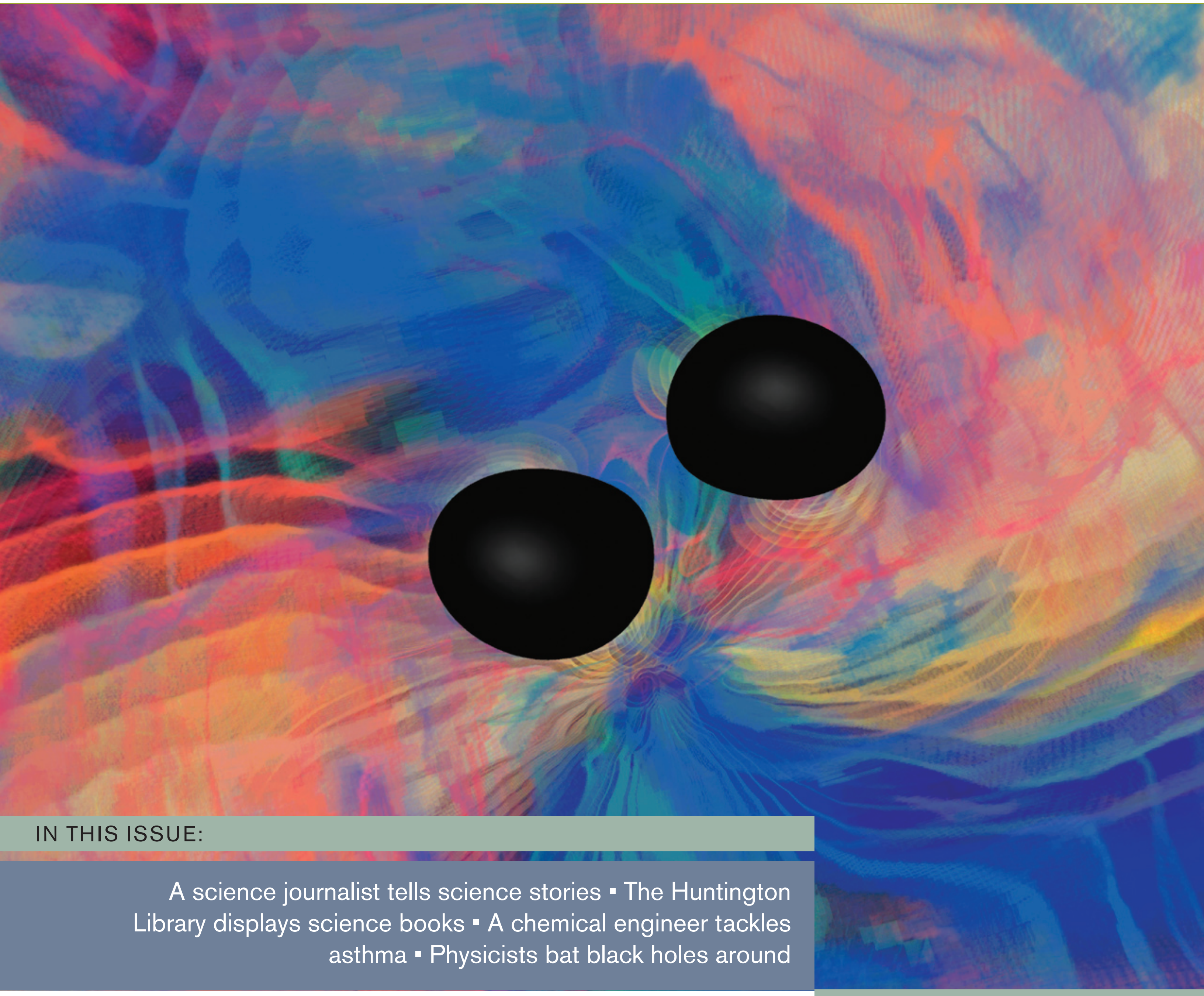
e&S

Engineering & Science

Caltech



IN THIS ISSUE:

A science journalist tells science stories ▪ The Huntington Library displays science books ▪ A chemical engineer tackles asthma ▪ Physicists bat black holes around

VOLUME LXXI, NUMBER 3, FALL 2008

California Institute of Technology

ON THE COVER

Merging black holes produce a clangor of gravitational waves. This snapshot is from a 2002 simulation by the Albert Einstein Institute in Germany, with assistance from the Zuse Institute Berlin and Louisiana State University. At the time, it was one of the most advanced ever done, tracing three quarters of an orbit. Now, thanks to a Caltech breakthrough, multiple orbits are routine. A Caltech-Cornell team continues to lead in producing the most accurate simulations to date. Read more on page 34.

50 YEARS OF *E&S*

50 YEARS AGO

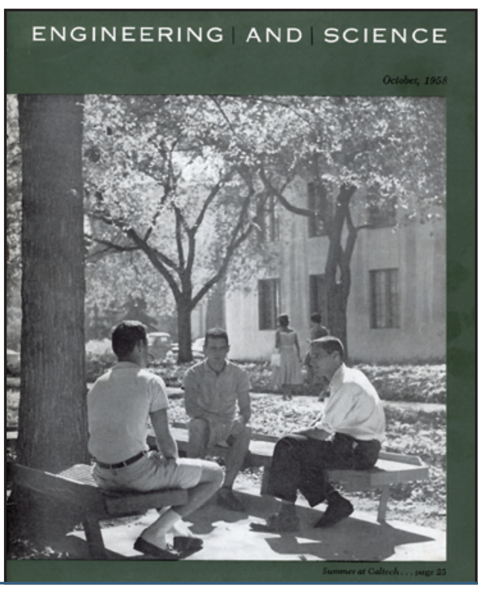
James Bonner (PhD '34), acting chair of the biology division, wrote about "stirring times in the world of biology." He described how methods for separating cells into their component parts, invented at Caltech and elsewhere, were allowing scientists to discover how proteins are synthesized.

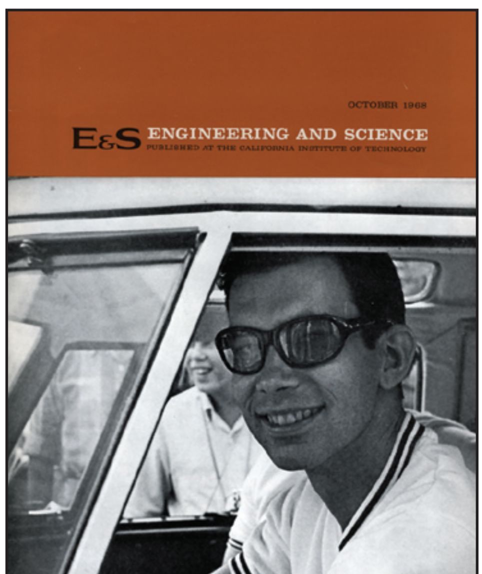
40 YEARS AGO

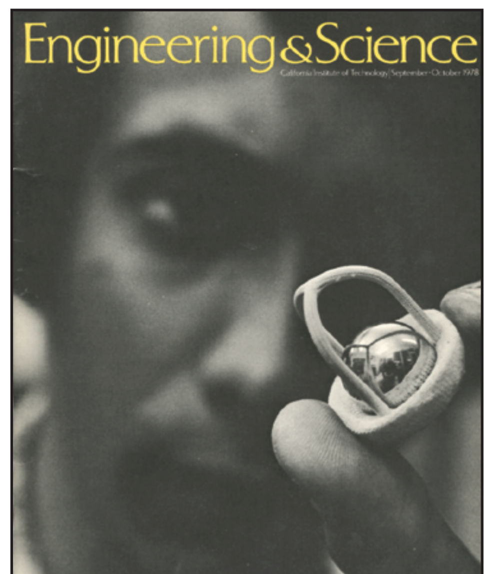
The summer of '68 saw the Great Electric Car Race, a cross-country competition between Caltech and MIT organized by Wally Rippel (BS '68), seen here at the wheel of his converted '58 VW bus. The Tech men took off toward Cambridge, while MIT's electrified '68 Corvair made its way to Pasadena. The trip, anticipated to be less than five days, took MIT seven and a half; Caltech rolled in more than 37 hours later. But after penalties were taken for things such as being towed and using a portable generator between official recharging stations, the tortoise had beaten the hare: Caltech's corrected time was 30 minutes faster than MIT's.

30 YEARS AGO

Chemical engineering professor William H. Corcoran and research fellow Ajit Yoganathan collaborated with local cardiologists to study the fluid dynamics of artificial heart valves. Yoganathan holds one such device for the camera.







As you might have noticed, *Engineering & Science* has a new look. We'd like to know what you think—e-mail your comments (or letters to the editor in general) to Douglas L. Smith, editor, dsmith@caltech.edu.

California Institute of Technology 1891

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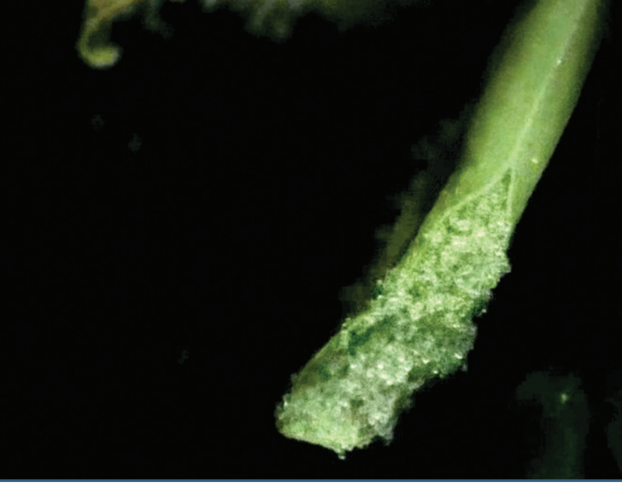
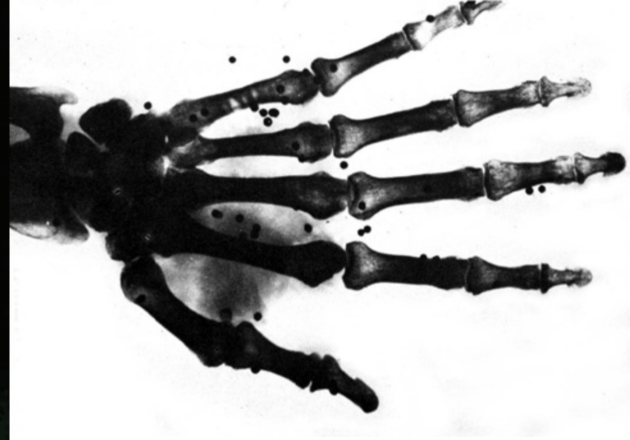

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No, it's not the latest Bond girl from the opening titles of the upcoming *Quantum of Solace.* Artist Lynn Aldrich wields a glue gun as she assembles *Pilgrimage: (Through the Wormhole)* via which visitors will travel between two spaces in the gallery.

THE ARTS PAGE

The beauty of deep-space astronomy and the inventiveness of contemporary art meet in OBSERVE, an exhibition being mounted at the Williamson Gallery at Pasadena's Art Center College of Design in collaboration with Caltech's Spitzer Science Center.

The event, organized by gallery director Stephen Nowlin and infrared astronomer Michelle Thaller, manager of Spitzer's education and public outreach program, features installations by five artists—two with Caltech/JPL connections—as well as a section on the Spitzer Space Telescope and a documentary film.

Lita Albuquerque's video walls turn the astronomers' gaze inward by mapping deep-space images onto a sphere representing Earth. Red lines of light, like string stretched between pushpins, connect sky and ground. As the sphere turns, the parallel lines from pairs of stars above the north and south poles carve out DNA's double helix on its surface.

Lynn Aldrich, an Art Center alum, is contributing the walk-through wormhole seen at left—a physical passage through metaphorical dimensions.

Dan Goods, another Art Center alum now at the Jet Propulsion Lab, is offering a rumination on time and distance. "We think we see the stars as they are right at this moment," he says. "But they're really at vastly different distances, so their light left them at different times in the past. Some of them died long, long ago, and now only exist as starlight." His exhibit features an enormous, Dali-esque wall clock whose hands move backward. As visitors walk through the 34-foot-deep room, however, they realize that the 12 spheres representing the hours are actually different sizes and different distances away. Speakers on the spheres will play back computer-processed, time-delayed recordings of visitors' voices. "The older the data, the more distorted it will be," says Goods. "They'll be redshifted, if you will, like the stars are talking to you."

George Legrady considers the use of imaging technology in the exploration of outer and inner space, as seen below.

And Daniel Wheeler's installation encourages visitors to explore beyond the visible by feeling for an object hidden inside a wooden cylinder. An infrared camera records their hands' exploration. These images, sent over the Internet to a series of screens on which other cameras are trained, get progressively distorted as they propagate through the gallery.

"When you get artists and scientists working together, you get serendipitous things that none of them intended as each person picks up on what the other is saying," says Thaller. "Every person brings their own set of filters into the conversation, and the result is you get these associations you wouldn't have thought of, and you say, 'Oh, wow, that's really cool.' We talk about things like quantum foam and light years without giving it a second thought, and then the artists show us again in a new way just how wonderful the stuff we're working on really is."

This cultural exchange began in August 2007, says Nowlin, noting that science has brought us "a lot of spectacular concepts that torque our everyday perception of reality—black-hole physics, multiple universes, string theories, time distortions—that challenge our human-centered cultural traditions and beliefs." This is "an exhibition about the newly unknown," he says. "Before science we knew everything, because we filled in the gaps with myths."

Nowlin has previously collaborated with Caltech scientists on *ear(th)*, a sound installation that translated displacement data from the Hector Mine earthquake into notes played on a robotic glockenspiel, and NEURO, a multi-venue exhibit that drew on the resources of Caltech's Center for Neuromorphic Engineering to inspire the work of a half-dozen artists.

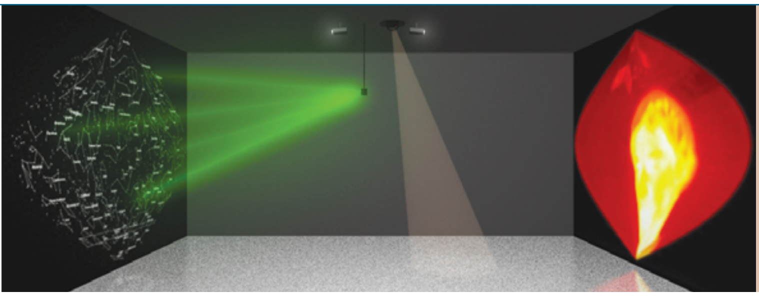
OBSERVE opens with a public reception from 6:00 to 10:00 p.m. on Friday, October 10, as part of ArtNight Pasadena, and runs through January 9, 2009. —*DS* e&s

AMERICA'S FIRST LADY OF ROCKETRY

Would you believe that a woman—and a college dropout, no less—invented the propellant that got America's first satellite, Explorer 1, into space? This fall, Theater Arts at Caltech (TACIT) presents the world premiere of *Rocket Girl*, the true story of Mary Sherman Morgan.

The year is 1957. Sputnik is beeping overhead. The Redstone rocket needs a 5 percent power boost to reach orbit. Finding the extra thrust without redesigning the entire system has become the task of the Rocketdyne Corporation, where Mary and her husband, Richard Morgan (BS '49), work. Written by their son, George, *Rocket Girl* is a tale of heroic battles against impossible deadlines, a saga known until now to none but a handful of old men.

Performances are for one weekend only in Ramo Auditorium: November 7 and 8 at 8:00 p.m., and November 9 at 2:00 p.m. e&s



We Are Stardust, by George Legrady, projects a map of the deep-space targets of Spitzer's infrared cameras on one gallery wall, on which a beam of green light traces the sequence of Spitzer's observations. On the opposite wall, an infrared camera mounted in the gallery ceiling simultaneously follows the same set of pointing instructions to project thermal images of the people moving through its field of view in the gallery space.

LOH DOWN ON SCIENCE ON AFN

The Armed Forces Radio Network, which reaches more than 20 million people in 179 countries, will begin offering a little dose of science four times daily, beginning in October. *The Loh Down on Science*, featuring public-radio personality Sandra Tsing Loh (BS '83), already airs on some 90 stations stateside. Each 90-second episode features Loh's patented off-kilter look at some aspect of science or technology. For more information, or to listen to past episodes, visit http://lohdown.caltech.edu/. e&s

BEAM ON!

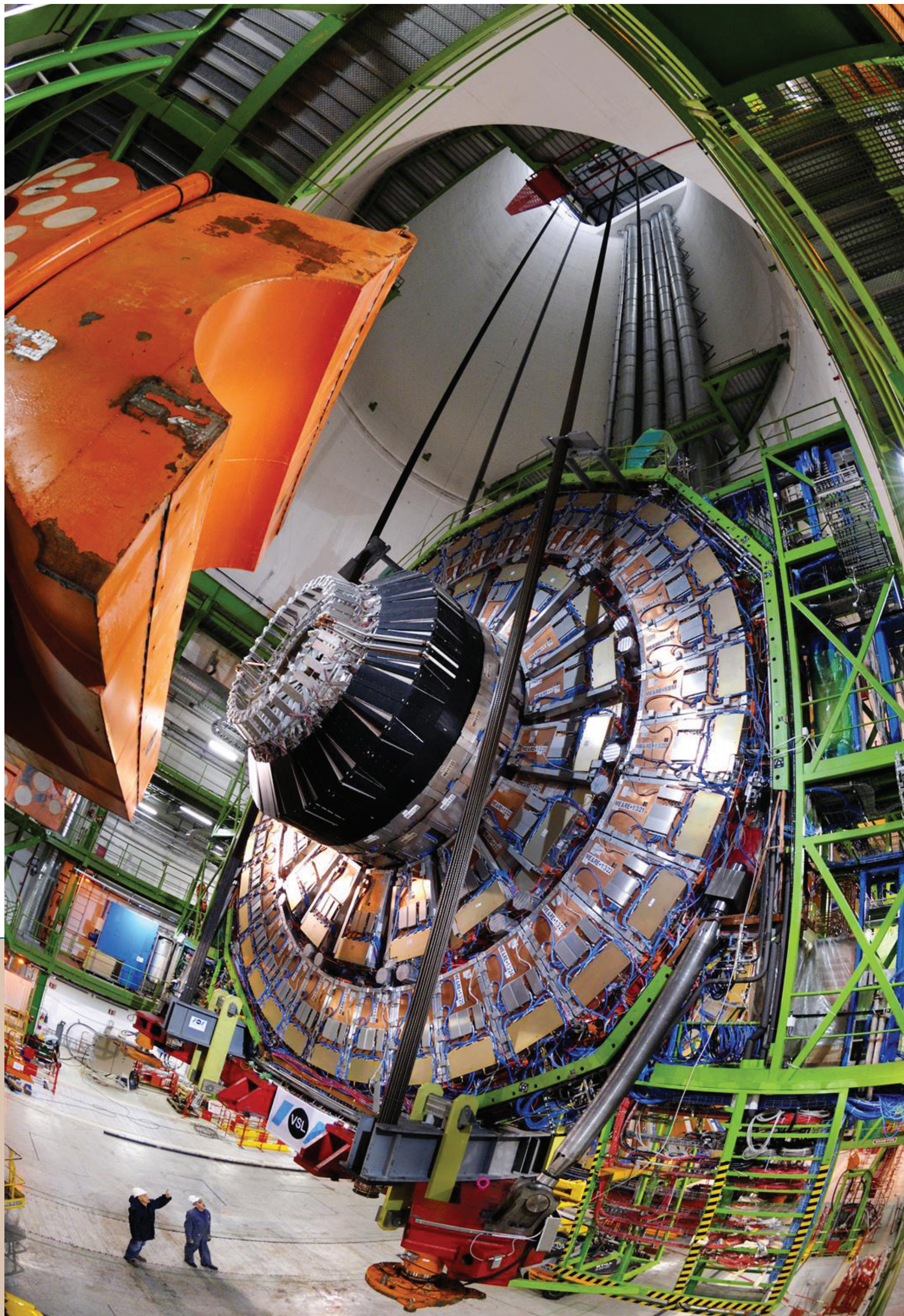
Watching the first slug of protons jog their victory lap around the Large Hadron Collider (LHC) was a bit like watching JPL land the Phoenix on Mars: would the nail-biting, brow-furrowing, breath-holding physicists in Mission Control burst into applause as the batch of high-energy particles reached its checkpoint? Or would their stunned silence indicate failure?

For 53 minutes, you couldn't cut this kind of tension with a knife.

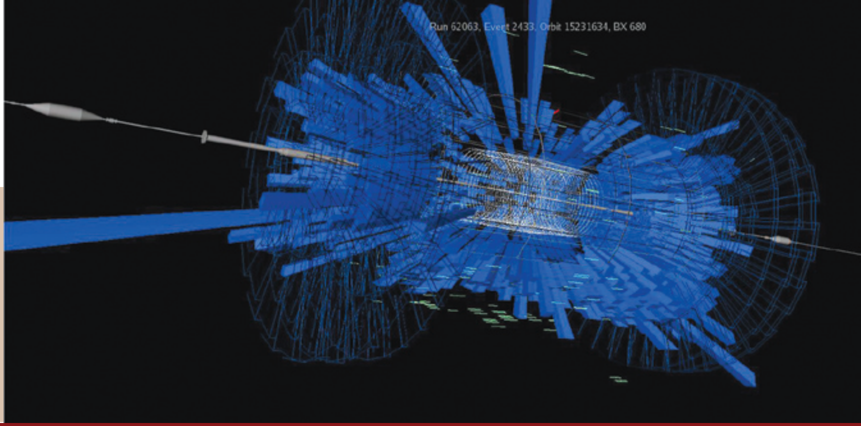
Fortunately for the LHC, it was all cheers at 10:30 a.m. on September 10 near Geneva, Switzerland, where CERN, the European Organization for Nuclear Research, operates the goliath physics experiment. The LHC's beam line, a ring 8.6 kilometers in diameter straddling the Swiss-French border, will recreate the conditions seen during the Big Bang. In the head-on collisions of billions of protons at a time, physicists have their fingers crossed that they will discover new particles, including the famed but as yet undetected Higgs boson.

As the LHC's controllers popped open champagne bottles, some 75 Techers in Pasadena celebrated the beam's first run at a midnight pajama party with pizza and beer, communicating via video conference with a dozen Caltech physicists in Geneva.

As soon as next month, two beams of protons zipping in opposite directions at 99.999998 percent the speed of light will collide at 10 trillion electron volts (TeV), ramping up to 14 TeV in the spring—about the energy released by four tons of TNT. At seven times the energy of the Tevatron at Fermilab, now the world's second most powerful accelerator, the LHC will push beyond the limits of what is known in physics as the Standard Model, which has so far described



The cavernous experimental hall that houses the Compact Muon Solenoid detector at CERN lies 100 meters underground and could easily be mistaken for a Bond supervillain's lair—perhaps the secret rocket base in *You Only Live Twice*. The detector's components were assembled on the surface and then lowered down the shaft with centimeters to spare—the first time such an approach has been tried. Here the final component, the 1,430-ton YE+1 end cap, is being mated to the detector on January 9, 2007.



This spray of subatomic particle debris from the proton beam hitting a tungsten block was one of the first images recorded by the Compact Muon Solenoid's detectors.

all the known interactions between particles with high precision.

Some 40 Caltech scientists under Professor of Physics Harvey Newman and Associate Professor of Physics Maria Spiropulu work on the LHC's Compact Muon Solenoid (CMS), one of two experiments searching for the Higgs particle. In anticipation of the terabytes of data soon to come, Newman has also directed a project that bops bits between computers at breakneck speeds—151 gigabits per second, or some 15,000 times faster than the best cable service in California.

Physicists hope the discovery of the Higgs will fill one of the gaping holes in the Standard Model—why do most particles have mass, and why are some particles heavier than others? If the model is correct, it's the interaction between the Higgs and other particles that creates mass. So the Higgs decays much more often into heavier particles, such as the Z or W bosons, than it does into lighter particles such as muons or electrons. If most physicists' hunches are right, the LHC will provide the energy needed to strip a 120–160 billion-electron-volt (GeV) Higgs particle from the wreckage of a proton.

The CMS is the heaviest CERN experiment, packing the weight of the Eiffel Tower into a volume 400 times smaller. Most of the weight is due to a massive metal coil that generates a 4-tesla magnetic field—enough stored energy in principle to lift the 12,500-ton magnet by 20 meters—which imparts a curve to the path of any charged particles created in the collision. The slower, heavier ones are the most affected—the more momentum a particle has, the straighter its course—allowing the momentum of each individual particle to be calculated by its trajectory through a nested set of detectors. Inside the magnet, a layer of lead tungstate crystals measures the energies of photons and electrons with high resolution, while layers of other materials capture the signatures of hadrons, a class of particles that includes protons, neutrons, and pions. Outside the magnet, another detector tracks muons, which come not only from collisions within the beam line, but from cosmic rays hitting air molecules in the upper atmosphere. Together, the system inventories the flurry of exotic particles from which the exceedingly rare Higgs signature must be plucked.

Because the Higgs will be so quick to decay, CMS isn't designed to capture the particle itself. Instead, the physicists will look for a decay of the Higgs into two photons, the massless carriers of light. Though this is a rare decay mode—only happening once in every ten trillion collisions—its signature should lurk in the crystals that Caltech has spent the last decade and a half perfecting.

Caltech physicists, including grad student Vladlen Timciuc, have analyzed the data from many millions of simulated proton-proton collisions, most of which result in bombardments of photons and pions well documented in other experiments. These simulations are crucial to separating false alarms from the true Higgs. "Yesterday's signal is today's background," says Timciuc, who will be looking through CMS data to find new particles.

CMS, located in Cessy, France, isn't the only station on the LHC hoping to find the Higgs. A competing experiment, ATLAS, takes place on the other side of the ring, on the Swiss side of the border. Though CMS is the better at seeing the two-photon signature of a Higgs decay, there is another possible outcome: one Higgs decaying into two Z bosons, each of which decays into two muons. Both experiments have equal sensitivity to the latter mode, so if one experiment sees it, the other should too. Though both the CMS and the ATLAS teams will race to publish first, Spiropulu

As the LHC's controllers popped open champagne bottles, some 75 Techers in Pasadena celebrated the beam's first run at a midnight pajama party with pizza and beer.

says it's a friendly competition.

"We cannot play war games," said Spiropulu. "We need each other."

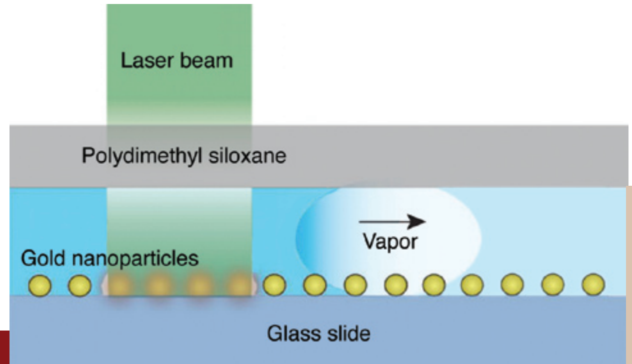
The LHC should start up in earnest on October 21, when the two proton beams will first run into each other. If the Standard Model is right, ATLAS and CMS should see a few Higgs decays a year. But being stood up by the guest of honor would just as exciting. Stephen Hawking recently made a $100 bet that the Higgs won't show.

"When do you give up on the Higgs?" asks Newman. "There is no other compelling explanation for how mass is generated, and people have gotten used to it."

With no Higgs, it would be back to the chalkboard for theorists. In the quantum world, forces are carried by particles—electromagnetism by photons, the weak force by W and Z bosons, and so on. A particle that supplies mass fits snugly in this framework. But if there's no Higgs, perhaps other particles will pop out of the collisions.

"Whenever you turn on a telescope, you see something new," says Sean Carroll, a senior research associate in physics at Caltech. "It's the same with particle accelerators." —*MC* e&s

Marissa Cevallos (physics '09) is the editor of the* California Tech *and a member of the women's Ultimate Frisbee team. She reported on LHC's first beam from Geneva, Switzerland, before starting a semester exchange program in Edinburgh, Scotland.



Adapted from Boyd, et al., *Analytical Chemistry*, Vol. 80, pp 2452–56, 2008.

A schematic of the bubble still.

A *REAL* MICROBREWERY

The happy art of distillation has been around for a good 5,000 years or so. But in the future, a household distillery could be essential for your health—and not by making moonshine for medicinal purposes. Caltech researchers have crafted the world's tiniest still to concentrate scant amounts of biomolecules, which could help detect the extremely low-abundance biomarkers that herald some diseases.

"Distillation is a well-established technology. You wouldn't think there'd be many new avenues to develop," comments David Boyd, a lecturer in mechanical engineering at Caltech who grew up in Alabama and is the lead author of a paper describing the work. "But in our approach, you don't need to boil the fluid anymore."

In a still, the vapor from a boiling liquid passes through a condenser, and the chilled condensate collects in a separate pot. If the liquid is a mixture of fluids with different boiling points, like ethyl alcohol in a watery corn mash, the lower-boiling one—the white lightning—will be concentrated in the condensate. Alternatively, boiling off the liquid leaves the heavier molecules behind, concentrating trace chemicals—the biomarkers—in the still pot. The catch, of course, is that the high heat will turn your precious proteins into so much gravy stock. Boyd and his colleagues have created a microstill that operates at room temperature, and thus could be used as a biomonitor.

The still is a microfluidic chip whose channels are studded with gold nanoparticles. Air bubbles, normally the bane of microfluidic designs, are actually the key to this one's success. Each bubble acts as a tiny still pot. A laser no more powerful than a classroom pointer zaps the gold nanoparticles behind the bubble. The particles quickly transfer the heat to the surrounding fluid, and a little bit of liquid on the bubble wall vaporizes, passes through the bubble, and condenses again on the cooler wall of the bubble's front. "Only the most volatile molecules cross over the bubble. Everything else is left behind," Boyd says. "Typically, air bubbles are a real annoyance, because they pin the flow in the fluid, and are hard to get rid of. We've learned to love them."

The bulk fluid stays at room temperature, preserving the fragile protein molecules intact, because of a unique heating property of gold in its nanoform. The particles absorb green light very strongly, "acting like antennas for visible light," says coauthor David

In the future, a household distillery could be essential for your health—and not by making moonshine for medicinal purposes.

Goodwin, professor of mechanical engineering and applied physics.

In a demonstration experiment, the team dissolved a blue dye in ethanol, then mixed it with water. As the mixture coursed through the microchannels, the color behind each bubble intensified, while the liquid in front of each bubble turned clear.

Moving even beyond clinical diagnostic tools, the ultimate goal is to use this microstill as part of a personal sensor, perhaps even one worn as a patch, to track the level of some substance in one's blood. "Say you are on some prescription whose optimum dose is 10 micrograms per liter of blood," says Boyd. "The still could concentrate that med so another part of the chip could measure it accurately, and automatically control the release of more of it as needed to maintain the activity level."

The paper, whose other authors are James Adleman (MS '04, PhD '08), a graduate student in electrical engineering, and Demitri Psaltis, Caltech's Myers Professor of Electrical Engineering, appeared in the April 1 issue of *Analytical Chemistry*. *—DS/EN* e&s

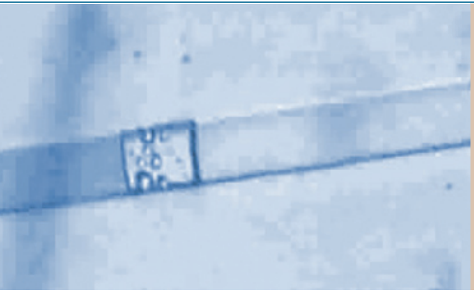
THE SOUND OF MOVEMENT

If you see the letters on this page in a rainbow of colors, or if hearing a certain word triggers the taste of cigarette smoke, you are a synesthete—one of perhaps every 100 people whose brains are wired in such a way that stimulating one sense activates another as well. Now, Caltech researchers have discovered a type of synesthesia in which sounds, such as tapping, beeping, or whirring, are heard when things move or flash. Synesthesias that trigger the senses of sight, touch, and taste are well known, but an auditory synesthesia had never been identified before.

Caltech postdoc and lecturer in computation and neural systems Melissa Saenz (BS '98) discovered the phenomenon quite by accident. "While I was running an experiment at the Caltech Brain Imaging Center, a group of students happened to pass by on a tour," explains Saenz, who, along with Christof Koch, the Troendle Professor of Cognitive and Behavioral Biology and professor of computation and neural systems, reports the finding in the August 5 issue of the journal *Current Biology*. "My computer screen was showing dots rapidly expanding out, somewhat like the opening scene of *Star Wars*. Out of the blue, one of the students asked, 'Does anyone else hear something when you look at that?' After talking to him further, I realized that his experience had all the characteristics of synesthesia: an automatic sensory cross-activation that he had experienced all of his life."

Intrigued, Saenz began to look for others with the same ability. (You can view the video—in a quiet location!—at http://www.klab.caltech.edu/~saenz/movingdots.html.) "I queried a few hundred people and three more turned up," she says. "Having that specific example made it easy. It just happens to be quite 'noisy' to the synesthetes, and was a great screening tool. When asked if it made a sound, one of the individuals responded, 'How could it not?' I would have been less successful had I just generally asked, 'Do you hear sounds when you see things move or flash?' because in the real environment, things that move often really do make sounds," like, for example, buzzing bees.

This may be why the phenomenon hadn't been detected before—people with it may not realize that their experience is unusual. "These individuals have an enhanced soundtrack in life,



A microphotograph of the real thing. The channel, 100 millionths of a meter wide, runs sideways; the bubble is the square in the middle. The spheres in the bubble are smaller bubbles—at 10 billionths of a meter in diameter, the gold nanoparticles are invisible at this scale.

Why don't pregnant women reject their own fetuses, which are packed with antigens from the father that are foreign to the mother?

rather than a dramatically different sensory experience," says Saenz.

The four synesthetes outperformed a control group in recognizing patterns of flashes similar to visual Morse code. Such patterns are normally easier to identify as beeps than flashes, so hearing a sound every time you see a flash should give you an advantage. The subjects watched a series of flashes and then had to guess if a second sequence, played afterward, repeated the same pattern. A similar test was given using sequences of beeps. Both the synesthetes and the control group performed equally well when given beeps, but the synesthetes responded correctly to the flashes more than 75 percent of the time, compared to around 50 percent—the level predicted by chance—in the control group.

Saenz and Koch suspect that as much as 1 percent of the population may experience auditory synesthesia. In fact, they think that the brain may normally transfer visual information to the auditory cortex in order to create a prediction of the associated sound. "At this point, very little is known about how the auditory and visual processing systems of the brain work together," says Saenz, who has begun brain-imaging studies to explore the connection. "Understanding this interaction is important because in normal experience, our senses work together all the time." —*KS*

ENGINEERING IMMUNITY

Caltech scientists are designing living tools that immune-system cells can use to fight disease, thanks to a $750,000 grant from the Skirball Foundation. The gift will expand the Engineering Immunity program founded by David Baltimore, the Millikan Professor of Biology, and Pamela Bjorkman, the Delbrück Professor of Biology and an investigator with the Howard Hughes Medical Institute.

For nearly 40 years, Baltimore has studied how genetic information gets from viruses into host cells. He codiscovered an enzyme that enables the RNA of certain viruses to make a DNA copy of its hereditary information—genetically engineering its host. DNA's transcription of information to RNA was well known, but no one knew that RNA could write back. That discovery so altered science that Baltimore and two other researchers won a Nobel Prize.

Engineering Immunity puts viral genetic-engineering capabilities to good use. Researchers in Baltimore's lab are designing highly customized, stripped-down viral molecules containing genetic components that inhibit real viruses and tumors. These molecules can sneak into your body's cells, inserting their protective cargo into the cells' DNA. Engineering Immunity project manager and lead scientist Lili Yang (PhD '04); then-

THE OUTER LIMITS

At the very edge of the solar system, Voyager 2 has sailed through the termination shock, where the solar wind abruptly slows as it presses outward against the ions in interstellar space. All of the spacecraft's fields and particles instruments returned data as it crossed the oscillating shock three times in a six-hour period on the night of August 31–September 1, 2007. (At least two other inferred crossings happened during telemetry gaps before and afterward.) A set of papers in the July 3 issue of *Nature* describes the conditions at the encounter, which were quite different from those observed by Voyager 1 in its single crossing four years earlier. The biggest surprise is that the shock is asymmetric—Voyager 1, traveling northward out of the plane of the solar system, crossed it at 14.1 billion kilometers, while southbound Voyager 2 hit it at a distance of a mere 12.6 billion kilometers.

Meanwhile, closer to home, the International Astronomical Union (IAU) has voted to accept Makemake (pronounced mah-kay mah-kay) as the official name for the dwarf planet previously known as Easterbunny. 2005FY9, as it is also known, was discovered by Rosenberg Professor of Planetary Astronomy Michael Brown's team on March, 31, 2005, four days after Easter. IAU rules say that trans-Neptune objects must be named for figures in creation myths; Makemake is the creator of mankind and the god of fertility among the Rapa Nui people of—you guessed it—Easter Island. —*DS* staff member Pin Wang (MS ’00, PhD ’04), now at USC; and Baltimore recently published a method for designing injectable versions of these molecules that are capable of selecting a specific cell type, such as the cells that kick off immune responses. This vastly reduces the risk, time, and cost involved in previous methods for genetically modifying human cells, which involved removing them, working with them in a laboratory, and then reintroducing them into the body.

Four years ago, the Skirball Foundation provided the project’s seed funding. Since then, the program has grown into a massive HIV- and cancer-research effort that extends far beyond Baltimore and Bjorkman’s collaboration to include teams at UCLA, USC, and Children’s Hospital Los Angeles.

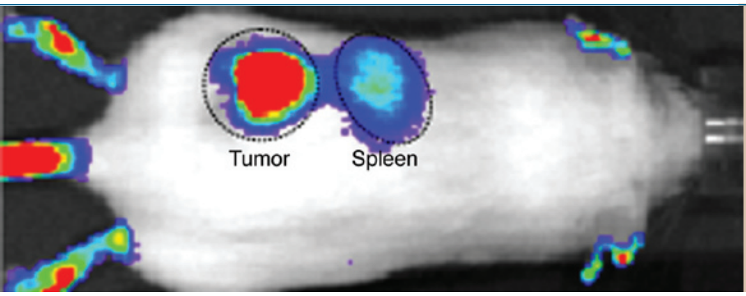
The new grant is intended to do just what the first one did—encourage research seen as too exploratory for most organizations to support. This new money will underwrite three immune-system studies, a breakthrough in any of which could lead to substantial improvements in an array of medical applications.

Yang plans to learn more about T cells—white blood cells central to cellular immunity—by actually watching them in action. She has developed a method for labeling the T cells of interest with a bioluminescent imaging gene, allowing them to be tracked in a live animal in real time. Biologists can now watch how T cells behave when they encounter the friend-or-foe tags known as antigens, when they kill tumor cells, and when they recede after the battle is complete. A wide range of experiments being done in concert with medical imaging under way at UCLA could significantly improve cancer treatments by identifying the critical conditions needed for immunotherapy to work.

Visiting Associate in Biology Daniel Kahn, an obstetrician affiliated with the David Geffen School of Medicine at UCLA, will study some newly recognized types of immune cells that may hold the key to a longstanding mystery: Why don’t pregnant women reject their own fetuses, which are packed with antigens from the father that are foreign to the mother? Could pregnancy-specific diseases like preeclampsia result from the immune system going awry? Finding the answers may not only strengthen treatments for pregnancy-specific conditions, but perhaps may improve the long-term success of organ transplants.

Finally, postdoc Ryan O’Connell will tackle RNA molecules called microRNAs or miRs. Discovered just a few years ago, miRs turn out to be powerful players in the development (or inhibition) of cancer. Three of them, called miR-155, miR-146, and miR-34, have been linked to cancers of the immune system but are also involved in immune-cell development and healthy responses to inflammation. These microRNAs may be able to trigger cells to proliferate, kill themselves, or stop replicating—properties that might be exploited to deal with cells that have run amok and begun growing abnormally.

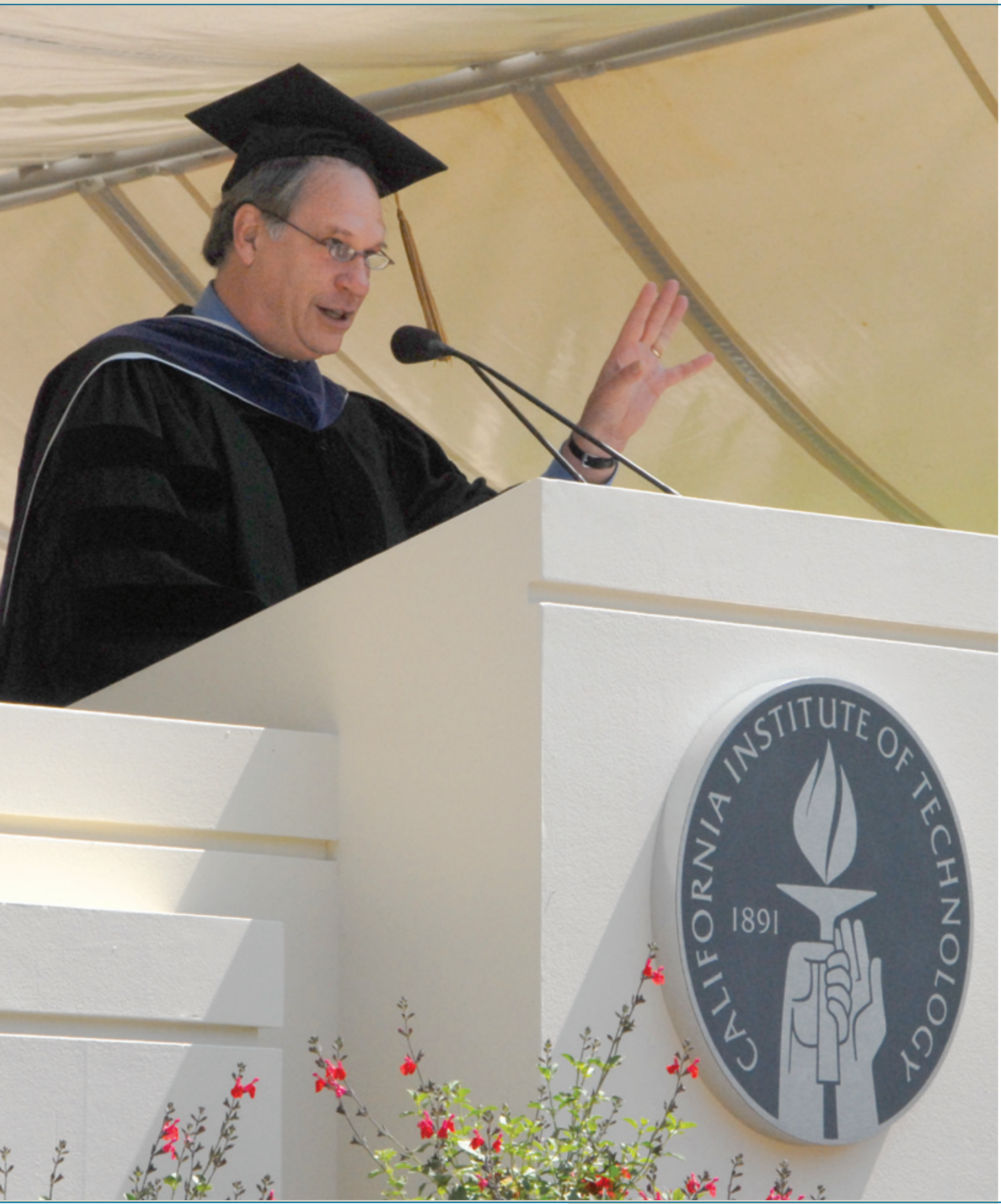
Engineering Immunity—started by one funder’s leap of faith in a speculative line of research—is paying huge dividends. Says Baltimore, “The Skirball grant was the most important grant I ever received. . . . The foundation took a chance in supporting an unproven notion.” With that “unproven notion” now going full steam in labs across Southern California, the Skirball Foundation is once again out in front in supporting science in its earliest, most basic stages. —*AW* e&s



This bioluminescence image of an anesthetized mouse injected with anti-cancer T cells shows that they gather preferentially in two spots: the spleen, where T cells hang out until mobilized, and the tumor. The red areas have the highest T-cell concentrations. Since this particular cancer, a melanoma, was derived from melanocyte-containing skin cells that display similar antigens, the hairless tail and legs also light up. Losing your melanocytes will cause skin depigmentation; losing a battle to melanoma is fatal.

Stories matter, and in a nation where belief in alien abductions is on the rise while belief in evolution is on the decline, the best way to defend science is to tell your friends a good story.

Tell Me a Story



Science journallist Robert Krulwich, who is seen on ABC and heard on NPR, was the featured speaker at Caltech's 114th commencement exercises on Friday, June 13.

Normally, if you're a science reporter at NPR or ABC, a trip to Caltech means that you call ahead, and you ask for a few precious moments with the world-class intellectual whatever. And you're ushered in, and you furiously take notes, all the time thinking, "Do I have any idea what this person is saying?" I'm sure you know the feeling.

So when I got my invitation asking *me* to give *you* guys a lecture, I thought, come on—what could I tell *you*? But I thought of something. And it's something that's going to happen to you, you sitting here with the black hats, in the next hour or two.

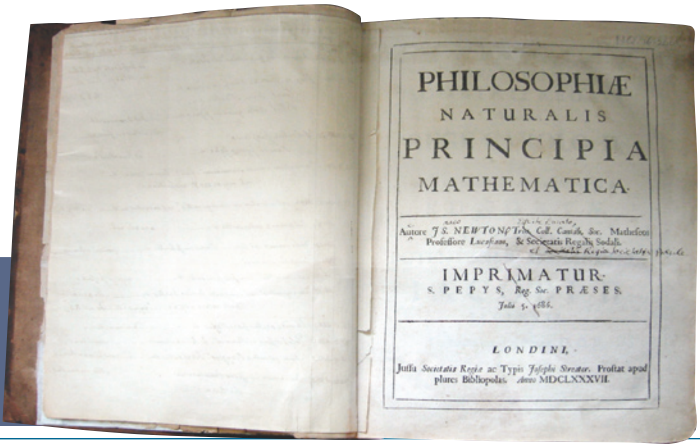
There you'll be, in your cap and gown surrounded by your family, and by friends, and by friends of friends, and somebody—maybe an uncle, a buddy, somebody—is going to turn to you and say, "So what have you been doing at Caltech? What were you working on?"

Not that they really want to know—but after all, you've been here for four years, or a different number, if you're a grad student, and you must have been doing *something* here, so it's only polite to ask.

And I know that a lot of you come from scientifically literate families. But let's assume that this relative, we'll make it a "he," is not a scientist. He's not an engineer. And the last time he had a thought, a complex thought about biology or math, was back in 11th grade . . . when he got a C- in both subjects and vowed never, ever to think about biology or math ever again.

But because this is *your* day, and because this person loves you, or because he

By Robert Krulwich



can't think of anything to say after "hi," he asks about your work.

And to make it still more interesting, let's assume that if you explain to this person what you've been working on, you might have to use certain words like "protein" or "quark" or "differential" or maybe "hypotenuse." And if you do, he is going to listen to you very, very politely, but upstairs, those words are going to mean not a whole lot. Because science is not his thing. He can lip-synch every word to 'NSYNC's "Bye Bye Bye," but "hypotenuse" is hard.

So . . . here's my question: When you are asked, "What are you working on?" should you think, "There's no way I can talk about my science with this guy, because I don't have the talent, or the words, or the patience to do it—it's too hard, and anyway, what's the point?"

Which, by the way, is not an unusual position. No less than Isaac Newton, and I mean *Sir* Isaac Newton, that one, was asked why he had made the *Principia Mathematica*, his earthshaking book about gravity and the laws of motion, so impossibly hard to read. He replied that he'd considered writing a popular version that people might understand, but—and I am quoting Newton here—"to avoid being baited by *little smatterers in mathematics*," that was his phrase, "little smatterers," he intentionally wrote the book in dense, scholarly Latin with lots of math so that only scholars could follow it.

In other words, Isaac Newton didn't care to be understood by average folks.

But here's the argument I want to make to you guys this morning, and you're not going to hear this advice often. You may never hear it again: *Do not do what Newton did*. No, no, no.

When a cousin or an uncle or a buddy comes up and asks you, "So, what are you working on?" even if it's hard to explain, even if you know they don't really want to hear it, not really, I urge you to give it a try. Because talking about science, telling science stories to regular folks, is important. In a way, it's crucial.

Scientists need to tell stories to nonscientists, because science stories—and you know this—have to compete with other stories about how the universe works, and how it came to be. And some of those other stories—Bible stories, movie stories, myths—can be very beautiful and very compelling. But *to protect* science and scientists—and this is not a gentle competition—you've got to get in there and tell your version of how things are, and why things came to be.

We all know about creation-science movements in America. But what you may not know is that such movements are spreading all over the world. In Turkey, there's a group led by a man named Adnan Oktar, a Moslem creationist. And his group produced a picture-packed 768-page "biology" textbook that's priced very, very cheaply, so schools can have it for next to nothing. And that textbook is now in schools all over Turkey. It's written in clear and simple language, using fabulous pictures, and the pictures are designed to "prove" that fossils show no evidence of evolution.

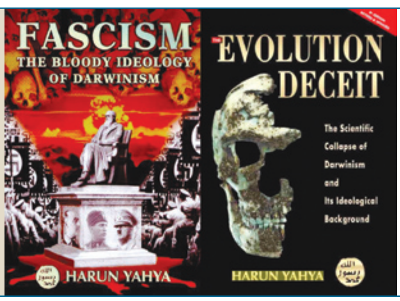
And this group's books, and their CD-ROMs, and their grocery-store magazines—they have grocery-store magazines!—are so inexpensive and so provocative, with titles like *The Bloody Ideology of Darwinism* or *The Evolution Deceit*, and their websites are so widespread, that in Turkey's high schools—which are not religious schools; they have a long secular tradition there—evolution and Darwin are getting less and less attention in the curriculum.

In 2006, when Turks were polled and asked whether it's true or false that human beings as we know them developed from an earlier species of animals, only 25 percent of the Turkish public said yes. That's a *very* low number. In Japan, 78 percent say humans evolved from a predecessor species. In the U.S., it's 40 percent. But that's above Turkey.

There was a debate, of course. And there's still one, sort of, except Mr. Oktar sued the people who opposed his views for slander, and managed to shut down their blogs. His followers attacked biology professors as "Maoists"—Maoists?!—for teaching evolution, which they called "nothing but a deception imposed on us by the dominators of the world system." High-school teachers in Istanbul were challenged because they taught evolution and not creation science.

And while Mr. Oktar was recently arrested for his role in a sex-ring operation, so he may be taking a break, creation science is now taught all over Turkey. And while Turkey may seem an ocean or more away, *it is not*. There are always Mr. Oktars who aim their

Two of the anti-evolution bestsellers that are changing the face of science education in Turkey. Harun Yaha is a pen name of Adnan Oktar.



In a typical episode, Ross is going on about opposable thumbs. He says, "Without evolution, how do you explain opposable thumbs?"
Replies Phoebe, "Maybe the overlords needed them to steer their spacecrafts."

stories right at *you*, right at the heart of a place like this, at the values that Caltech has always honored from the beginning.

I know you spent long nights cramming and sweating under the weight of too many assignments and too many tests and too many papers from too many professors who didn't realize that there were *other* professors who were making you do the same tests, but somewhere in that nightmare of work, you may have noticed that your teachers were giving you more than tension headaches; they were giving you values. A deep respect for curiosity. For doubt. Always doubt. For open-mindedness, for going wherever the data leads, no matter how uncomfortable. For honesty. For discipline. And most of all, the belief that anybody, no matter where you are from, no matter what your language, religion, politics, age, or temperament—I mean, this place has seen *monstrous* egos, and bongo players and people who dress in Viking hats—but if you can learn to how to sit down in a laboratory and think in an orderly way, and if you have the patience to stare and stare and stare and stare looking for a pattern in nature, you are welcome here. It may be boring. It may be sometimes very exhausting. But there's a freedom, a *freedom*, in this way of looking that is precious in the world. And that freedom can be attacked, or defended, with stories.

Stories matter.

After all, what is a science experiment? You make up a story that may or may not be true, and then you test that story in the real world to see what happens.

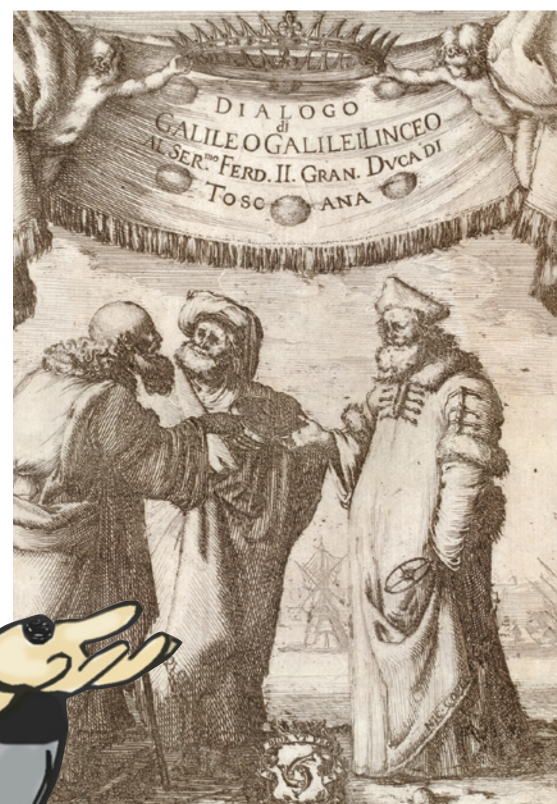
So, for example, let's say you're in Pisa around 1590, and a guy named Galileo comes up to you and says, "Hello there." (He actually probably wouldn't say it that way, but still.) "You see I have a cannonball in my right hand, and in my left hand I have a musket ball, which is much lighter. Now, sir, if I told you that these two balls, if dropped from the same high place at the same time, would hit the ground simultaneously in spite of their five- or tenfold difference in weight, would you like to see me try?"

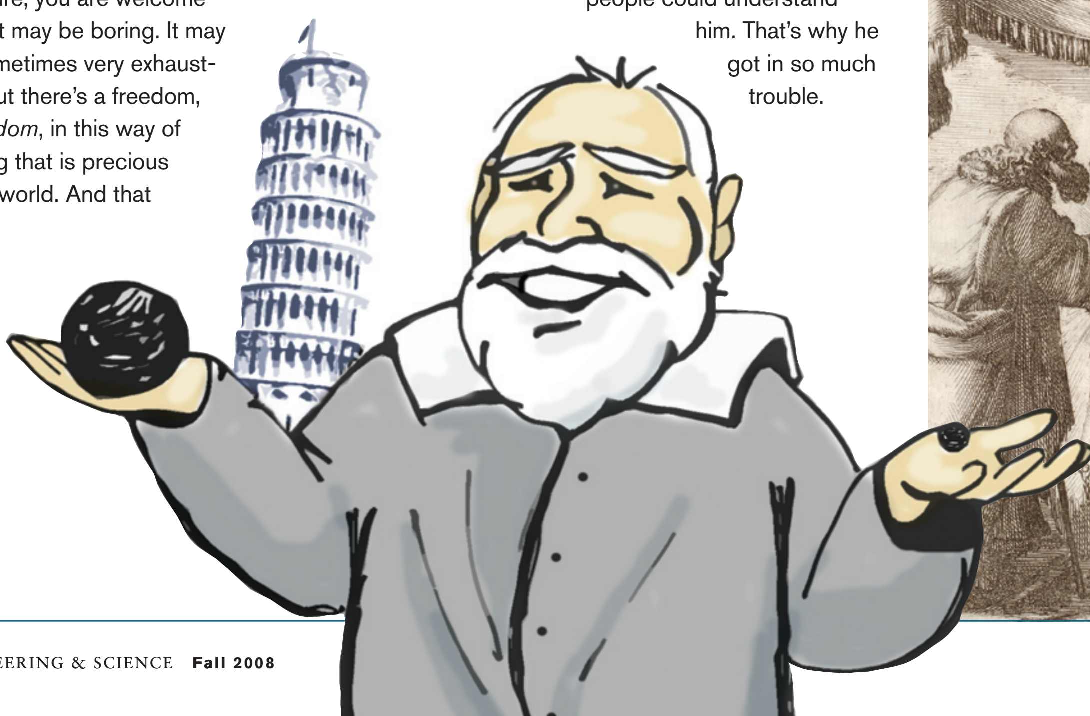
Whether Galileo actually did this or not—if he proposed this to you, wouldn't you stick around? Just to see how it comes out?

Galileo, for my purposes, is the great Un-Newton. Unlike Newton, he had a flair for narrative, a storyteller's sense. Unlike Newton, he wanted to tell people what was on his mind. Unlike Newton, he thought the people could understand him. That's why he got in so much trouble.

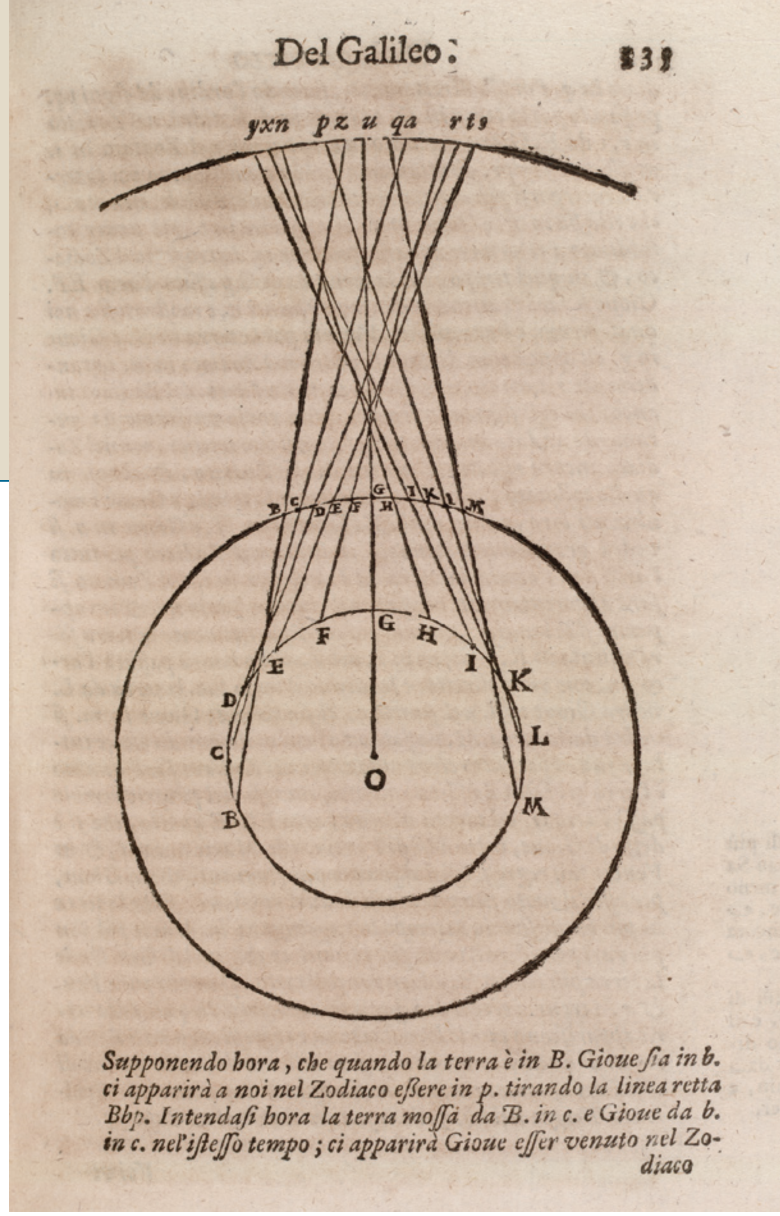
His famous book, the *Dialogue*, about the sun being the center of the solar system, wasn't written in Latin. He wrote it in Italian, for a mass audience. And the writing was gorgeous. It was poetic, it was combative, it was funny. It's a running conversation between three good friends who spend four days together, arguing, eating, and boating through Venice in gondolas—the argument being, is the earth the center of the solar system, or might it be the sun? The book has pictures, little line drawings that he made; and he put in marginal headings to break up the text, so you wouldn't have a big sheet of writing. And while there are numbers, he doesn't get to them until two-thirds through the book, and if you skip the numbers you don't miss that much.

So because Galileo's book was so easy to read, and such a page-turner, it so threatened the established order that Galileo, as





In this page from the *Dialogue*, Galileo explains Jupiter's retrograde motion—in which it appears to slow, reverse course, and then move forward again against the background stars—as a consequence of both Earth and Jupiter orbiting the sun, with a faster-moving Earth on the inside track.



you know, was put under house arrest. And it wasn't just his *science* that was alarming. I think it was the power of his storytelling. That's what made him extra dangerous, because stories have this power.

People *like* them.

E. O. Wilson, a great scientist and a great storyteller, wrote that "science, like the rest of culture, is based on the manufacture of narrative. . . . We all live by narrative." He doesn't know the half of it.

I work in radio and television. I can go on prime-time TV (and I have) and do an hour on string theory, and talk about multiple dimensions, and space-time curvature, and supersymmetries. This is very odd, very hard stuff, and yet a whole lot of people, a few million people, will sit there and watch the whole time, apparently—I like to assume—quite fascinated.

But the program ends, and then you have a bunch of ads—maybe seven commercials and one network I.D.—and three-and-a-half to five minutes pass, and the next program comes on, on the very same channel. This one is about extraterrestrials landing in anti-gravity machines to examine the breasts of innocent cocktail waitresses, and the same people who were watching the previous hour sit there with same sense of awe and fascination, and they kind of believe this one, too!

People are not discriminating about stories. Truth? Fiction? Eh . . . whatever. It's like the endless back-and-forth between Ross and Phoebe on the TV show *Friends*. Ross is a paleontologist. He studies dinosaurs. Phoebe is his masseuse friend. She doesn't study anything, but she knows everything. And in a typical episode, Ross is going on about opposable thumbs.

He says, "Without evolution, how do you explain opposable thumbs?"

Replies Phoebe, "Maybe the overlords needed them to steer their spacecrafts."

So people can slip very easily from reason to fantasy, and they believe both. They don't feel a need to be consistent. They just want to be absorbed, swept away. So when you tell stories to Americans, really to anybody in the world, you have to remember there are lots of Phoebes. Stories with gripping visuals and good punch lines, stories that make intuitive sense, that make sensual sense—to your eyes, to your ears, to your touch—can convince. They have power. You may not believe that two balls, one heavy, one light, dropped from the same high place will land together, but if you see it with your own eyes, *that* you remember.

As science gets harder, metaphor becomes more useful, and even necessary. More and more of what science teaches about the world is not intuitive. It makes no sensual sense.

Far left: Boy, have I got an experiment for you! Left: On the title page of his *Dialogue On the Two Chief World Systems*, Galileo pays homage to, from left, Aristotle and Ptolemy, whose views he demolishes, and Copernicus, who comes out the winnner.

The Grand Canyon bears witness to the magnificent violence hidden in a torrent of old raindrops.

This starts early, in high school. If I slap my hand on a hard surface, like this lectern, the outer electrons in my hand and the ones in the wood repel one another. This is the electromagnetic force, as you know. Electrons just don't like being around other electrons, so the reason my hand doesn't go through the surface is that two platoons of electrons on a line of scrimmage got in each other's faces.

So Mary Schweitzer gets the bone fragment in the mail, and although Bob the Dinosaur was about 70 million years old, almost immediately when she looked at it, she said, "This is not a Bob. This dinosaur is a girl, and she's pregnant."

That's harder, though—to add faces, and motives, and football analogies to electrons. There are some of you, probably on the faculty, who will say, "You can't talk about nature that way. It distorts what's true. What's true is what you see in equations, in the math, that points to these laws."

But I go back to my man Galileo, who was maybe the first, in Western tradition anyway, to honor mathematics as the primal force of knowledge. The logic of the universe, he said in his book *The Assayer*, is "written in the language of mathematics . . . without which . . . one is wandering around in a dark labyrinth." But having honored math, Galileo was very happy to create beautiful metaphors, to invent marvelous characters, to draw pictures; he knew how to light that labyrinth so the rest of us could see inside. Because the more abstract and mathematical science gets, the more we need to imagine something concrete. As the physicist and author Alan Lightman [PhD '74] has said, "we are blind people inventing what we don't see."

And yet many scientists remain wary of metaphors, of adjectives, and even of the active voice—"It was observed that . . ." sounds much nicer to these people, for some reason, than "I saw." And I can tell you from personal experience that they do *not* like talking to reporters because they think, "Whatever I say, this 'journalist' person is going to turn it into something stupid, and cartoony, and wrong." Yeah, you're applauding. And maybe it's true. But I was happy to learn that scientists are just as nasty about each other.

My favorite example is a pair of letters from Werner Heisenberg and Erwin Schrödinger, two of the 20th century's great physicists. Schrödinger liked to think in pictures, his most famous one being the image of a cat in a box who paradoxically is both alive and dead at the same time—don't ask. The point is, Schrödinger loved pictures. And Heisenberg, he loved numbers.

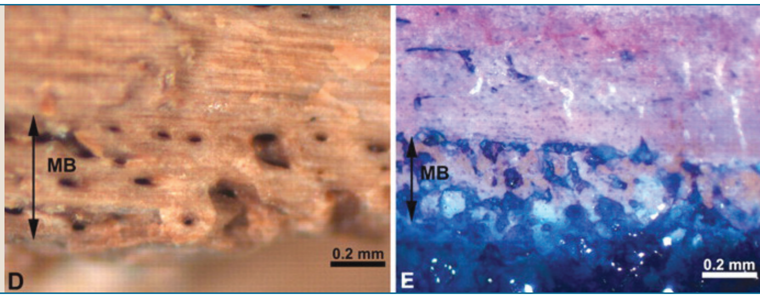
When Schrödinger read Heisenberg's papers, they were so mathematical that he wrote he was "*repelled*"—his word—"by the methods of transcendental algebra . . . [that so lack] visualizability."

And Heisenberg answered back, oh yeah? Well, he probably didn't say it that way, but he did say that the more he reflected on Schrödinger's work, "the more *disgusting* I find it." And "disgusting" is a quote. It's Heisenberg's word.

So there is a tension among scientists between two kinds of truth: math and narrative.

But the job we face is to put more stories out there about nature that are true and complex—not dumbed down—and that still have the power to enthrall, to excite, and to remind people that there's a deep beauty, a many-leveled beauty in the world. What scientists say is hard-won information, carefully hewn from the world. It's not the offhand opinions of a tribe of privileged intellectuals who look down on everybody.

It's my sense that if more scientists wanted to, they could learn how to tell their stories with words and pictures and metaphors, and people would hear and remember those stories and not be as willing to accept the other folks' stories. Or at least there'll be



Right: The photo labeled D is a micrograph of Bob's femur, and the one labeled E is an emu tibia. "MB" stands for "medullary bone," which is the calcium-storage tissue.
Opposite page: Mary Schweitzer and Bob's smaller cousin, an albertosaur.

Schweitzer, et al., *Science*, Vol. 308, pp. 1456-60, June 3, 2005.

a tug of war, and I think that the science stories will, surprisingly, very often win.

I remember standing on the rim of the Grand Canyon looking down on that enormous hole created by running water, endlessly running water, fed by a distant Colorado rain, and thinking, "How did this beautiful thing happen?" And in my head I heard a line written by Loren Eiseley, a great, great scientist and writer, a line I had read in college, which described "the magnificent violence hidden in a raindrop."

And when I looked back at the canyon, and at the roaring river there, that's what I saw: magnificent violence hidden in a torrent of old raindrops.

Now we can't all be *that* good, and even when we try, we don't always win. Again, I'm thinking of Ross, poor Ross, and the show *Friends*. He tells Phoebe that he's seen fossils from all over the world, and "you can literally see them evolving through time."

And Phoebe says, "Really? You can actually see it?"

And Ross says, "You bet. In the U.S., China, Africa, all over."

And Phoebe says, "See, I didn't know that."

And Ross says, "Well, there you go."

And Phoebe says, "Huh. So now, the *real* question is: Who put those fossils there, and why?"

So yes, science stories don't always win, but at the very least it should be a tug of war. And if you tell them right, they have the power to change minds.

On my way here, I read a story in *Smithsonian* magazine that's a good example of what I'm talking about. Imagine that you're sitting on your porch with a friend, a non-science friend, and as you sit there, a robin, an ordinary robin, wanders onto the lawn and you say to your friend, "You see that robin? Did you know that robins, in fact all birds, are directly descended from dinosaurs? And in a way, that robin is a small, feathery, modern dinosaur? Huh?"

And if your friend is like my friends, she'd say, "What? What are you. . . . Go away!" But don't go away. Instead, you could tell her this story, which is how I'm going to conclude.

Eight years ago, Bob Harmon, who works for the Museum of the Rockies, was having lunch in a canyon somewhere in Montana and he looked up at a big rock face and he saw a bone sticking out of the wall, just a bit. That bone turned out to be part of a *Tyrannosaurus rex*, one of the best-preserved examples of a *T. rex* ever found anywhere. And after three years of carefully, carefully, carefully chipping away, they got a 2,000-pound skeleton out of the wall. The dinosaur was named "Bob," in honor of Mr. Harmon, and on the way out, for various logistical reasons, they had to break a leg bone. Some of the fragments were sent to scientists around the world, including one at North Carolina State University named Mary Schweitzer.

So Mary Schweitzer gets the bone fragment in the mail, and although Bob the Dinosaur was about 70 million years old, almost immediately when she looked at it, she said, "This is not a Bob. This dinosaur is a girl, and she's pregnant."

When women get pregnant, they use the calcium from their bones to build the skeletons of their developing fetuses. And if the mother is a *bird*, she also needs calcium to build eggshells.

Mary had studied birds, and she knew that in the cavities within their bones, pregnant birds grow a special kind of spongy bone that acts as a calcium reservoir. It gets drawn down as the eggs are laid, so that the bones themselves don't get weakened. And when Mary looked at the dinosaur-bone fragment, she saw just what pregnant birds have.

The most primitive birds today are the emu and the ostrich, so just to be sure, she called a bunch of ostrich breeders in North Carolina and said, "Anybody have a dead

She’ll glance at a little bird pecking for worms on the lawn, and she’ll travel 70 million years back to a time and a place that creationists say did not exist, but now, because of your story, your friend has a pregnant tyrannosaurus in her head with the unfortunate name of Bob.

female? I need a leg bone here.” And a few months passed, and the phone rang, and it was a farmer saying, “Ya’ll still need that lady ostrich?”

So Mary and her two assistants collected the dead ostrich, which was in the farmer’s backhoe bucket, and drove it back to Raleigh, and what do you know? The former ostrich had been a pregnant former ostrich, and the bones looked pretty similar. The next year, Mary published a paper in *Science* with the dinosaur bone right next to an emu bone, which looks even more like Bob’s.

And since then, another *T. rex*, this one in Argentina, was found to have the same calcium structure—more evidence that when you look deep inside dinosaurs and deep inside birds, what you see is very, very similar. Which gives us yet another reason to think that the robin in your front yard *is* an itty, bitty dinosaur.

If your nonscience friend listens to that story, and leans in a little, and hears how scientists work with bones and dead birds in buckets, patiently looking for patterns, you have just placed a sword in her hand. The next time somebody tells her that scientists are know-it-alls who toss off opinions, that science is an elitist plot, she would think, “wellllI, but I *did* hear this story . . .” and the scientific method gets a little more defense, a little protection.

But better than that, the next time your friend sees a robin, she’ll see, I hope, more than a robin. She’ll glance at a little bird pecking for worms on the lawn, and she’ll travel 70 million years back to a time and a place that creationists say did not exist, but now, because of your story, your friend has a pregnant tyrannosaurus in her head with the unfortunate name of Bob. Which makes robins and sparrows and chickadees and crows and all birds just a little more amazing, and a little more delightful to look at. Which means, *you win*. The creationists can’t beat delight. You have smote them with your story.

So ladies and gentlemen of the class of 2008, mindful of the fact that this place, this institution, with its culture of intellectual freedom, and respect for truth, and love of inquiry, not to mention illegal bonfires on city streets and basketball teams that lose 207 games in a row—but not the women’s team; I heard about their astonishing two-game, back-to-back winning streak, yes, yes!—*you* know, you *know*, that when you receive your degree today, you are part of, and you are celebrating, something very rare, and very precious, and very fragile in our world. This place celebrates freedom, and because you are now free men and women, you have to protect what you’ve been given by helping others who haven’t been here and who never are coming here to understand the value of what you do. And what your teachers do, and what their predecessors have done. Which is why, an hour or so from now, when your brother, or your aunt, or your mom asks you, “So what have you been up to while you’ve been here?” take a chance. Find the words, find the metaphor, share the beauty, and tell them what’s on your mind.

Tell them a story. e&s

Robert Krulwich regularly appears on ABC’s* World News*,* Nightline*,* Prime Time Live*, and* Good Morning America*. He is also a regular on National Public Radio’s* Morning Edition *and* All Things Considered*, and cohosts* Radio Lab*, a science show for people who don’t listen to science shows. His beats include science, technology, and economics; he once created an opera (in Italian!),* Ratto Interesso*, to explain how the Federal Reserve regulates interest rates.

Krulwich joined NPR in 1978, and served as economics reporter until 1985, when he joined CBS News. Since 1994, he has been an ABC News correspondent. He is also a regular correspondent on the PBS investigative series* Frontline*.

His* Frontline *coverage of campaign finance in the 1992 presidential elections earned him an Alfred I DuPont—Columbia University Award, and his investigation of privacy on the Internet, “High Stakes in Cyberspace,” won an Emmy, as did his ABC special on the cultural history of the Barbie doll.

Other honors include the George Polk Award from Long Island University, the Eleanor Nealon Extraordinary Communicator’s Award from the National Cancer Institute, and the American Association for the Advancement of Science’s Science Journalism Award.

This article was edited by Douglas L. Smith.

Beautiful Ideas; Beautiful Books

by Daniel Lewis

The Burndy Library's 67,000 volumes are now part of the Huntington Library's science and technology collection. Here's a tour of some of the landmarks of Western thought that will be on display at Caltech's neighbor and counterpart research institution in the humanities.

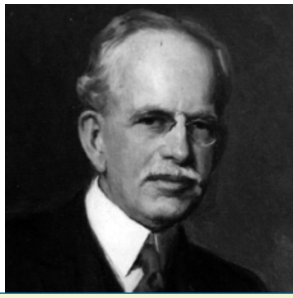
The Huntington Library has had formidable holdings in the history of science and technology for a long time, but the arrival of the Burndy Library in 2006 has given us the premiere collection in North America, and one of the largest in the world. The Burndy acquisition is the biggest in our history, second only to the founding trove amassed by Henry Huntington himself. Nearly 100 works from the combined collection, tracing the evolution of Western civilization's worldview from Ptolemy to the present, will be on permanent public display beginning on November 1. I'll tell you more about the exhibit in a moment, but first I'll describe the Burndy Library and its acquisition by the Huntington.

The man who assembled the Burndy collection, Bern Dibner, was born in the Ukraine in 1897 as Abraham Bernard Dibner. The family came to the United States in 1904, and he graduated with an EE degree from what was then the Polytechnic University, but is now part of NYU, in 1921. Bern D., as he was known to his friends, made his fortune by inventing the first solderless electrical connector. He founded the Burndy—a play on his name—Engineering Company in 1924, using $650 he had received in compensation for a workplace accident where he almost got one of his fingers amputated in a printing press. Twenty-four patents later, Burndy connectors can be found in everything from power lines to PCs.

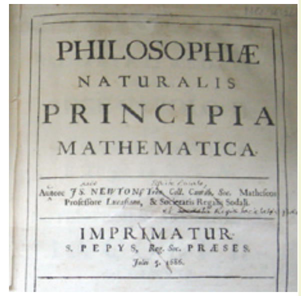
The Burndy Library started in 1930, when Bern read a book about Leonardo da Vinci called *Men and Machines*. Bern was captivated by da Vinci, and was fascinated from that moment on with the history of science and technology. He spent a year at the University of Zurich in 1936 to study the subject further, and in the course of doing so began buying books. Bern continued to collect avidly until his death in 1988, and his library now holds about 67,000 volumes, manuscripts, and artworks, not to mention an eclectic assortment of scale models, antique electrical equipment, and other objects.

To guide his collecting, Bern wrote what has become one of the standard bibliographies of the history of science. This book, *Heralds of Science*, lists 200 landmark works in 11 areas: astronomy, botany, chemistry, electricity, general science, geology, mathematics, medicine, physics, technology, and zoology. Before the Burndy came to the Huntington, we had 121 *Heralds*. The Burndy had 126. Together we have 176 of the 200. The exhibit will showcase some three dozen of them, plus other works, for a total of approximately 100 rare books and manuscripts from both collections.

Above: Bern Dibner collected more than books, as this assortment of pocket sundials from the 16th through the 19th centuries attests. Right: The Burndy's books occupy roughly a mile of shelf space.



Caltech and the Huntington have deeply entwined roots. In 1906, astronomer **George Ellery Hale**, the founding director of the Mount Wilson Observatory overlooking Pasadena, was in the process of turning sleepy Throop Polytechnic into modern-day Caltech. At the same time, he began a campaign to persuade his San Marino neighbor Henry Huntington, a railroad magnate who collected rare books and paintings, to create a research center from his holdings. When the Huntington Library and Art Gallery was founded as a freestanding institution in 1921, Hale was one of the first trustees appointed. Ever since, many Caltech humanities faculty have made the Huntington their second academic home, and the ties between the two institutions, while mostly informal, have had many tendrils in the form of fruitful collaborations.



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

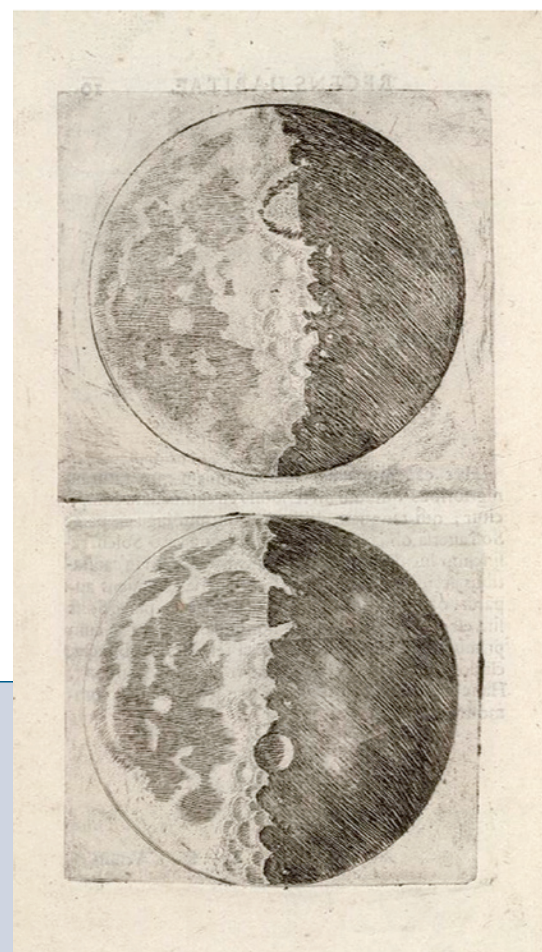
Newton's hand-revised *Principia* was later owned by Edmond Halley, who underwrote the publication of the first edition—the Royal Society's book-printing budget for the year had been exhausted on a history of fishes.

The Huntington, for example, had George Ellery Hale's copy of *Sidereus Nuncius*. *Sidereus Nuncius*—the *Starry Messenger* or *Starry Message*, depending on how you translate the Latin—was published by Galileo in March of 1610 as an edition of 550 copies. It was the telescope's birth announcement, and it spread across Europe like wildfire through dried kindling. It was in its pictures—the ones in the first 50 copies were hand-drawn by Galileo himself; the other 500 copies had engravings made from his drawings—that the world first saw that celestial bodies were not perfectly smooth, regular spheres, as taught by the ancients. The moon had craters, and bright spots on its dark side that were the tops of lofty mountains. This is a half-million-dollar book, and we now have two copies, because the Burndy also had one. The Library of Congress doesn't have even a single copy. It's an incredibly rare work, and it will be in the display.

One *Herald* the Burndy had that we didn't—a natural, given Bern's interest in all things electrical—is Robert Boyle's *Experiments and notes about the mechanical origine or production of corrosiveness and corrosibility*, printed in 1675. For us to acquire an English book that we were lacking on science from the 15th, 16th, or 17th centuries is highly unusual, because we're very close to complete. (It, alas, will not be in the exhibit.)

The Burndy contains one of the world's three greatest collections of print and manuscript material by Isaac Newton—the Grace K. Babson collection. We don't actually *own* this material; it is on permanent deposit here from Babson College in Wellesley, Massachusetts. The Babson has Newton's personal copy of the *Principia*, which he revised by hand in preparation for the second edition. It will be on display, where it may look familiar to some of you—the Babson loaned it to us a couple of years ago for our Newton exhibit. The Babson contains more than 500 printed editions of his work, including books from his personal library, and approximately 50 Newton manuscripts. Before we acquired the Burndy we had exactly one—a draft of a letter of recommendation he wrote for somebody.

Also on deposit at the Burndy is the Volterra collection, one of the world's strongest collections in 18th- and 19th-century physics. It was assembled by the Italian mathematician and physicist Vito Volterra (1860-1940) and belongs to the Republic of Italy, so we had to get their permission to move it. Fortunately, we had great connections—one of our curators, Mario Einaudi, is



When Galileo turned his telescope on the half moon, he saw what could only be craters and mountains—blemishes on a heavenly body presumed to be perfect—thrown into sharp relief by the sun's sidewise light. He even calculated the mountains' heights.

The Huntington Library delivers more than 350,000 items per year to the hungry eyes of some 1,700 visiting scholars, making it one of the most heavily used set of rare materials in the United States outside of the Library of Congress.

About 75 people a day use the reading room, and the Huntington gives out the largest number of fellowships of any private American institution—about 140 annually—to support full-time study for anywhere from a month to a year.

This hotbed of activity occurs largely invisibly, behind doors closed to the half-million or so members of the public who come to see the Gainsboroughs, the gardens, and the galleries.

the great-grandson of the first president of Italy after World War II. We didn't have to go dropping his name, as it turned out, but we were ready to.

These acquisitions mesh with the Huntington's holdings in a lovely way. We have the Mount Wilson Observatory's directors' papers—800 linear feet of them, running all the way up to the late 1980s. We also have the papers of Edwin Hubble, who, surprisingly, was never Mount Wilson's director, and more than 3,000 photographs of buildings, activities, and people at the observatory. These history of astronomy materials are my most heavily used group of collections. We have a spectacular compilation of Charles Darwin materials—the largest assemblage of his printed works in North America, plus about 60 original Darwin letters. We also have really wonderful holdings on the history of civil engineering, endowed by Trent Dames [BS '33, MS '34], of Dames and Moore Engineering. [William Moore, also BS '33, MS '34, was his civil-engineering classmate at Caltech.] The Burndy brought the Victor Darnell collection on bridge engineering, and a really nice collection on color and color theory, which is a great match for us as well.

The Burndy came with an endowment of $11.6 million. This includes an acquisition budget, so we can continue to grow our collection, and supports five staff positions, including mine. The others are a full-time conservator, whose job is the physical care and feeding of the books and manuscripts; a cataloger for the new acquisitions; a reader-services person; and an associate curator to assist with the increased volume of users these new works are bringing us. The endowment also funds eight research fellowships a year.

THE BURNDY COMES WEST

Since 1993 the Burndy Library had been housed at MIT, at the Dibner Institute for the History of Science and Technology. However, MIT wanted to go off in a different direction, and the Dibner family's 15-year lease—MIT owned the building—was running out. David, Bern's only child, and Fran, David's wife, began discussions with several institutions on the Burndy's future home, and so in early 2005 we were asked to submit a letter of interest. There were 16 applicants, one of whom made the mistake of saying, in the midst of the process, that they'd already gotten the collection. That was it for them when David found out.

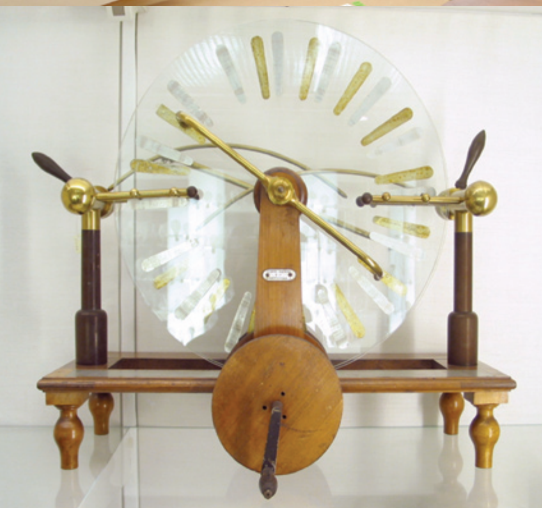
David died unexpectedly in September 2005 and was succeeded as president of the library board by his son Brent. Ultimately, of course, they picked the Huntington. We made a very solid case: we're well known; we're heavily used; we have a program for managing historical collections; we didn't have to build a new building; and we're not sway to the political vagaries of a university, where a new president could come along and say, "we don't really want to collect the history of science anymore."

Once all the agreements had been negotiated and the papers signed, we still had to move the collection cross-country. It took all of October 2006 to pack everything. The books and manuscripts were pretty straightforward, but there were also huge oil paintings of eminent scientists, and busts, and ceramic figurines, and all those other artifacts.

There are 650 objects in the collection, and they're odd, strange, fascinating, and wonderful—everything from a rhino's horn to some of the world's largest fluorescent lightbulbs. Bern had a spectacular lightbulb collection—some very important ones of Edison's own design and manufacture, hand-labeled by Edison himself, up through modern bulbs. They were one of the few things on display at the Dibner Institute at MIT, where you could see them in a circular Plexiglas carousel in the foyer.

All of these items were carefully bubble-wrapped and boxed by a bunch of obsessive-compulsive types—I think they used up the national supply of packing peanuts. Some things had to

Left: A small portion of the lightbulb collection, laid out on foam pads in the basement, awaits its permanent home. Right: One of Thomas Edison's hand-labeled specimens. Amazingly, it fits a modern-day light socket.



Left: This Wimshurst static-electricity generator is the biggest artifact in the collection—the wooden base alone is the size of a coffee table. Above, left: It, and many of the other larger pieces of scientific hardware that will not be on display have not yet been uncrated.
Above: Other strange and wonderful items Bern acquired include, from left, a Leyden jar (an early capacitor for storing static electricity), a bust of Leonardo da Vinci, a model of the Apollo moon lander, a rhinoceros horn, and a porcelain Ben Franklin. A bust of Bern himself can be seen over da Vinci's right shoulder.

be crated individually, like the Wimshurst static-electricity generator with its huge, hand-cranked glass disk. That crate is probably six feet by six feet by two feet. The smallest items were an assortment of electrical switches; oddly enough, Bern didn't save any Burndy connectors, although there is a vintage Burndy crimping tool.

We had to decide whether to ship this stuff worth, conservatively, a hundred million dollars discreetly and quietly, or with sirens running and heavily armed security guards. We went for the clandestine approach, under cover of darkness. It took six tractor trailers to haul it all, and we didn't want a conspicuous convoy, so every four days we would load up one truck. We had to load each trailer not by contents or weight, but by insurance value so that the risk was dispersed across all six trucks. One box in each trailer had a GPS unit, so that if something went terribly wrong and the truck disappeared, we could find it—in theory, anyway, because we assumed it would take a long time for the thieves to break into every carton and find the tracking device, if they even suspected its existence. Loading took a couple of hours, so each truck would leave Cambridge around midnight. The first truck left on November 1, and the last one arrived in San Marino just before Thanksgiving.

A BESTIARY OF BOOKS

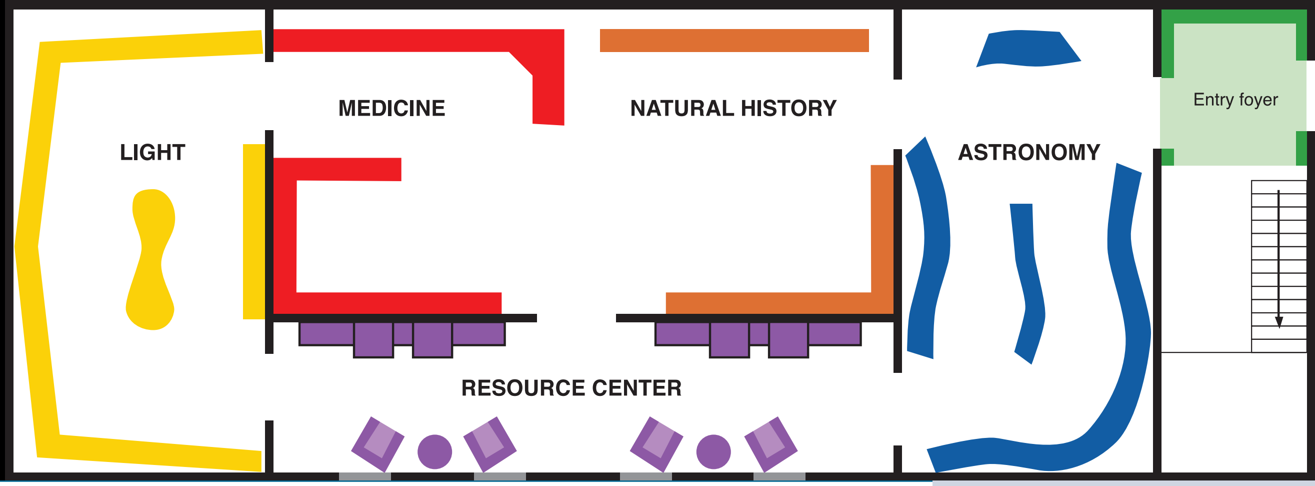
The Dibner family stipulated that we mount a permanent history of science exhibit, plus one temporary one every three years in our regular rotation. For the permanent one, we're using the former Arabella wing of our exhibition hall—a gallery of about 2,800 square feet, which had been filled with many wonderful examples of European decorative arts that have now been moved into the Huntington mansion with the rest of the European art. We had to get permission from all of the 30-odd surviving Huntington family members to do this, because it's written into our trust indenture that that wing be a memorial to Henry's wife, Arabella Huntington.

The exhibition, in the renamed Dibner Hall of the History of Science, will open to the public two years to the day after the first truck hit the road. It will be much more than just old books in locked cases. There'll be 15 audio stations where you will be able to hear Michael York read translated passages from these books as you look at them, and touch screens where you can flip through digitized scans of pages not on display. Karina White, our in-house exhibit designer, and I have been working very hard with Gordon Chun Design up in Berkeley to make this interactive, so that every section will include at least one thing that you can actually *do*.

The exhibit's title is "Beautiful Science: Ideas That Changed the World." Our goal is to impress upon the public that scientific knowledge is modified, improved upon, and sometimes overturned as we strive to understand the universe's workings more accurately. A beautiful idea broadens the imagination—a shift in scale, or in perspective, or in the concept of what is possible. And the expression of these ideas can have physical beauty as well: drawings, photos, even equations. But the history of science is far more than a cavalcade of triumphs. We try to show why one path was taken and

Incunables (*incunabula*, in Latin) are European books printed from movable type before January 1, 1501—that is, before the end of the century in which Johannes Gutenberg lived. (He died in 1468.) The Latin word means "baby clothes" or "things of the cradle," and these books are from the infancy of printing.

At left is a capital letter from the 1495 incunable of Aristotle's *De Caelo et Mundo*.



The exhibit layout.

not another, examine the interplay between theory and experiment, and analyze the relations between broad scientific trends and the work of individual scientists.

We've focused on four subjects that play to the strengths of our collections: astronomy, natural history, medicine, and light. You might look at this list and ask, "Well, where's chemistry? Where are mathematics, physics, technology?" In fact, they're all there. Chemistry, for instance, shows up in all four sections. I think this speaks to how science really works: a discipline emerges, and then it enters into the service of other disciplines.

You enter through the astronomy gallery, which has black walls and ceiling. Overhead, printed in reverse so that they're white on black, are the 12 signs of the zodiac on large panels, as depicted in a set of 17th-century star charts by John Flamsteed, England's first Astronomer Royal and the founder of Greenwich Observatory. The display cases below will be fiber-optically lit from within. I'm hoping it'll be quite striking—we're really going for the "wow" factor. I also really want visitors to get the best possible look at the works themselves. We've put the Plexiglas covers just a couple of inches above the books, so that you can peer at their exquisite detail "up close and personal."

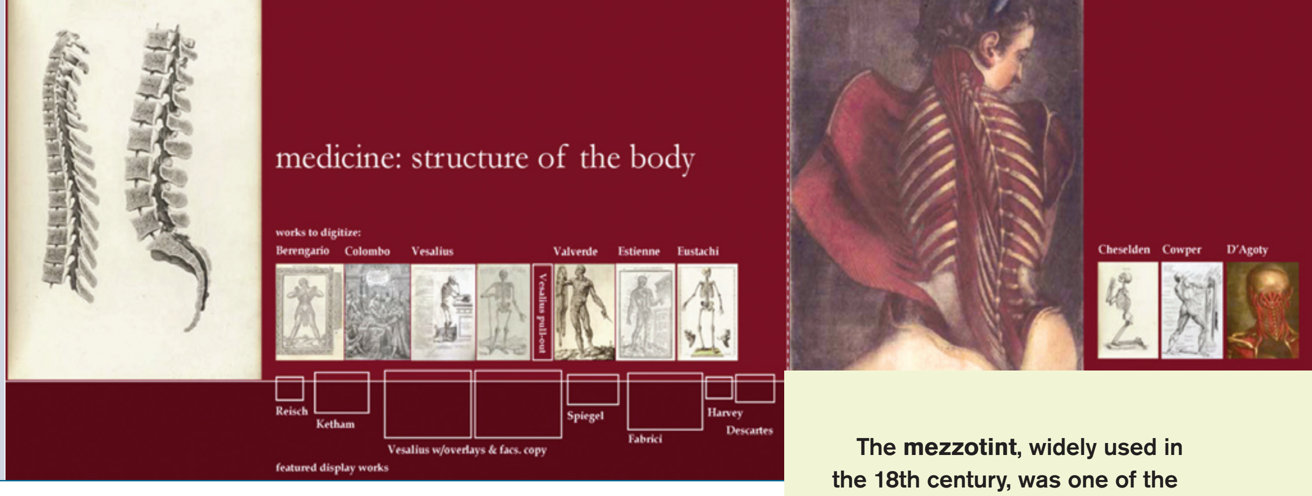
One sequence of cases, which I call "Location, Location, Location," starts with Aristotle and a 1495 incunable of *De Caelo et Mundo*, or *Of the Heavens and the Earth*, with commentary by Thomas Aquinas. Next to it is the oldest item in the exhibit, a manuscript version of Ptolemy's *Almagest*, a second-century AD Greek work. The *Almagest* was lost to human knowledge for centuries until a copy was found in the Middle East and translated into Arabic in the ninth century, and thence eventually rediscovered by Europeans. Our copy, in Latin, was transcribed by monks in the south of France in 1279. Ptolemy, like Aristotle, placed a fixed, unmoving Earth at the center of the cosmos, and the *Almagest* describes how the sun, moon, planets, and stars orbit us in nested circles within circles. An eminently practical work, it gives methods for predicting the positions of these heavenly bodies that were not superseded until Nicholas Copernicus (*De Revolutionibus Orbium Caelestium*, 1543; we have the second edition, printed in 1566) dethroned Earth in favor of the sun and Johannes Kepler (*Astronomia Nova*, 1609) replaced the circles with ellipses. There's a touch screen between Ptolemy and Copernicus where you'll be able to play with models of their two universes.

Next comes Galileo's 1632 *Dialogue Concerning the Two Chief World Systems*—his defense of Copernicus that got him in trouble with the Pope—and the annotated *Principia*. Earth gets pushed even farther from the center of affairs in 1750 by Thomas Wright, who proposed in his *An Original Theory or New Hypothesis of the Universe* that the Milky Way was "an optical effect due to our immersion in what locally approximates to a flat layer of stars." And finally, you arrive at the expanding universe filled with innumerable galaxies, as seen in Edwin Hubble's logbook of his observations through the 100-inch Hooker telescope atop Mount Wilson, from first light in 1917 to 1923.

From astronomy you'll move to natural history, where I'm running a 27-foot bookshelf containing nothing but editions—some 250 of them—of *On the Origin of Species* along

Kepler's supernova—the bright pink star above and to the right of the moon, and about an inch away from it at this scale—shines on the astronomy gallery's east wall as it would have appeared from the Huntington on February 13, 1605 at 5:45 a.m. This supernova, the second to be seen in Europe in 32 years, helped undermine the ancient view of the cosmos as being perfect and unchanging. Painted by noted astronomical artist Chris Butler, the mural is accurate down to the colors of the stars.

Right: Part of the wall design for the medicine gallery. D’Agoty’s mezzotint “Flayed Angel” contrasts with William Cheselden’s more prosaic views of the spine (*Osteographia*, 1733).



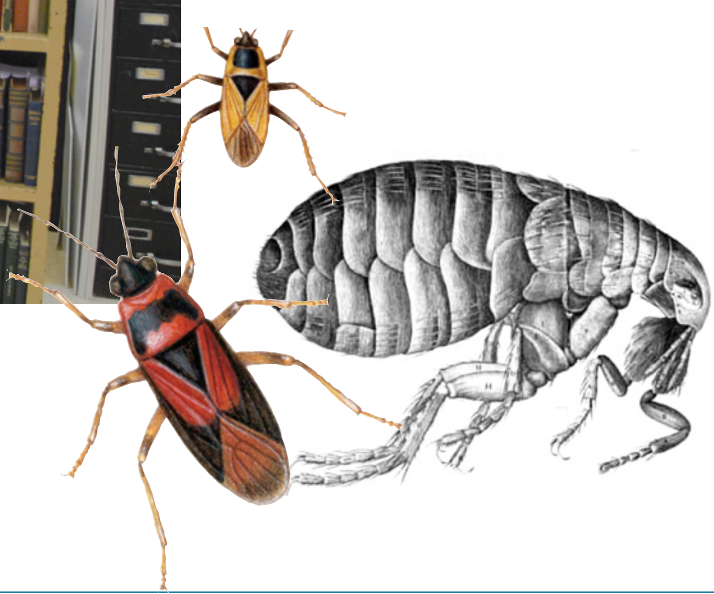
two walls. This assemblage includes not only the English first edition, but first editions in several other languages, and shows the power of this idea over time. Incidentally, Angus Carroll of the Darwin Papers Project at Cambridge University and I are doing a census to see how many copies of the first edition remain. Some 1,250 were printed, and perhaps 800 have survived. It’s now a $100,000 to $200,000 book, so if you’re ever at a garage sale and you see a copy bound in a green cloth with gilt letters, and on page 20, line 11, the word “species” is spelled “speceies,” grab it. Bookending the evolution display you’ll see a manuscript of Aristotle’s *De Animalibus* from circa 1275 on one side, and on the other we’ll have a copy of Gregor Mendel’s *Experiments in Plant Hybridization* from 1866 and Watson and Crick’s April 1953 *Nature* paper announcing the discovery of the structure of DNA.

The opposite corner of the gallery features observations of animals real and imaginary, including drawings of fleas and even smaller creatures made by Robert Hooke, using a newfangled tool called the microscope. Hooke’s 1665 *Micrographia*, which you’ll see there, was an instant bestseller in London. Diarist Samuel Pepys, for one,

The mezzotint, widely used in the 18th century, was one of the earliest ways to print color on a page. The plates, usually copper, were roughened with a finely serrated tool—a process that could take more than a day in itself—and then the picture was drawn with a pointed scraper and shaded with rounded burnisher. The smoother these tools made the copper surface, the less ink it held, allowing for exquisite control of light and shadow. As in modern printing processes, a separate plate had to be prepared for each color, making the entire operation very labor-intensive.

Above: Dan Lewis and Karina White peruse one of the 250-odd copies of the *Origin of Species* chronologically arranged on two book trucks. (The first edition is top left on the blue truck.) Note Flamsteed’s star chart in the background.

Right: Beautiful bugs from the 1830s, drawn by the team of Meunier, Prêtre, and Vaillant, and Robert Hooke’s flea.



Left: Andreas Vesalius's *De Humani Corporis Fabrica*, or *On the Fabric of the Human Body* (1543), is the first modern anatomical text. Its detailed drawings showed dissected figures in "living" poses.
Right: The first medical X-ray photograph, taken in 1896, shows dozens of buckshot lodged in the hand of Prescott Hall Butler, a wealthy New Yorker. His surgeon, Dr. William T. Bull, removed them, using the image as a guide.

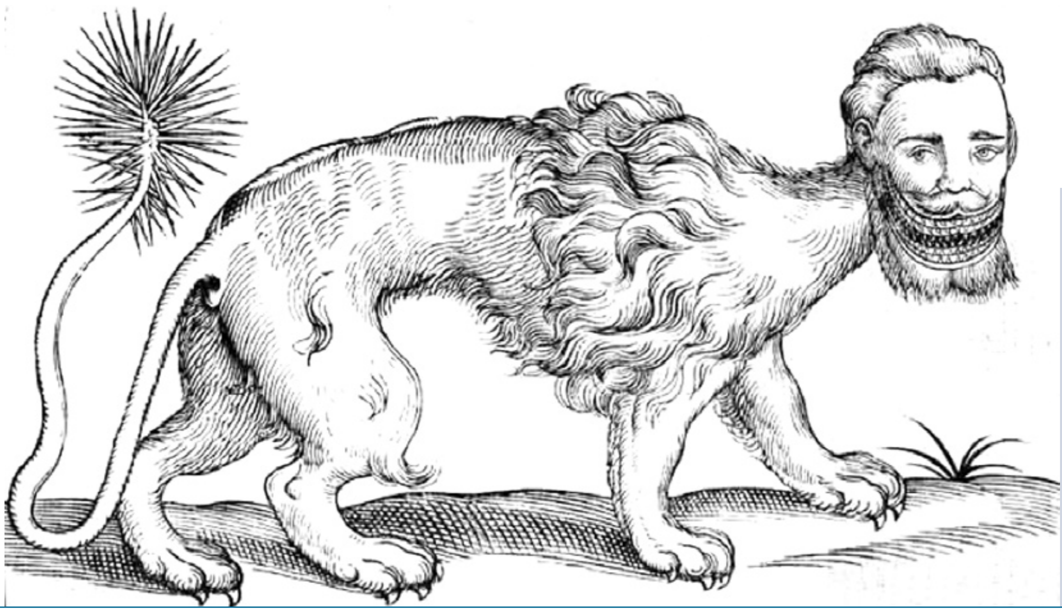
It's now a $100,000 to $200,000 book, so if you're ever at a garage sale and you see a copy bound in a green cloth with gilt letters, and on page 20, line 11, the word "species" is spelled "speceies," grab it.

"sat up all night staring at it in amazement." You'll be able to look at a flea yourself, using replicas of one of Antony van Leeuwenhoek's pocket microscopes that sit next to his collected works. Making the microscopes was a bit of a challenge: we had to figure out how to mount the flea so that it wouldn't fall out when you handled the instrument, how to get the lighting right, and how to subtly alter Leeuwenhoek's design so that you won't poke your eye out with the thumbscrew.

The history of medicine shares the same gallery. The first thing you see is the anatomical display, which features images of skeletons and muscles starting in 1543 with Andreas Vesalius and ending with Gray's *Anatomy*, which was the definitive work on the subject nearly 150 years before a TV show borrowed the name. Well, actually, the *first* thing you see is a 10-foot-tall copy of a 1746 Gautier D'Agoty mezzotint known as the "Flayed Angel." It's a full-color rendition of a young woman whose back has been laid open like an angel's wings to reveal the bones and sinews beneath. The walls here will be a deep, rich red, and again the effect should be quite striking. (We'll also include a 1653 reprint of William Harvey's treatise on the circulation of the blood.)

Cheek by jowl with anatomy is a section on healing. This starts with copies of works by Hippocrates, Galen, and Avicenna that were printed in the 1500s, and runs through Edward Jenner's 1798 description of smallpox vaccination to some Pasteur manuscripts from the 1870s. In the middle are two herbals—the pharmaceutical catalogs of the day—from the 1500s and 1600s, and an array of bottles filled with the odiferous extracts of some of the plants mentioned therein. There's also an astonishing work from circa 1517 called the *Field Book of Wound Surgery*. Written for army doctors, this is not for the faint of heart, as 16th-century weapons had relatively low velocities and thus rarely cut cleanly into or through anything. Dealing with the extensive tissue and bone damage thus caused has an unusual kind of beauty: saving lives.

Bern collected some of the earliest X-ray pictures ever taken, including the very first diagnostic one, showing self-inflicted buckshot in the hand of a careless hunter.



Early natural-history books mixed the real and the fantastic, and Edward Topsell's *Historie of Foure-Footed Beastes* (1658) is no exception. The manticore seen here is a red-pelted man-eater with the body of a lion, a tail that shoots quills, and a human-like head—except for the three rows of serrated teeth and the mouth that runs ear to ear.

Lewis admires a particularly ornate lightbulb filament, as a portrait of Sir Goldsworthy Gurney (1793–1875) looks on. Gurney tinkered with steam-powered carriages for use on the public roads, and invented the high-intensity Bude light that replaced the limelight in theaters—which may explain his expression.

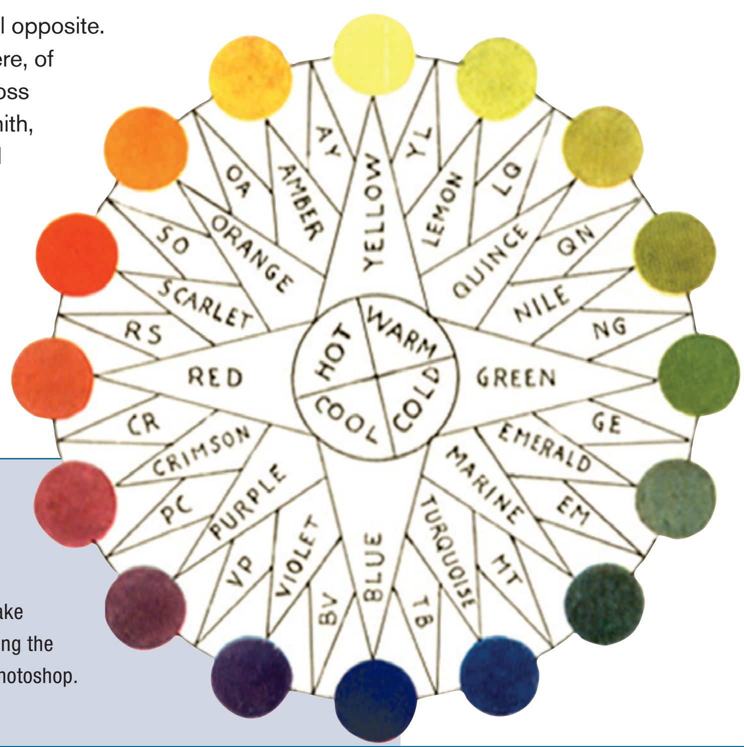
Physicist Michael Pupin at Columbia University in New York made a famous photograph of it within nine months of Roentgen's invention of the X-ray tube. The original photograph will only be on display for the first few months, as it is very sensitive to ultraviolet light, and then it will be replaced by a facsimile.

Light sensitivity, incidentally, is a big preservation issue. It's high on the list of reasons why people tend not to do permanent exhibits of rare books. You have to turn the pages of a colored work every 12 weeks so that the inks don't fade. Simply leaving an old book open is hard on it. You have to rotate the book out every couple of years in order to prevent the binding from slumping to the opened page, which is why it's good to have several copies of each work in reserve.

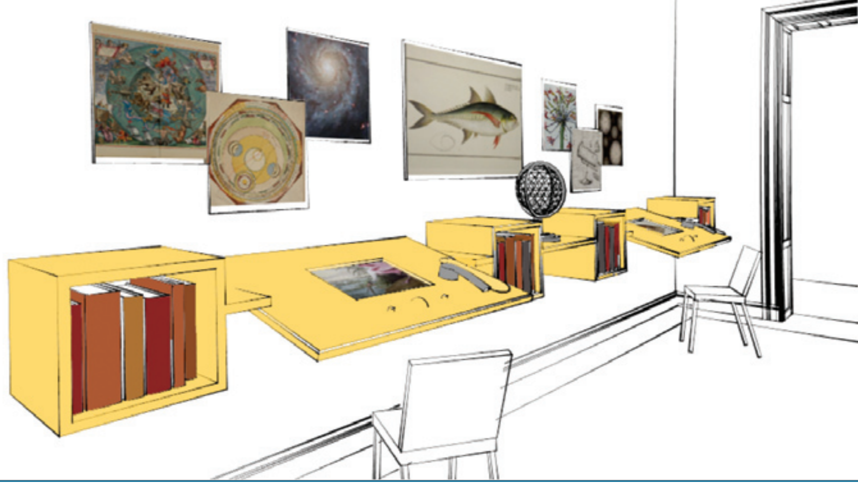
Light is the subject of the fourth gallery. There's a lot of science in here, because we also treat electricity and magnetism. We start with Ibn al-Haytham, known in the West as Alhacen or Alhazen, who flourished just after the turn of the first millennium, and whose works were printed in a seven-volume set in 1572. Alhacen invented the scientific method of hypothesis and experiment, which he used to prove that light entered the eye in straight lines from the outside world, rather than being emitted from the eye as Euclid and Ptolemy held. We'll reproduce an experiment that he used—but did not invent—a camera obscura, which is a box where a pinhole in one wall projects an image on the interior wall opposite.

Newton's *Opticks* is in here, of course, and in a burst of gross overkill, I recruited Greg Smith, who consults up at JPL and designed all the lenses for all the cameras on the current Mars rovers, to make Newton's prism experiment work just right. This is the one where white light goes through a prism and gets broken up into its component colors, which fall on a card. If the card is removed, a second prism recombines the colors back into white light. You see it a lot in science center exhibits, but it generally looks crummy—the light isn't bright enough, and the rainbow is too small. So Greg helped us get just the right kind of glass and work through the other details, and I hope we'll have an effective demonstration. We'll also have a bunch of treatises on color theory, including Boyle's monumental *Experiments and Considerations Touching Colours* from 1664. On the opposite wall you move from color to spectroscopy with a section that includes Norman Lockyer's 1878 *Studies in Spectrum Analysis*, which recounts his discovery (independently made by Pierre Janssen in France) of helium—by its lines in spectra taken of the edge of the sun during the solar eclipse of October 1868. Helium is the only element to have been identified in space before it was found on Earth.

The resource room will also have a 300-year-old book you can actually leaf through. There's no substitute for the immediacy of handling a rare book, turning the pages yourself, and I want people to have that experience. My more conservative colleagues think this is a terrible idea.



Right: A color wheel from *A working system of color for students of art and nature* by Frederick Leroy Sargent, printed circa 1927.
Far right: This diagram from the same book shows how to make a gradual transition from one color to another by slowly altering the proportions of the two—a gradient filter in the days before Photoshop.



A rendering of the resource room.

Spectroscopy segues into electricity and magnetism, as represented by works by Volta, Faraday, Maxwell, and even Benjamin Franklin. Nikola Tesla is here, and, of course, Thomas Edison—this is where Bern's lightbulbs will live. We're even going to light some of them up. I've been consulting with Lee Johnson at JPL, a research engineer whose day job is developing ion-drive technologies and who knows everything there is to know about electricity and an amazing amount about lightbulbs, and we think we've got it all figured out. Oxygen is a hot filament's worst enemy, so we'll keep the bulbs in nitrogen-filled display cases in case the bulbs' vacuum seals are leaking. We'll run them at about 10 percent of their designed wattage, just enough to make the filaments glow, so there will be all these beautiful orange loops and swirls from all the different filament designs.

Accessible from all the galleries is the resource room, which will have workstations where you can download additional materials, or watch any of nine interviews we've done, mostly with scientists, about what constitutes a beautiful idea in science. But primarily, the resource room is a place for people to sit in overstuffed chairs and actually *read*. After all, we're a library. I want people to be able to read, with their own eyes, translations or modern versions of the works on display. We'll also have books about the collection's subject matter, and books by scholars who made use of the collection.

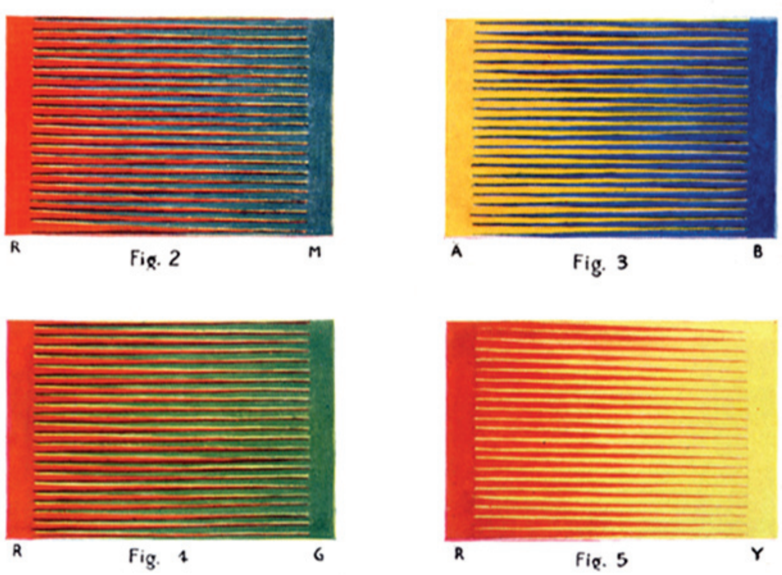
The resource room will also have a 300-year-old book you can actually leaf through. There's no substitute for the immediacy of handling a rare book, turning the pages yourself, and I want people to have that experience. My more conservative colleagues think this is a terrible idea. But there are works that aren't terribly expensive that we can replace readily, so we'll see how it goes. If the book gets shredded into a million pieces in a week, I won't try it again. But if it holds up for six months or a year, I'll just buy another one. You'd be astonished at how durable 300- to 500-year-old paper is. Or 800-year-old vellum, from before the printed era. Bindings wear out, but paper does so much more slowly—unless it's modern paper, with really short fibers made from wood pulp.

Beautiful ideas, expressed in beautiful books—you must come and see them! e&s

Daniel Lewis is the Dibner Senior Curator of the History of Science and Technology at the Huntington Library, Art Collections, and Botanical Gardens in San Marino, California. He has a BA in English from the University of Redlands and earned his PhD in history at the University of California, Riverside, in 1997 with a dissertation on the history of Mexican railroads titled "The Empire Strikes Out: The Southern Pacific of Mexico, 1881–1950." He came to the Huntington as a postdoc after stints at institutions including the Smithsonian and Oxford, and has been a curator at the Huntington for 11 years, overseeing the history and the history of science and technology collections.

Lewis recently turned his PhD thesis into a book, **Iron Horse Imperialism: The Southern Pacific of Mexico, 1881–1951,** ***now available in paperback.***

This article was adapted from Lewis's Seminar Day talk, given May 17, 2008, by Douglas L. Smith.



When Asthma Strikes

Pollen has long been believed to cause asthma, a disease that affects hundreds of millions worldwide. But it's also known that pollen grains are too big to get deep into the lungs, where asthma strikes. So how does pollen trigger asthma? Now researchers think they know the answer.

More than 14 years ago, on a summer night, thunderstorms swept through England, and from the rain and lightning emerged one of the largest asthma epidemics in history. Up to 10 times more asthmatics flooded emergency rooms than normal. In the North Thames region, over a thousand people went to the hospital complaining of asthma attacks. In other areas, several hundred checked into the emergency rooms. Many of those people had never had asthma before. Most people don't think about epidemics as occurring in one evening, but this one hit during the night of June 24, 1994. A huge number of people suffered from a very dangerous disease over a very short period of time.

The cause of this countrywide asthma attack was linked to pollen, which the American Lung Association lists as one of the triggers of asthma. Although pollen has long been considered a cause of asthma, the exact mechanism is unknown. For decades, scientists have known that pollen grains are too big to penetrate deep into the respiratory tract, meaning pollen shouldn't be able to trigger asthma. It's been a real puzzle.

The correlation between pollen and asthma, as measured by the medical community, has been only qualitative. As of now, we think we've got a pretty good hypothesis. But ultimately, we'd like to find an even more detailed and quantitative explanation.

At the same time, we're working on ways to minimize the prevalence of asthma attacks by providing real-time warnings. The World Health Organization estimates that asthma affects 300 million people. In 2005, asthma killed 255,000 people. I may not be able to cure the disease, but I'd like to be able to tell parents, school teachers, and school principals when it might be a good idea for asthmatic children to stay indoors.

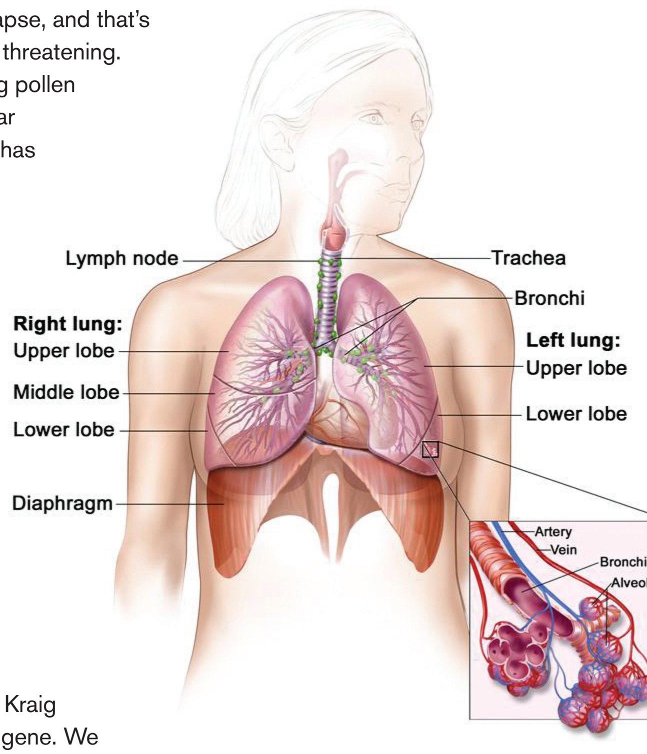
Asthma is a disease of the respiratory tract, which starts with the nasal passage and the trachea, or windpipe. The trachea eventually splits into two tubes called bronchi that go into each lung. The bronchial tubes in turn go through about 18 different generations of branching inside your lungs, Don't sneeze! The morning wind stirs up ryegrass pollen near Eugene, Oregon.

By Richard C. Flagan

each time shrinking in diameter. The branching ultimately leads to the bronchioles, which connect to the alveoli, the structures where gas is exchanged. The alveoli, which look like a bunch of grapes, have lots of surface area to absorb oxygen—about 70 square meters, bigger than some New York City apartments. In the upper portion of the respiratory tract, the tubes are lined with cartilage rings that provide structural support. But by the time you get past somewhere between the fifth and eighth branching, that support diminishes dramatically, and this is where asthma strikes.

When you inhale, you flex your diaphragm to expand your bronchial tubes, bronchioles, and lungs, increasing their volume and lowering their internal air pressure to below that of the outside air. Since air always flows from high to low pressure, air is drawn into your lungs. When you exhale, your muscles relax, and your respiratory system gently compresses, decreasing its volume and increasing the air pressure so air flows out. An asthma attack happens when the bronchial tubes and the bronchioles—which are normally up to three millimeters in diameter—constrict due to some kind of irritation. Problems arise during exhalation, when the bronchioles are already narrowing. Further constriction from asthma makes it harder for air to flow out, and if it's hard for air to flow out, there's no room for fresh air. That makes it difficult to breathe, and you often hear wheezing from asthma sufferers. The lung also reacts to irritation by pushing air out, which constricts the bronchioles even more. The bronchioles could collapse, and that's when asthma becomes life threatening.

My lab has been studying pollen in the Willamette Valley, near Eugene, Oregon. The area has many square miles of commercially grown ryegrass, which makes for longer-lasting green lawns and produces one of the most allergenic pollens associated with asthma. The picture on the opposite page shows the morning wind spreading the pollen. It looks like fog, but it's not—it's pollen. It makes me sneeze just looking at it.

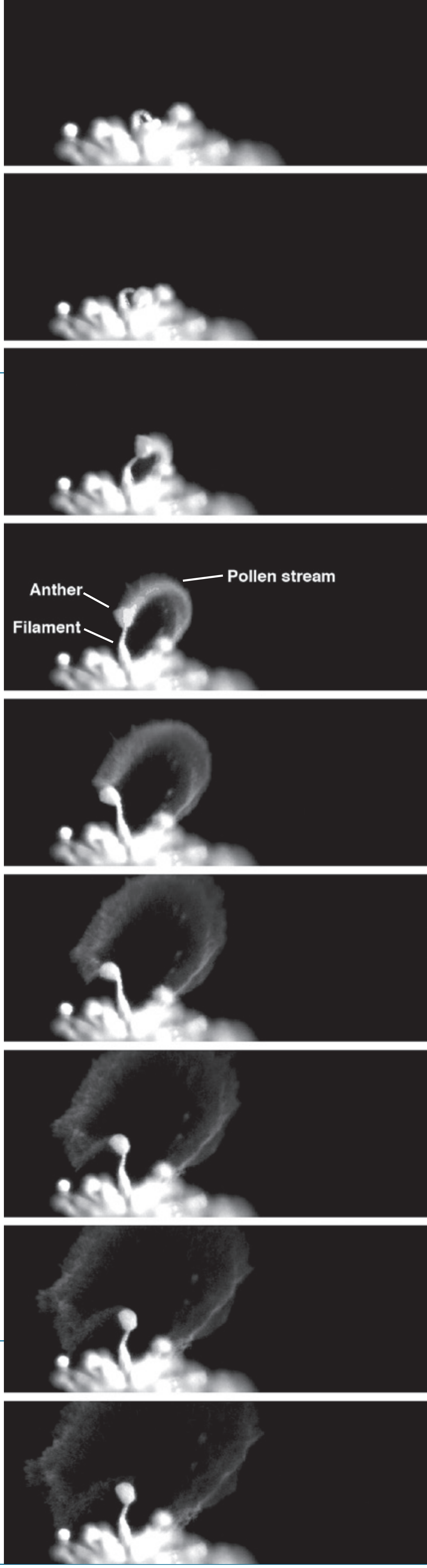


In the summers of 2005 and 2006, we worked with Kraig Jacobson, an allergist in Eugene. We collected and analyzed pollen samples, measured the allergens, and looked at data from local clinics and hospitals. The data shows a strong visual correlation between the amount of respiratory allergens and the number of emergency room visits, but we need a lot more data for any clear, statistically confident conclusions.

Every flowering plant species makes pollen grains of unique shapes and sizes. People measure pollen by counting grains, a very tedious exercise in which people stare through a microscope to identify them. Pollen grains range from about 20 to 100 microns in diameter (a micron is a millionth of a meter).

Some plants depend on insects or birds to pollinate, producing sticky pollen to better attach to the pollinating animal. The pollens that we're studying aren't sticky, but have evolved to disperse in a gentle wind. Photographs of pollination often show a cloud of pollen dispersing from the plant, but in nature, pollen doesn't become airborne spontaneously—only when it's disturbed. In most pictures of that sort, someone's hand is actually shaking the branch.

A ryegrass flower opens up during the day when the sun dries the air. The outer layer dries and tears open, exposing the pollen grains inside.



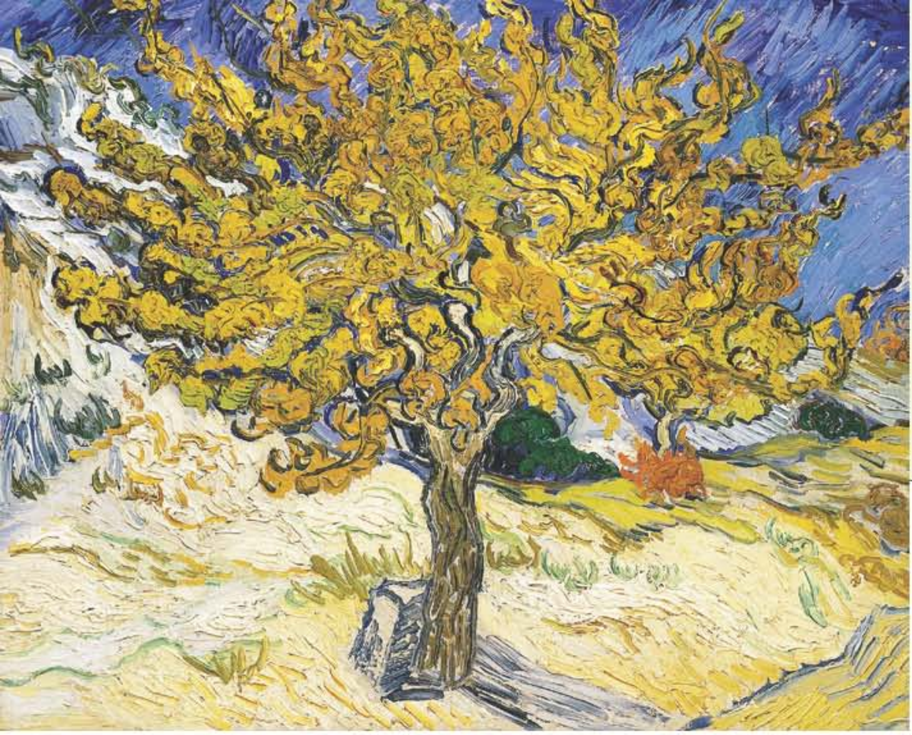
After the pollen is released, wind carries it to a random landing spot. If it happens to land on a female flower, then there's an exchange of genetic material to fertilize the seed. Once the pollen lands on the flower, something called a tubule grows out of the aperture, which is a small opening on the pollen grain's tough outer wall. An extension of the cell wall, the tubule stretches out, seeking out the flower's embryo sac, which will eventually become a seed. Ryegrass pollen tubules can extend tens of times the diameter of the original pollen grain in a matter of hours—it's really an amazing process.

Pollen is held in the male flower's anthers. When the anthers, the pollen is released. Much of the classical botany literature anthropomorphizes what happens, saying that the anthers "disperse" the pollen upon opening, as though there's an active compulsion on the part of the plant to do so. But usually there's no propulsive motion—when you disturb many plants, the pollen falls straight down or gets carried away with the wind. When a ryegrass flower opens in still air, most of the pollen just sits there. In the summer of 2004, Grace Lu, a high-school student from Kennesaw, Georgia, worked in my laboratory as part of the Research Science Institute, a national program that puts high-school students in college labs. She took some absolutely fantastic pictures that show the three-millimeter-long ryegrass flower exposing its pollen to the environment. The flower, which looks like a little pea pod, opens up during the day when the sun lowers the humidity. The outer layers dry out, shrink, and tear open, but when the humidity rises at night, the outside soaks up some water and partially closes back up. The intermolecular forces between the pollen and the surface of the anther, called van der Waals forces, are powerful enough to hold the pollen in place until something causes it to fall down. But releasing pollen in this way is not always the case, as you shall see.

FASTER THAN A SPEEDING POLLEN GRAIN

While looking at the wind speeds required to pull stray pollen off plants, we made an amazing observation. One day in March 2005, Boswell Research Fellow Phil Taylor, a botanist in my lab at the time, brought in some flowers from a mulberry tree. Mulberry flowers are only a few millimeters in size, and they cluster around individual stems. He put one of these stems in a test tube and got ready to run the experiment. But when he looked back, he saw a halo of pollen around the flower on the tabletop as far as 10 centimeters from the plant. How did the pollen get so far? I did a back-of-the-envelope calculation and found that the pollen had to leave the flower at a velocity of about 200 meters per second. Now, the speed of sound is roughly 340 meters per second, so the pollen was traveling incredibly fast. Naturally, we had to ask how this works.

We didn't have any instruments fast enough to capture this phenomenon, so I enlisted the help of Michael Dickinson, the Zarem Professor of Bioengineering,



Left: Van Gogh's *Mulberry Tree,* October 1889, Norton Simon Art Foundation, gift of Mr. Norton Simon. Far left: These time-lapse images capture the mulberry tree slinging its pollen into the air. The time between each frame is 1/2,000th of a second.

who uses high-speed cameras that shoot 10,000 frames per second to study insect flight. Along with a graduate student in his lab, Gwyneth Card, we filmed the mulberry plant releasing pollen. We didn't get good pictures until late in the season, when the plants were weak and couldn't expel the pollen with much vigor. At the peak of the season, we couldn't catch it with a 10,000-frame-per-second camera—the movement was too fast. We'd record one frame in which nothing's happening, and in the next, there's a streak showing the pollen's path. By measuring that distance, and assuming it was covered in 1/10,000th of a second or less, we calculated that the pollen was shot out at speeds as high as 237 meters per second. That's 530 miles per hour, or Mach 0.7. We took several measurements, and found speeds ranging from a few tens of meters per second to a couple hundred. Our film is the fastest recorded motion of any living thing on this planet—and it's a tree. At its peak, mulberry pollen can beat a cheetah in a race, albeit only for 10 centimeters.

Now when you discover something like this, you want to find out if anyone else has ever seen it before. We dug through the literature and found an early reference from Pliny the Elder, a Roman naturalist from the first century AD. He states, "The germination, when it has begun, bursts forth all over the tree at the very same moment; so much so, indeed, that it is accomplished in a single night, and even with a noise that may be audibly heard," [Pliny the Elder, *The Natural History, Book XVI, The Natural History of the Forest Trees,* eds. John Bostock and H. T. Riley]. The editors footnoted the noise as "a mere fable, of course." But I've heard that noise. It's real. An orchard of mulberry trees might very well produce a rustle. This story reminds us that we always want to read the literature. It's very dangerous to think that we're the first to see (or hear) something.

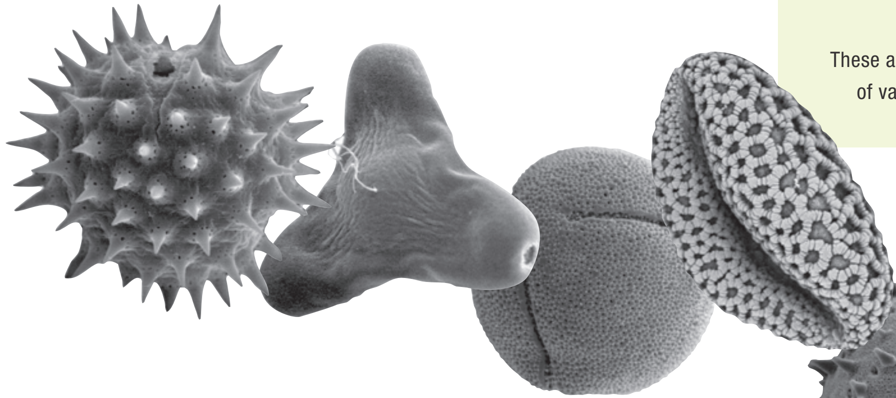
The high-speed camera showed that the mulberry flower releases its pollen like a catapult. The catapult in this case is the stamen, the flower's male organ. It's composed of a stalk, called the filament, and at its tip is the anther, which holds the pollen. In mulberry flowers, stamens are grouped into fours, and each filament is bent over. At night, the flower absorbs water from the air, which increases the pressure inside the filament, causing it to begin straightening and pressing against another part of the flower called the pistillode. Tension builds. The low humidity of the next day's warm air leads to a slight movement of the filament as the exposed parts dry. This causes the fine hairs on the anther to tear, which helps the anther open and expose the pollen. The filament ultimately slips past the pistillode, releasing the built-up elastic energy and flinging the pollen out at high speeds. The entire straightening of the filament takes less than 25 microseconds.

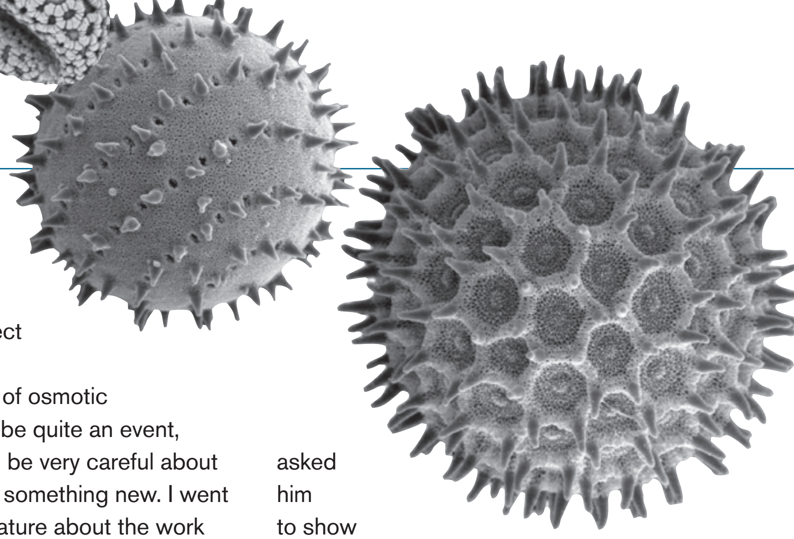
Our film is the fastest recorded motion of any living thing on this planet—and it's a tree.

BIG POLLEN, TINY BRONCHI

Let's step back for a moment and look at what happens when a particle enters our respiratory system. Where particles get deposited is a function of their size. Big particles—those larger than 20 to 30 microns in diameter—have too much inertia to be sucked deep into the lungs, and instead deposit in the upper respiratory tract, which goes from the nose to the throat. But as the particles get smaller, the efficiency with which they are deposited drops off dramatically and they penetrate deeper, finding their way into the lower respiratory tract, which starts from the bronchi on down. The smallest particles make their way to the lower airways of the lung—deep in the bronchial region, where they may deposit, leading to an inflammatory response that induces bronchial constriction. The particles associated with respiratory irritations, such as cigarette smoke, viruses, and diesel soot, are all very small, and this is where they wind up. But pollen is huge, and although it covers a wide range of sizes, it's too big to get into the lower regions of the respiratory system.

A five-year-old child running around the park, for example, might get 10 to 20 nanograms (billionths of a gram) per hour of material in the throat and the first few branches of the bronchial tubes. Deeper in the bronchial region, the total mass drops down to about 100 picograms (trillionths of





These aren't medieval weapons—they're scanning-electron-microscope images of various pollen grains.

a gram). And as you get down even lower, you're down to the really tiny masses—so small, it's sometimes hard to make them add up to a grain of grass pollen. For instance, if we have a pollen count of 100 particles per cubic meter, 10 or 20 particles might be deposited into the nose or throat—enough to trigger hay fever.

The conclusion seems to be that pollen is too big to cause asthma, even though asthma is often linked to pollen. Furthermore, asthma incidence has doubled throughout the world despite improvements in air quality. Asthma epidemics also accompany thunderstorms, and in many cases patients show high sensitivity to grass pollen. The mystery, then, is how pollen causes asthma.

In 2000, before he came to Caltech, Phil Taylor and Bruce Knox at the University of Melbourne published a paper that caught the eye of Michael Glovsky, a Pasadena allergist and immunologist, who is now also a visiting associate in chemical engineering at Caltech. The paper described what happens when you put pollen in water. The pollen undergoes something called osmotic shock, causing it to rupture. Osmosis is when water diffuses across a membrane separating, say, a low-salt concentration from a high-salt concentration. In a high-humidity environment, water diffuses into the pollen grains, increasing the pressure until they burst like overfilled water balloons. The cytoplasmic material inside the pollen spills out into the water, producing small fragments that include bits of organelles and hundreds of starch granules, some of which contain allergenic proteins. Glovsky proposed that we explore how this phenomenon may affect asthma attacks.

Now, the discovery of osmotic shock would seem to be quite an event, but again, you have to be very careful about claiming you've found something new. I went back to some old literature about the work of Robert Brown, the Scottish physician-turned-botanist who observed Brownian motion back in 1827. Brownian motion is the random movement of small particles suspended in a liquid or gas. This movement is a key piece of evidence for the existence of atoms and molecules, which bump into the particles and cause them to move. Many people think that Brown did his experiment with pollen, but the grains are too big for Brownian motion. In fact, he did it with small particles within the pollen grain and with those fragments that come out of the pollen, so he had observed rupturing pollen more than 150 years ago.

We invited Taylor, who had just earned his PhD in Melbourne, to come to the lab that summer. For his doctoral thesis, he had proposed a mechanism for how pollen is dispersed into the air. He speculated that once shed from the plant, the pollen lands on leaves, the grass, and the ground. The pollen then gets wet from rain, morning dew, or high humidity, and ruptures. After the water eventually dries up, a breeze blows the pollen fragments away. When he arrived, I asked him to show me how his hypothesis worked. I had been working on a new method for detecting explosives in luggage by looking for chemical traces on the outside of the bag. I had looked at how air could blow particles off a surface into my sampler, so I was familiar with the underlying physics of this scenario. Taylor's idea was plausible, but I didn't think the wind would be strong enough to carry away the pollen fragments. We made a small wager: I told him to put the particles on a small, glass slide, let them dry, and then try with any air supply in our lab to blow the pollen off. He couldn't do it, even with 100 pounds per square inch of pressure, and I got a very nice bottle of Australian wine. So a month after he defended his thesis, Taylor disproved its main hypothesis.

Still, we thought the essence of his argument about the wet and dry cycle was correct. Every day, he would go out and gather pollen from different plants around campus and bring it back to the lab for analysis. Then, one day, he came in complaining that his feet were wet from walking through the morning dew. This got him thinking about what happens to a flower when it gets wet, so we started studying flowers. We put ryegrass flowers in a glass box and lowered the humidity inside, simulating the dry sun during the day. The flowers' outer layers dried and opened. The flowers closed again when we raised the humidity to simulate nighttime conditions. Then, to explicitly see the effect of water, we sprayed mist on the flowers. When we lowered the humidity again, the flowers opened and exposed both pollen grains and fragments. In previous experiments, when we didn't spray water mist, which ensures pollen rupture, we just got big particles. So we learned that water, or humidity sufficiently high to rupture pollen grains, was crucial to producing asthma-causing particles.

Taylor ended up staying at my lab as a postdoc, and we continued working on the problem, studying rupturing pollen grains and looking for ways to blow pollen off surfaces. For example, we calculated how strong the wind must be to sweep pollen away. The surfaces of a flower's anthers and pollen grains are polymers of known composition. We approximated the pollen as a small polymer sphere and estimated the strength of the van der Waals forces needed to bind it to the surface. From that, we could calculate the necessary wind speeds, which depend on the size of the particle. We found that dislodging a typical pollen grain would require a wind blowing at over 100 meters per second—that's greater than hurricane speed. This result, of course, isn't very realistic, since plants still pollinate, people still get hay fever, and asthma epidemics still hit when there are no hurricanes.

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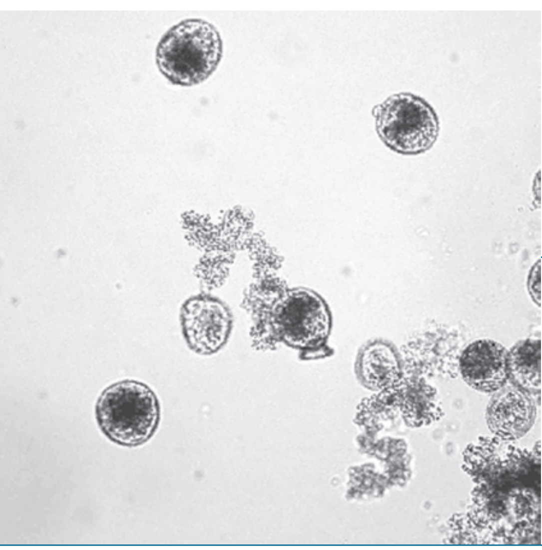
It turns out that for Taylor's original idea to work, the pollen has to rupture in the special environment provided by the anthers in the flower. An anther's surface isn't smooth, but has many tiny bumps that make a textured surface. The surface of the pollen grain itself often has texture as well, and the tiny bumps reduce the contact area between the grains and the anther, minimizing the van der Waals forces between the two. The tiny bumps result in very low adhesion (and a hydrophobic surface—that is, one that's water-repelling), allowing the pollen to be swept up more easily than the initial wind-speed calculations had suggested.

Now we have the smoking gun. Although we still need to measure allergens with a higher time resolution, to get a more quantitative, detailed understanding of how pollen causes asthma, we have a plausible mechanism for how this process works, and it works for most plants. After the pollen ruptures because of the presence of water—high humidity, rain, or morning dew, for example—the fragments are trapped inside water droplets, which bead up due to the hydrophobic surfaces in the flower. Once the water dries, wind disperses the fragments, which are small enough to reach the bronchioles in the lung.

Since plants only disperse their pollen once a year, we have to take our measurements on whatever plants happen to be pollinating at the time. Fortunately, at least for us, one prolific pollinator is a tree found on the Caltech campus—the Chinese elm, which produces highly allergenic pollen. In 2004, we monitored airborne Chinese-elm pollen levels during its mid-August to mid-September pollination season. A staff scientist, Ann Miguel, took data from the roof of Keck Laboratory using a device called an impinger, a glass tube filled



Pollen grains rupture via osmotic shock. Water diffuses into the grains, causing them to burst like overfilled water balloons. This phenomenon disperses pollen fragments, which may contain asthma-causing allergens.

Right: Caltech's pollen group in front of a row of Chinese elm trees on campus. Naturally, these highly allergenic trees line the athletic fields and tennis courts. From left to right are Michael Glovsky; James House, visiting associate in chemical engineering; and Richard Flagan.
Far right: Chinese elm tree flowers.

with water. As air is bubbled through the tube, the pollen collects in the water. We measured the number of pollen grains and their distribution, and found that there were huge numbers of smaller particles that can penetrate far down into the bronchioles. At the same time, we measured temperature, humidity, and wind speeds to see if we could find any correlations. We saw high pollen counts until the Santa Ana winds—hot, dry winds that sweep through Southern California every summer—came, killed off the flowers, and blew away the pollen. Two weeks after the Santa Anas, we still saw small peaks of allergen-containing pollen fragments, even though trees had long since stopped releasing pollen into the air. These spikes occurred about two days after night-time humidity rose above 80 percent. So even though there was minimal pollen in the air, there were still asthma-causing pollen fragments, implying that pollen counts aren't good warnings for asthma epidemics.

We're also looking at how thunderstorms—the catalyst for that epidemic in England—fit into the picture. We don't know the details of how thunderstorms cause asthma epidemics, but we have a plausible idea. Dry updrafts blow pollen grains into the clouds, where high humidity causes them to rupture. Downdrafts and outflows then bring the pollen fragments back toward the ground, increasing the asthma risk. Thunderstorms also build electric charges, and positive ions from the ground can attach themselves to pollen. The electric charges may help the pollen rupture, but no one's sure yet. Unfortunately, Southern California is not the best place to study this problem, since we only get a few thunderstorms each year.

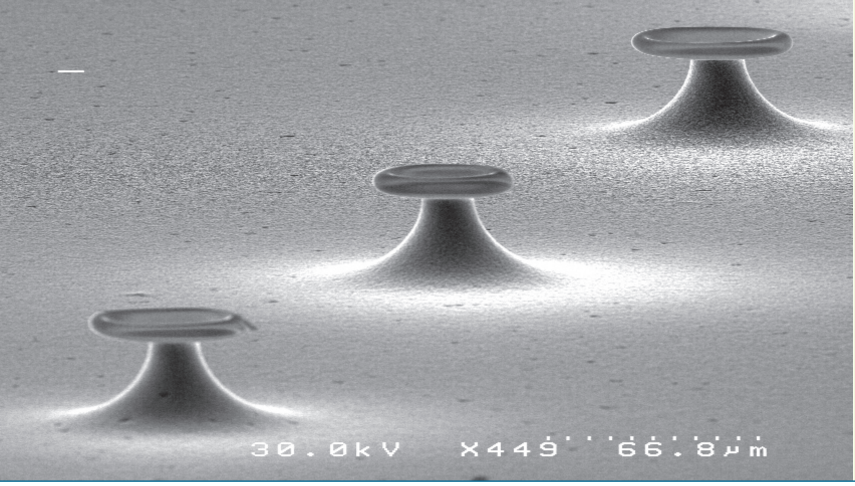
SAVING LIVES

Now that we've looked at how pollen is dispersed, we can think about how to measure its risk. The pollen count is an after-the-fact measurement that tells people when to worry about hay fever. But by the time enough data has been taken to produce accurate pollen counts, people are already sneezing. And while hay fever is a huge problem, it's not a life-threatening disease like asthma.

Counting pollen isn't a good measurement for gauging asthma risk because it doesn't attack the right range of particles. We need to measure the respirable allergen, the pollen fragments that are capable of depositing at a rate of nanograms per hour in the bronchioles. These allergens vary dramatically from day to day—and probably even hour to hour—so we need a highly sensitive, fast-responding airborne allergen detector. We're working to adopt antibody assays that people use in biochemistry laboratories all the time.

To do an antibody assay, you adhere an antibody to a surface. You put in your antigen, the allergen in this case, which binds very selectively to the antibody. Then you bring in another antibody that's labeled with fluorescent dye. This second antibody binds to the allergen-antibody couplet, and the whole thing lights up when under ultraviolet light, betraying the allergen. But this technique requires a lot of steps, two expensive antibodies, and a lot of time. It's not practical for making real-time measurements.

With Andrea Armani, an assistant professor at USC and a former graduate student [PhD '07] in the lab of Kerry Vahala, the Jenkins Professor of Information Science and Technology and professor of applied physics, we're developing a device that just may help us give real-time asthma warnings. This new tool is several orders of magnitude more sensitive than conventional assay techniques. The device, called an optical resonator, depends on a phenomenon known as the whispering-gallery mode. You may have experienced this when you go inside a rotunda and stand at one end of the



A scanning-electron-microscope image of the resonator. Light zips around the donut-shaped structure at its resonant frequency. When an allergen binds to an antibody attached to the ring, the resonant frequency changes according to the number of allergen molecules binding, allowing researchers to measure its concentration.

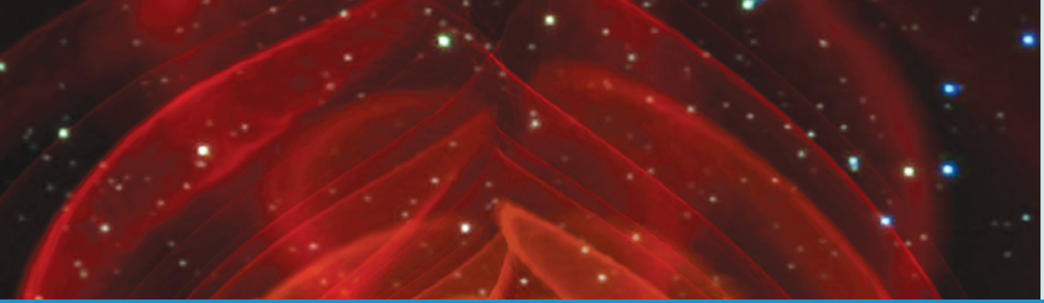
dome. You can speak in a whisper and the sound will bounce along the circular wall to the far end, where someone else can hear you. The resonator is a miniature version of the rotunda and does exactly the same thing, but with light. We shine light from an optical fiber into a little donut-shaped piece of silicon sitting atop a sloped pedestal. The ring is about 80 microns in diameter—about the width of a human hair—and seven microns thick. The light races around the perimeter at a resonant frequency that depends on the size of the ring. If we put an antibody that binds to our allergen on the ring, and pump in liquid containing the allergen, it binds to the antibody, and its presence shifts the resonant frequency of the light. By measuring the shift, we can detect single antigen-molecule binding events.

To make the resonators, we start with a block of silicon that has a two-micron layer of silica (also known as silicon dioxide, the chief ingredient of glass) on its surface. We use lithography techniques—the same techniques that are used in making microelectronic devices—to turn the silica layer into an array of glass disks on the surface of the silicon. We then etch away the exposed silicon between the disks to make an array of glass-topped pillars. The underlying silicon etches faster than the glass on top, so the etching process undercuts the glass disks to make pedestals. Then we zap each disk with a laser, which melts the perimeter of the glass disks, causing it to bead up and thicken into a donut. Next, we couple each disk to an optical fiber and immerse the array in a liquid under a cover slip. We can inject microliters of liquid containing the material we want to analyze into this microaquarium.

Right now, the device is still on the optical bench, hooked up to expensive machines. While we're using the resonator to measure biological molecules in the air, others may use it to solve other problems in biology or environmental science. For example, Rosen Professor of Biology and Professor of Bioengineering Scott Fraser is using it to learn about embryo development. In terms of measuring allergens, we're still far away from making a portable instrument, but it has the potential to help prevent not only asthma attacks, but also asthma-related deaths. And that's nothing to sneeze at. e&s

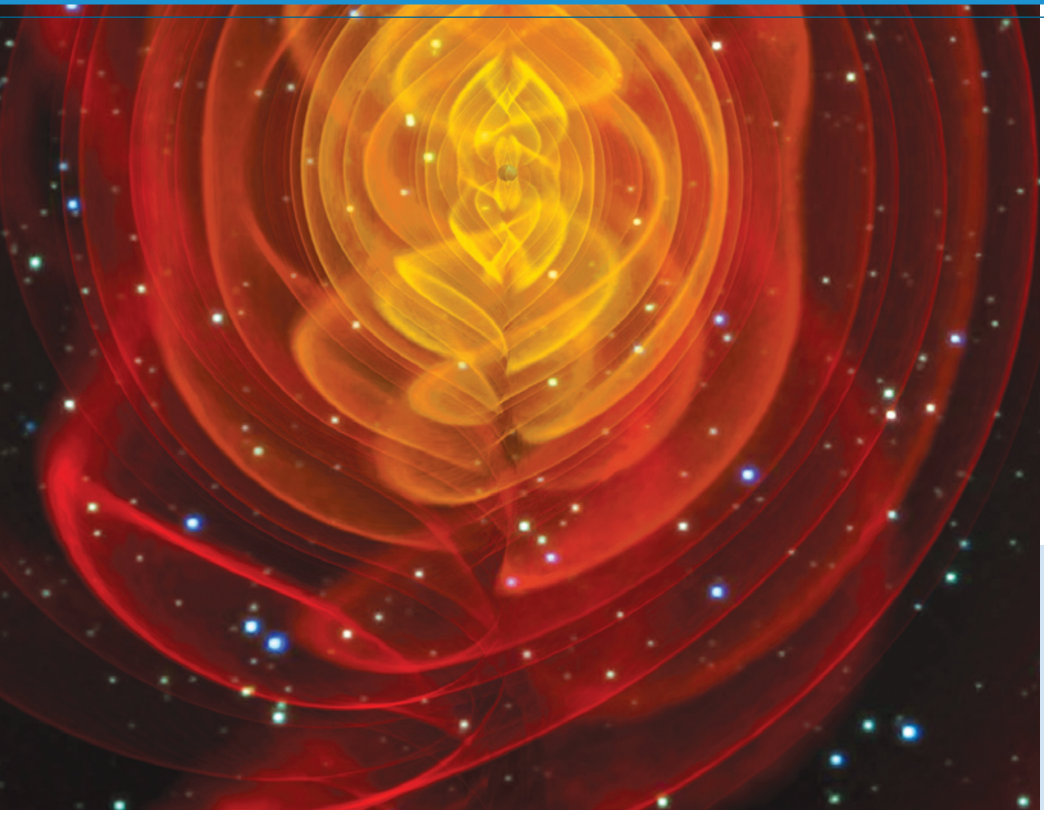
Richard C. Flagan is executive officer for chemical engineering, the McCollum–Corcoran Professor of Chemical Engineering and Professor of Environmental Science and Engineering. Before joining the Caltech faculty in 1975, he earned his BSE (1969) in mechanical engineering at the University of Michigan, and an SM (1971) and PhD (1973) from the Massachusetts Institute of Technology. Among his many awards and honors are the American Chemical Society's Award for Creative Advances in Environmental Science and Technology in 2007, the Fuchs Memorial Award from the American Association for Aerosol Research in 2006, the Thomas Baron Award in Fluid-Particle Systems from the American Institute of Chemical Engineers in 1997, and the David Sinclair Award of the American Association for Aerosol Research in 1993. In 2004, Lund University in Sweden awarded him an honorary doctorate of technology.

This article was adapted from his May 2008 Seminar Day talk by Marcus Y. Woo.



A still from a movie of two black holes colliding. Taken from a simulation by the team at NASA Goddard, this image shows the merged black hole in the center and what the resulting gravitational waves would look like (in orange).

Crashing Black Holes



After struggling for years, physicists have now succeeded in simulating black-hole collisions, heralding a new era in physics.

On Thanksgiving morning in 2004, Frans Pretorius made a few last-minute changes to his computer code. Pretorius, a Caltech postdoc, was struggling with a problem that had baffled theoretical physicists for decades—simulating the collision of two black holes. A black hole, whose gravity is so strong that even light cannot escape its pull, is indeed a strange creature—but not a rare one. Black holes are the inevitable fate of massive stars, and since those stars often exist in paired systems called binaries, astronomers suspect that black-hole binaries are scattered all over the cosmos. As two black holes whirl around each other at nearly a third of the speed of light, they create ripples in space-time, the fabric of the universe. To Earth-bound physicists, these as yet undetected ripples, called gravitational waves, will tell the story about the black-hole pair's dance and ultimate union, lending insight into how gravity—and the universe—works. But to read the ripples, you'll need simulations to know what they'll look like. Unfortunately, the math behind the science is so complicated that no computer had ever run for more than a fraction of an orbit before the inevitable program crash. Pretorius, however, had an inkling that this time might be different.

He was applying an approach developed a few years prior by David Garfinkle, now at Oakland University in Michigan. By Thanksgiving, Pretorius's code was still not working. But the night before, Carsten Gundlach, a visiting researcher from the University of

By Marcus Y. Woo

The idea of a black hole actually goes back to 1783. John Michell, a British natural philosopher and geologist, reasoned that a "dark star" could exist if light couldn't escape its gravity. Newton's laws showed that a star's escape speed—the speed needed to leave its gravitational pull—is proportional to the square root of its mass divided by its radius. So if the radius were sufficiently small for a given mass, the escape speed could be greater than the speed of light.

Southampton in England, had proposed a few more minor tweaks. "I decided that if I had a few minutes free, I'd try it," Pretorius recalls. Because the problem is so complex, he ran the revised program with the simplest possible test case—a single, stationary black hole—and even this scenario was far from trivial.

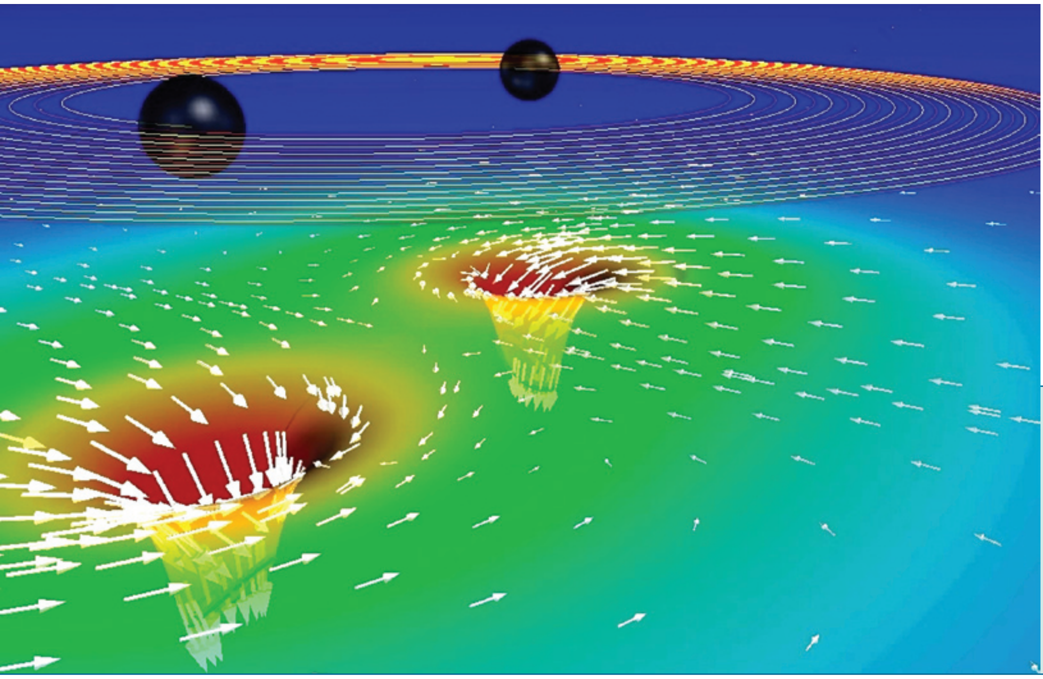
He tapped into the power of the Lonestar cluster at the University of Texas, Austin, which combines 5,200 processors to form a supercomputer. Even with such muscle, the simulation would take hours to run, giving him and Gundlach ample time for a holiday dinner at a fellow researcher's house. On Sunday morning, when the simulation was done, he scanned the numbers. "At that moment, I knew it would work," he recalls. "That was very exciting." Unlike all the simulations tried before, his was stable. And if it worked for one black hole, it should work for two.

Over the next six months, Pretorius put a binary system through one full orbit with a merger at the end. He then published his results in *Physical Review Letters*. Six months after that, two other groups, from NASA Goddard Space Flight Center and the University of Texas, Brownsville, independently published their own work, heralding a new era in gravitational physics. Pretorius, however, was not only the first to succeed, but his method was unique—and he did it largely on his own.

"It was really an outstanding piece of work," says Lee Lindblom (BS '72), a senior research associate in theoretical astrophysics. The intellectual genealogy of the Goddard and Brownsville groups originated at the Albert Einstein Institute in Germany, Lindblom says, so their methods were similar. "Frans came from left field—he didn't come from that group—and used a rather different approach, a different version of Einstein's equations. And as soon as the other groups realized this could be done by this upstart guy, I think they went crazy and worked 24 hours a day. I think they were pretty close, and in a few months, they were able to put it all together."

Since then, groups from around the world have gotten in on the act. Pretorius has moved to Princeton and into different fields, but the Caltech team, led by Lindblom and Mark Scheel, a senior research fellow in physics, and under the oversight of Feynman Professor of Theoretical Physics Kip Thorne (BS '62), and a Cornell group, led by Thorne's old student, Saul Teukolsky (PhD '74)—together, the largest numerical relativity group in the country—carry on. Their simulations are the most accurate of any so far, orders of magnitude beyond Pretorius's initial work. Ultimately, they'll be able to recreate merging black holes of any size, spin, and orbit. But this work wouldn't be where it is had it not been for one late night in November 1976.

That evening, Thorne found solace in the streets of Pasadena. He needed fresh air and he needed to think, debating with himself whether to propose that Caltech get involved in an ambitious new gravitational-wave detector. The risks, as he later noted in *Black Holes and Time Warps*, were enormous. There was no guarantee of success, and the project would be expensive—not only financially but also in terms of energy and time. But, after months of internal struggle, he went for it. Almost two decades later, LIGO, the Laser Interferometer Gravitational-Wave Observatory, spearheaded by Thorne; Ronald Drever, now professor of physics, emeritus; and MIT's Rainer Weiss, was born.



This snapshot from one of the Caltech–Cornell team's simulations depicts two black holes prior to merger. The colored surface represents the curvature of space-time. The arrows represent the flow of space, similar to the flow of water in a whirlpool.

An aerial view of the LIGO facility in Livingston, Louisiana.

ERGO, LIGO

In 1916, Einstein declared that mass or energy bends space and warps time, and this curvature of space-time is what we experience as gravity. Newton's apple falls not because the ground is pulling it down, but because Earth is curving the space-time around it. The apple is just following the bends of space-time.

Any bit of moving matter—say, coalescing black holes, an orbiting Earth, or even a gesturing hand—creates waves of space-time that propagate across the cosmos just as a tossed rock sends ripples across a pond. Suppose you arrived at the pond an instant later. In principle, you could look at the ripples' patterns and deduce the rock's size and trajectory. A softball-sized one would splash while a pebble would barely disturb the shimmering surface. In similar fashion, gravitational waves betray their source. And it turns out that the most likely source, colliding black holes, may be fairly common.

Although the precise number is hard to pinpoint, a large portion of stars exist in binary systems. In fact, astronomers like to joke that three out of every two stars is a binary. Many of the universe's binaries are pairs of massive stars, and if they're at least about ten times heavier than the sun, they'll collapse into black holes once they've exhausted their fuel. As the brand-new black holes continue to revolve around each other, gravitational waves carry away energy and angular momentum, sending the holes into a death spiral until they crash and trigger an explosion of gravitational waves.

The Milky Way is whizzing toward the Andromeda Galaxy at 120 kilometers per second, and the two are slated to meet in a few billion years.

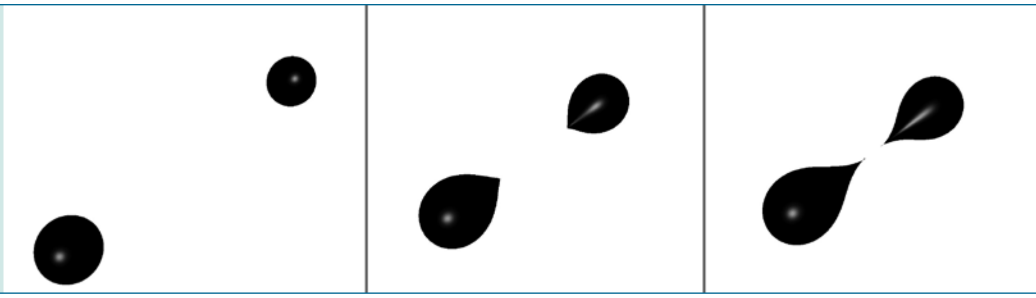
While these signals are the target for LIGO, there's another kind of gravitational-wave factory that makes space-time ripples of lower frequencies, ripples likely to be visible only to a future space-based observatory called the Laser Interferometer Space Antenna (LISA). These factories are merging supermassive black holes, behemoths millions to billions of times more massive than the sun, and they would set off the strongest gravitational waves.

These humongous holes inhabit the centers of galaxies, which fly through the universe like Frisbees. Once in a while, galaxies get too close, succumb to their mutual gravity, and smash into each other. Amid the swirling stars and gas, the two giant holes find each other and merge. In fact, our own galaxy, the Milky Way—which has its own black hole of three million solar masses—is whizzing toward the Andromeda Galaxy at 120 kilometers per second, and the two are slated to meet in a few billion years. At Andromeda's center awaits a black hole almost 50 times bigger than ours.

Still, there's no way to know for sure how many black holes there are, since by definition you can't see them. "The uncertainty is one of the reasons why the first detections with LIGO will be so interesting," says Stan Whitcomb, chief scientist for LIGO. He says that given what's known about stellar evolution and LIGO's sensitivity, the instrument should detect anywhere from roughly one merger per century to one per year. Although that may not sound too promising, upgrades planned for 2014 will boost those rates more than a thousandfold.

Like pond ripples, gravitational waves

These time-lapse snapshots show two black holes on a direct collision course. The black holes' surfaces are called the event horizons. Note how the horizons extend toward each other before merging.



In general, Einstein's equations are impossible to solve without a computer. But there are a few simple cases in which all you need is pencil and paper. In 1915, the same year Einstein introduced his theory of general relativity, an astrophysicist named Karl Schwarzschild solved the equations for a stationary sphere—a nonspinning black hole. Not only did he do it by hand, he did it while fighting for the German army on the Russian front, where he would die from an illness the following year. His work, however, lives on as an important contribution to science.

weaken over distance, and they may travel millions of light-years to get to Earth. When they do, even the strongest waves will stretch and squeeze space-time by no more than one part in 10^{21}. Measuring such puny waves, then, takes breakthrough technology.

LIGO has to detect motions as small as 10^{-16} centimeters—a thousand times smaller than a proton. As its name suggests, the observatory is an interferometer, an L-shaped structure whose arms stretch four kilometers. A laser at the junction fires half its beam down each arm. To keep stray gas molecules out of the beams, the beams are encased in steel pipes 1.2 meters in diameter, evacuated to one-trillionth of normal atmospheric pressure. At about 8,000 cubic meters, the vacuum system is one of the biggest in the world. At each end of each arm is a mirrored test mass, a 10-kilogram cylinder of ultrapure fused silica. The two beams bounce back and forth between the test masses, and are eventually recombined where the arms meet. If all's quiet in the universe, the light waves will match up peak to peak and trough to trough. But if a cosmic cataclysm sends a gravitational wave our way, the arms will alternately stretch and shorten, shifting the laser beams out of phase with each other. Because the shift is minuscule, the beams bounce back and forth about 100 times to accumulate a difference big enough to measure.

After nearly a decade of construction, LIGO went online in 2002. There are two nearly identical observatories—one in Hanford, Washington, and one in Livingston, Louisiana. Having two detectors allows you to spot where the waves are coming from. Double detections also help confirm a signal; if both say they saw a wave, then chances are they really did.

You need to screen out false detections because LIGO is extremely sensitive, capable of picking up ocean waves crashing onto a rocky shore hundreds of miles away, and even the stealthy shifts of creeping geological faults. According to Lindblom, researchers even detected an airplane flying overhead. They saw the vibrations caused by the sound of the plane's engines and measured its Doppler shifts—the shifts in frequency that depend on the plane's motion relative to an observer—and compared them with known flight plans to confirm that they had indeed detected the airplane.

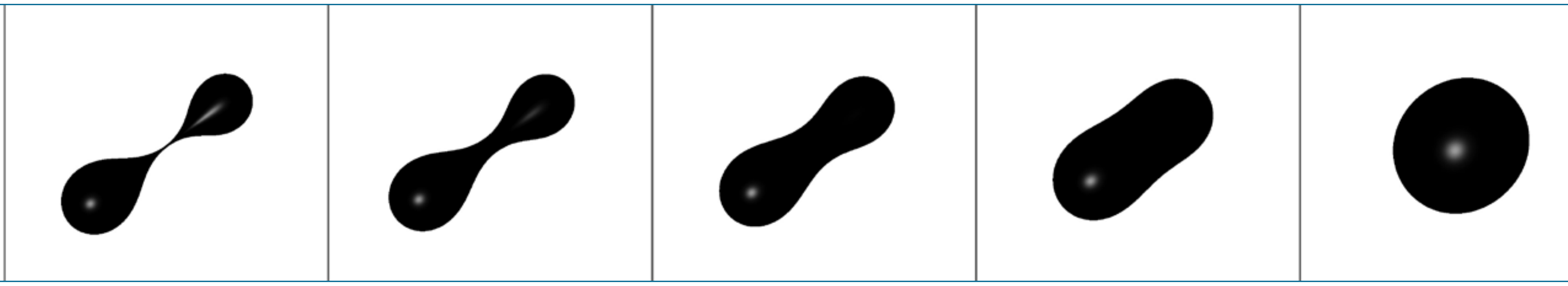
As in the airplane example, the key to discerning sources from noise—and from each other, such as distinguishing between systems with different masses—is to know what you're looking for. Picking out a merging black-hole binary is akin to picking out a single voice in a noisy restaurant. Just as cupping your ears won't necessarily help you eavesdrop on dinner conversations, LIGO's great sensitivity won't necessarily help if you can't interpret what you see. And that's where numerical simulations come in.

NUMBER TRICKS, NINJA, AND KICKS

The mid-1990s saw vigorous efforts around the world to simulate black-hole mergers. But as the 20th century came to a close and LIGO came online, progress was slow. "At that time, nothing worked," Lindblom remarks. "The field was a mess." Success was measured in terms of fractions of an orbit, Pretorius says. Physicists could get the black holes to begin their dance, but if the two spiraled in too close, the code crashed before they could consummate their union. Each fix would extend the simulation a bit farther along, but the crash was inevitable—solving one problem just revealed another one. Taxpayers had invested a lot of money in LIGO, and the space-based version, LISA, was already in the works. Thorne became worried.

"I decided that we really needed to become involved to try to push things forward," Thorne says. So, in 2001, Caltech plunged in with the group at Cornell, which had been working on the problem since the 1980s. He began building a team, and he recruited Lindblom, who had been splitting his time between Caltech and Montana State University studying neutron stars (neutron stars are black holes' less-dense cousins), and Mark Scheel from Cornell as its leaders. The team attacked the problem head-on.

The challenge isn't the physics, but the math and how to program it. Some of Einstein's equations are called constraint equations, which are conditions that the solution must satisfy at all times. Consider a marble rolling on a table. Newton's equations of motion—the ones you learned in high school—describe how the marble moves around. The constraints confine the marble to the table's surface.



“In the last few years, it’s been about the physics. It’s very exciting.”

Solving Einstein’s equations, of course, isn’t exactly easy. There are 10 equations with usually thousands of terms, and just keeping track of all the numbers is practically impossible. As powerful as computers are, they’re far from perfect. For example, numbers such as π or 1/3, whose decimal forms go on forever, must be truncated to fit in the memory. The discrepancies between the true and truncated values pile up, causing the errors to grow exponentially until the constraint equations are violated, and the marble flies off the table.

“People realized that the standard way of writing Einstein’s equations was bad,” Lindblom says. “That’s one of the things where our group made a lot of contributions, in figuring out what was killing everybody. Then Frans [Pretorius] and the other groups found stable ways of writing the equations, and once they did that, they were up and running.”

The trick was a mathematical method called constraint damping. Consider a constraint equation that requires a certain term to be zero. You can add that term to the equations and not change anything, because you’re adding nothing. Then you can rewrite the equations such that when errors cause the constraint term’s value to change, the new terms push the constraint back toward zero. In other words, the program has a negative-feedback system to keep the violations down. Figuring how to do that, Thorne says, was a mathematical tour de force.

Another obstacle is the singularity that lurks in the black hole’s belly. A singularity is a point where space-time has collapsed to infinite gravity—and infinite curvature. The mathematical equivalent of dividing by zero, it’s where Einstein’s theory of general relativity breaks down. But the researchers realized that what happens inside the black hole doesn’t matter.

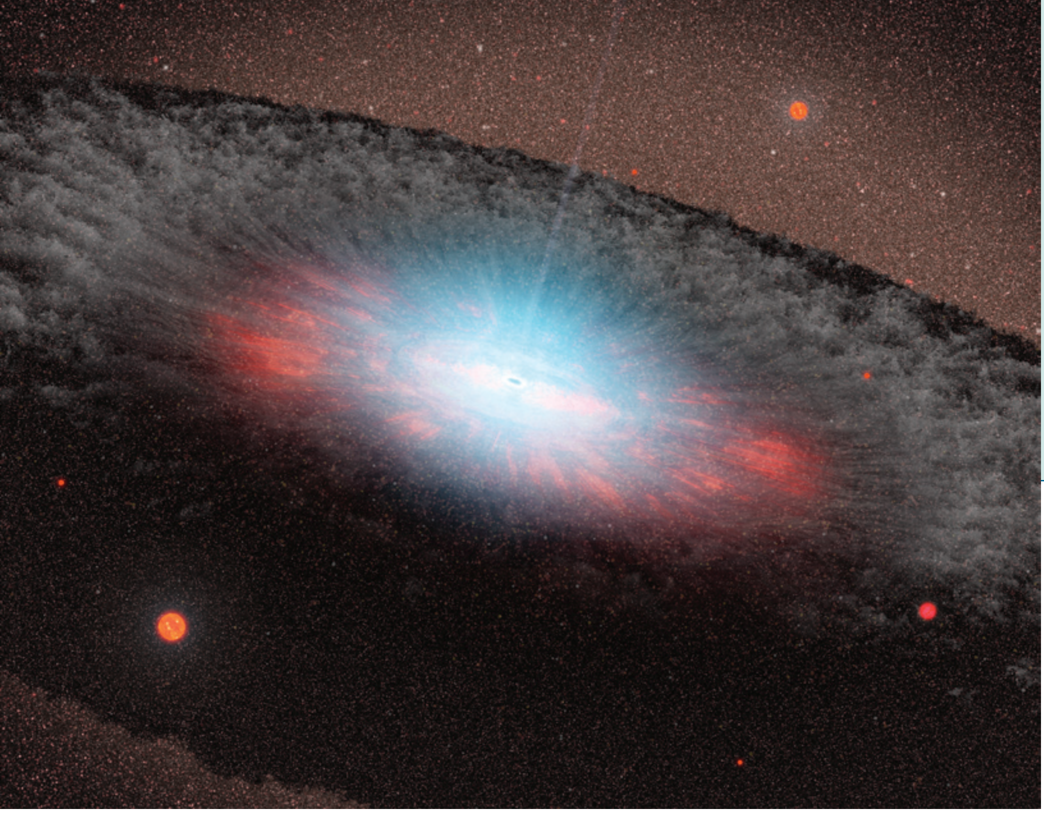
A black hole’s voracious appetite only comes into play when you get really close to one. From a distance, they behave as any star or planet would. If the sun were to be replaced by a black hole of the same mass, Earth would not be any different—aside from the lack of sunlight and resulting mass extinctions. As you get closer to a black hole, however, the beast begins to reveal itself. Once you cross the so-called event horizon, you’ve been swallowed—the gravitational pull is so strong that not even light can escape. This, then, is the black hole’s “surface,” beyond which communication with the outside universe is impossible. What happens inside the black hole stays in the black hole, so the program need only run until the event horizon is encountered, avoiding the messiness of the singularity.

The black holes move in their orbits, of course, adding another challenge to the simulations. The computer code imposes a grid onto the black hole and calculates how much space-time is curved at each of the grid’s points. Other groups had kept the grid stationary while the hole moves. But the Caltech–Cornell team was devising a more accurate method, which needed the grid to follow the hole’s motion, Lindblom explains, so the researchers had to invent techniques to glue the coordinates to the black holes.

Which brings us back to Pretorius’s Thanksgiving weekend in 2004. His achievement triggered an exceptional period in the field, Lindblom says. Simulations featuring multiple orbits are now routine, and after years of doing nothing but programming, scientists are returning to the physics that originally drove their research. “It was very disheartening that we spent so much time on just coding and mathematical analysis,” Pretorius says. “In the last few years, it’s been about the physics. It’s very exciting.”

Armed with the new methods, researchers, including those at Caltech, have been involved in a game of hide-and-seek witih each other involving virtual binary black holes. This experiment, called NINJA, for Numericial INJection Analysis, is designed to find out how good physicists are at spotting black-hole pairs amid LIGO’s background noise. One team submits a simulated data set, and the data are then buried in statistical noise. Other teams then sift through the noisy data to try to determine the masses, spins, and orbital shapes of the black-hole binaries. So far, the seekers are winning.

On another front, researchers at the Rochester Institute of Technology have shown that colliding supermassive black holes can trigger a “kick” that sends the coalesced monster careening through space at up to 4,000 kilometers per second. Furthermore, they’ve found that the speed and direction of the kick depends on the



An artist's conception of a supermassive black hole at the center of a galaxy. The gray matter is a torus of gas and dust, and as it's devoured by the black hole, tremendous amounts of heat and radiation are released, represented by the blue color.

pair's initial spin alignment—and not their masses. This surprising result could help pin down the rules of how supermassive black holes form. Astronomers believe that nearly every galaxy harbors one at its center, and some scientists have suggested that the hole is formed through multiple mergers. But 4,000 kilometers per second is more than enough to escape a galaxy's gravity, so mergers may not be an efficient way to build these gravitational goliaths.

SIMULATING EXTREME SPACE-TIMES

The Caltech–Cornell team, however, wants to study the gravitational waves from merging black holes in unprecedented detail, with the high accuracy that LIGO needs. To do this, the team decided to pursue a numerical technique that is the most accurate yet—but also more unforgiving.

All previous calculations had relied on so-called finite-difference methods. Consider again the marble on the table. The equations that govern the marble's motion describe its changes in position over time. Mathematically, this change is infinitesimally small from moment to moment. But a computer doesn't know what "infinitesimally small" means—it needs an actual number. Finite-difference methods approximate these changes as tiny, discrete steps, so that the marble would roll around in steps of, say, 0.1 millimeters.

But there's another technique, called a spectral method, that exploits the smoothness of space-time. The curvature around black holes changes gradually—there are no sudden jumps or shocks. Roughly speaking, spectral methods approximate the answer as the sum of a series of well-understood mathematical functions. The more functions in the series, the more accurate the answer. With this technique, the calculation converges toward the exact answer far faster than with finite-difference methods.

Of course, there's a catch. Spectral methods are more complicated and delicate—so much so, in fact, that the SXS project (for Simulating eXtreme Space-time), as the Caltech–Cornell effort is known, and two smaller groups in France and Germany are the only ones in the world who use them. Finite-difference methods allow for some leeway, Lindblom says. Even if the mathematics isn't strictly correct, finite-difference codes will still give you an answer that's not terribly wrong. "But spectral-method codes just tend to blow up. They just won't compute anything unless you've done every single thing right."

Only in the last year have they succeeded, Thorne says. "We are now doing mergers and getting very high accuracy waveforms for use in LIGO data analysis—waveforms that have higher accuracy than LIGO is ever likely to need, even decades into the future." But this level will be needed for LISA, which will make more accurate measurements.

Because of the computer code's increased complexity, SXS has yet to fully automate its merger simulations. The researchers are having to stop the program numerous times and adjust it before starting it up again. But, they say, automated simulations of complete mergers will soon be routine. Thorne says, "We're playing catch-up in the sense that [other groups are] able to do a given problem sooner than we are, but they can't get the precisions that LIGO and LISA require."

Because of all the money and time put into gravitational-wave detectors, simulating black hole collisions is the main task at hand. But the physicists haven't forgotten that black holes—with their ability to slow clocks, bend light, and drag space-time around themselves like whirlpools—are the universe's funhouses. Black holes are where weird stuff happens, and the team is using

Discovered by Charles Messier in 1773, the Whirlpool Galaxy lies 23 million light-years away. That's a lot of frequent-flier miles.

their computing techniques to learn all about the bizarre drama of extreme gravity. For example, Caltech's Cornell collaborators are simulating a black hole devouring a neutron star, a gruesome ordeal in which the latter is torn apart and swallowed.

Another puzzle relates to overcoming the obstacle of overly complicated math. As two black holes coalesce, Einstein's equations have to be used in all their gory detail. But when the black holes are still on their approach and extreme gravity has yet to kick in, physicists use the post-Newtonian approximation—a mathematical tool that mixes a bit of Newton's physics with a bit of Einstein's. A bridge between the classical and relativistic depictions of gravity, it avoids the complications of Einstein's equations. The question is when and how the approximation stops describing physics and starts spitting out nonsense. Now, with their high-accuracy simulations, Thorne says, they can find this transition and see how the approximation breaks down. "We can see how far you can trust it and when you have to abandon it."

Part of what makes the region around black holes so weird and complicated is that it's nonlinear—curvature begets more curvature. Thorne likens it to an avalanche, in which falling snow grabs more snow, which in turn accumulates even more snow. Along with Assistant Professor of Physics Yanbei Chen (PhD '03) and a few graduate students, and armed with the Caltech–Cornell team's simulations of spinning, colliding black holes, Thorne is trying to understand how this avalanche behaves. "That's a process we're just beginning, and we see it as a major direction. I don't know any other groups that are pursuing that at the moment, but it's a big thing for us."

Next, Thorne says, they might confront a topic more commonly associated with science fiction—wormholes. A wormhole is like a black hole, in that its powerful gravity keeps photons on a short leash. But whereas a black hole is a dead end, a wormhole is a tunnel that connects two places in the universe, conceivably serving as an intergalactic shortcut for space travelers. But before you plan your trip to the Whirlpool Galaxy, note that some theorems say wormholes would collapse into a singularity, according to Thorne. But no one knows exactly how a wormhole collapses—or if something can prevent the collapse.

LIGO has yet to detect anything, but as in all science, a nondetection is still a result. For example, on February 1, 2007, a gamma-ray burst lit up an area of the sky occupied by the Andromeda Galaxy. Conventional observations had led many astronomers to believe that this particular burst was from a relatively weak source in Andromeda, perhaps a collision between two neutron stars. If such a collision had happened as close as Andromeda, it would produce lots of detectable gravitational waves. But it would also have produced an even brighter burst in electromagnetic waves, which astronomers didn't see. So when LIGO didn't see anything, a neutron-star collision in Andromeda was pretty much ruled out. Instead, the source was probably either a collision farther away, or a so-called soft-gamma repeater—a single neutron star whose strong magnetic field produces rapid, successive bursts of gamma rays, but hardly any gravitational waves. So far, the data suggests the latter is more likely.

Last June, LIGO scientists published the results of a year-long study on the Crab Pulsar, a spinning neutron star whose birth was recorded by Chinese astronomers in 1054. A neutron star is so dense that its atoms have collapsed, its protons and electrons squishing together to make neutrons. Although it's almost a perfectly smooth sphere, a neutron star, with a typical radius of 10 kilometers, can be deformed by a few centimeters. And these tiny bumps are enough to generate gravitational waves as the star whirls around its axis at breakneck speeds. The Crab Pulsar, for example, spins some 30 times per second. The waves carry energy away and slow down the pulsar's spin. Astronomers had already known this pulsar was slowing down, and had carefully measured how fast it was losing energy. But when LIGO didn't detect any gravitational waves, the researchers could set a limit as to how spherical the pulsar could be, concluding that if the pulsar were 10 kilometers in radius, any deformities couldn't be more than one meter in size, beyond what's physically possible. The scientists then showed that gravitational waves could account for no more than 4 percent of its energy loss. The rest must be lost elsewhere, almost certainly through the rapidly spinning magnetic field, researchers say.

Despite these useful results, LIGO will only be truly successful if it sees something. Earlier this year, the National Science Foundation began funding for Advanced LIGO, a seven-year, $200 million project to improve LIGO's sensitivity tenfold—a leap that would mean physicists should see anywhere from 16 to 2,700 mergers per year, according to scientists. And if LIGO still doesn't find anything, we may have to revamp our understanding of gravity—as big a potential shakeup as any in science.

The 1960s and early 1970s have been dubbed the Golden Age of general relativity. During those 15-odd years, physicists at Caltech and elsewhere transformed an intellectual curiosity into a field that continues to inspire. Now, more than three decades later, we may stand at the brink of yet another Golden Age. For physicists, it's about time. e&s

Combining optical and X-ray data from the Hubble and Chandra space telescopes, this image reveals the Crab Pulsar in detail. Shock waves carry wisps of matter, seen in the picture as rings, out at half the speed of light. Jets of radiation shoot out perpendicular to the rings.

Maarten Schmidt (left) and Donald Lynden-Bell (center) receive the Kavli Prize from Crown Prince Haakon Magnus in Stockholm.

SCHMIDT WINS KAVLI PRIZE

Maarten Schmidt, the Moseley Professor of Astronomy, Emeritus, has been awarded the $1 million Kavli Prize for his contributions in astrophysics. He is one of the seven first recipients of the prize, and shares the astrophysics award with **Donald Lynden-Bell**, of Cambridge University, who was a Caltech postdoc from 1961 to 1962.

Schmidt and Lynden-Bell are known for discovering that quasars are galaxies harboring supermassive black holes billions of light-years away—and not stars in our own galaxy, as was once believed. The Kavli Astrophysics Prize Committee said, "Maarten Schmidt and Donald Lynden-Bell's seminal work dramatically expanded the scale of the observable universe and led to our present view of the violent universe in which massive black holes play a key role."

In 1963, using the 200-inch Hale Telescope on Palomar Mountain, Schmidt studied the visible-light spectrum of quasar 3C273. He discovered that its spectrum was shifted toward longer wavelengths, a phenomenon called the Doppler effect, in which the emitted light from a source depends on its motion relative to the observer. Called a redshift, this difference in wavelength meant the quasar was speeding away from Earth at 47,000 kilometers per second. Looking at the spectrum of another quasar, the astronomers found it was sprinting away at twice the speed of 3C273. Schmidt calculated that these objects lay beyond our galaxy, and he immediately realized that they must be emitting hundreds of times more energy than the 10 billion stars of the Milky Way. Later, researchers learned that this glut of energy spews from a volume of space no larger than the size of our own solar system. It was Lynden-Bell who suggested that a supermassive black hole feasting on matter at the center of distant galaxies was generating the prodigious amounts of energy. And after studying the evolution and distribution of quasars, Schmidt discovered that quasars were more abundant when the universe was younger.

"I'm delighted with the award. It is in particular a most pleasant surprise after so many years," Schmidt says. "After all, it's been 45 years since I found the red shift in quasar 3C273."

Schmidt was the executive officer for astronomy at Caltech from 1972 to 1975 and chaired the Division of Physics, Mathematics and Astronomy for the following three years; he then served as the last director of the Hale Observatories from 1978 to 1980. Despite being named an emeritus professor 12 years ago, he has continued his research, studying ever-more-distant quasars and peering farther into the universe's past.

The other Kavli Prize recipients are being recognized for contributions in nanoscience and neuroscience. The prize was established through a partnership between the Norwegian Academy of Science and Letters, the Kavli Foundation, and the Norwegian Ministry of Education and Research, and the Norwegian Ministry of Foreign Affairs. The winners received the prizes at an award ceremony in Oslo on September 9. —*EN* E&S

HONORS AND AWARDS

R&D magazine has honored the work of Liepmann Professor of Aeronautics and professor of bioengineering **Morteza Gharib** (PhD '83) and his team, including **Emilio Graff** (PhD '07) and postdoctoral fellow **Francisco Pereira** with the R&D 100 Award. The group designed a camera that creates a three-dimensional image by extracting information from a series of images. The researchers say the camera has a myriad of applications, including underwater surveillance, analyzing a person's gait, and assisting surgeries. The award recognizes 100 of the most significant, commercialized technologies from the past year.

Julia Greer, assistant professor of materials science, has been recognized by *Technology Review* magazine as one of the world's top innovators under the age of 35 for her work with materials on a nanoscale level. Selected from more than 300 nominees by a panel of expert judges and the editorial staff of *Technology Review*, the TR35 is an elite group of accomplished, young innovators. —*JW* E&S

OBITUARY

NEW DIVISION CHAIRS

Andrew Lange, the Goldberger Professor of Physics, has been tapped as the new chair of the Division of Physics, Mathematics and Astronomy. Lange has been at Caltech since 1994, developing experiments to study the early universe.

Richard Murray (BS '85), the Everhart Professor of Control and Dynamical Systems and director of Information Science and Technology, is now the interim chair of the Division of Engineering and Applied Science. Having served as the chair from 2000 to 2005, Murray will hold the position until the next division chair is found. e&s

PHILIP G. SAFFMAN

1931-2008

Philip Geoffrey Saffman, an influential teacher and noted researcher in fluid mechanics, died peacefully after a long illness on Sunday, August 17, in Pasadena. He was 77 years old.

Saffman, the Theodore von Kármán Professor of Applied Mathematics and Aeronautics, Emeritus, studied vortex instability and the dynamics of arrays of vortices. In particular, he looked into the phenomenon of viscous fingering, which became known as the Saffman–Taylor instability. This occurs when a low-viscosity fluid is injected into a higher-viscosity fluid.

His work with vortices also led him to a new mathematical analysis of the wake turbulence caused by jets as they take off, resulting in a theory describing the conditions behind several aircraft accidents.

"Saffman was one of the leading figures in modern fluid mechanics," said Dan Meiron, the Jones Professor of Applied and Computational Mathematics and Computer Science. "His research had an impact in almost every part of the field." A prolific scholar with a dry sense of humor, he was able to focus on the essence of a problem and explain its complex results in a simple way, Meiron said.

Saffman even formed an unlikely collaboration with his neighbor, Ruddock Professor of Biology and Nobel Laureate Max Delbrück. Delbrück was studying the diffusion of protein and lipid molecules in biological membranes, and he would walk around the corner to Saffman's house for ideas. In 1975, the two scientists from disparate fields published a paper, "Brownian Motion in Biological Membranes," that remains well cited today.

Born in Leeds, England, Saffman received his BA, MA, and PhD from the University of Cambridge. In 1964 he accepted Caltech's appointment as a full professor in fluid mechanics within the Division of Engineering and Applied Science. He was named von Kármán Professor in 1995.

He was a Fellow of the American Academy of Arts and Sciences and in 1988 was elected a Fellow of the Royal Society, England's premiere scientific organization. He also received the Otto Laporte Award from the American Physical Society.

Saffman served as associate editor for both the *Journal of Fluid Mechanics and Physical Review Letters* and was most recently an editorial board member for the journal *Studies in Applied Mathematics*.

Saffman is survived by his wife, Ruth; children Louise, Mark, and Emma; and grandchildren Timothy, Gregory, Rae (née Sarah), Jenny, Nadine, Aaron, Miriam, and Alexandra. *—JW* e&s

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