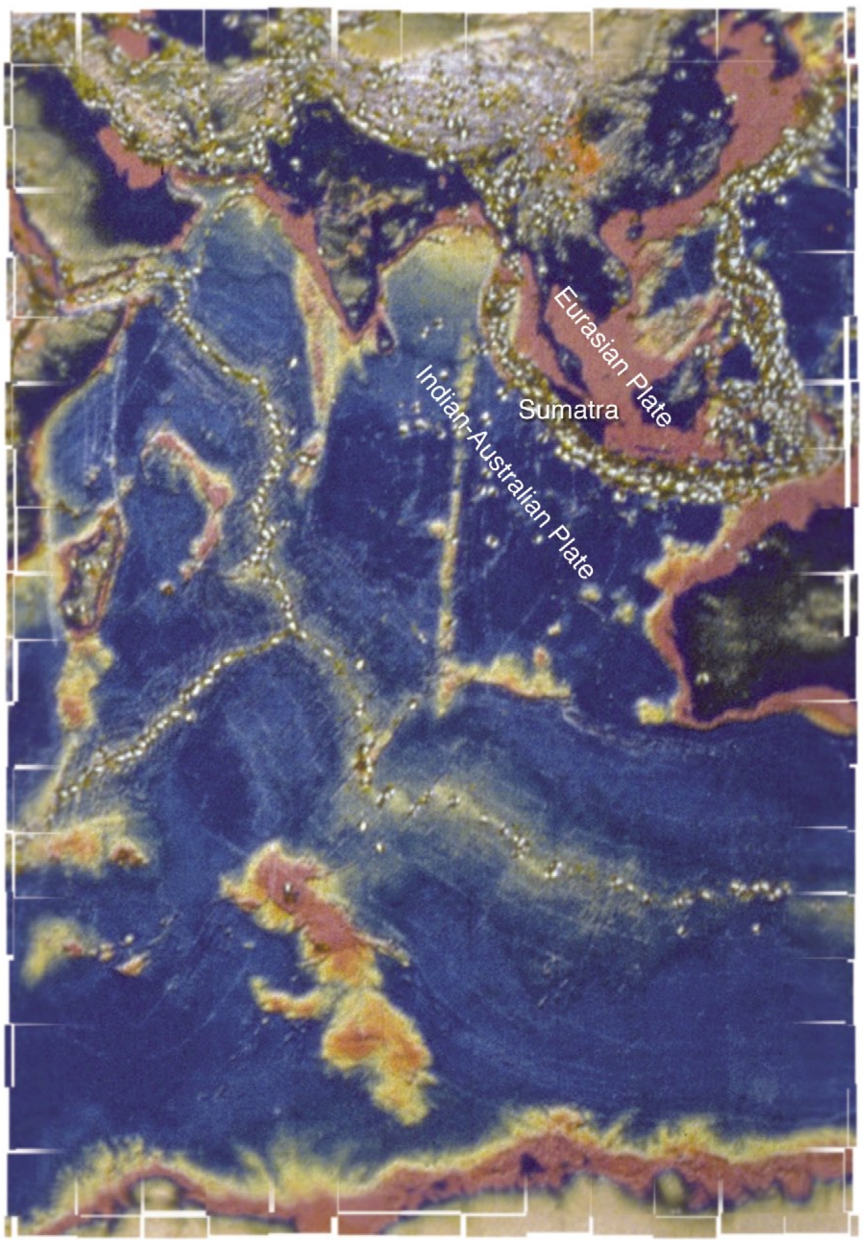
17 – Bob Paz; 18 – Don Eigler & Erhard Schweizer; 19, 22 – Chris Toumey

The Great Sumatra Quake

by Mark Wheeler



Geologist Kerry Sieh was at home on Christmas Day, 2004, working on his laptop, when word first came via e-mail that a magnitude (M) 8.5 earthquake had struck the Indonesian island of Sumatra. Normally, when scientists like Sieh hear about big earthquakes, the initial reactions are the human one, concern about people, along with that of the "science nerd," as he puts it—a lot of excitement, a lot of new data to eyeball, and the chance "to connect to big Earth processes." But with this earthquake, which ultimately proved to be one of the largest ever recorded, at a probable magnitude (M) of 9.3, Sieh didn't have the typical reaction of a geologist.

This one was all personal.

Sieh has been studying Indonesia for more than a decade. To get to the remote places in the field where he and his colleagues go, they travel by boat, helicopter, horse, and their feet, often wading through water and trampling through jungle. Because there are few hotels, when they aren't sleeping on their boat they politely knock on the doors of villagers, explain what they're doing, and commonly end up eating meals and sleeping in the homes of people Sieh now considers friends.

In the hours following the first report, Sieh stayed glued to his computer screen, trying to e-mail people he knew in Indonesia—no luck. As he examined the pattern of aftershocks, he became increasingly concerned. The longer the rupture zone, the greater the magnitude, and the 1,300-kilometer-long band of aftershocks hinted that the fault had broken for a much greater distance than originally reported—even the revision to M 8.9 a few hours later seemed a bit too small. Still, regardless of which side of 9 the magnitude was on, an earthquake of that size strongly implied tsunamis. That's when Sieh really began to worry. "It was emotional for me when I started realizing people I held near and dear might be dead, or their property and livelihoods lost," he says. (The temblor, and the massive tsunamis it generated, resulted in

Opposite page: Earthquakes (white dots) mark the boundaries of Earth's tectonic plates. Sumatra lies along the border of the Indian-Australian and Eurasian plates. (Map prepared by Don Anderson, MS '58, PhD '62, Crafoord laureate and McMillan Professor of Geophysics, Emeritus, and David Sandwell, UC San Diego.)

300,000 dead or missing Indonesians.)

It took the next couple of weeks before he learned that the tsunamis that hit the areas where he was working were only a meter or so high, and that no one he knew died. But that hasn't stopped him from worrying. Sieh's research focuses on a different segment of the fault, several hundred kilometers from December's epicenter. Historically, earthquakes along this segment have struck with regularity, often in clusters, and his research had revealed the time was fast approaching for another large one. And when the fault finally breaks from the strain that's slowly been accumulating, it will break big time, with big, damaging earthquakes, probably followed by big, damaging tsunamis.

Last summer, Sieh and his colleagues traveled from village to village on several islands off Sumatra's west coast, handing out brochures and posters, educating the locals about the danger sleeping right under their feet, and advising them on what they can do to avoid a tsunami should a big earthquake strike (the advice can be boiled down to "run like hell—uphill"). In the months following the December quake, he has watched with growing concern as hundreds of aftershocks have marched south toward his segment of the fault. They included a large, M 8.7 earthquake just a few hundred kilometers away on March 28, followed on April 10 by two strong M 6.7 and 6.5 quakes that occurred right in his segment. They may be aftershocks or, worse, foreshocks of the big one he knows is coming, "sometime in the lives of your children," as he put it to the Indonesians he spoke to. The prospects of a giant earthquake like the one in December would be very bad news for the denizens of Padang, a coastal city of about one million that lies 200 kilometers due east of this segment. Padang has not been damaged from the recent quakes, but it is being shaken repeatedly. And it could be next.

So what do you tell these people? "In the lives of their children" could mean 70 years from now, or it could mean tomorrow. People in Padang are already terrified from all the shaking, and fearful of tsunamis. It's simple and doable to tell people living in small villages to run uphill in the event of a giant earthquake, but in a city of one million? Even if a tsunami warning system was in place—

Right: These *Porites* coral heads off the west coast of the island of Simeulue were uplifted about 90 centimeters by the December 26 earthquake.

The poster distributed by Sieh and colleagues was printed in English, Indonesian, and Mentawai.

and one isn't—how fast and how far can that many people run, Sieh asks, if they have a 15-minute head start, which is the maximum likely notice if such a warning system was installed? Imagine the panic. Imagine the deaths. Simply put, he says, Padang is another disaster waiting to happen, one that could be as terrible as Banda Aceh, and it is a big challenge to do anything about it.

Sieh, Caltech's Sharp Professor of Geology, is a founder of the field of paleoseismology, the study of prehistoric earthquakes. His PhD thesis (Stanford, 1977) was a history of the displacement of California's San Andreas fault over the last 10,000 years. (The San Andreas is a strike-slip fault, meaning that its two sides slip horizontally past each other during an earthquake. The Sumatran earthquake, on the other hand, was on a thrust fault, where the two sides of the fault move more or less vertically.) While he has conducted research on faults both near and far-flung—the Red River fault in China and the Chelungpu fault in Taiwan, the Denali fault in Alaska, numerous faults under Los Angeles, and, of course, Sumatra—the San Andreas had dominated his work until the 1990s. In fact, his most recent paper on it, published in 2004, showed that about 95 percent of the slippage on the San Andreas occurs in rare but big earth-

Two coral victims of the great Sumatran earthquake. Far left: A *Pocilopora*. Left: A *Meliopora*.

quakes. This is bad news for Angelenos who had been hoping that the stresses might be relieved by many small earthquakes instead.

But for as much as he's learned about the San Andreas, it remains frustratingly enigmatic—running through several major urban areas, it is, to put it simply, a geologic mess. "We still do not understand why earthquakes have occurred on the fault with such great irregularity," he says, although he has a couple of suspicions. One is that, given that California is riddled by faults, a nearby one may break and give a kind of geologic "belly punch," as he puts it, to the San Andreas. This may change the stress level, "causing it to fail sooner—or later," he says. Or, by the very nature of it being a fault, "you can have something fundamental about the nature of a crack. If you drive at a crack from the sides it can be irregular spatially, in terms of how much it slips, and also irregular in terms of time—how long until it will slip."

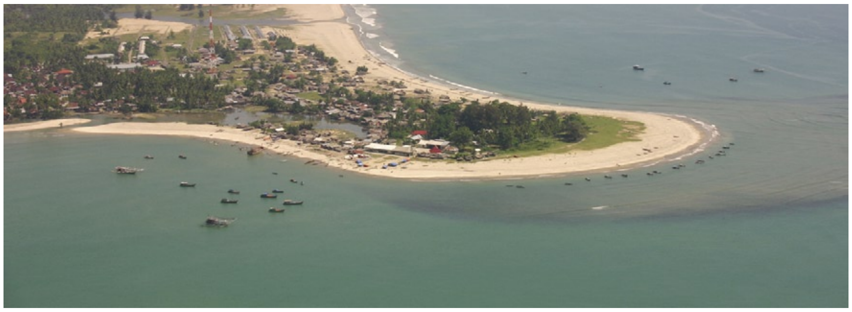
And getting data from the San Andreas is a hassle. For one thing, it's labor-intensive and expensive—"you need to bring in a big diesel backhoe on a flatbed truck to excavate a trench that's about a meter wide and about 5 meters deep, then you have to put up shoring to support the walls," says Sieh. "You have to find the right site where the layers are accumulating at the right rate, that has carbon you can date, and then it takes a couple of months to get reliable analysis from a lab." Because all living things contain radioactive carbon-14 that begins to decay at the time of death, and scientists know what that rate of decay is, measuring the remaining level of C-14 in a sample of say, peat, gives the date when it died, give or take 50 years or so. "The problem, though, is that material can blow or fall in and get caught in a layer and fool you," says Sieh. "So with all these limitations, around 1990 I came to the realization I was going to be an old man before I figured this thing out, and I may not be able to figure it out at all in my lifetime."

"All I could think about was damn, if the San Andreas fault just had some coral, we could do some really good dating."

Then three things happened, roughly around the same time: two Caltech colleagues developed a new dating technique, Sieh read an article about coral, and he got invited to Sumatra. The dating method uses uranium found in corals. Uranium is brought up from the earth's deep interior in igneous (volcanic) rocks, and then leaches out into the environment. It's everywhere. And it decays at a known rate—uranium-238 decays to uranium-234, which decays to thorium-230, which eventually decays to lead-206, which, finally, is stable. "All the daughter products decay at different rates down to lead," says Sieh. "And as they decay, certain ratios exist between the daughter products. And if we can figure the ratio between the two, we can determine the age of a 500-year-old sample to within two years." Which is exactly what Caltech's Gerald Wasserburg, Crafoord laureate and MacArthur Professor of Geology and Geophysics (now emeritus), and graduate student Larry Edwards (PhD '88), now a professor at the University of Minnesota, did. "So as I was learning about this method all I could think about was damn, if the San Andreas fault just had some coral, we could do some really good dating," says Sieh.

Next, early in 1991, Yehuda Bock, a colleague at the Scripps Institution of Oceanography, had a project to measure strain accumulation along the Sumatran plate boundary. He was also trying to figure out how fast the Sumatran fault, which runs down the backbone of the island, was slipping over the millennia. Since it, like the San Andreas, was a strike-slip fault, he turned to Sieh. "So off I went to Indonesia for a week, charging around the mountains looking at this fault," says Sieh. Back in Jakarta for a little R & R, he was catching plates collide five kilometers beneath the Indian Ocean at what geologists refer to variously as the Sumatran trench or Sunda trench. It's here that the Indian-Australian plate begins to subduct—slide beneath—the Eurasian plate, and into the earth's interior. And it's not going down easily. The two plates move in a jerky fashion, remaining locked together in a tight embrace for centuries until a sudden slip of a few meters occurs, generating a large earthquake. When one plate slides under another, it's called a thrust fault. But this fault is so large it is commonly referred to as a megathrust.

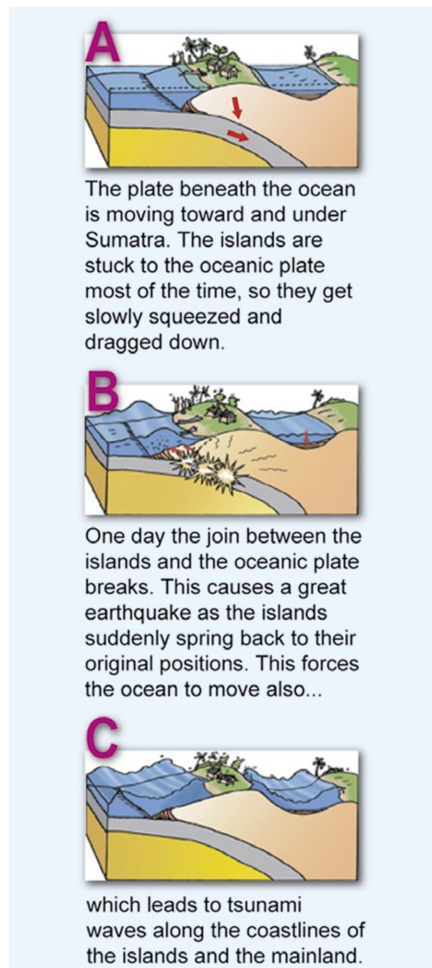
A small necklace of islands sits on the Eurasian plate, right on top of the megathrust. Because the two plates are locked, these islands are slowly being pulled down by the subducting Indian-Australian plate, only to rebound when the plates move freely during earthquakes—resetting the clock, as



Is this town, which sits on a promontory near Padang, a disaster waiting to happen?

some sun at a public swimming pool ("instead of the one at my hotel, where it's all rich Westerners; I like to be in the 'stream of life' of the local folk, watching the kids and the parents"). That's when it hit him. He had brought along a paper about corals by another colleague, Fred Taylor, from the University of Texas. Taylor described measuring how much the earth had risen during an earthquake by looking at coral heads that had been raised out of the water, had died, and were now growing at a lower level. "That's when I had one of those rare moments in my scientific career—a chill up my spine, a true eureka moment," says Sieh. "I realized that if I could find a warm, low-latitude (where coral would exist), big subduction zone, one that's unaffected by neighboring faults, like the San Andreas is, I could do a clean paleoseismic history that might inform us about future earthquakes." He realized he was sunning himself directly on top of just such a zone, one that had been relatively unexplored by other scientists—"It's tucked away in a corner of the world that just doesn't have a lot of scientific traffic," as he's said in the past.

Sumatra, the largest island in Indonesia and the sixth largest in the world, doesn't just have a double whammy in terms of tectonics, but multiple whammies. There is the Sumatran fault Sieh worked on, and there are volcanoes running the island's length. Last April, during a time of frequent aftershocks, Mount Talang, located about 40 kilometers east of Padang, spewed ash 500 meters into the air, adding to the misery of people already terrified about earthquakes and tsunamis. (Western Sumatra is also home to Toba Lake, which fills a 100-kilometer-long caldera that formed 73,000 years ago atop Toba volcano. Fortunately, it's still asleep.) Then there's the boundary between the Indian-Australian and Eurasian plates, which runs 5,500 kilometers beginning near Myanmar, curving past Sumatra, then heading toward Australia. This source of Indonesia's recent woes lies about 200 kilometers off Sumatra's west coast, where the



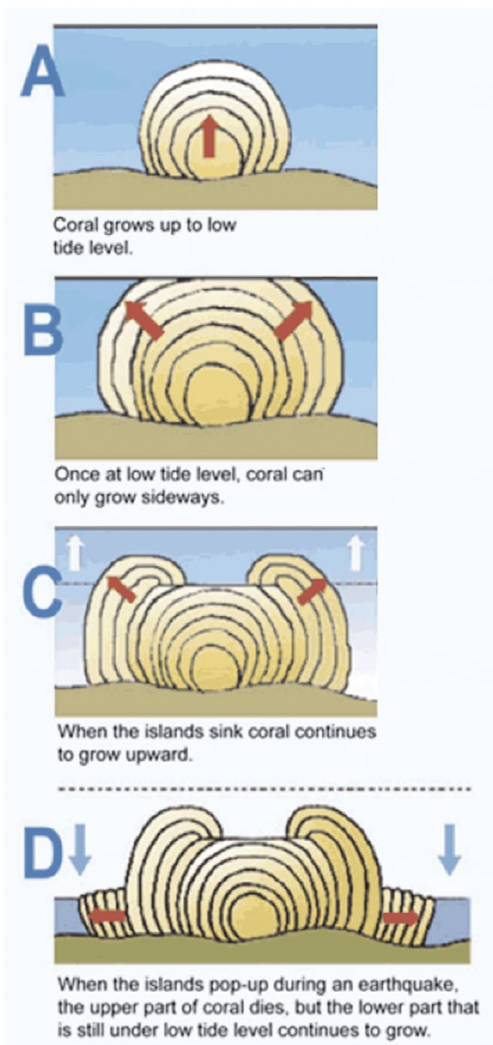
This panel from the poster shows why the offshore islands are slowly sinking, and why their rebound during earthquakes causes tsunamis.

it were. The islands allow easy access to the coral heads Sieh needs to study. All in all, he says, "It is just a perfect, natural laboratory, a bonanza for science." Sieh looks at a segment of the megathrust that runs from the equator to about four degrees south latitude. He collaborates with a number of colleagues, most often Danny Natawidjaja and Bambang Suwargadi from the Indonesian Institute of Science (Natawidjaja, MS '98, PhD '03, is his former graduate student), and Caltech staffer John Galetzka, who spends virtually all of his time in the field, taking coral samples and installing, repairing, and downloading data from the Global Positioning System (GPS) stations that precisely measure any tectonic movement. All of them serve as science ambassadors to the locals, who wonder why these crazy Westerners ask permission to chop up a coral, hack a circle in their farmland or the nearby jungle to install some bizarre-looking machine, or pay money to sleep on their floor.

Over the course of the last decade, Sieh has primarily relied on the heads of *Porites* coral. Specimens of this bowler-hat-shaped coral (Remember the hat worn by Oddjob in the 007 movie *Goldfinger*?) can be large enough to stand on, and can weigh tons. Growing in annual bands much like tree rings, the long-lived corals serve as "nature's seismometers," as Sieh puts it, recording, to within centimeters, sea-level changes caused by uplift and submergence of the earth. "The coral grows right up to the sea surface, then flattens out like a plate and begins to grow out to the sides," says Sieh. "So each time the island sinks, raising sea level, the coral grows higher; when the island is uplifted and the sea level drops, the coral is raised out of the water and dies." The coral is cut into slabs with a waterproof chainsaw, and the samples sent off to Larry Edwards's lab in Minnesota for uranium dating. (For an animation of the coral's growth and die-off, see: http://www.gps.caltech.edu/~danny/research/coralanimation_gif.gif.)

The GPS station at the airport in Sinabang, the capital of Simeulue Island, close to the epicenter of the December quake, showed that the entire island lurched 2.33 meters to the southwest, while its northwestern shore rose 1.65 meters. This is what commonly happens with Sumatra's offshore islands, says Sieh: "a long-term trend toward submersion

Top: Kerry Sieh. Bottom left: Danny Natawidjaja in the helicopter. Bottom right: John Galetzka.



Right: Another panel shows how *Porites* corals record sea-level changes. Far right: The top of this newly emerged *Porites* microatoll off the northern tip of Simeulue shows that the head was submerging in the years before the earthquake.

This uplifted reef is on the westernmost tip of Simeulue, looking roughly south. The original shoreline is the thin, beige strip of sand where the vegetation ends.

and tilt." Most of the network's GPS stations have to be visited in person to download their data, but they are slowly being upgraded to communicate by satellite. That way, Sieh will get readings within hours in the comfort of his Caltech office—no more anxiously waiting days or weeks.

When Sieh hustled to Sumatra after Christmas (ironically, on a long-planned trip), he described the area of uplift in an e-mail (see http://today.caltech.edu/gps/sieh/): "Even though [we've] been studying ancient evidence of the slow sinking and fast emergence of the Sumatran coral reefs, we were astonished to find ourselves walking through a pristine marine ecosystem, missing only its multitude of colors, its fish, and its water. Corals of every shape and size rested lifeless on the reef platform—branching corals, massive corals, staghorn corals, fire corals, brain corals, whorls, fans. And here and there a poor crab. Even though the tsunami had raged across the reef, there was scant evidence of any breakage of the delicate whorls and dendritic corals that crunched beneath our feet. But a fishing boat in the trees beyond the shoreline and an overturned, two-ton, umbrella-shaped *Porites* coral head were testimony to the power of the tsunami. The scene was the marine equivalent of a village on the flank of a volcano after the passage of a nuée ardente (a destructive 'glowing cloud')—life quick-frozen in place at the moment of death."

After the M 8.7 March earthquake, John Galetzka noted, in an e-mail, "At Lahewa on the north coast of Nias Island there was no tsunami, only intense shaking. Thirty-two people died from building collapses and fires that swept through the town. The harbor rose about two to two-and-a-half meters due to tectonic uplift."

Sieh notes that the 8.7 quake extended to near the equator. He suspects the fault could have broken even further, but was stopped by an "aseismic zone." This is a piece of the fault next to his area of study that has more elastic properties than his study zone, allowing stress to build up much more slowly. And while an M 8.7 should be strong enough to generate tsunamis, this one generated only very slight ones. The reasons aren't yet clear, but the March quake occurred under relatively shallow water, so there may just have been less to displace.

On Tello, a tiny island on the equator near the epicenter of the March earthquake, Galetzka found a dead GPS unit. Apparently, people had grown suspicious of it. "Since no earthquakes had occurred in their lifetimes before the machine was put in, they figured the GPS was to blame," he says. "So they cut its wires!" He told the full story in an e-mail: "As we were trying to repair the vandalized station, the situation could have easily tipped into chaos had it not been for some cool heads there to keep things calm. At one point we were even told to stop repairing the station. Later that night there was a community meeting called by the district supervisor to try to dispel the

A typical GPS installation. The gray dome on the tripod in the background houses the GPS unit proper, and the open cabinet under the solar panel contains the electronics.

These old, now-flooded rice paddies are near the nothern tip of Simeulue. They apparently re-surfaced after the earthquake.

numerous rumors about our GPS station and other things regarding giant earthquakes and tsunamis. My colleagues, Bambang Suwargadi and Imam Suprihanto, gave an excellent oral presentation and answered questions from the audience. Because satellite telemetry has been re-established to the Tello station, we'll soon know if the citizens believe us or not."

Between earthquakes, says Sieh, the islands are slowly being dragged under water at a rate of about a half an inch a year. "The villagers know this," he says. "They can see their boardwalks and harbors sinking." On a helicopter survey of the islands after the December quake, he was intrigued when he spotted what appeared to be rice paddies on the northern tip of Simeulue Island where none had been before. He believes the newly emerged paddies had been slowly flooded by the ocean, only to reappear after the quake. Along the fault in Sieh's study area, the Indian-Australian plate is cool, not very dense, and locked against the Eurasian plate. As the plate subducts, it becomes hotter, more gooey, and denser. "So as the lower part sinks down," he says, "it stretches and pulls on the upper part; that's what's pulling the islands down. And eventually, it's going to snap."

Snap indeed. This particular segment has been resisting now for about 200 years. Sieh's coral evidence shows that large earthquakes occur regularly—often in pairs—every 200 to 230 years. His research shows that clusters of quakes occurred in the 1300s and 1500s, and one in 1797 (M 8.2), and 1833 (M 8.7), all probably accompanied by tsunamis. In fact, he has an historical account, recently translated from the Dutch, of tsunamis inundating Padang in 1797 and 1833. "It describes a 150-ton boat that was picked up and carried through the city, just mowing down houses as it went," he says. "So our inkling is that these earthquakes are roughly periodic." Given the 200- to 230-year average, this suggests another quake is coming due. "It's a quandary," he says. "We have better information about the recurrence history of this section of the subduction zone than nearly any other subduction zone in the world," yet science can't say with any certainty what, exactly, is going to happen tomorrow. "That's why I tell the local people that another earthquake will occur sometime in the lifetime of their kids." It could be 70 years from now—or it could be tomorrow.

After the December earthquake, Sieh and other geologists thought it likely that the segments of the Sunda megathrust immediately to the south would be closer to failure. The pattern of aftershocks that followed confirmed this opinion, and, sure enough, in March the M 8.7 quake struck. Debate continues as to whether this quake was an aftershock or a new earthquake in its own right, but the point, says Sieh, "is this earthquake, like the earlier one, is one of the few great earthquakes of the past 40 years." The approximate 300-kilometer length of its rupture is a very significant piece of the fault, although the December 2004 quake ruptured more than 1,000 kilometers. "Many of us wondered if the December earthquake would trigger another significant event," says Sieh. "Nature has now answered that question." Adding to the woes of the

Top: This picture of Lahewa harbor on the north coast of the island of Nias was taken at high tide on February 15. Bottom: This photo, taken at low tide on April 24, shows another 2 to 2.5 meters of uplift as a result of the March 28 earthquake. The yellow line approximates the new high-tide mark.

Uplift is not the only thing changing the coastline—this beach is moving inland, rather than seaward. Natawidjaja (on the left of the group) is standing where the grass used to end before the December 26 earthquake. The locals say that this erosion has taken place since the tsunami, not during it.

Indonesian people is the danger that the portion of the San Andreas-like Sumatran fault nearest to the December quake has been put under increasing strain as well. It runs right through the already devastated Banda Aceh area and down Sumatra's backbone.

So what will become of the Indonesian people? Do they face an existence of recurring devastation, especially those that live in large cities like Padang? With the destruction, the deaths, and the aftershocks that continue to hammer Sumatra, Sieh says many people in Padang are in a near-constant state of panic. Galetzka was in the city in mid-April when the two 6-plus aftershocks struck. They even scared him. "I was really thinking those weren't aftershocks, but foreshocks of the larger quake that's coming," he says. "It was a very unsettling experience." Many Indonesians now understand—having learned the hard way—that they live on top of one of the most violent seismic zones in the world. On some of the smaller islands, Galetzka reports, people have taken steps to reduce their risks, establishing new communities in the interior on higher ground. And they've made escape routes from the villages near the sea. Others are less reassured. In April, Sieh was hearing from friends that many people on the offshore islands were convinced they were about to sink; ferries to the mainland were running full every day.

Residents of Padang know earthquakes will come, but they don't know what to do. About 10 percent, estimates Sieh, are not waiting for their government to advise them. They've "voted with their feet," he says, leaving behind homes and jobs to flee into the hills or south to Jakarta. Sieh shared an e-mail from an Indonesian friend in Padang: "May be you have heared about earthquake at nias, north sumatra, and you know kerry many people and TV inform that tsunamies will come to Padang in this month. it's true kerry? but now I'm afraid if it's become because my parents don't want to leave from here, they don't believe what I and people say, I've tried to persuade them. . . ." Sieh wrote back, "No one knows if the big earthquake and tsunami will come to Padang soon. It could be tomorrow or it could be in 30 years. No one knows, so you should not believe anyone who says that they know it will happen soon. Where do your parents live in Padang? If they live close to the beach, then perhaps they should think about moving farther away."

Sieh is not optimistic. Because of his outreach efforts last summer, the media wanted to talk to the geologist who had "predicted" a large earthquake was imminent. "Reporters asked me if Indonesia will do anything, and I said I was skeptical," says Sieh. "Then they asked if this was because Indonesia is a third world country, and I said no, it's because they're human." He pointed out how long it's taken Los Angeles to retrofit buildings and bridges. He noted that after an earthquake people stockpile food, water, and flashlights with fresh batteries. Then the water gets used, the food goes bad, and the batteries die as the memory of the earthquake fades. There *are* things Indonesia could do—begin moving Padang's city center several kilometers back from the shoreline, and turn that into parkland, he suggests; construct buildings with first floors whose walls will break away in the event of a tsunami, allowing the water to pass through. (Instead, Padang recently built a new marketplace—a gathering place for people!—mere feet from the waterfront.)

Meanwhile, Sieh will continue, and possibly expand, his own efforts at educational outreach, but hopes to find a nonprofit organization and possibly a funding "angel" that will take over. "It's a terrific place to be from a scientific standpoint, but from a humanitarian point of view, it's an odd place to be in as a scientist," he says. "I never expected this would become a component of my work. But I guess that's what science in the public interest is all about." □

PICTURE CREDITS:
25-31 – Kerry Sieh; 25 – Catharine Stebbins; 27, 28 – Sambas Miharja; 30 – John Galetzka

THE SUMATRAN FAULT SYSTEM, INDONESIA

NOT WORKING 9-TO-5

Last April, dropped off by helicopter onto a remote and windswept Himalayan ridge at an altitude of 15,000 feet near the Tibet border, the last thing Caltech's John Galetzka expected to see was another human being. Yet as he worked alone to install a Global Positioning System (GPS) station, one in a network of stations used by Caltech geologists to measure ground movement, he was surprised to notice a lone figure approaching on foot. It was a pilgrim, says Galetzka, a Nepalese man who, it turned out, had built a small Buddhist shrine on the same ridge and had come to pray. Galetzka shared halting pleasantries with the man, and the two got on with their day. Galetzka spent the next 24 hours on the mountain, working and suffering from altitude sickness. That included spending a freezing night in a sleeping bag, huddled under a shelter he roughed together from an equipment tarp.

For Galetzka, it was just another day at the office.

Clearly this is not your typical nine-to-fiver. While Galetzka is a bona fide staff employee, you'll almost never find him sitting behind a desk. For that matter, you'll rarely find him sitting anywhere at Caltech, in Pasadena, or within the continental United States. Last year he spent all of four weeks here. Galetzka doesn't have an office, doesn't rent or own an apartment or house, doesn't own a car. Most of his time is spent either in Nepal, Indonesia, or Taiwan, where he works as a "senior research assistant" (read: field guy) for Caltech geologists Kerry Sieh and Jean-Philippe Avouac. He came to Caltech after serving a four-year stint as a U.S. Army Ranger and earning a geology degree at the University of Oregon. He was hired by the U.S. Geological Survey in Pasadena in 1996, but resigned to work with Sieh and Avouac in 2002. Today his primary responsibilities are to install and repair the GPS stations and to download the data the geologists count on to measure local ground movement caused by tectonic activity. To do this, he travels by boat, helicopter, on horseback, and on foot, scouting out new locations to place the stations, then introducing himself to the local populace in order to negotiate permission to use a piece of their land. "It's a crazy job," laughs Galetzka, who is 37 and, as you might have guessed, single; "But I love it. Lots of travel and a lot of physical challenges."

When the December 26 quake struck, Galetzka was visiting a friend who runs a clandestine humanitarian group in a nearby country run by a military dictatorship. It took him four days on foot, dodging roving military bands and avoiding land mines, before he made it back across the border to meet up with Sieh. With their colleagues, the pair spent the next six weeks getting a firsthand look at the geologic effects of the earthquake, distributing relief supplies, and checking on friends. They downloaded data, made repairs, and continued educating locals about future earthquakes and tsunamis.

Just last summer, the group had spent time educating villagers about earthquakes and tsunamis; now, to the locals, their warnings seemed prophetic. "One of the things we told them to do was to run to the GPS station," says Galetzka. "We try to place our stations on high ground to get good satellite reception, so it was a simple way

Below, left: John with the backpack he rigged for transport of materials and gear to the GPS site atop the hill above the village of Perak Batu, on the east coast of South Pagai island. Below, right: John coaching our helicopter in for the landing at the GPS station on the island of Simuk.

John and a citizen of Silabu village, on the west coast of North Pagai island, in the process of installing our GPS station there.

to get across an important message in case of a tsunami." He adds that some villagers believe it was the GPS stations that had saved them. "We tried to tell them no, but on one island they had begun to relocate their village around the station. People were settling in, building shelters."

No one he knew was killed, but he saw massive destruction while traveling upriver toward Banda Aceh. "Everything was completely flattened except for a few very strong structures," he says. "You could see dump trucks and bulldozers clearing rubble. Fires were smoking. People were salvaging metal. There were others in hazmat suits. It was a surreal scene." While he was installing a GPS station in another town south of the city, a teenage boy came by to watch. "He was off at school in Banda Aceh at the time of the tsunami," Galetzka says. "He had returned and found that his home, family, and village were gone. I was amazed at the boy's steady demeanor. He had probably cried so much that he couldn't grieve anymore." □—*MW*

Living Through a Big One

Muhammad Oman lives in Gunungsitoli, a city on Nias Island off the west coast of Sumatra. Early reports state that as much as 80 percent of the city was destroyed by the March 28 M 8.7 earthquake. Sieh notes that Gunungsitoli, like many Indonesian cities, has been built on sedimentary, reclaimed swampland close to a river mouth. Here is Oman's eyewitness account, courtesy of a colleague of Sieh's.

"My [hardware] shop is small and only one floor. The other shops [next door] were owned by Chinese and were three or four stories high. They all slept on the top floor or on the roof in hot weather. When the quake started they all ran downstairs to get outside. We were all afraid there would be a tsunami and we were all told to run to high ground if a big quake hit us.

"The Chinese always have three sets of security doors, and when the power failed they could not unlock them fast enough (before their building fell). Almost all the bodies were found on the ground floor.

"I ran for my front door but everything fell off the shelves and I could only get it open a crack before it jammed. I could see the houses going down all along the street one after the other, like they had bombs under them. . . boom, boom, boom.

"Some shops like mine survived because their walls run east-west. The [earthquake] waves shook us from east to west and I was thrown up in the air and kept falling down. Then the fires started all around. The flames lit up the town, and my friends helped me to open my door and get out.

"A few hundred meters away the ground rises, and a low hill is the site of a Catholic school built by German missionaries 80 years ago. The old timber buildings are in perfect condition and packed full of families who have fled the flatland. Next door a modern concrete structure is standing without a crack. They are built on bedrock." □—MW

Above: Detail of tsunami damage in a town along the southwest coast of Simeulue.

Right: Among the debris at Sirombu, NIas, people are building a temporary structure to house them while they build a more permanent replacement for their lost home.

Art and Science: A Da Vinci Detective Story

by John Brewer

This is the story of the most sensational art trial of the first half of the 20th century, the case of Hahn versus Duveen. It begins in 1920, when a reporter from the *New York World* telephoned Sir Joseph Duveen, the self-described most powerful art dealer in the western world. Duveen, an Englishman, was in New York, where he habitually spent half of the year, having recently arrived from his London office. (His firm also had a gallery in Paris.) Suave, cigar-smoking, and turned out in the finest suits, Duveen was always available to the press, which he was prone to see as the publicity department of his firm, Duveen Brothers. The business thrived on the titillating gossip and sensational revelations he leaked to the newspapers. During the interview Duveen was asked about a painting that had recently been offered by the French wife of a young American airman to the Kansas City Art Institute for a vast sum, rumored to be either $225,000 or $250,000. Harry and Andrée Hahn claimed that their picture was a Leonardo da Vinci, the original version of the picture known as *La Belle Ferronière.* The version of the picture in the Paris Louvre was therefore a mere copy. The claim was, of course, sensational. In 1920 there was no authenticated painting by da Vinci in any American collection, either public or private, and the arrival of a work of the master in a Midwestern city would have been an incredible coup, quite apart from the satisfaction it would have given Midwesterners to pull one over on the grandee collectors and galleries of the East Coast. But Duveen, much of whose wealth had been made supplying those grandees with Old Master art, was having none of it. Though he had never seen the picture or even a photograph of it, he condemned it, adding for good measure that any expert who authenticated it was not an expert at all. The real *Belle Ferronière*, he told the reporter, was in the Louvre and not on its way to Kansas.

Mrs. Hahn sued Duveen in the New York courts for slander of title, claiming his reckless and irre-

Erich Lessing/Art Resource Inc.

Which of these is the real Leonardo da Vinci? Is it the painting of *La Belle Ferronière* on the left that hangs in the Louvre, or the one on the right owned by Andrée Hahn?

Andrée Hahn and her *Belle* caught the imagination of the media, who saw them as two similar, beautiful, foreign ladies. The *Illustrated London News* even framed Andrée Hahn's photo in their four-page spread on the trial. (Courtesy of the *Illustrated London News* picture library.)

sponsible act had ended negotiations in Kansas and made it virtually impossible to sell the picture elsewhere. She hired herself a fancy New York lawyer, the improbably named Hyacinthe Ringrose, and sued Duveen for the enormous sum of $500,000 in compensation, a figure endlessly repeated in the newspaper reporting on the case.

Duveen had always been a newshound, but in the Hahns and Mr. Ringrose he met his match. They set out to fight him not only in the courts, but also in the columns of the press. They spent a good deal of time painting a wonderful back story for their Leonardo. They claimed that the picture had been a wedding gift to Andrée from her aristocratic aunt, the Comtesse Louise de Montaut. It had been smuggled out of France and into Belgium in a basket of washing, before being shipped to the United States. Andrée herself was portrayed as a French aristocratic beauty, gallantly rescued as a war bride by Harry, the dashing Midwestern aviator, sometimes said to have been on General Pershing's staff. She and the woman portrayed in her Leonardo—foreign and beautiful—became as one. The Hahns' romance and the romance of Leonardo were intertwined.

While Ringrose sought sympathy for the young couple, he also encouraged Duveen and the experts he employed to examine the painting. Duveen obliged by paying a succession of American experts to visit Ringrose's office, where the picture was displayed. He also sent photographs to many of the European experts he used to authenticate pictures. Within a year he had a fat file of experts' opinions, all condemning the American Leonardo as a copy.

Armed with this information but confronted by the possibility that any attribution or opinion based on photographs would be challenged by Ringrose, Duveen decided on a publicity coup. He would ship the American Leonardo to Paris, take it to the Louvre, and place it next to the French *Belle Ferronière*. His experts would then evaluate the two pictures. The plan was not easy to accomplish. The

Louvre, as one might expect, was not happy about this stunt, and it required all of Duveen's clout to allow the highly publicized comparison to take place. The Hahns wanted a fat fee (they got $2,000 and all expenses) to allow the picture to go. But in 1923 Duveen overcame all obstacles, and assembled a star-studded panel of 10 experts to examine the pictures. These included Bernard Berenson, the most famous art connoisseur of the day; Roger Fry, artist and Bloomsbury denizen who had been curator at the Metropolitan Museum of Art in New York; and the directors of the London National Gallery, the Irish Free State Museum in Dublin, the Imperial War Museum, and the Rijksmuseum in Amsterdam. A number of well-known amateur experts on Renaissance art, such as Maurice Brockwell and Sir Herbert Cook, also testified, together with one scientist, Arthur Pillans Laurie, professor of chemistry at Heriot-Watt College in Edinburgh, who was not on Duveen's original list but had volunteered his services. As the *New York Tribune* put it: "Such a confluence of eminent authorities on art as was never seen before on land or sea filed within the sacrosanct enclosure of the Louvre this morning." The experts were interrogated by lawyers from both sides, and a huge transcript of their deliberations was returned to New York for submission at the trial. Almost without exception they denied that the Hahns' picture showed the hand of Leonardo.

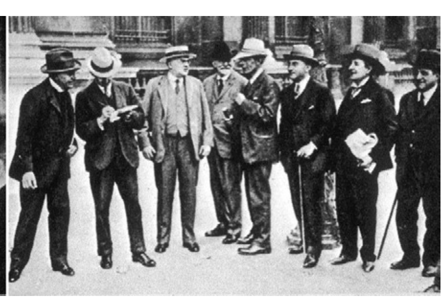
The case dragged on a further six years. Duveen seems to have expected the Hahns to settle or withdraw from the case, but they felt, as it turned out quite rightly, that they had made serious inroads into Duveen's experts' testimony. As Mr. Hahn commented to the *New York Herald*, he "did not consider that the European experts' opinion would hold much weight with the American jury." Eventually the case came to trial in the supreme court of New York in February 1929. A jury of ordinary New Yorkers—including two real-estate agents, a hotel receptionist, and a vendor of women's wear—had to decide on the authenticity of the American Leonardo. No juror had any pretense to art connoisseurship or expertise.

The trial lasted for six weeks and ended with a hung jury: the press revealed that nine of the jurors were in favour of Mrs. Hahn and her picture, with only three on the side of Duveen. Shortly before a retrial was to take place, Duveen settled out of court for the not-inconsiderable sum of $60,000 plus legal expenses.

As I have emphasized, the struggle between Duveen and Hahn was carried out as much in the newspapers as in the courtroom. No art case was ever more extensively reported. In an age which was far more richly endowed with newsprint, stories ran not only in the big-gun newspapers of New York, but in almost all the major cities in the United States, as well as many, many smaller towns. In Europe the French, Italian, and German press, but above all the papers in Britain, carried extensive coverage. Copies of the two pictures were displayed in Midwestern department stores, and Macy's sold versions of the picture—"we admit it's a copy"—for $17.95. There were huge queues of people wanting to attend the trial, and papers reported that in the final days, before the verdict, the courthouse was filled with the cream of New York society, or, as the *New York World* put it, "Boiled Shirt Gallery Waits Verdict of La Belle Jury."

Why was the case of such extraordinary interest? To understand this, we need to backtrack a moment and look at what was happening in the art market in the 1920s, and how the work of Leonardo fitted within it. The case happened during what was the art market's greatest ever peacetime boom. The emergence of new wealth in post–Civil War America, particularly during the Progressive era, together with the decline of wealth in Europe radically transformed the global market for

A courtroom scene during the trial.



Duveen gathered his experts together at the Louvre so they could examine both versions of *La Belle* side by side. (Courtesy of the *Illustrated London News* picture library.)

Old Masters. In the late 19th century European agricultural rents collapsed as cheap grain imported from the United States produced a precipitate fall in food prices. The flower of the British and European aristocracy, the holders of most of the continent's cultural treasures, faced mounting debts and possible insolvency. The Europeans disgorged their cultural riches, and the American millionaires, helped by Duveen, bought them. A list of these rich American collectors—one that included Cornelius Vanderbilt, J. P. Morgan, Isabella Stewart Gardner, Benjamin Altman, Peter and Joseph Widener, Henry Walters, Henry O. Havemeyer, William Randolph Hearst, Henry Clay Frick, Henry Huntington, Samuel H. Kress, and Andrew Mellon—is an inventory of the triumphs of American capitalism in coal, iron and steel, retailing and banking, communications, and transport.

The scale of this collecting was unparalleled. When J. P. Morgan died in 1913 his artworks were valued at some $60 million. Benjamin Altman, who also died that year, left paintings worth $20 million. William Randolph Hearst was spending about $5 million a year at the peak of his collecting. And Samuel H. Kress amassed 3,210 works

Sir Joseph Duveen waits to go into the New York courtroom at the start of the trial.

of art. But these famous, often obsessive collectors, the men and women Duveen liked to work with, were only the most visible manifestation of a much broader phenomenon in which America's wealthy citizens appropriated the cultural treasures of Europe, decorating their houses in what is best described as plutocratic pastiche.

At first other rich collectors, notably the European and English branches of the Rothschild family, took part in this spending spree, but by the decade before the First World War all the top prices were paid by Americans. The tremendous competition among the American superrich for a relatively small number of high-prestige works pushed their prices higher and higher and shaped a market that soon became the object of prurient curiosity in the public at large. These developments were reported in the American press in a very particular way. They were patriotically portrayed as a consequence of a distinctive American, entrepreneurial style of collecting carried out by businessmen (the many female collectors, including Isabella Stewart Gardner, were generally overlooked) who were able to outbid and outwit European owners and collectors, using their modern superior business acumen and experience. This was depicted as a very American phenomenon; there was no suggestion, for example, that these collectors might be aping the manners and lifestyles of European aristocracies and merchant elites.

At the same time, a new body of experts emerged, self-anointed connoisseurs, whose arcane skills could be used to manipulate the market. These experts were viewed suspiciously by the American press, because, although they were necessary to authenticate works, they were also in a position to deceive collectors and the public. They were the gatekeepers between commerce and transcendence, or the alchemists who transmuted art into gold. The connoisseurs determined the authenticity of the art object and thereby transformed it into a commodity. And the volatility of the market—shifts in prices and fashions—was blamed on them.

Duveen was strongly associated with this new vision of American collecting. He assiduously cultivated the most important—that is, wealthy—collectors, bought many of their greatest treasures, and tried hard to monopolize their business, seeking to keep them away from rival dealers. Working with monopoly capitalists, he publicly portrayed himself as the monopolist of great Old Master art. He liked to project an image of total power. Even as he copied their business practices, Duveen persistently maintained the fiction to his clients that price was not important—that it only mattered to have the best—even while the publicity about the market was all about dollars and cents. He played on the idea that what was being bought had a certain transcendental value that was humanly universal, eternal, unbounded, and beyond the quotidian, a value whose commercial worth was determined by the fact that it wasn't commercial but an expression of the human spirit. You cared about attribution because you wanted to be sure you were buying a Leonardo. But you bought a Leonardo because it was agreed to be one of the highest forms of human expression. You were buying something mysterious, wonderful, and intangible. The power of the collector lay in magnanimously making this experience available to a larger public.

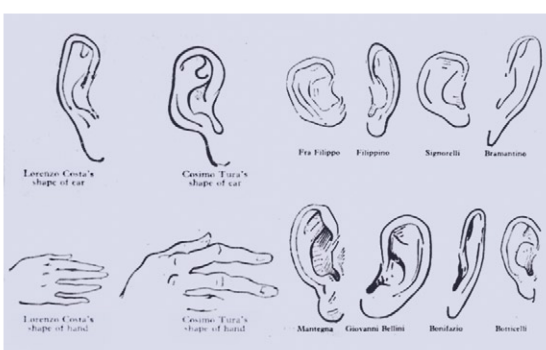
Leonardo seemed eminently well cast as the forefather of the engineers, designers, and businessmen who were transforming the United States into the world's greatest industrial power.

The high end of the art market concentrated on a relatively small number of painters. Roughly speaking, this Olympian clan included the Italian artists discussed in the first major history of art, Giorgio Vasari's 1550 book *Lives of the Artists*, led by Michelangelo, Raphael and Leonardo; a few Dutch and German artists, notably Rembrandt, Rubens, Vermeer, Hals, and Holbein; a cluster of British portraitists, especially Reynolds, Gainsborough, and Romney; and a few southern Europeans like Velázquez and El Greco. Wealthy collectors did not want Old Masters, or high-quality old pictures; they wanted works by great artists. They wanted not just an artwork but a piece of cultural capital, one that enabled them to share in the experience of the creator's genius.

Because the art object's allure rose from its expression of the genius of the artist, the key sign of a picture's worth was the hand of the master. Publicly, at least, the assumption was that there were three types of art on the Old Master market: originals (bearing the sole hand of the master), copies (acknowledged), and fakes (works of deception). Experts were aware of a more complex picture connected to workshop practices and collaborative or divided labor, but there was a constant pressure on them to push works into a positional relationship to "the original."

Leonardo in particular had both universal appeal and a special place in America. His star had waxed in the 19th century, as he came to be identified as a thoroughly modern man. The Brooklyn *Daily Eagle* described him as "the best-balanced genius in human history. He was painter, military engineer, courtier, politician, mechanical inventor," adding that he was "the Edison, (Panama Canal) Goethals, and Sargent of his Time." Leonardo seemed eminently well cast as the forefather of the engineers, designers, and businessmen who were transforming the United States into the world's greatest industrial power. His masculine image (no hints of his homosexuality here) was complemented by his reputation as the painter of the eternal feminine. By the late 19th century he was best known as the creator of the *Mona Lisa,* the portrait of an enigmatic woman that was probably the most famous painting in the world.

But Leonardo's work also had a particular association with forgery and copying. One of the most notorious Leonardo fakes was the *Profile of a Maiden*, owned by none other than the father of modern connoisseurship, Giovanni Morelli, and bequeathed by him to a friend, Donna Laura Minghetti. Like the Hahns' *Belle* some years later, the Minghetti portrait was taken to the Louvre, and also examined by experts in London. Bernard Berenson authenticated the work, and it was sold to an American collector, Theodore Davis. Yet by the second decade of the 20th century it had been exposed as a fake, executed by a 19th-century Italian sculptor and restorer of pictures named Tricca. This discomfited Berenson, who dropped all mention of the picture but remained prominent in the growing literature that voiced misgivings about the number of fakes on the market. Nor was this the only case. The most sensational Leonardo story of all, the theft of the *Mona Lisa* from the Louvre in 1911 by an Italian painter-decorator, and its recovery two years later in Florence, led a whole series of owners to claim that their version of the *Mona Lisa* was the original, and the recovered work a copy. In 1926, during the period of Hahn versus Duveen, there was a major panic in France when an American art dealer showed what he claimed to be the true *Mona Lisa*. Hundreds of French



Giovanni Morelli revolutionized connoisseurship in the late 19th century by using anatomical features, such as the shape of the ears and hands, to identify the artist.

Bernard Berenson, an American of Lithuanian origin, lived in gentlemanly style in a villa near Florence, and promoted himself as a discerning connoisseur of Italian Renaissance art. He is shown here contemplating the Canova sculpture of Pauline Bonaparte, Napoleon's sister, in the Borghese Gallery, Rome.

citizens thronged into the Louvre to ensure that "their" *Mona Lisa* was still there.

The case of Hahn versus Duveen not only raised questions about the authenticity of a particular (and potentially extraordinarily valuable) picture, it raised, in stark terms, the question of whether the 20th-century art world was to be governed by the aesthetic opinions of a self-anointed elite of connoisseurs, or by the rigorous strictures of modern science. Duveen set out to vindicate not only his condemnation of the Hahn picture, but the entire system of attribution and connoisseurship on which his hugely profitable business depended. In the five days at the beginning of the trial when he was cross-examined by the Hahns' lawyer S. Lawrence Miller, he went to great lengths to disparage the Hahn Leonardo, commenting on its ugliness and poor execution, and also devoted a great deal of time to instructing the jury and the general public on how to judge pictures.

He emphasized the role of longtime experience and acquaintance with great pictures, the importance of first impressions in viewing a work, and the power of the connoisseur to discern the hand of the artist just as a reader can recognize the handwriting of a friend. His views were borne out by the defense's evidence—both the experts' views recorded in Paris and the testimony of connoisseurs in court. Sir Martin Conway, one of Duveen's English experts, justified his rejection of the Hahn picture by saying, "I simply look at the Hahn picture and the impression produced on my mind is that it is not by Leonardo." Maurice Brockwell said, "[I]t is a question of psychology, not of the magnifying glass; it is the mind of the great master that we see, the spiritual content, the psychological correlations." Another of Duveen's experts, the Irishman Robert Langton Douglas, described his use of "constructive imagination." Berenson spoke of the importance of "accumulated experience upon which your spirit acts almost unconsciously." The first look was what established the attribution. Though Berenson (and others) looked to the techniques of his mentor Giovanni Morelli—using small details such as ears and fingers to make attributions—this technical work was always subordinate to a powerful first impression in attributing pictures, and to what Berenson himself described as "a sixth sense." The subsequent gathering of evidence was merely a coda, a corroboration of a view that had been made by the expert's eye.

These connoisseurs had a good deal invested in presenting themselves as aesthetes and persons of refinement, part of a long gentlemanly tradition of amateur and socially distinguished critics of art. No one knew this better than Bernard Berenson, known as B.B., who was widely regarded as the most discerning connoisseur of Italian renaissance art. After 1912, B.B. was regularly used by Duveen, who paid him a whopping 25 percent of the profit on works he expertized, and that Duveen subsequently sold. B.B.'s authority as an expert undoubtedly came from his exceptional "eye," but it was reinforced by his self-presentation as a gentleman of refinement, and his manner of living at his villa, I Tatti, in Settignano outside Florence.

Like Berenson, most of the connoisseurs were self-taught, and had no expert qualifications or formal training. There was no sense of belonging to a professional group with a career path, qualifications, institutional grounding, and accepted standards of conduct and competence. When Duveen's lawyer, Louis Levy, drew up a list of questions asking about the qualifications of the Paris experts, he was told that most would not answer because they found such questions impertinent and ungentlemanly. Even when the witnesses agreed over the Hahn picture, they could not resist disparaging one another, questioning the skills of colleagues in a way that played into the hands of the Hahns' lawyers. This mirrored the many personal and critical disagreements by which this art world was riven. As Douglas commented during the trial, "Experts fight like cats and dogs."

They were deeply hostile to technical tests, forensic investigation, and archival research, regarding it as ungenteel, too scientific, and too academic. Sir Martin Conway testified that he had "no interest in technique or the way that a great master paints, whether he paints with wax or oil." When Duveen's lawyer suggested they use an X-ray expert to support them, Duveen wrote: "I would rather not have X-ray evidence introduced into the case. I do not believe in it, and if I am asked on the stand if I approve of X-rays, I shall frankly say 'No.'" Berenson repeatedly poured scorn on technical knowledge of pigments, X-rays, and chemical analysis as matters beneath a gentleman connoisseur. Here is a typical exchange during the cross-examination by Hyacinthe Ringrose:

HR: There is a picture in the Prado labeled da Vinci?
BB: Yes.
HR: Is it not by Leonardo da Vinci?
BB: No.
HR: Have you ever seen it?
BB: Yes.
HR: Is it painted on wood or canvas?
BB: On wood, to my recollection, but I may be mistaken. That is not interesting. It is not interesting on what paper Shakespeare wrote *Hamlet*.

Sterling & Francine Clark Art Institute Library, Williamstown, MA.

The writing below this photo of the Hahn *Belle* says: "This is the photograph to which I refer in my letter of January 16, 1922—in which letter, I explain my solemn conviction that the portrait here reproduced is not by Leonardo da Vinci. R. Langton Douglas, director of the National Gallery, Dublin."

Or again:

HR: Now, do you know with what oil he mixed his pigments?
BB: No.
HR: Didn't he say in his book *Trattato della Pittura*, which you say you read, that he painted all his pictures with a mixture of walnut oil and not with linseed oil?
BB: I will take your word for it, it is of no interest for me.
HR: Can you tell me the difference between a picture painted in walnut oil and linseed oil?
BB: I certainly can't, and I defy you to do so, too. It is all perfect humbug.

As one of the Hahns' lawyers later wrote, "Practically all of the defendant's witnesses knew nothing about pigments or technique, essential elements in the equipment of any real expert." Imagination, used by most of Duveen's witnesses, frequently read into a painting something which was in their mind only and not visible in the painting, such as "psychological correlation, sixth sense, and rhythmic coordination." This sort of wordsmanship worked well in the intimate surroundings at I Tatti or in the dark shadows and warm lights of Duveen's showrooms when the rich collector, the dealer, and the expert huddled round a picture. But as Duveen and his experts were to find out, connoisseurship looked a lot less convincing in the harsh light of a courtroom, where the facetiousness, flippancy, and arrogance of the experts—R. Langton Douglas, for example said, "Frenchmen know nothing about painting and there are no authorities in the Louvre"—did not come over well.

The Hahns' lawyers were also able to show that Duveen's experts had changed their minds. Many of them had once publicly acknowledged that they did not see the Louvre's *Belle Ferronière* as a work by Leonardo. The history of the attribution of the Louvre picture is complex, but for our purposes it is enough to know that received wisdom in the early 20th century was that the work was either of the Milanese school or the work of Leonardo's pupil Boltraffio. Yet in the courtroom nearly all of Duveen's experts, with only one doubter, confirmed that the Louvre picture was definitely by Leonardo. Their firm attribution, exposed in court as a sharp change of mind, fed the accusation that the experts were kowtowing to Duveen's wishes. And though there is no evidence of Duveen's direct intervention, it is hard to explain the change in expert opinion (which then later shifted back to its earlier position), except as a defensive response to the public attack on conventional connoisseurship. Nor was the situation helped when the Hahns' lawyers exposed the often long-standing financial arrangements that Duveen had had with his experts, paying them for their attributions and opinions.

Of course the point at issue in the trial was the authenticity of the Hahn picture, not the work in

Between 1936 and 1945, Dutch artist van Meegeren embarrassed art experts and museum directors with his Vermeer forgeries, many of which ended up in renowned collections. His *Lady and Gentleman at a Spinet,* right, was purchased by a wealthy Amsterdam banker. In 1968, measurements of uranium-226 and lead-210 levels in the white paint used in the suspect Vermeers showed conclusively that they had been painted less than 50 years ago, rather than in the 17th century.

the Louvre, but Duveen had claimed that it was his sure knowledge that the Paris picture was the original *Belle Ferronière* that enabled him to dismiss the Hahn picture without ever having seen it. This was in response to the accusation of the Hahns' counsel that "to call the painting a fraud without ever seeing it was reckless, and that is proof of malice," for the Hahns had to demonstrate not only that their picture was genuine, but that Duveen's condemnation was irresponsible and malicious. To that end they were greatly helped by a letter Duveen wrote in August 1920—before the conversation with the *New York World* reporter that led to the lawsuit—in which he had said, "The Louvre painting is not passed by the most eminent connoisseurs as having been painted by Leonardo da Vinci, and I may say that I am entirely in accord with their opinion."

The basis of the Hahns' prosecution could not have been more different from Duveen's defense. They depended on the analysis of pigments, the use of X-rays, and the painstaking recovery of the picture's provenance. Harry Hahn contrasted "the air-spun conjectures, subjective guessings, sixth-sense flairs, and, in certain instances, downright dishonesty produced by members of the Duveen clan" with "reliable historical documentation" founded on the "objective and scientific nature of accurate historical research."

The use of science and history to expose the feebleness of connoisseurship was, I want to stress, a radical move, though it may have been forced on the Hahns because they had great difficulty in securing the support of art experts, beyond the one French official who had attributed the picture to Leonardo back in 1916. Their only expert witness at the trial, a Russian named Chernoff, was a painter and an expert in pigments. But using pigment analysis and X-rays was bold and innovative, not least because such scientific analysis was in its infancy. Today, of course, there are a variety of techniques, used routinely in such conservation labs as that at the Getty, that enable scholars to date a work of art and learn not only of what materials it is constructed but of the processes by which it was made. The use of ultraviolet light, infrared analysis, X-rays, polarized light microscopy, carbon dating, and autoradiography, in which pictures are exposed over time to low levels of radiation in a nuclear physics laboratory, can all reveal a great deal about a picture and make it extremely difficult for any forger to succeed. Thus the famous van Meegeren forgeries of the 1930s and 1940s that bamboozled Vermeer scholars were conclusively shown to be fakes by a dating process based on the proportion of a certain lead isotope in the lead-based paint. Nowadays it is even possible to identify different hands in a work using high-resolution digital scans.

But even today, with much more sophisticated technology, experts, including those who are especially skilled in using these scientific techniques, warn of the limits of this type of investigation. As the late Walter McCrone, the analyst who claimed the Shroud of Turin is daubed with 14th-century pigments rather than Christ's blood, emphasized, analytical techniques cannot demonstrate that a work is by a particular artist, though they can prove that it is not. They can refute but not demonstrate an attribution.

Moreover, the effective use of such techniques is not merely a matter of technology, but depends on the art-historical knowledge and technical experience needed to interpret the scientific results obtained. This became very clear in the Hahn trial. The Hahns used X-rays to sustain their claim that their picture had been cut off at the bottom when it had been transferred from wood to canvas in 1777.

X-ray of the Louvre *Belle*, made by a young Harvard graduate student.

But the only X-ray expert they could call was a medical radiologist—a doctor—with no knowledge of pictures, and when Duveen, against his better judgment, countered with an X-ray of the Louvre *Belle Ferronière*, his expert was a young researcher and graduate student from Harvard University. In 1923, when the Hahn picture went to the Louvre, there was no scientific laboratory attached to the museum, and it was only in the 1930s that labs began to open in the major museums.

Ironically, the most systematic scientific examination of the Hahn and Louvre pictures was carried out by one of Duveen's experts, Professor Laurie, though as I have stressed, he pressed his services on Duveen, and the dealer was not always sure that his contribution was especially helpful. Laurie was the author of two studies, *Materials of the Painter's Craft* (1911) and *Pigments of the Old Masters* (1914), but his art-historical knowledge was confined to Dutch and British art of the 17th and 18th centuries. As befits a scientist, he was extremely cautious. In Paris, after examining both pictures with a microscope and failing to find what he called "dating pigments" that would prove the pictures to be later works or copies, he "would not testify as to who painted either . . . nor did he pretend to be an expert on technique and did not want to be drawn into artistic questions." But what he did say, which was seized upon by the Hahns' lawyers, was that the Louvre picture contained "neither lapis lazuli, vermilion, Naples Yellow, or a non-fading green, which were the finest and most prized paints," and that "the red ochre used in the bodice is termed barn painters' paint." He further stated that "the greens are verdigris crystals which have faded." Compared with the pigments used in the Hahn picture, the lawyers claimed, "the paints . . . are of the most ordinary and inferior kind, and not such as would be used by a master in da Vinci's time."

The Hahns' efforts to discredit traditional connoisseurship and the sort of highfalutin claims it made were remarkably successful with both the judge and jury. Justice Black, who had a lawyerly sense of hard evidence and a strong commitment to proof on the basis of facts, was withering, both in the court and in his written opinion, about Duveen's experts. "It required," he remarked, "some mental agility to follow some of the experts from their positive testimony on the stand to the diametrically opposite views they had expressed in their books long before." "Beware experts," said Black to the jury. "Because a man claims to be an expert does not make him one . . . I have profound respect for critics whose conclusions rest upon facts . . . the opinions of any other kinds of experts are as sounding brass and tinkling cymbals. Some of them expound their theories largely by vocal expression and gesture; others wander into a zone of speculation founded upon nothing more tangible than 'psychological correlation.' I do not say that this is as absurd as it sounds to the layman, but it is too introspective and subjective to be the basis of any opinion a jury can pin its faith upon."

The attack on connoisseurship and the rather bold commitment to science on the part of the Hahns had a political and patriotic dimension. The Hahns' counsel portrayed the struggle with Duveen as a conflict between the little man, a Midwesterner and an American (bear in mind that Hahn ran a car dealership), and the rich, cosmopolitan, European monopolist. Headlines like that in the *Indianapolis Star*—"Lad from Kansas Corn Belt Starts Fight that Jars Art World"—were common. Throughout the press there was much talk of American common sense and Midwestern levelheadedness.

Because the trial ended with a hung jury and an out-of-court settlement, the struggle between the Hahns and Duveen resulted in an unsatisfactory

stalemate. Duveen later conceded he was much distressed by the case, and he seems to have courted publicity thereafter through visible and uncontroversial acts of philanthropy rather than bruising and spectacular litigation. Berenson, as his wife explained to Duveen, felt horribly wounded and exposed. The case, written up in Harry Hahn's *The Rape of La Belle,* published in 1946, remains a key piece of evidence for a populist conspiratorial view of the art world.

The Hahns won an agreement that Duveen would not make any more comments on the picture, but the power that he and the experts still exerted on the art market meant that the American *Belle* remained unsold. Subsequent attempts up to the present to sell the picture have foundered, not least because of the reluctance of experts to give a public opinion on the status of the work. (The Hahn family continues to speak of an art market conspiracy.)

The events of the 1920s point to an important moment in the history of the Old Master art world, one in which, for the first time, connoisseurs and experts had to deal with the claims of a more scientific investigation of paintings. The response of these experts was typical of many who face a new way of looking at the world, both dismissive—claiming such new insights to be worthless—and defensive—fearing the intrusion of different methods into a well-established field of humanist scholarship. The Hahns' enthusiasm for science may have been tendentious, a trifle naïve, and in many ways premature, but it pointed towards the sort of connoisseurship that was to develop in the future and has become conventional today—one in which the accumulated visual acuity and art-historical experience of the humanist scholar works with, rather than against, the precise findings of the scientific investigator to produce a richer and more complete knowledge. Isn't that just the sort of collaboration that a humanist teaching at Caltech should applaud? □

After earning his BA ('68), MA ('72), and PhD ('73) in history at the University of Cambridge, John Brewer taught there for three years before moving to Yale and then Harvard, where he was a professor of history and of history and literature from 1980 to 1987. He then moved to UCLA, where he was, simultaneously, a professor of history, the director of the William Andrews Clark Memorial Library, and the director of the Center for Seventeenth- and Eighteenth-Century Studies. The European University Institute in Florence offered him a chair in cultural history in 1993, and he taught there for six years before returning to the U.S. in 1999 to take up the Sullivan University Professorship in English and History at the University of Chicago. In 2001 he came to Caltech as a Moore Distinguished Scholar, was persuaded to stay, and is now the Broad Professor of Humanities and Social Sciences and professor of history and literature. Brewer is one of the leading historians of eighteenth-century Britain, although his interests range much further, and include European cultural history, the history of social science, the history of consumerism, and, most recently, art markets and values. The author of many books, his Pleasures of the Imagination: English Culture in the Eighteenth Century *was awarded the Wolfson History Prize. The Watson lecture on which this article is based, given on April 13, can be viewed on the Streaming Theater website, http://today.caltech.edu/theater/.*

Olfaction: A Window into the Brain

by Gilles Laurent

On the facing page, postdoc Glenn Turner (PhD '00) savors the aroma of a fresh cup of coffee. As the many different volatile chemicals in coffee waft into his nose, the olfactory receptors detect tens to hundreds of them, but his brain doesn't let him know it, because by a two-stage process of pattern recognition, his brain reconstructs this complex blend into one percept, "coffee." At the top of this page are some of the odors used in the Laurent lab.

Smell is an "old" sense. In primates, including humans, olfaction has been overtaken by vision, but it has kept its ancient connections to the emotional parts of the brain. In this article, I will try to summarize some of what we know about the inner workings of the olfactory brain, and the possible implications for our understanding of the nature of memories.

Natural odors often contain tens and sometimes hundreds of different types of molecules. The volatile oil secreted by scent glands inside a ranunculus flower, for example, contains 3,4,5-trimethoxytoluene, 2-phenylethylacetate, dimethyl salicylate, ten fatty-acid derivatives, six benzenoids, and much more besides. The smell of freshly ground coffee is a cocktail of 200 to 300 volatile components. And perfumes—man-made fragrances—are complex mixtures of both animal and plant oils or their synthetic analogs. Yet we perceive these odors as single entities—"ranunculus," "coffee," "Chanel No. 5." And having bound them into single entities, it's very hard for our brains to dissect out the chemical constituents again. This was demonstrated in 1998 by two Australian scientists, Andrew Livermore and David Laing, who prepared eight bottles of odors, the first of which contained one odor component, the second a mixture of two components, and so on, and asked people to smell each bottle and identify the components. Fifty percent got it right when there was just one component, but the success rate dropped to 15 percent with two components, and 4 percent with three, while with four components or more, no one could dissect out any of the odors. Even "Noses," people who design complex odors such as perfumes, fared no better.

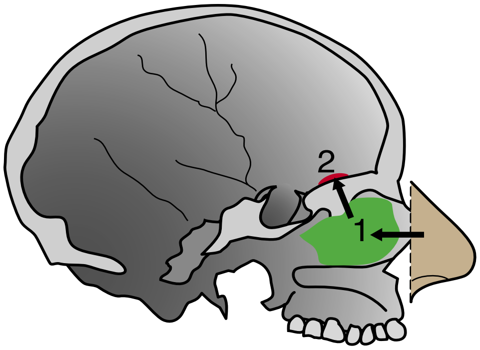
This illustrates a key aspect of olfaction. It's a "synthetic" sense that puts many disparate chemicals, each with its own associated percept, or sensory impression, together into a singular percept from which the components cannot be dissected out. Olfaction has another interesting property, common to the other senses also: the perception of an odor usually varies little over a wide range of intensities. If you smell jasmine at a variety of different strengths, you still identify it as being the same thing, jasmine.

We call this property concentration invariance. The way the brain forms singular and invariant percepts from very complex stimuli, such as chemical mixtures, is a fundamental pattern-recognition problem. Brains solve pattern-recognition problems much better than any machine built today. Sensory neurobiology, which is what we do in my lab, helps us understand how brains solve these problems.

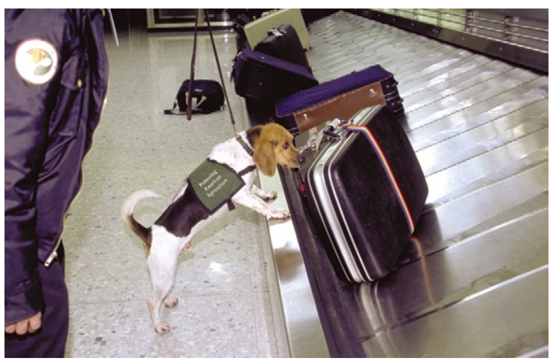
Complex chemical mixtures are not the only odors animals deal with. There are other kinds of smells used by animals as signals for very particular purposes, such as cues to locate food sources. The life cycle of the female malaria mosquito, *Anopheles gambiae*, for example, depends on one meal of human blood, and it locates its prey—us—by detecting a single chemical, 4-methylphenol, that is present in our sweat, but whose concentration varies between one person and another. This is the opposite of the way "general" odors are perceived: the mosquito seeks just one particular component within a complex smell.

There are also smells, often referred to as pheromones, that convey information between members of the same species. Octyl acetate is one such example; released by honeybees from a gland in their abdomen, this odor orients other bees to the location of their hive, and bees drop some in the flowers they've visited so that other bees are guided to the food source. Sex pheromones are another example. In animals from worms to elephants, they're secreted by one sex to attract the other, and can be detected in minute amounts over very large distances.

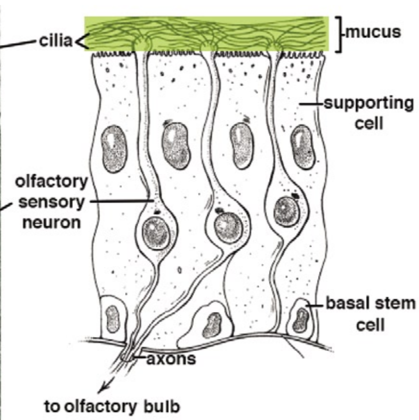
So the olfactory sense is quite complex. At one extreme, mixtures of hundreds of components are perceived as single odors, while at the other extreme, specific signals that are very simple chemi-



Above: In humans, odors are detected by neurons lining the nasal cavity (1), and processed in the olfactory bulb (2). Right: Dogs owe much of their olfactory superiority to the turbinate bones at the back of the nose. (Old English sheepdog skull courtesy of the Mammalogy Section, Natural History Museum of L. A. County.)



USDA beagles are trained to sniff out fruit from airline passengers' luggage to prevent the accidental introduction of harmful fruit flies into California. Neurobiologists like fruit flies, citrus growers don't. (Photo: Ken Hammond, USDA.)



L. Buck & R. Axel, *Cell*, 1991, 65, 175-187, with permission from Elsevier.

The proteins that catch odor molecules are in the membranes of cilia sprouting out of the top of receptor neurons. One neuron that has slipped down from its supporting cells is shown above, with the head magnified 17,500 times in the inset. Intact neurons still embedded in the epithelium have even more cilia. (SEMs courtesy of R. M. Costanzo, Virginia Commonwealth University.)

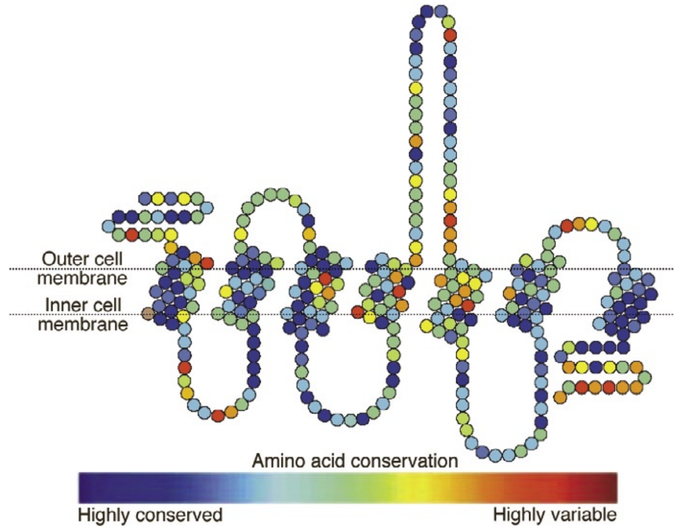
cally can be perceptually extracted from a complicated context. How do our brains make sense of this kind of chemical world?

The odor detection pathway begins in our nose, when we breathe in. Air goes into the nasal cavity, and affects a large population of receptor neurons—specialized nerve cells—embedded in a nasal epithelium, or mucosal layer, that carpets bony structures at the rear of the cavity. These bony projections are called turbinates, and they greatly increase the surface area of the nasal epithelium, and hence the number of receptor neurons. Turbinates are particularly well-developed in dogs, which explains in large part why dogs are so good at detecting odors. In a medium-sized dog, the turbinates have a total surface area the size of a large pizza. In humans, they're the size of a large cookie.

Growing out of the ends of the receptor neurons, and projecting into the nasal cavity, are many hairlike cilia. These lie in a layer of mucus—one with which we're all intimately acquainted—to stop them from drying out. The cell membranes of these cilia contain specialized receptor proteins. Odorant molecules in the air bind to these receptors and start a series of reactions that transform the chemical signal of the odor into a set of electrical signals that the brain can deal with.

In 1991, Linda Buck, working in Richard Axel's lab at Columbia University, identified the molecular structure of these receptor proteins, a discovery for which the two scientists were awarded the 2004 Nobel Prize in Physiology or Medicine. Many people had spent years trying to identify the olfactory receptors without success, but Buck decided to narrow her search of the genome to genes for G-protein-coupled receptors—a large receptor family characterized by a looped protein chain that crosses the cell membrane seven times—because they were already known to be receptors for some of the other senses, and for certain chemical neurotransmitters. She also hypothesized that these kinds of receptors would have a large number of variants,

The G-protein-coupled odorant receptor protein is a long chain of amino acids that loops seven times through the cell membrane. In this diagram, the amino acids have been colored according to their variability in the many types of this receptor protein. It's thought that odor molecules bind in one of the pockets formed where the chain crosses the membrane.



P. Mombaerts, *Nature Reviews Neuroscience*, 2004, 5, 263-278, adapted from A. H. Liu *et al.*, *Genomics*, 2003, 81, 443-456, with permission from Nature Publishing Group & Elsevier.

to detect many different odor molecules, and that they would be present at high density in the olfactory epithelium and nowhere else. Using this logic, and a lot of hard work, Buck finally identified the olfactory receptors.

We still don't know the three-dimensional structure of these receptors, but we can make educated guesses based on the known structure of related proteins. We think that some of the loops that cross the membrane may form little pockets in which the odorant molecules find binding sites. When they bind, the receptor protein probably changes shape, and this sets up a cascade of molecular events that ends with the generation of electrical impulses for signaling to the brain.

Although Buck and Axel had expected to find a lot of variation in the gene sequences of these receptors, they were still astonished at what they found. In parts of the looping receptor protein chain, the order in which the amino acids are strung together is so variable that some animals, such as the rat, have over 1,200 different receptor types. On average, mammals have about 1,000 types, fish and birds between 100 and 200, roundworms (*Caenorhabditis elegans*) 1,000, and fruit flies 60. Humans have only 600 different odorant receptor genes, but almost half of these are "pseudogenes" that no longer function, leaving us with only 350 receptor types in our nasal mucosa.

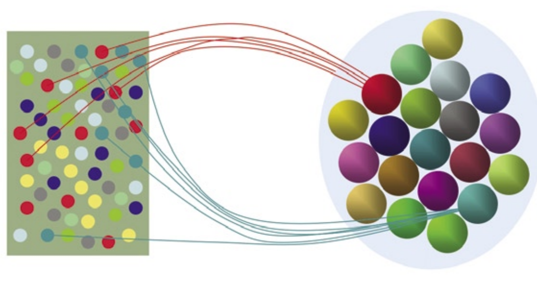
It's still much more than the receptor types found in other senses. Our sense of vision, for example, uses only four types of photoreceptor, and three of these have very slightly different sensitivities to wavelengths of light so that we can see color. (The largest number of photopigments known so far in a single eye is about 12, in the mantis shrimp.)

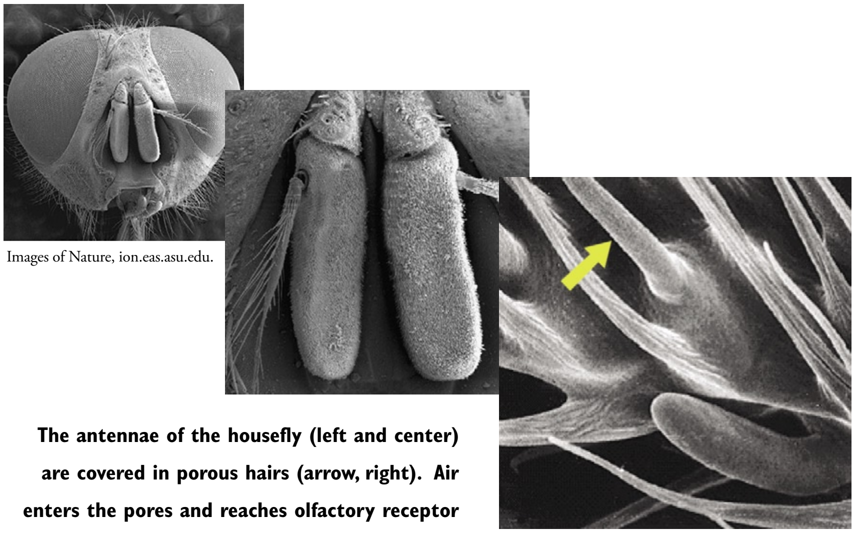
Interestingly, when the receptor genes of mammals, flies, and worms were compared, no sequence homology was found. In other words, the genes had probably not evolved from a common ancestor: different types of animals had come up with their own particular (but related) designs for olfactory receptors independently throughout evolutionary history. Such convergent evolution, as it's called, happens a lot in biological systems. The single-lens eye design, for example, has evolved independently at least eight times in the animal kingdom.

(As an aside, the system that generates responses to pheromones is in another region of the nose called the vomeronasal organ, and this organ sends its output to a different part of the olfactory bulb. The vomeronasal system also has a large number of G-protein-coupled receptor types, about 300 in mammals, that are separate from the ones that deal with other odors. But that's for another article.)

Individual receptor neurons in the cilia of the nasal epithelium express, or turn on, only one type of receptor gene. This implies that each receptor neuron, in principle, has a single sensitivity, given to it by the order of the amino acids in its receptor protein. Receptor neurons that express the same gene are sprinkled around the nasal epithelium in a fairly random fashion within large, overlapping "zones." All these neurons send their axons to the olfactory bulb, where they terminate in ball-shaped structures called glomeruli. But here's the surprise—all axons of the same receptor type converge on the same glomerulus. By implication, this means there are about as many glomeruli as there are receptor types. And with the exception of the roundworm, this extraordinary organization is

In an amazing feat of organization during development, each type of receptor neuron, near right, sends its axon to the same glomerulus, far right.



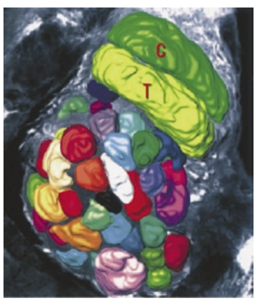


Images of Nature, ion.eas.asu.edu.

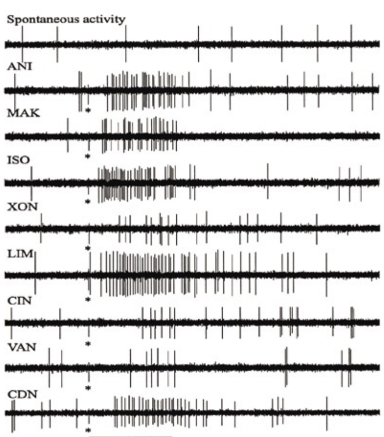
The antennae of the housefly (left and center) are covered in porous hairs (arrow, right). Air enters the pores and reaches olfactory receptor neurons at the base of each hair.

J. Riesgo-Escovar *et al.*, *J. Comp. Physiol. A.*, 1997, 180, 151-160 by permission of Springer Science & Business Media

R. Kanzaki *et al.*, *Chemical Senses*, 2003, 28, 113-130, Oxford University Press.

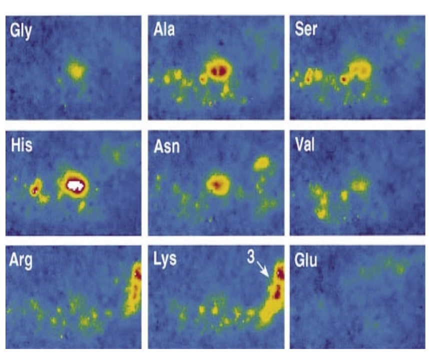


This male silkmoth's glomeruli, packed into the antennal lobe, have been individually colorized. The big ones labeled C and T are part of the pheromone system.



Reprinted with permission from P. Duchamp-Viret *et al., Science*, 1999, 284, 2171-2174. © 1999, AAAS.

Left: The top row is an electrical recording from a resting rat olfactory receptor neuron, while each row below corresponds to a different odor given for two seconds to the same neuron. All the odors caused a change in the firing pattern, but in different ways.
Below: In the zebrafish olfactory bulb, different subsets of glomeruli fluoresced on receiving impulses from the receptor neurons in response to nine odors—in this case, amino acids.



R. W. Friedrich & S. I. Korsching, *Neuron*, 1997, 18, 737-752, with permssion from Elsevier.

found in almost all the animal species that have so far been looked at.

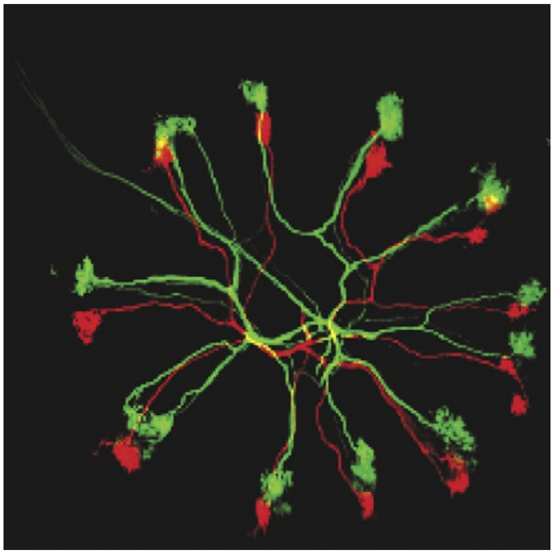
Much of the work in my lab is focused on insects, whose equivalent of a nose is a pair of antennae covered in porous hairs. These pores allow air to diffuse in and reach sets of receptor neurons at the base of each hair. The total number of receptor neurons depends on the species of insect, but some very olfactory insects such as moths can have several hundred thousand. The fruit fly *Drosophila melanogaster* has 1,300 in total, which express 60 different receptor types. The output of the receptor neurons goes to the antennal lobe, a structure analogous to our olfactory bulb, and terminates in about 45 glomeruli. This small number of glomeruli makes the fly, and other small animals, very useful for olfactory studies: the glomeruli can be characterized, named, and recognized from one animal to the next within the same species.

Does each olfactory receptor respond to a single odor molecule, or to a set of different molecules? Some receptors do seem to be specific to just one molecule. Recent results from Sperry Professor of Biology David Anderson's lab indicate that when a fruit fly is presented with carbon dioxide, a molecule that flies recognize as aversive, only a single glomerulus is activated. This suggests that the receptors connected to that glomerulus respond mainly (possibly solely, though this is hard to prove) to carbon dioxide, and (again possibly) no other glomeruli in the antennal lobe detect it.

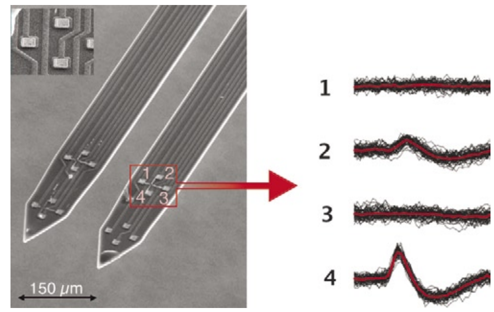
If, however, one receptor always responded only to one single molecule, flies, which have only 60 receptor types, would be able to smell just 60 different chemicals. We know that is not the case. We also know, from physiological studies, that when individual receptor neurons are presented with different odors, they react to quite a number of them. We see this when we record their action potentials, as shown on the left. If a single receptor neuron, with only one type of odorant receptor, can respond to a variety of odors, it implies that an odor is detected by a population of different receptor neurons. In other words, each odor is defined by a certain combination of receptors; the code is combinatorial.

As different receptor neurons converge on different glomeruli, a single odor should also activate several glomeruli. Two German scientists, Rainer Friedrich and Sigrun Korsching, devised an experiment to test this. They added single odors—amino acids—to the water of zebrafish, and monitored the activity in the fishes' olfactory bulbs. Different amino acids did indeed activate different populations of glomeruli. The perception of an odor must therefore result from the brain's interpretation of combinatorial activity patterns. My group studies how the brains of insects (locusts, honeybees, and fruit flies), zebrafish, and rats do this.

In the glomeruli, the receptor neurons connect with other neurons called projection neurons.



Silicon probes with tetrads of electrodes fused to the surface, below, simultaneously record the electrical activity of up to 25 neurons in an insect's brain. Each probe records pulses from neurons in the vicinity, and software decodes the distribution of the signals. If the neuron is close to electrode 2, electrode 2 records a large signal, but if the neuron is even closer to electrode 4, this electrode records an even larger signal. Electrodes 1 and 3, farther away, detect very small signals.



M. Roukes

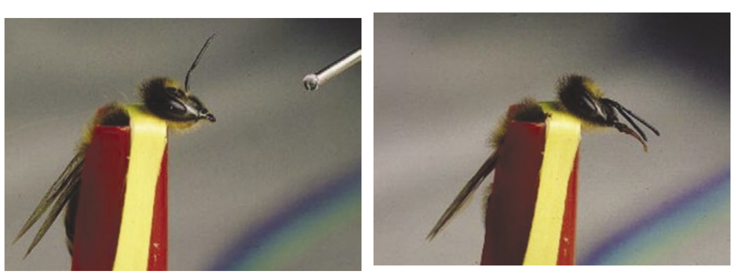
In this locust antennal lobe imaged by Sarah Farivar (PhD '05), two projection neurons, one red and one green, connect with at least 12 different glomeruli.

These come in different shapes in different species: in fish, reptiles, and amphibians, a single projection neuron connects with several glomeruli, while in mammals and flies, one projection neuron connects with only one glomerulus. The locust has about 800 projection neurons, plus 300 neurons of another kind called local neurons, which have no axons, but have many branches that cover most of the glomeruli, and are critical for shaping and synchronizing the activity of the projecting neurons.

With 100,000 receptor neurons converging on just 800 projection neurons, what is being computed? To find out, we can insert tiny glass, metal, or silicon probes into the locust's olfactory circuits, give it an odor to smell, and observe the effect. Some of our probes carry groups of four electrodes, each of which detects electrical signals generated by neurons in the vicinity. The distribution of signals picked up by these electrodes can be decoded by triangulation in such a way that we can record and characterize the responses of up to 25 neurons simultaneously. By repeating these recordings many times, we can follow the activity of a large fraction of all the neurons present.

We also use another technique in which we penetrate the membranes of individual neurons with ultrafine glass microelectrodes, which allows us to record the electrical activity of single neurons while the animal is responding to odors.

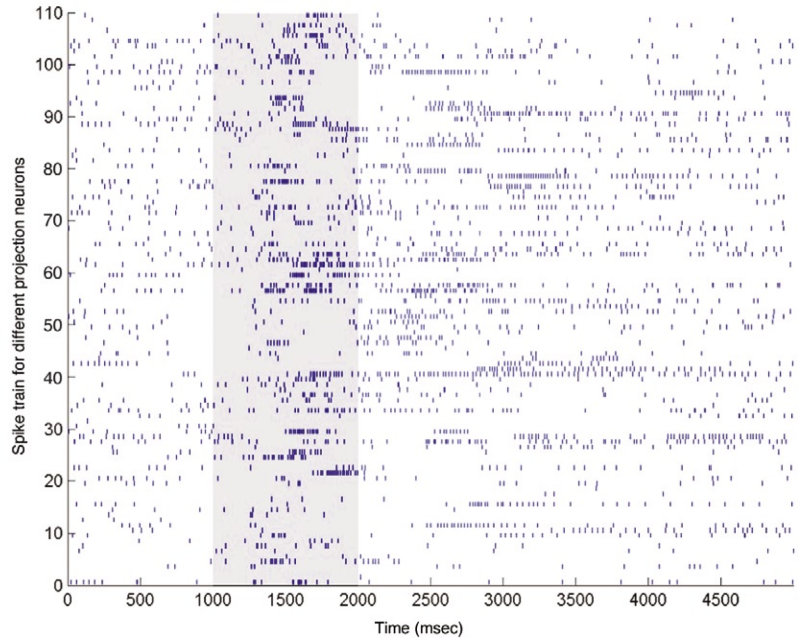
We can record all this electrical activity, but how can we gauge the insect's perception of odors and its discriminative power? To shed some light on this, we've also been doing behavioral studies on honeybees using the classical paired-stimulus conditioning experiments developed by a German scientist, Randolf Menzel, and colleagues. We put the bee in a harness that leaves the head free, and give it a puff of odorant. If the bee has never experienced the odor before, it orients its antennae, and that is pretty much it. Then we puff the odor again, and at the same time give the bee a drop of sugar solution at the same concentration as flower nectar. The bee learns to associate the odor with this sugar reward, and the next time it smells that odor, it sticks its tongue out in anticipation (even if it doesn't get a reward). This learned behavior is called a proboscis extension reflex; we can use this to probe the bee's ability to recognize an odor, and to distinguish it from other odors. By analyzing the time it takes for the bee to extend its proboscis, and the consistency or persistence of its responses, Mark Stopfer, a postdoctoral fellow in my lab at the time, was able to quantify the degree to which it can recognize odors, and get some idea of how it senses and perceives them.



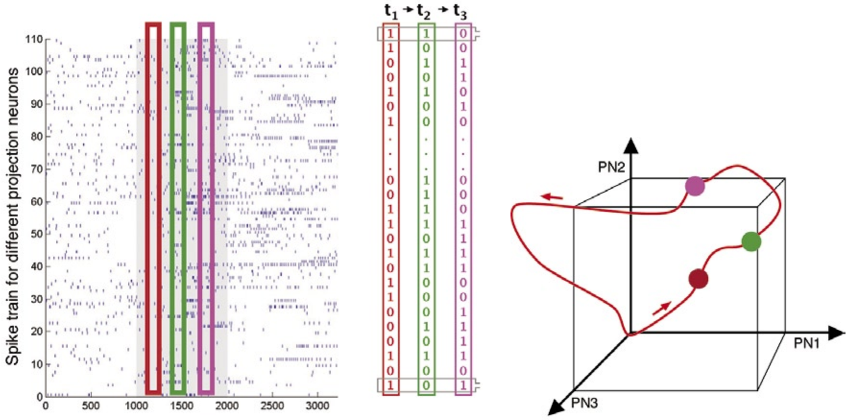
When a honeybee recognizes an odor, the antennae move forward and the bee sticks out its tongue, or proboscis, in anticipation of a reward. (Courtesy of Brian Smith, Ohio State University.)

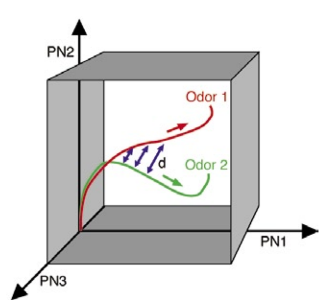
Going back to our electrophysiological recordings, the chart on the next page shows the kind of data we get when we use silicon probes to record

Mark Stopfer, NIH



Each row of the chart above is a recording of pulse patterns from a different locust projection neuron before, during (shaded box), and after a puff of odor. Each of the 110 projection neurons responds to the odor in a different way, characteristic of that neuron and that odor. Imagine the chart as sheet music—the neurons are drummers, and each one beats a different rhythm. To make sense of the cacophony, the score is broken down into very small time slots, below, each one drum-beat wide. During one interval, each drummer either hits the drum (1) or doesn't (0). When done for the entire score, a 110-dimensional graph of the activation trajectories over time can be drawn, like the one on the right (for three dimensions only).





Right: When the pulse patterns for two similar odors are superimposed, right, distance d between the trajectories increases over time—though it's a very short time. It takes less than 0.3 seconds for the brain to optimize the differences between the odors.

from populations of projection neurons before, during, and after the locust experiences an odor. Each line represents the activity of a different projection neuron. You can see that many of the neurons change their response patterns in a very characteristic way when the odor is presented: some respond early, some late, and yet others have complicated pulse patterns that are typical of that neuron and that odor. If the odor is changed, we see a different activation pattern across the neuronal population.

To make sense of charts like this, we break the activity pattern into very short windows of time, during which each neuron will have either fired or not fired. Then we transform the data into a column of ones (neuron fired) and zeros (neuron didn't fire), as in computer binary code. By moving the window forward incrementally, we can digitize the whole data set and draw a multidimensional graph (for the chart shown here, it would be a 110-dimensional graph) that plots the activity of each neuron. This gives us a trajectory for the activation pattern of the neurons over time in response to one odor. We can then repeat the experiment with other odors, and compare the trajectories defined by the same neurons.

This becomes interesting when we superimpose the graph of one odor onto that of a very similar odor. The two trajectories are more or less the same at first, but move further and further apart with time in a process we call decorrelation. As each odor activates the system, the system starts to interact with itself, and the representations of the odors become more and more characteristic—that is, they overlap less and less with the representations of other odors. This happens so quickly that the representations are optimally separated within 100 to 300 milliseconds.

Billiards provides a useful analogy of what's happening here. Imagine that the population of neurons that displays this complicated pattern is a set of red balls, and the odor is a white cue ball.

M. Heisenberg, *Nature Reviews Neuroscience*, 2003, 4, 266-274, with permission from Nature Publishing Group.

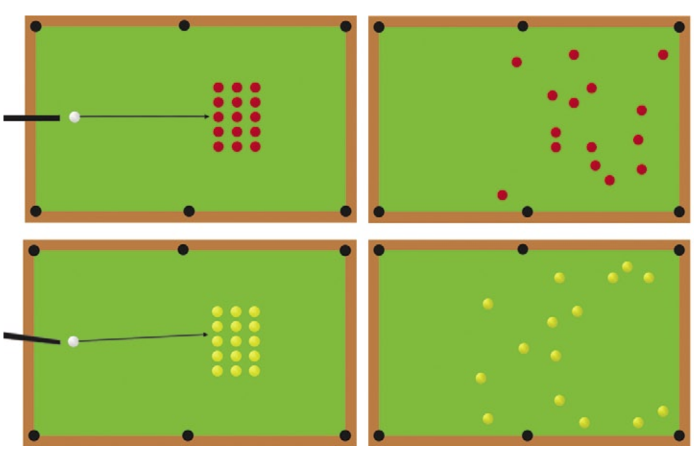
Behind a fruit fly's lovely big eyes is a very complex brain. Areas connected with olfaction include the antennae (red dot and arrow), the antennal lobes (red), and the two mushroom bodies (blue). Kenyon cell dendrites are in the swollen upper part of the mushroom body above the stalk, the calyx. The optic lobes (green), subesophageal ganglia (yellow), and central complex (orange) are also shown.

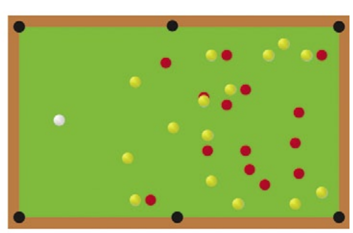
We hit the cue ball and, after some time, the red balls spread out into a particular pattern as a result of interacting with each other—like the projection neurons in the brain. We repeat this on an adjoining table with a set of yellow balls, but this time change the input just a bit by hitting the cue ball at a slightly different angle. The cue ball now hits the first ball at a different position, and the yellow balls spread in a different way than the red balls. When we compare the positions of the red and yellow balls, we can see quite a difference. Although the difference between the two input conditions was very small, the change in the output is very large. In other words, the difference has been amplified. That's basically what we think is taking place in this olfactory circuit. The remarkable thing is that this near-chaotic process is very sensitive to the input, but very reliable nevertheless. Finding the rules of such nonlinear dynamical problems is one of our goals.

It seems wasteful that hundreds of thousands of olfactory receptor neurons converge on their respective glomeruli in an amazingly precise way, but that this precision is then thrown away when seemingly disordered patterns of activation are generated in the projection neurons. But there's a good reason for it. A system that amplifies small differences in signals runs the risk of also amplifying noise, in this case noise coming from the receptors. Noise fluctuations would make the output of the projection neurons unreliable: the averaging that results from this kind of convergent design is precisely one way to reduce such fluctuations.

The projection neurons—which now contain all the information the animal has about the odor—go to a region of the insect brain called the mushroom body, a structure analogous to the vertebrate olfactory cortex. Here they connect with tens to hundreds of thousands of tightly packed neurons called Kenyon cells. From behavioral and molecular work in other insects, we know that the mushroom body plays a key role in the formation and recall of olfactory memories. Knowing how Kenyon cells represent odors thus promises to get us closer to understanding the nature of odor memories.

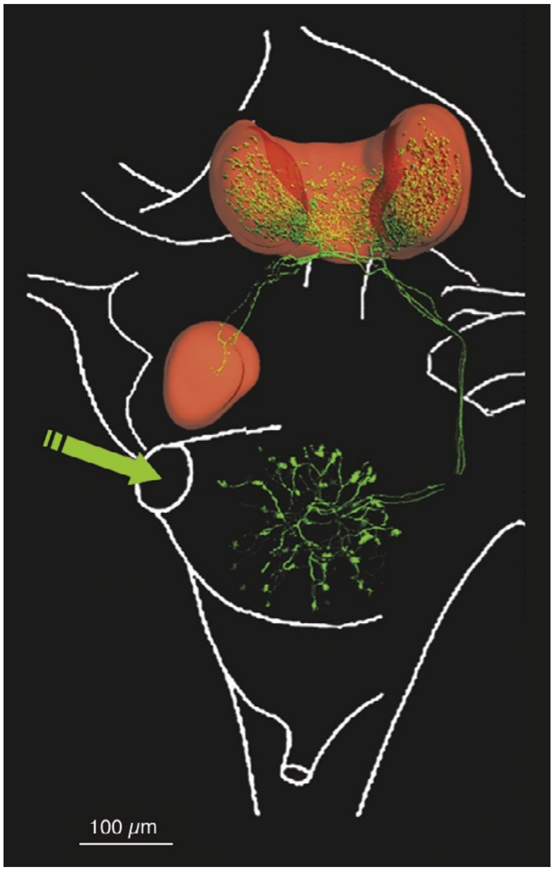
The locust has 800 projection neurons connecting to 50,000 Kenyon cells. With such a large mismatch in numbers, how are these nerve-cell populations interconnected? When Ron Jortner, a graduate student in my lab, recorded simultaneously from both projection neurons and individual Kenyon cells to assess the probability of connec-





In these two billiard games, one with red balls and the other one with yellow, a small change in the angle of the cue stick when it hits the white ball causes a large change in the way the balls eventually disperse.

In this composite of a locust's olfactory brain prepared by Sarah Farivar, the arrow shows where the antennal nerve brings input from one of the antennae. To the right of the arrow, green projection neurons connect with glomeruli in the antennal lobe. Their long axons run up to connect with Kenyon cells in the calyx of the red mushroom body at the top, and some also connect with the egg-shaped lateral protocerebrum, also colored red.

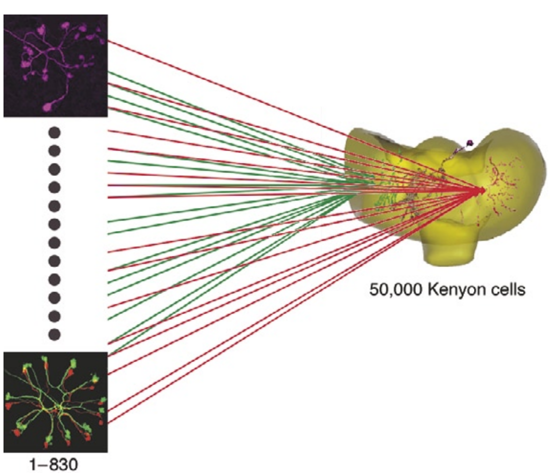


tion between them he found, surprisingly, that the probability was about 0.5. In other words, each Kenyon cell seems to connect on average to half of the input population, that is, to 400 projection neurons. The number of ways in which 400 neurons can be selected out of 800—the number of possible connection patterns—is about 10^{240}. It's an *enormous* number. To put it in context, there are about 10^{10} seconds in a century, and there have been about 10^{19} seconds since the beginning of the universe. With 10^{240} possible combinations of projection neurons to choose from—assuming random connectivity—almost every Kenyon cell is likely to sample a combination of inputs that is very different from that sampled by the other Kenyon cells. Each cell will therefore gain a picture of the state of the projection neuron population very different from that gathered by any other Kenyon cell.

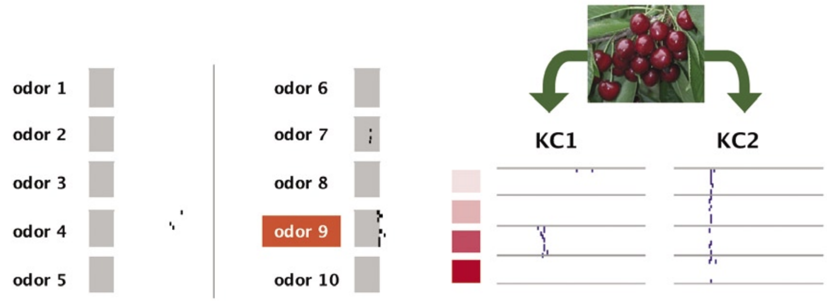
It follows that the responses of individual Kenyon cells will be very specific; a given cell should respond only to particular combinations of activated projection neurons, maximally different on average from those experienced by the other Kenyon cells. This is what two of my graduate students, Javier Perez-Orive (PhD '04) and Ofer Mazor, found when they sampled the responses of a selection of Kenyon cells to a wide variety of odors. Most of the Kenyon cells could not be activated by any of the odors they used in their experiments, but this was not unexpected, as with tens of thousands of simple odors and a near-infinite number of ways to combine them, it would have been practically impossible to test all possible odor stimuli. They did, however, find a "successful" stimulus for some, and of those successfully stimulated cells, most responded to only one odor among 20–30 odors tested.

With results such as these, we may begin to explain the synthetic nature of olfaction—the fact that when we smell cherry, we don't smell all the chemicals that make the odor of cherry. If our own brains contain bottlenecks equivalent to the Kenyon cells of insects, we can see how their synthetic property—their tuning to particular combinations of chemicals and only to those combinations—provides no information about the odor components. There's no receptor neuron in the antennae or nasal epithelium that recognizes cherry as such. There's no projection neuron in the antennal lobe or olfactory bulb that recognizes cherry as such. But in the mushroom body (and possibly in the olfactory cortex) lie cells that recognize cherry from the specific pattern of neural activation generated by the particular combination of chemicals contained within that odor.

Interestingly, monomolecular odors also often activate many different receptor types, and are therefore effectively identical to mixtures. Each odor, whether simple or complex, is represented by a specific pattern of coactivation in the antennal lobe (where the receptor neurons converge on the projection neurons) that is in turn recognized by



This is a simplified schematic of the linkages between projection neurons and two Kenyon cells. The real picture is far more complex, as each of the 50,000 Kenyon cells is estimated to connect with about 400 projection neurons out of 830.



Kenyon cells are so specific that they only recognize one, or at most a few, odors. In the experiment on the left, in which 10 odors where tested on one Kenyon cell by Javier Perez-Orive, PhD '04, the cell responded reliably only to odor 9. The odor of cherries, right, produced the same pattern of electrical activation in Kenyon cell 2 over four different odor concentrations, while Kenyon cell 1 responded to this odor only at a certain concentration.

very few cells within a large population of pattern recognizers, each of which is tuned to different combinations. In other words, Kenyon cells have no way of knowing whether an odor is made of one or more molecular components. This may explain why we generally fail to perceive, when smelling an odor, whether it is mono- or multimolecular (as illustrated by Livermore and Laing's experiment that I described at the beginning of this article). Kenyon cell responses provide no information about this feature.

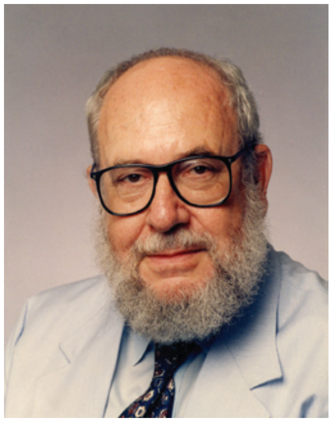
Neurons that respond highly selectively, as Kenyon cells do, have in a few instances also been found in other parts of the brain. Researchers of vision hypothesized their existence some forty years ago, and named them "grandmother" cells, following the proposition that a unique pair of cells might encode one's maternal and paternal grandmothers. No one really believes that representations in the brain are this specific. Such uniqueness is dangerous—a random activation of one cell could cause erroneous perception, or damage to one's grandmother cells would erase their memory for ever—but there is increasing evidence that the brain contains very sparse representations carried by extremely specific and invariant neurons. This makes such neurons very difficult for physiologists to find. If you put an electrode in a randomly selected neuron, you would have to try an enormous set of possible stimuli before you got a response (as my graduate students found). Our research into olfaction is, however, giving some valuable insights into how such kinds of high-level synthetic representations arise from the organization and dynamics of neural circuits.

The study of the sense of smell is a fascinating area of neuroscience. It already allows us to explain some perceptual qualities of olfaction, and may provide us with relatively simple solutions to complex and general pattern-recognition problems. Classifying and recognizing patterns is, after all, what our brains do best. □

PICTURE CREDITS: 42, 43 – Bob Paz; 42, 44 – Doug Cummings

Enjoying a day out of the Beckman Institute's basement are, left to right: front row, Bede Broome, Ofer Mazor, Vivek Jayaraman, Benjamin Rubin, Laurent Moreaux, Mala Murthy, and Sarah Farivar; back row, Gilles Laurent, Maria Papadopoulou, Jonathan Young, Roni Jortner, Glenn Turner, Kai Shen, Stijn Cassenaer, and Mattias Westman. Laurent lab members who missed out on the beach are Cindy Chiu, Suzi Yorozu, Mikko Vähäsöyrinki, and Sidra Golwala.

Gilles Laurent, the Lawrence A. Hanson Jr. Professor of Biology and Computation and Neural Systems, grew up in Morocco and France, and spent his student days in Toulouse, where, in 1985, he earned both a PhD from the University of Toulouse and a doctorate in veterinary medicine from the Ecole Nationale Vétérinaire. He then left both France and veterinary science to study neuroscience and electrophysiology at the University of Cambridge, before joining Caltech as an assistant professor in 1990. He became an associate professor in 1996, a full professor in 2000, and was named the Hanson Professor in 2002. His current interest is olfaction, but he also studies how single neurons perform nonlinear operations such as multiplication. He is married to another Caltech neuroscientist, Professor of Biology and Howard Hughes Medical Institute Associate Investigator Erin Schuman. This article is adapted from a Watson lecture given on February 23, 2005, which can be viewed on Caltech's Streaming Theater website, http://today.caltech.edu/theater/.



Thomas K. Caughey
1927 – 2004

At a memorial service held May 5 for Thomas Kirk Caughey, the Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering, Emeritus, who died December 7, 2004, colleagues paid tribute to the talented Scotsman who came to Caltech as a graduate student and stayed there all his life.

Caughey was a leader in the fields of dynamics and vibrations, fluid-induced forces in turbomachinery, stochastic nonlinear systems, and structural monitoring and active control of large structures. His awards included the Freudenthal Medal and the von Kármán Prize, both from the American Society of Civil Engineers.

A native of Rutherglen, Scotland, he became interested in acoustics and engines (especially quiet electric engines) because of the noisy tugs on the river Clyde, whose single-cylinder engines could be heard for miles around. At Glasgow University, he earned undergraduate degrees in both electrical and mechanical engineering in 1948, then worked at Howden & Co., an engineering company, where he devised an automatic machining system for a new type of rotary compressor that earned him a welcome on the shop floor.

A Fulbright scholarship took him to Cornell in 1951, where he earned an MME in 1952. That same year he came to Caltech, where he earned his PhD in just two years. Caltech made him an assistant professor in applied mechanics in 1954, and a full professor in 1962. He was named the Hayman Professor in 1994, and the Hayman Professor, Emeritus in 1996.

One of his former graduate students, Sami Masri, now a professor at USC, said, "He was without a doubt one of the most, if not the most, influential member of the community of workers in the vibration field. His contributions are without parallel and have touched every engineer currently working in dynamics and control."

Chris Brennen, the present Hayman Professor of Mechanical Engineering, talked about his collaboration with Caughey and Allan Acosta, the Hayman Professor of Mechanical Engineering, Emeritus, in the late 1970s on a NASA-sponsored research project motivated by problems in the development of the space shuttle's main engine. Their research led to 31 ABC (Acosta, Brennen, Caughey) papers and resulted in defining a new set of fluid-structure rotordynamic forces and instabilities. "That research epitomized his genius," Brennen said. Caughey's engineering experience was invaluable in the design and fabrication of a unique experimental facility whose success has yet to be bettered. Recently, that 30-year-old Caltech facility was dismantled by NASA and transported to Huntsville, Alabama, where it is being put to use again.

Amnon Yariv, the Summerfield Professor of Applied Physics and professor of electrical engineering, told the audience that Caughey also influenced his work in the field of lasers. "Back in 1974," he said, "I became interested in the topic of noise and lasers. Lasers are said to be ideal generators of pure light, but a laser is a nonlinear oscillator and has random noise, which limits its usefulness." When Yariv tried to eliminate the noise, he ran into mathematical problems. On mentioning this to Caughey one day, Caughey said, "You know, I've written a paper 14 or 15 years ago which you may find interesting." Yariv found that the mathematics in this paper was tailor-made for the laser field.

Caughey had a vast practical knowledge of the design of mechanical, electrical, and electronic devices, and was called in to fix things in other parts of Caltech. According to Acosta, Physical Plant often asked him to solve problems such as corrosion in the swimming pool and noisy cooling fans on the power plants. The astronomers asked him if he could stop the dome of the 200-inch Hale Telescope from lurching when the direction of rotation was changed; Caughey told them all it needed was a dedicated screw. (Several people at the memorial service commented that he would also have been able to fix the faulty microphone on the podium.)

Paul Jennings, provost and professor of civil engineering and applied mechanics, who was a graduate student in his class in the days when Caughey was a "skinny, young hotshot." remembered how Caughey was "blazingly fast on the blackboard," something that also left a lasting impression on Per Reinhall, another of Caughey's graduate students and now a professor at the University of Washington. Many spoke of Caughey's amazing breadth of knowledge, and how he was equally comfortable discussing dynamics, cars, politics, and abstract mathematics. His great love was classical music, and he was an active and much-valued member of the Coleman Chamber Music Association for many years.

Caughey treated everyone with the same courtesy, be it the president or the gardeners, and was a generous and supportive colleague. In the words of Jim Knowles, the Kenan Professor and Professor of Applied Mechanics, Emeritus, "A man of extraordinary accomplishments and striking modesty."

He is survived by his wife, Jane; children Penelope, Catherine, Christine, and William; four grandchildren; and six great-grandchildren. □—*BE*

In 1959, Caughey designed a portable earthquake-making machine, a.k.a. an eccentric-mass vibration generator that was the forerunner of the shaking machines used by civil engineers around the world today.

Faculty File

Cornelius J. Pings

Cornelius John Pings (BS ’57, MS ’52, PhD ’55), a former vice provost, dean of graduate studies, and professor of chemical engineering and chemical physics at Caltech, died last December 6 of cancer. He was 75.

After earning his doctorate in chemical engineering, Pings served on the Stanford University faculty, then joined the Caltech faculty in 1959. His research was in applied chemical thermodynamics, statistical mechanics, and liquid-state physics. He served as vice provost and dean of graduate studies from 1971 to 1981, then went to the University of Southern California as provost and senior vice president for academic affairs. In 1993, he became president of the Association of American Universities, where he served until 1998.

Pings was chairman of the Committee on Science, Engineering, and Public Policy, president of the Western College Association, and chairman of the Pasadena Redevelopment Agency.

In 1989, Caltech honored Pings with the Distinguished Alumnus Award. He was also a member of the Caltech Associates President’s Circle. He is survived by his wife of more than 40 years, Marjorie; his son, John; and his daughters, Anne and Mary. ☐—*RT*

Cornelius Pings was on our cover in January 1962. Pings, on the left, and research fellow Brian Smith are determining the optical properties of liquid argon.

Chris Brennen, above right, who was recently named the Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering, has also won this year’s Richard P. Feynman Prize for Excellence in Teaching. Students praised his perpetual enthusiasm and lucid teaching style, which included riding his bike into the swimming pool to demonstrate fluid mechanics.

New NAS and AAAS Members

Newly elected to the National Academy of Sciences are **Richard Andersen**, the Boswell Professor of Neuroscience; **James Eisenstein**, the Roshek Professor of Physics; and **Wallace Sargent**, the Bowen Professor of Astronomy, as well as **Roger Blandford**, a former Caltech faculty member and visiting associate in physics.

New fellows of the American Academy of Arts and Sciences include **Andrew Lange**, the Goldberger Professor of Physics; **Barry Simon**, the IBM Professor of Mathematics and Theoretical Physics; **David Tirrell**, chair of the Division of Chemistry and Chemical Engineering and McCollum-Corcoran Professor and professor of chemistry and chemical engineering; and **William Bridges**, the Braun Professor of Engineering, Emeritus.

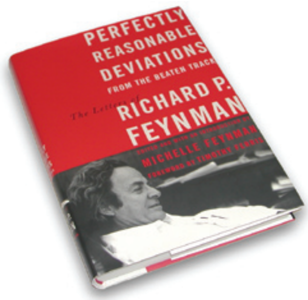
Honors and Awards

David Goodstein, Caltech’s vice provost, professor of physics and applied physics, and Gilloon Distinguished Teaching and Service Professor, has had his book *Out of Gas: The End of the Age of Oil* (New York: W. W. Norton & Company, 2004) chosen by the *New York Times Book Review* as one of its 100 Notable Books of the Year for 2004. In the book, Goodstein sees difficult choices facing human society worldwide as global oil production peaks in the near future.

Mark Konishi, Bing Professor of Behavioral Biology, and Fernando Nottebohm of Rockefeller University have jointly received the American Philosophical Society’s 2004 Karl Spencer Lashley Award for their work illuminating the physiological basis of the vocal-learning abilities of certain birds. Konishi was recognized for his experiments demonstrating that birds “depend heavily on their ability to monitor their own voice, both to produce previously memorized songs and to maintain them once developed.”

Chris Martin, professor of physics, has received his second NASA Public Service Medal, in recognition of “exceptional scientific achievement in ultraviolet astrophysics and contributions to the success of the Galaxy Evolution Explorer.” Martin is principal investigator for JPL’s Galaxy Evolution Explorer, or GALEX.

John Preskill, MacArthur Professor of Theoretical Physics, has been chosen as the 2005 Lawrence C. Biedenharn Lecturer at the University of Texas at Austin.



Perfectly Reasonable Deviations from the Beaten Track: The Letters of Richard P. Feynman
edited by Michelle Feynman
Basic Books, 2005
486 pages, $26.00

To compile this book of letters written by her father, Michelle Feynman sifted through the contents of 12 filing-cabinet drawers photocopied from the Feynman Papers and shipped out to her by the staff of the Caltech Institute Archives. After winnowing out the technical papers, she picked the best of the personal letters, added family letters and photos stored in her basement, and compiled this fascinating insight into the everyday life of Richard Feynman.

The letters are ordered more or less chronologically, and letters are next to their replies. The first is from October 1939, when the 21-year-old graduate student writes to his mother from Princeton (he includes a mathematical puzzle for his father), and the last was written six months before his death in February 1988. As well as letters to his mother, endearing letters to his sweetheart, then wife, Arline, who was dying of TB, and letters written in hotels abroad to Gweneth, Michelle's mother, whom he married in 1960, there is correspondence with colleagues, the media, people trying to give him honors he didn't want, and surprisingly long replies to members of the public.

There's something of interest on every page, and it's fun to dip into the book at random and follow a thread of correspondence (but it's hard to stop.) Much of the charm of these letters is that they are in Feyman's own voice, untouched by copyeditors. His writing style, though perhaps not always grammatically correct, is vibrant and energetic, and he comes across as a charming, considerate, humble, and very amusing person.

With a foreword by Timothy Ferris, and an introduction by Michelle on what it was like having Feynman as a father (great fun), everybody, even if new to Feynman, will enjoy reading this glimpse into almost five decades of his life. □—*BE*

Strange Angel: The Otherworldly Life of Rocket Scientist John Whiteside Parsons
by George Pendle
Harcourt, 2005
368 pages, $25.00

In 1952 rocket scientist Jack Parsons lost his right arm and the right side of his face to an explosion at his house on Orange Grove Avenue, in Pasadena, California. Still conscious, he was rushed to Huntington Memorial Hospital, where he died. In the aftermath of the explosion, the public learned of a remarkable pioneer in the field of rocketry, for whom the occult was as important a realm as that of science.

As much historical sketch of Southern California, Caltech, rocketry, and the Ordo Templi Orientis as a life of Parsons, *Strange Angel* starts with his horrific death, then flashes back to his idyllic boyhood growing up in a wealthy family on Orange Grove Avenue, next to the "Huckleberry Finn playground" of the Arroyo Seco. Dyslexic, Parsons nonetheless developed an interest in explosives, chemistry, and rocketry, and gained friends such as Ed Foreman and Frank Malina (MS '35, Eng '36, PhD '40), with whom he carried out rocket experiments at Caltech. Forced off campus in the wake of too many unnerving explosions and mishaps, the "Suicide Squad," as they were known, leased six acres in the upper Arroyo Seco, threw together some ramshackle buildings, and began what ultimately became JPL.

Dreamer, poet, science-fiction enthusiast, and temperamental idealist, Parsons yearned to apply the methods of scientific experimentation to "magick" fully as much as to rocketry. In the '30s and '40s he played a key role in developing the Jet-Assisted Take-Off (JATO) program, and in the founding of JPL and Aerojet, but increasingly turned to the occult as he found himself left behind by the more businesslike world of postwar rocketry, which had little place for mavericks and romantics.

Strange Angel is a fast-paced and fascinating look at the life of a man beckoned on to dissolution and destruction by the very idealism and talent that made him an important and creative force in the field of rocket propulsion. □—*MF*

Astro Turf: The Private Life of Rocket Science
by M. G. Lord
Walker & Company, 2005
253 pages, $24.00

Part personal memoir, part meditation on family life, and part history of the space program and of JPL, *Astro Turf* explores the cultural complexities underlying the deeply human endeavor of reaching out to other worlds, and the ways in which the very humanity of that endeavor was for decades obscured and even stifled by a kind of masculine mystique.

Beginning with a 1997 creativity seminar conducted at JPL by Mars Exploration director Donna Shirley, during which M. G. Lord experienced a reemergence of memories about her father, and concluding with the successful landings of the Mars rovers Spirit and Opportunity in 2004, Lord undertakes her own voyage of discovery as she seeks to understand her father's emotional absence from his family at a time when Lord's mother was dying of cancer. Because he was working on the Mariner project at the time, the book comes to encompass much else as well, including the FBI's persecution of Frank Malina, JPL's first director; the role of science fiction as inspiration, as much for Lord herself as for scientists and engineers; and the changing perception of gender among those who have engaged in interplanetary exploration over the past half century. □—*MF*

South Houses Ready for Renovation

For more information on how you can help with the renovation of the South Houses, please contact:

Jennifer Chen
Caltech Mail Code 5-32
Pasadena, CA 91125
626-395-5705
jchen@dar.caltech.edu
http://www.one.caltech.edu

there's only one.caltech
THE CAMPAIGN

Community. Identity. Tradition. Caltech's distinctive housing system has shaped undergraduates' lives for decades. Likewise, the students who come to Caltech go on to shape their own fields of study as leaders in academia, industry, and government. To enhance these students' undergraduate experience, Caltech has made renovation of the undergraduate houses a top priority.

Built in 1931, the South Houses complex comprises four of Caltech's seven undergraduate residential houses: Blacker, Dabney, Fleming, and Ricketts. Designed as much more than mere dormitory space, the South Houses were built around courtyards, hallways, and alleys, allowing students to interact with each other and build strong camaraderie by eating, studying, and living together in close quarters. But the residences were built 74 years ago, before the common use of residential air conditioning, and well before the advent of computers. In addition to the usual paint and carpeting, then, extensive infrastructure upgrades will be required to make the houses meet the needs of today's students.

Renovation of the South Houses will include bringing electrical and plumbing systems up to code, modernizing the data network, and providing access for students with special needs. Restoring and maintaining architecturally significant elements of the residential complex is also a key objective of the project. The renovation will provide enhanced dining services, more shared space, and more private study areas. What's more, all of the renovation, new construction, and landscaping will complement plans for the proposed Campus Center by creating an interconnected system of plazas, dining facilities, and gathering places for the student community. These and other improvements are expected to play a significant role in Caltech remaining competitive at recruiting the country's most promising students each year.

With the $36.4 million project set to begin in June 2005, Caltech's Development office is pursuing gifts from Institute alumni and friends through the "There's only one. Caltech" campaign. To date, more than $5 million has been committed to the South Houses renovation. Among these gifts, a $1.5 million unrestricted bequest distribution from the estate of Fred V. Maloney has been directed to support the project.

In addition to this bequest, Fred (BS '35, MS '36) and Marvis Maloney had contributed more than $1.6 million dollars during their lifetimes through outright gifts and charitable remainder unitrusts. These contributions established the Fred V. and Marvis B. Maloney Scholarship and Fellowship Fund and provided funding for graduate-student housing. Unrestricted bequest provisions such as the Maloneys' provide the Institute with enormous flexibility in responding to its most urgent challenges and opportunities.

For the 14 months the renovation is expected to take, Moles, Darbs, Flems, and Scurves will live in temporary modular housing units that have been installed in the northeast part of campus. The South Houses complex is set to reopen in September 2006, in time for the start of the 2006–2007 academic year. □

Engineering & Science

California Institute of Technology
Pasadena, California 91125