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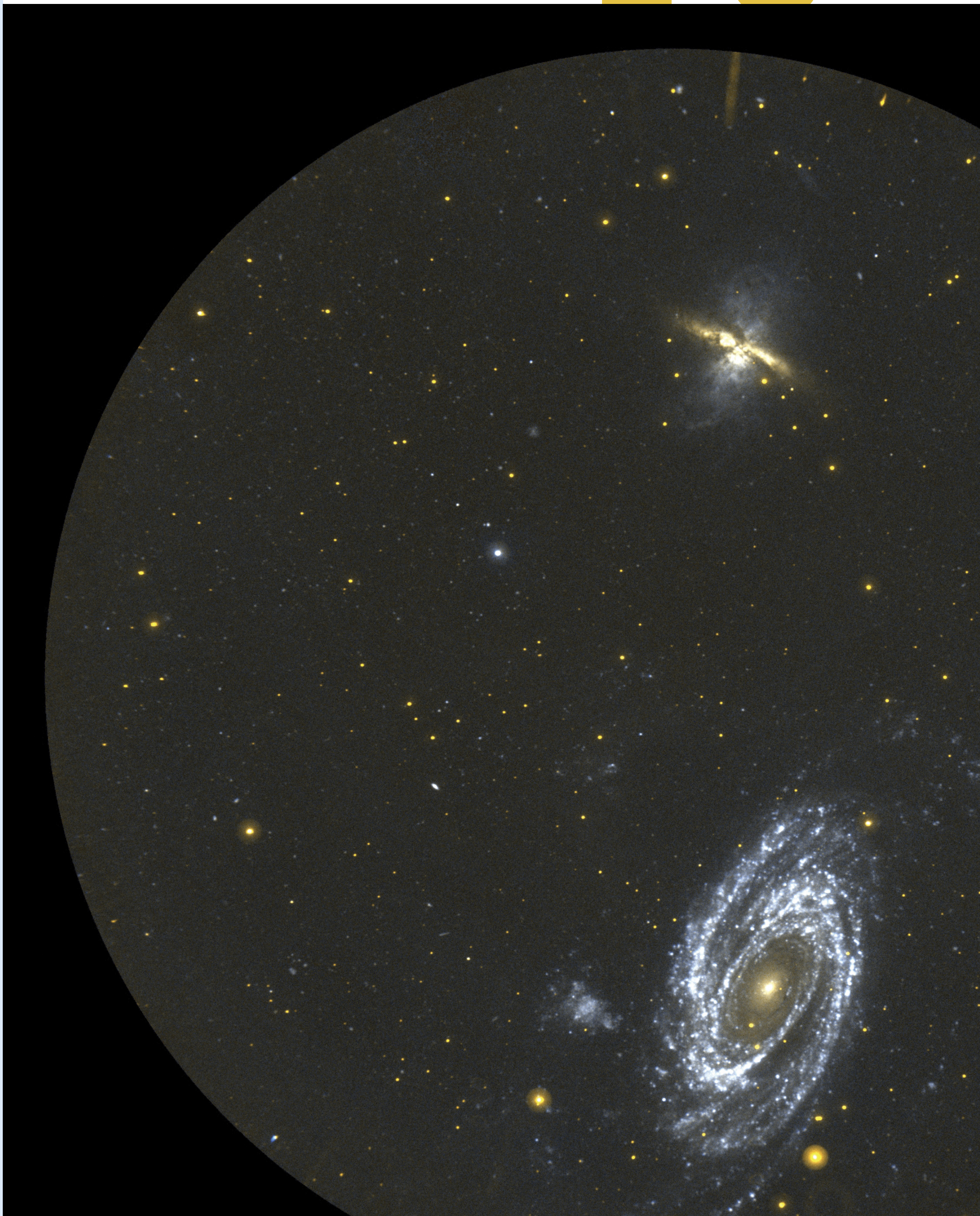
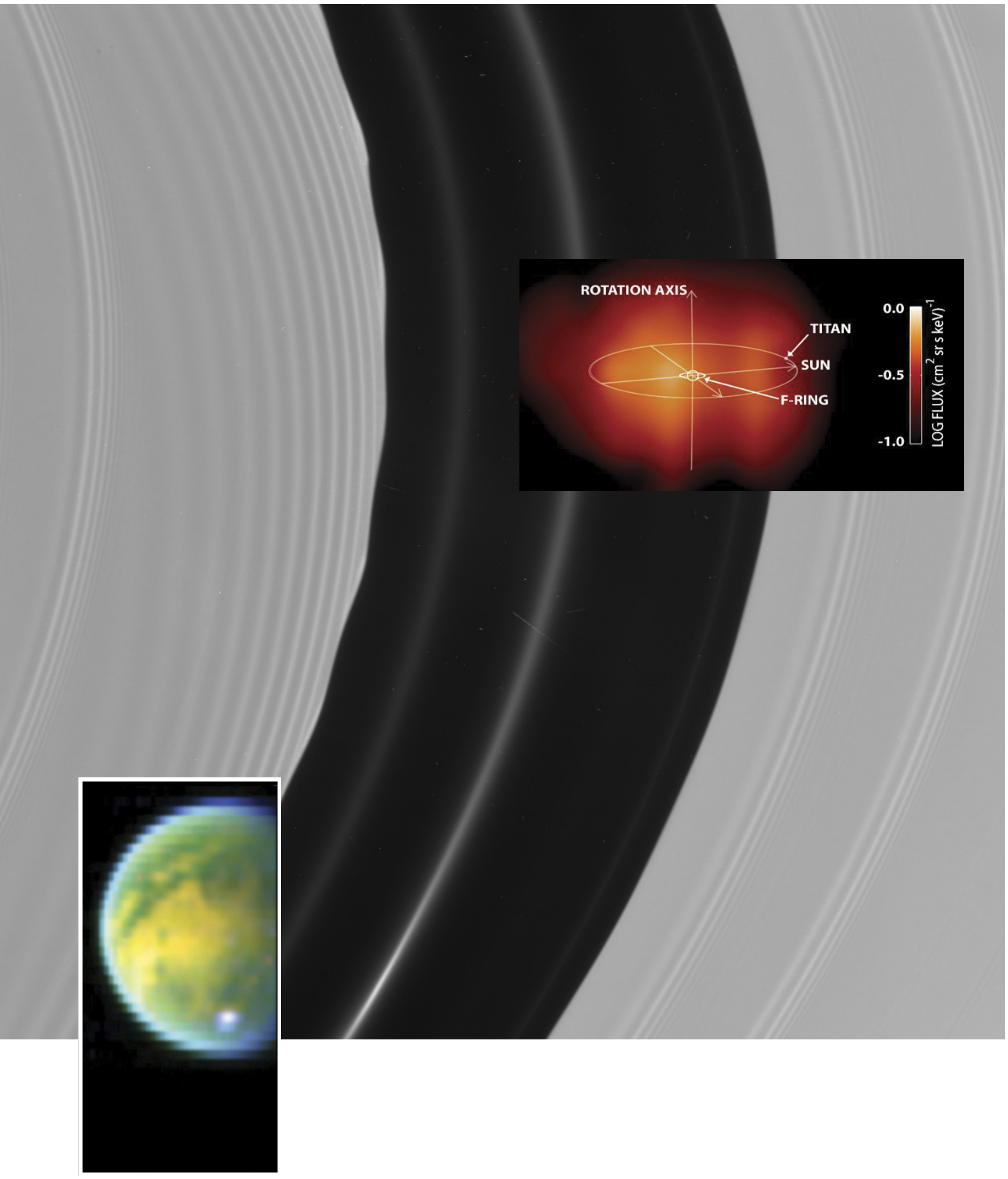
E&S
Engineering and Science

Volume LXVII,
Number 2,
2004





As Cassini begins its four-year Saturnian tour, it shot the rings in unprecedented detail. At left is the Encke Division, kept clean by Pan, a small moon whose gravitational wake is revealed by the inner ring's scalloped edge and spiral ripples. Cassini also found that the gaps between the rings contain dark "dirt," spectroscopically very similar to Phoebe's dark surface (see page 2).

Earlier, the ion and neutral camera—the first ever sent into space—looked at Saturn's magnetosphere (red, top inset), an envelope of charged particles that, unexpectedly, extends beyond Titan.

Planet-sized Titan (bottom inset) has a dense, opaque, methane-rich atmosphere into which Cassini will drop the ESA's Huygens probe in December. The first pass by Titan netted this view (shot in infrared bands where the atmosphere is transparent) in which yellow areas are hydrocarbon-rich (alas, no methane seas were found), green is water ice, and white is a methane cloud at the south pole.

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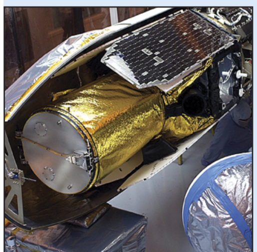

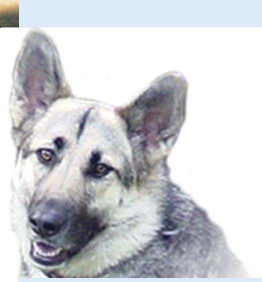

Departments

On the cover: As seen by the Galaxy Evolution Explorer (GALEX) at ultraviolet wavelengths, M 81, the spiral galaxy at lower right, and M 82, the starburst galaxy above it, appear to be interacting, abetting star formation. M 81's tails of hot, young stars are flung far wider into space (this field of view is roughly twice the diameter of the moon) and the blasts of dust from M 82 are much brighter than can be seen at other wavelengths. For more on the small Caltech spacecraft's new view of the universe, see the story beginning on page 8.

Engineering & Science (ISSN 0013-7812) is published quarterly at the California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125. Annual subscription $10.00 domestic, $20.00 foreign air mail; single copies $3.00. Send subscriptions to Caltech 1-71, Pasadena, CA 91125. Third class postage paid at Pasadena, CA. Published by Caltech and the Alumni Association. Telephone: 626-395-3630.

PICTURE CREDITS: Cover, 8-14 – NASA, JPL; inside front cover, 2, 3 – NASA, JPL, Space Science Institute, Johns Hopkins, U. of Arizona; 5 – Doug Smith; 6-7 – NASA, JPL, Cornell, USGS, MSSS; 18 – U.S. Army, National Atomic Museum; 27, 42, 43 – Bob Paz; 28 – Doug Cummings; 36 – Beckman Instruments; 37 – Don Ivers; 38 – Floyd Clark; inside back cover – Sheryl Gorchow-Stuart, CARMA

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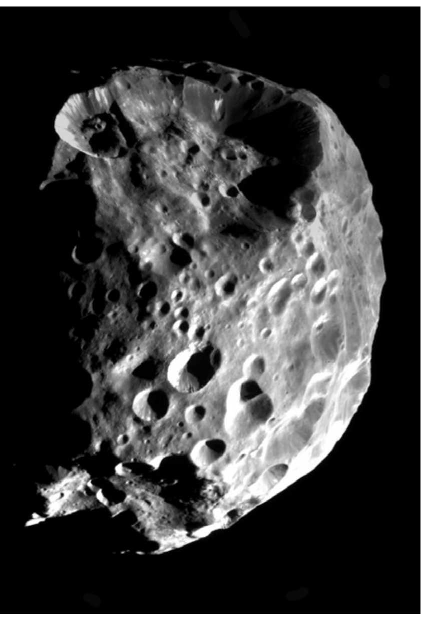
Twins Separated at Birth?

Two JPL-led missions have given us our closest looks yet at two icy bodies from the outer reaches of the solar system. But although both objects presumably came from the Kuiper Belt, which lies beyond the orbit of Pluto and contains rubble from the solar system's formation some four and a half billion years ago, their recent histories are very different. Comparative studies of the two will no doubt tell us quite a bit about how the solar system evolved.

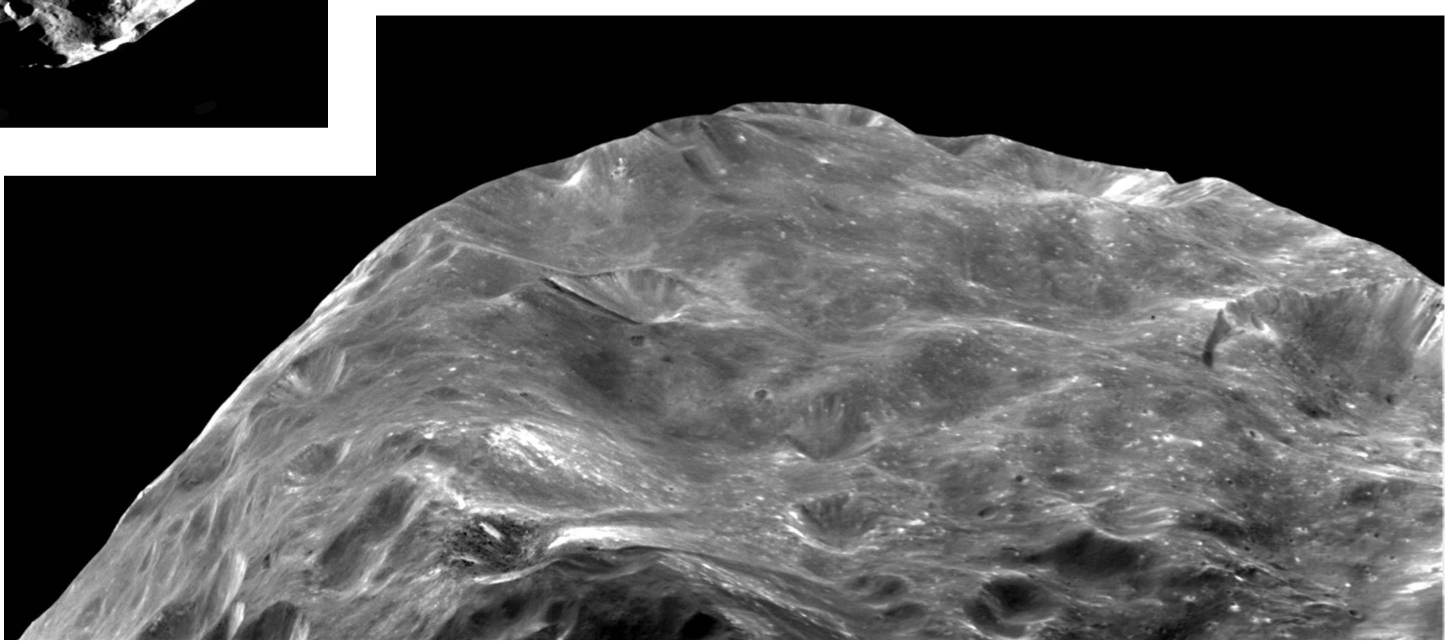
One of them, 214-kilometer-diameter Phoebe, is now a moon of Saturn, which it orbits in the wrong direction—a sure sign that it's not from around there. But assuming it didn't wander much closer to the sun before it was captured, it should be a pretty pristine sample of the material from which the solar system condensed. On June 11, the Cassini spacecraft trained all its instruments on Phoebe from a distance of about 2,068 kilometers—a thousand times closer than the Voyager missions' best view. (Cassini slipped into orbit around Saturn on the evening of June 30, Pasadena time.) The results show that Phoebe's surface is a patchy mix of water and carbon-dioxide ice, water-bearing minerals, solid organic compounds similar to those found in primitive meteorites, things that might be clays, and some unidentified materials. Its bulk density was measured at about 1.6 grams per cubic centimeter—much lighter than most rock but somewhat heavier than ice, suggesting a mix of ice and rock similar to Pluto and to Neptune's moon Triton. Temperature maps show that Phoebe cools off rapidly at night, suggesting a loose, porous surface; radar maps also indicate a dirty, rocky exterior.

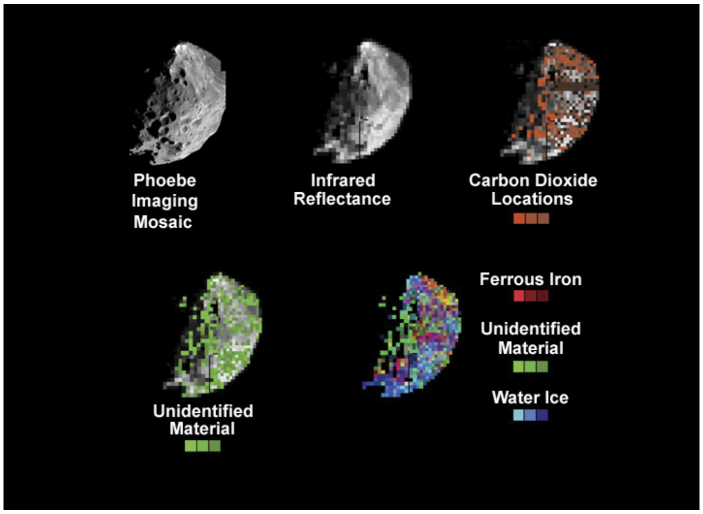
Meanwhile, a spacecraft named Stardust reached the halfway mark on its mission to sample the dust surrounding Comet

Below: This mosaic of the entire moon shows that Phoebe's dark coating is sliding down the walls of the large crater at the north pole, revealing a bright interior.



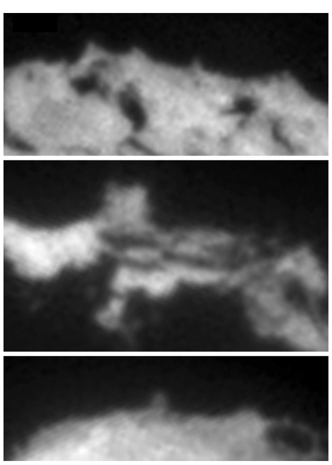
Below: A crater in Phoebe's southeast quadrant exposes at least two alternating bright and dark layers hundreds of meters thick. The layers may be blankets of bright subsurface material that were ejected from other craters and acquired dark patinas as they aged. Bottom: The south polar region has crater walls over 4 kilometers high, and numerous small craters penetrate the dark surface. In both shots, each pixel is 80 meters wide.

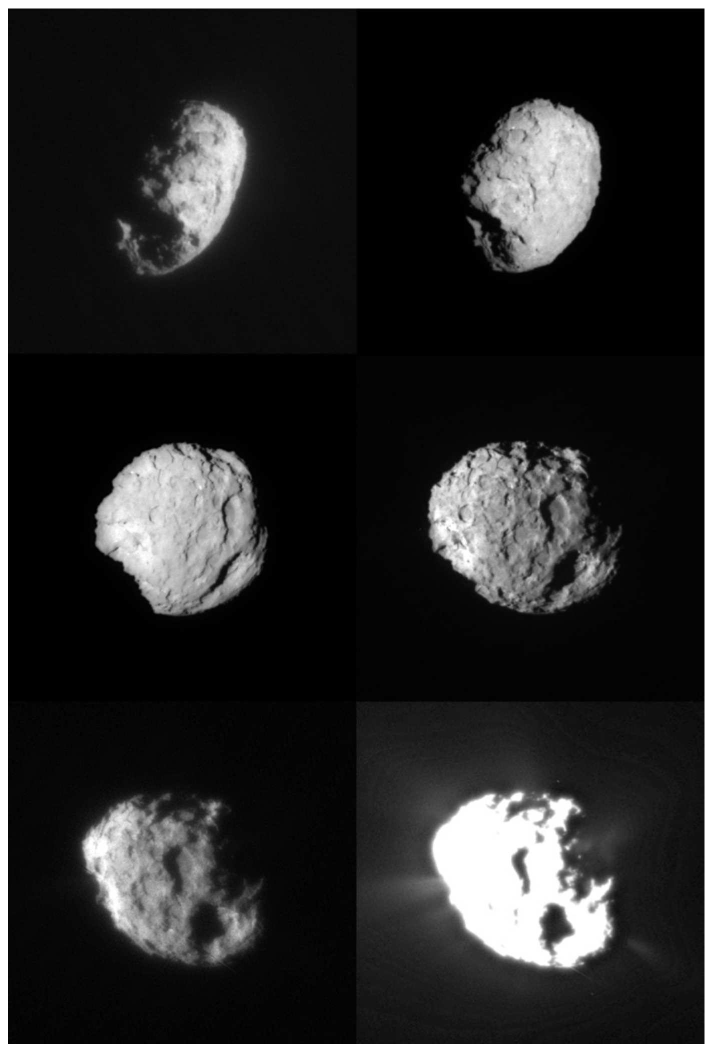




Above: Data from Cassini's visual and infrared mapping spectrometer, and a reference photo (upper left). The frozen carbon dioxide bolsters a Kuiper belt origin for Phoebe.

Wild 2 and return the material safely to Earth in 2006. On January 2, Stardust flew to within 236 kilometers of the comet's nucleus, collecting thousands of particles and taking hits from raisin-sized debris chunks in the process. At six minutes before closest approach, the spacecraft, which is half a light-hour from Earth, had to figure out on its own how to roll sideways to just the right angle so that the rotating mirror on the navigation camera would keep the comet's head in view as it went by—a feat equivalent to shooting a movie of a passing telephone pole from the side-view mirror of your SUV—at 13,000 miles an hour. These pictures, the most detailed ever of a comet's nucleus, were released to coincide with four papers on the encounter published in the June 18 issue of *Science*. The images show a 5.1-kilometer-diameter body with a surface rigid enough to support towering spires and mesas like those seen in a Roadrunner cartoon—vastly different from the fluffy snowball scientists expected to see. And instead of being fairly quiescent, more than two dozen jets shoot out in all directions. Presumably, uneroded bits of the nucleus between jets (which can blast out from just below the surface at hundreds of kilometers per hour) become the spires. □—*DS*





Right: A set of views from Stardust's flyby of Comet Wild 2, adjusted to constant scale, begins at upper left. The bottom right image has been overexposed to highlight the jets.
Left: Small mesas and pinnacles 100 meters tall can be seen on the comet's limb.

Quantum Memories?

No, not in some futuristic computer, but in human brains. Postdoc Mike Sutton, along with Erin Schuman, an associate professor of biology at Caltech and an associate investigator for the Howard Hughes Medical Institute; undergrad Nicholas Wall; and Girish Aakalu (MS '99, PhD '02) have found that the release of a single packet of a substance called glutamate can alter the junction between nerve cells. Adjusting the strengths of these junctions' connections is thought to be at the heart of learning and memory. The report appears in the June 25 issue of *Science*.

Neurons communicate at synapses, tiny gaps between the ends of nerve fibers, where one nerve cell signals the next by secreting chemicals called neurotransmitters that jump the gap. These chemicals, which include glutamate, are manufactured within the neuron and stored in pouches called vesicles. So the dumping of one vesicle's contents—some 10,000 molecules' worth of neurotransmitter—into the synapse is the elemental unit of synaptic communication. "This is known as the 'quantal' nature of synaptic transmission," says Sutton, "and each packet is referred to as a quantum." A typical burst of neuronal activity leads to the release of dozens of vesicles in less than a second, but the spontaneous opening of just one, called a miniature excitatory synaptic event, or "mini" for short, was thought to have no biological significance—mere background chatter.

Sutton didn't set out to look at minis, but at how changes in synaptic activity regulated protein synthesis in the receiving cell. The original experiment was designed to remove all types of activity from the cell, so he could add things back incrementally and observe how protein synthesis was affected. "We were going on the assumption that the spontaneous glutamate release—the minis—would have no impact, but we wanted to formally rule them out," he says.

Sutton first blocked the action potentials—electrical signals in the sending cell that cause glutamate release. Normally, a cell receives hundreds of glutamate packets from its neighbors every second. But when the action potentials are blocked it receives only the minis, which arrive about once per second. Sutton then blocked both the action potential and the release of any minis. "To our surprise, the presence or absence of minis had a very large impact on protein synthesis in dendrites," he says. (Dendrites are the neuron's treelike branches that collect incoming signals and send them on through the cell to a long fiber called the axon, which in turn makes synapses with other dendrites.) It turned out that the minis inhibited protein synthesis, which increased when they were blocked. Further, says Sutton, "it appears the change in synaptic activity needed to alter protein synthesis is extremely small—a single package of glutamate is sufficient."

Sutton notes that it is widely accepted that synaptic transmission involves the release of different numbers of glutamate packets, adding, "Minis may provide information about the characteristics of a given synapse (for example, is the signal big or small?), and the postsynaptic or receiving cell might use this information to change the composition of that synapse. And it does this by changing the complement of proteins that are locally synthesized." This ability to rapidly make more or fewer proteins allows for quick changes in synaptic strength. Ultimately, he says, this ability may underlie long-term memory storage.

"It's amazing to us that these signals, long regarded by many as synaptic 'noise,' have such a dramatic impact on protein synthesis," says Schuman. "We're excited by the possibility that minis can change the local synaptic landscape. Figuring out the nature of the intracellular 'sensor' for these tiny events is now the big question." □—*MW*

It's sometime between 1:00 and 4:00 a.m. on Saturday in the Avery House lounge. Ruth Nickerson (seated, in red), Melissa Xin (seated, in blue), and, standing, from left, Dan Pragel, Diana St. James, and Lynne McGrath read *Julius Caesar* to Yogesh Sharma and Ken Kuo (at table).

All's Well That Ends Well

Caltech students are normally more comfortable with space-time than with sonnets, but that all changed for 24 hours. From 4:00 p.m. Friday, May 28, and continuing nonstop through 4:00 p.m. Saturday, Caltech students, staff, faculty, JPL employees, and spouses and friends of the same read aloud almost every single word Shakespeare ever wrote—all 39 plays and 154 sonnets, plus the verse masterpieces "The Rape of Lucrece" and "Venus and Adonis"—so much material that it had to be read in five sessions simultaneously in order to fit it all into 24 hours.

By anyone's standard, that's a lot of Shakespeare, but Readathon co-organizers Nicholas Rupprecht, Ryan Witt, and Parag Bhayani think it's worth the effort. All three have appeared in Caltech's annual productions of Shakespeare's plays, and were excited about a public reading of the seldom-performed works, albeit sans costumes and props.

The lack of costume changes was a good thing, as the speaking parts per play vastly outnumbered the readers. Rupprecht, a junior in mathematics, figured out the cast assignments, trying to match the genders of characters and readers as often as possible while minimizing situations where readers had to hold up both ends of a conversation. "A few of the plays had only three readers," says Rupprecht. "But the histories were a nightmare because they tend to have so many speaking parts and there's so much interaction between characters. It took me about an hour and a half on each history to figure out how to split the play up into four roles."

Rupprecht signed himself up to read continuously for the entire 24 hours, but the student most likely to suffer from a literary identity crisis was Matt Wroten, who pulled 20 of the 60 roles in *Henry VI*

From left: Readathon organizers Bhayani, Rupprecht, and Witt.

Part 2. "That's what he gets for picking Benedick in *Much Ado About Nothing,*" explains Rupprecht, noting that the role is one of the most coveted in all of Shakespeare.

And if you missed it, the odds of a repeat performance (or something similar) next year are "extremely good," says Rupprecht. Until then, photos and other info can be found at http://shakespeare.caltech.edu. □—*RT*

Think and Click

We're one step closer to the day when paralyzed patients will be able to use brain impulses to operate computers, robots, motorized wheelchairs—and perhaps even automobiles. In the July 9 issue of *Science*, Caltech neuroscientists Sam Musallam, Brian Corneil, Bradley Greger, Hans Scherberger, and Richard Andersen report that monkeys can move the cursor on a computer screen just by thinking about it.

The Andersen lab's approach departs from most previous work, which relied on signals from the portion of the brain's motor cortex that controlled the portion of the body that the prosthetic was intended to replace. The new study demonstrates that higher-level signals, also referred to as cognitive signals, emanating from the posterior parietal cortex and the high-level premotor cortex (both involved in higher brain functions related to movement planning), can be decoded as well. Says Musallam, this work "shows that a variety of thoughts can be recorded and used to control an interface between the brain and a machine."

The study involved three monkeys, says Andersen. "We have him think about positioning a cursor at a particular goal location on a computer screen, and then we decode his thoughts. He thinks about reaching there, but doesn't actually reach, and if he thinks about it accurately, he's rewarded."

Besides picking up the "goal signals" that told where the monkey was thinking of reaching, the researchers also recorded "value signals." The reward for performing the task varied, and the monkeys were told in advance what reward to expect. (The type of fruit juice or the size of the sip could be changed, for example.) The monkey's reaction to the promised reward was the value signal.

Since the goal signals are high-level and abstract, they could be used to operate a

Postdocs, from left, Dane Boysen (PhD '04), Calum Chisholm (PhD '03), and Tetsuya Uda, the vice president, president, and chief technical officer respectively of a startup company called Proton Power, collaborated with four UC Berkeley MBA students to snag the $25,000 grand prize in Berkeley's sixth annual business plan competition. They plan to market an economically viable fuel cell developed in the lab of Associate Professor of Materials Science and Chemical Engineering Sossina Haile (*E&S* 2003, No. 1).

Watson Lectures Set

Next fall's Watson lineup begins on October 13, when David Goodstein, vice provost, professor of physics and applied physics, and Gilloon Distinguished Teaching and Service Professor, will tell us what's going to happen as the world's petroleum production starts to run dry. Then, on October 27, Michael Dickinson, the Zarem Professor of Bioengineering, will explain how flies fly, or, more accurately, how they control their in-flight maneuvers. On November 10, Christof Koch, the Troendle Professor of Cognitive and Behavioral Biology and professor of computation and neural systems will take us along on his quest for consciousness (see the story beginning on page 28). And finally, on January 26, 2005, Paul Dimotakis (BS '68, MS '69, PhD '73), the Northrop Professor of Aeronautics and professor of applied physics, will describe Caltech's role in helping determine the cause of the breakup of the Space Shuttle *Columbia*. As always, the lectures are at 8:00 p.m. in Beckman Auditorium; admission is free. Streaming videos of the lectures are posted online at http://today.caltech.edu/theater/ about a week after the event. □

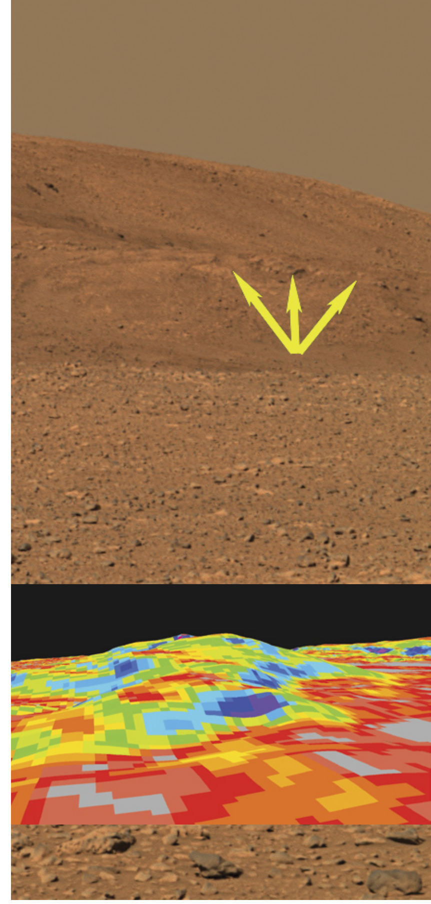
number of devices, and once the patient's goals are decoded, the prosthetics themselves could perform the lower-level calculations needed to achieve them. In other words, a prosthetic arm could use the goal signal "reach up and to the right for the apple" to trigger the calculation of the trajectory commands for that movement.

And since the brain is a busy place, with thoughts leaping about like, well, monkeys, the value signals could be used to help the prosthesis figure out whether you really want the apple or are just trying to decide what to snack on. Such a filtering system might be needed to keep the arm from responding to every fleeting thought.

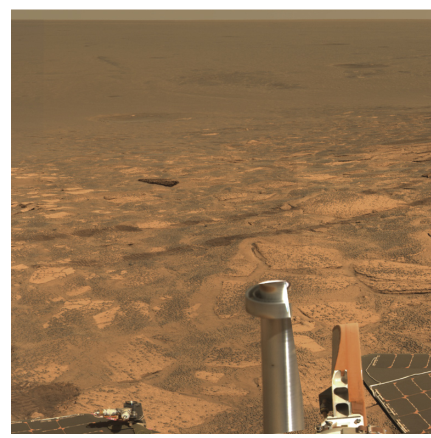
The value signals can also be used to fine-tune performance. "These signals could be rapidly adjusted to expedite the learning that patients must do in order to use a device," Andersen says. And he notes that value signals might be useful for monitoring the patient's moods more effectively. "It's like reading a patient's body language," says Musallam. "You can pick up how someone is feeling, without them having to tell you directly."

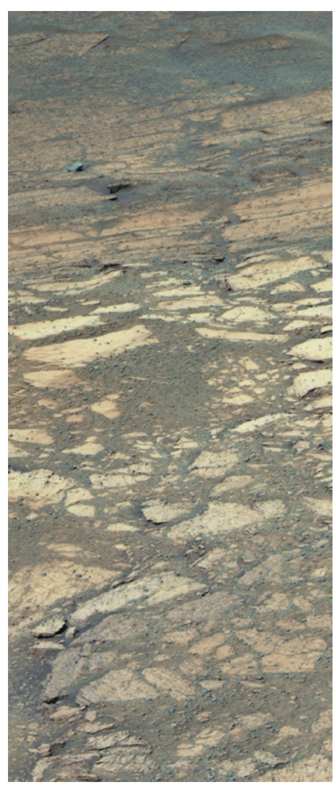
Says Andersen, "This suggests that a large variety of cognitive signals can be interpreted, which could lead, for instance, to voice synthesizers that operate by the patients' merely thinking about the words they want to speak."

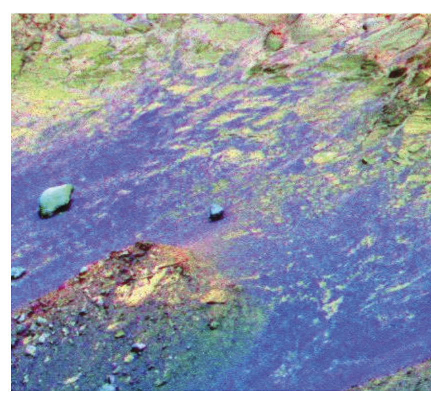
Andersen is the Boswell Professor of Neuroscience. Musallam and Greger are both postdocs in his lab; Corneil and Scherberger are former members of the lab, now at the University of Western Ontario and the Institute of Neuroinformatics in Zurich, Switzerland, respectively. □—*RT*

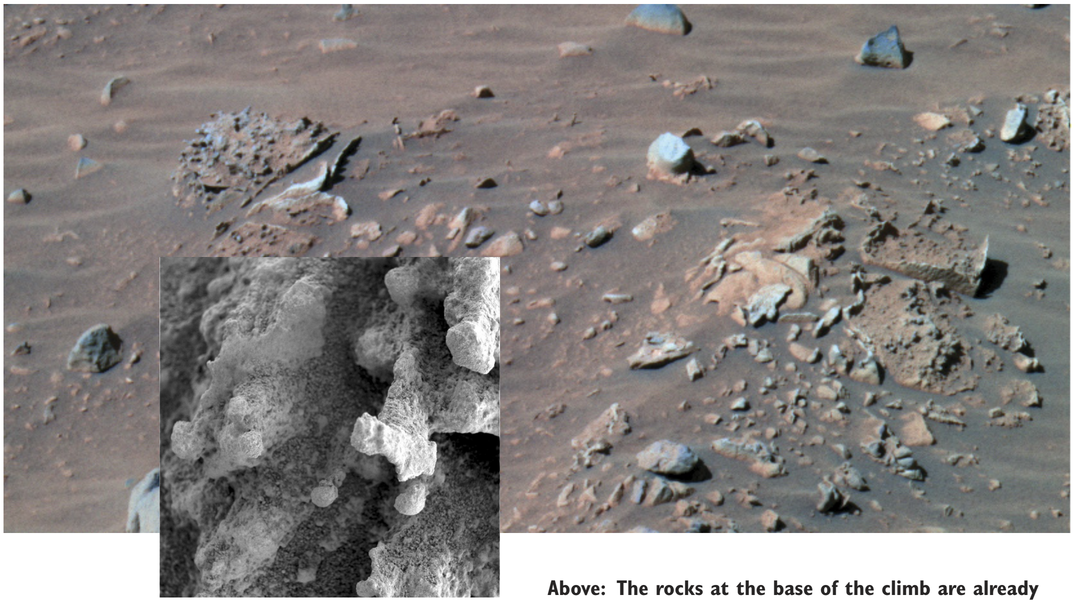


Right: After driving more than 3.4 kilometers from its landing site, JPL's Mars rover, Spirit, has reached the base of the Columbia Hills. This view, from about 300 meters away, shows boulder-strewn slopes and what may be an outcrop (arrowed) along the ridge line of the closest flank, called "West Spur." How to get there is the question—the elevation map (inset) from JPL's Mars Global Surveyor shows slopes from gentle (red) to steep (blue). The most direct route goes through the big blue-purple patch, so the rover team may try the longer but safer approach around to the left.

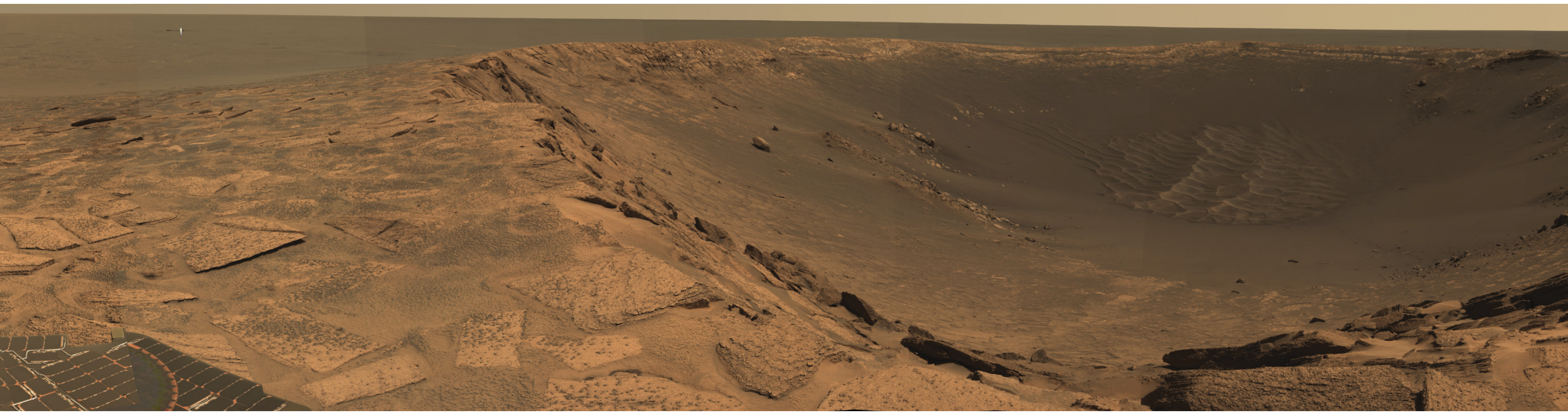


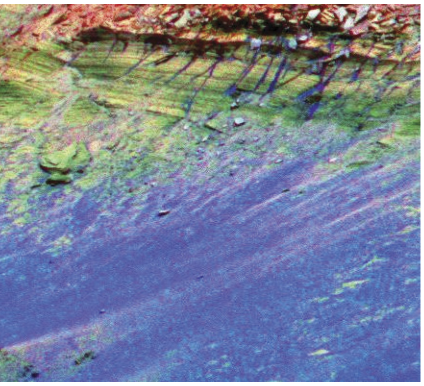




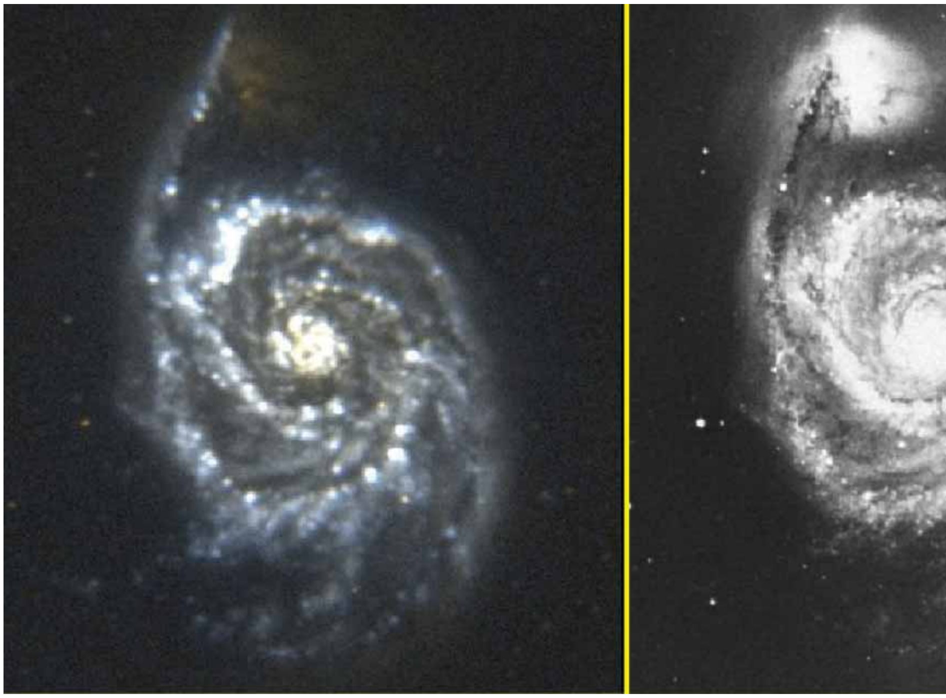


Above: The rocks at the base of the climb are already intriguing—this false-color image shows a weird, knobby rock, dubbed "Pot of Gold" (upper left), that is unlike anything ever seen on Earth. A close-up (inset, shown 1.5 times actual size) from Spirit's microscopic imager reveals that the knobs are on the ends of stalk-like protuberances, like the eyes on a crab. And the Mössbauer spectrometer shows that Pot of Gold contains hematite, although it is not yet clear if water was involved in its formation. Other rocks, like those at the right of the image, look like loaves of bread whose crusts remained intact as the interiors rotted away. Some rocks are so far gone that only the crust remains; in one striking 3-D image (http://photojournal.jpl.nasa.gov/catalog/PIA06286), a delicately balanced piece of crust resembles the head of a cobra poised to attack.





Meanwhile, Spirit's twin, Opportunity, is beginning a gingerly descent into a high-school-stadium-sized crater called Endurance. The rover entered at the left-hand side of the panoramic view (above), after JPL engineers tried it at home on a 25-degree sandy slope (far left, opposite page) littered with rocks and simulated Martian "blueberries"—the hematite-rich granules discovered at Opportunity's landing site that are all over this part of Meridiani Planum. The real blueberries can be seen in this false-color picture (middle, opposite page) of the rocks at Opportunity's current location, some five meters below the crater's rim. At least three bands of rock, distinguishable by their color and texture, are visible downslope of the rocks currently being examined, hinting at a complex past that geologists hope to unravel by methodically moving to progressively deeper strata. And a broad assortment of mineral types can be seen in a false-color image (left) of the crater's rim: the cyan blue is basaltic rocks, the dark green is a mixture of iron oxide and basalts, and the reds and yellows are sulfate-rich dusty materials.



Galaxy Evolution:
The View from the Ultraviolet

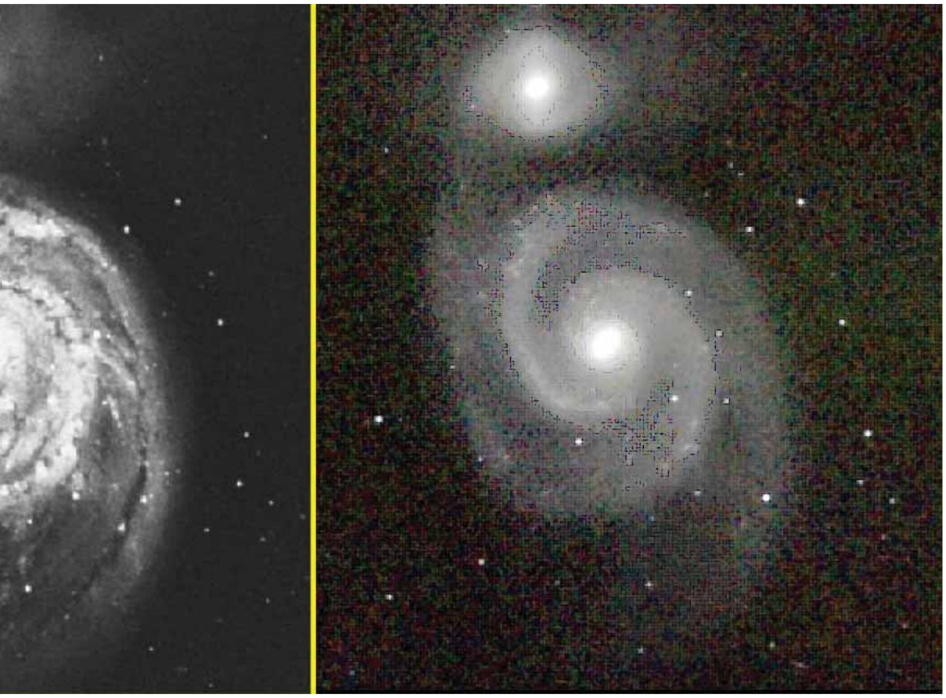
by D. Christopher Martin

Galaxies are amazing machines for forming stars. Out of a ball of gas at a density of one atom per cubic meter, a star emerges that has the density of water—about 10^{30} times denser than it started out as. How galaxies manage to form stars out of this very tenuous gas is a process that we do not yet understand, but GALEX (Galaxy Evolution Explorer) has been orbiting Earth for the past year to help us try to find out.

Most scientists believe that the universe was born 13.6 billion years ago in a cosmic explosion, the Big Bang. Quantum mechanics led to fluctuations in the energy density of the universe, which gravity caused to collapse into lumps. The lumps fell together into larger and larger lumps, finally forming very large lumps, or galaxies containing 100 million to 100 billion stars, as well as gas and dust.

In a way that we don't understand, dark matter (and we don't even know what that is) somehow acts as a framework, a foundation on which galaxies are built. We think dark matter forms "halos," into which the kind of matter we're familiar with—normal gas made of hydrogen and helium—falls and forms a dense core. This core eventually becomes a galaxy. We can simulate the formation of these dark matter halos because the physics is very simple, but the collapse of gas and the evolution of a galaxy out of it has very complicated physics, too vast in scale to be simulated or even described in terms of equations.

This has led to a problem. Theorists' very simple models predict that, when we look at the sky, we'll see a mix of galaxies: old ones whose stars formed long ago, and young ones that are



Different wavelengths reveal different features of the spiral galaxy M 51. The near infrared (right; a 2MASS image) shows old stars in the companion galaxy at the top and stars of various ages in the main galaxy. More definition can be seen in the optical wavelengths (center; Digital Sky Survey—DSS), as dust appears along with younger stars in the spiral arms. In GALEX's ultraviolet view (left), the companion galaxy with its old stars has completely disappeared and all that is visible are the youngest, hottest stars forming in the spiral arms.

still forming stars. And that's what we do see, which is reassuring. But the models also predict that the old galaxies are going to be small and the galaxies that are still forming stars will be large. Unfortunately, the old galaxies that we see are large, and the star-forming ones are medium to small. So there's a fundamental failure in the model predictions.

GALEX was originally proposed to map the sky in ultraviolet wavelengths, which had never been done before. Although mapping the sky in any new part of the electromagnetic spectrum leads to a wide variety of astrophysical applications, we designed the mission around a particular scientific question: How do galaxies evolve over time in the universe? One of GALEX's major goals is to understand the mechanism that turns gas into stars. And one of the ways of doing this is to measure the average rate of galaxy building, what we call the star-formation history of galaxies over time, from the Big Bang to today. This history is also the history of element building in the universe. By elements I mean the "heavy" elements—carbon, nitrogen, oxygen—those that form planets, solar systems, and life. Heavy element formation occurs in massive stars, which burn hydrogen into helium, helium into carbon, oxygen, neon, magnesium and so on. Then they become unstable, explode in supernovae, and deposit those heavy elements in the surrounding gas and even beyond the galaxy; they can generate huge superwinds that deliver these materials out into the intergalactic medium, and this is how the universe became polluted with the heavy elements that later formed solar systems.

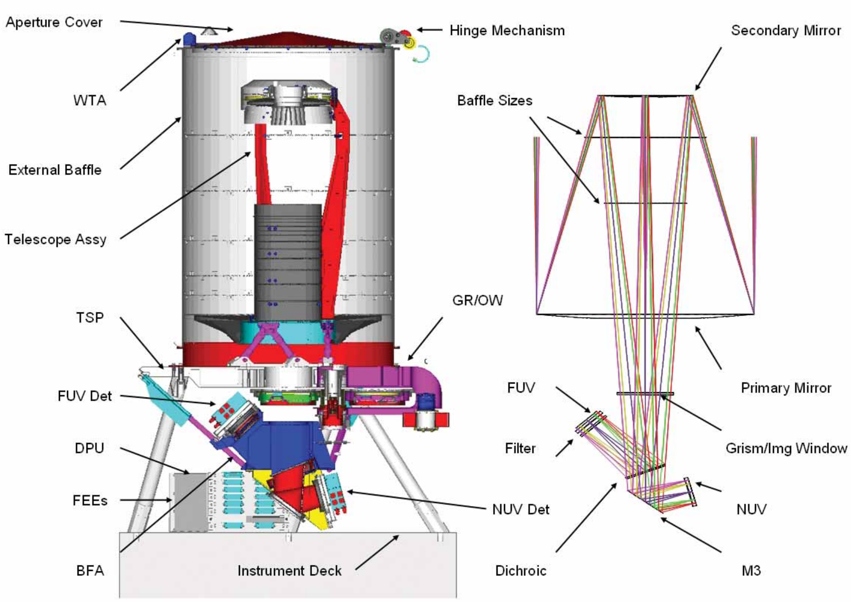
In a way, astronomy is similar to geology, because in both we can actually look back in time. Of course, in geology, you look back in time by going down into the ground, and as you go downward you go deeper and deeper into the geological ages of the Earth. Astronomers can do a similar thing because light travels at a finite speed. So when we look at more distant galaxies, we are seeing them at an earlier age of the universe. And astronomers have a further advantage: the fact that the universe has been expanding since the Big Bang. If you think of the universe as a balloon, with every galaxy being on the balloon's surface, then as you blow up the balloon, the galaxies that are close together will move away from one another relatively slowly, while the galaxies that are farther apart will move away from one another faster. That allows us to measure distances very easily by just measuring a galaxy's velocity, which we can do by comparing its spectrum with that of a local galaxy. The faster a galaxy is moving away from us, the more its light gets stretched, causing its spectrum to be shifted to longer, or redder, wavelengths.

For example, the light from a galaxy that is moving away from us at half the speed of light left the galaxy 5 billion years ago, so we are viewing the galaxy about 8 billion years after the Big Bang. Those that are moving away at 0.9 times the speed of light are seen only about 2 billion years after the Big Bang. We can look at different layers of cosmic time by looking at more and more distant galaxies.

The history of star formation in a galaxy can be quite complicated, with stars forming throughout the galaxy's life. Also, stars live to various ages; they can be a million, 10 million, or many billions of years old. In many bands of the electromagnetic spectrum, we can see stars with a wide range of ages, so we get a blurred picture of the galaxy's construction. Above are images of M 51 in three different wavelengths. In the near-infrared image at the right, you can see a companion galaxy, consisting of old stars, and the main galaxy with old and young stars. In optical wavelengths you start to see the dust and the younger stars in the spiral arms.

But if you look in the ultraviolet, something really interesting happens: the old stars in the companion galaxy and in the smooth spiral arms disappear almost completely. You see only the stars that formed recently in the spiral arms. When stars are born in collapsing clouds of gas, a range of masses is formed, all the way from a hundred solar masses down to maybe a few tenths of a solar mass and even less. Stars over this range of masses have very different properties. The most massive stars are very hot and incredibly bright—as much as a million times more luminous than the sun. And they live very short lives, because they're burning up so fast. So, if you start out forming a collection of stars at various masses and

GALEX is a little satellite, only about the height of a man. The telescope's primary mirror is 20 inches in diameter. The solar panels, spread out here as they would be in space, provide the spacecraft's power, and although the mission is planned to last 29 months, GALEX could easily keep on observing for years—provided its electronic components, which have no backups, don't fail. Right: The satellite is tucked neatly inside the nose cone of the Pegasus rocket, which, after being hauled to 40,000 feet under an L-1011, launched it into orbit.



GALEX's innards illustrate how to pack sophisticated equipment into a very small space—elegantly. The light-path drawing on the right shows the light hitting the primary mirror, bouncing up to the secondary mirror, and then down to the optical wheel assembly (green in the left-hand drawing), where it is shunted to either the imaging window or the grism, then on to the dichroic beamsplitter, which parcels out the light to the far-ultraviolet and the near-ultraviolet detectors.

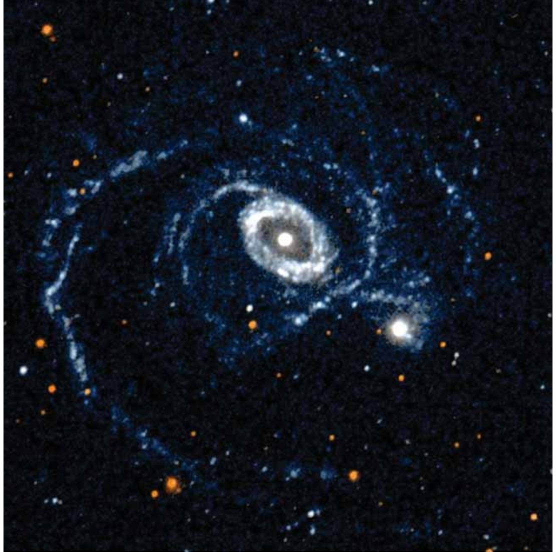
let that collection age, the hottest stars, which radiate at the shortest wavelengths, in the ultraviolet (the radiation's wavelength is inversely proportional to the temperature of the source), die off first. After 10 million years, the hottest stars are gone; they've blown up into supernovae and formed black holes. After 100 million years, the less hot, less massive stars (but still radiating in the ultraviolet) are gone, and so on. As the population continues to age, you lose the progressively lower and lower masses. By looking in the ultraviolet, you get a picture of what has happened in about the last 100 million years; it's like taking a short exposure shot of a scene in order to freeze the action and understand what's going on at that moment (although our moment is 100 million years long).

The basic idea of GALEX is to use the ultraviolet as a tool to study and understand star formation and galaxy building. We can study star formation in nearby galaxies and compare it to that in distant, younger ones. First we want to know the answer to the simple question: when did the stars form in galaxies—early on or late in their lives? Then we want to try to understand why the history was that way.

The mission is a wide-ranging partnership led by Caltech—a collaboration that includes the Jet Propulsion Laboratory, Johns Hopkins University, and UC Berkeley, as well as teams from France and South Korea. GALEX is a NASA Small Explorer, only a little more than 6 feet long and weighing 617 pounds. Its half-meter telescope observes at two bands—the far ultraviolet (the most blue) and the near ultraviolet. As you can see in the illustration at left, a typical photon hits the primary mirror and then the secondary mirror. Then it passes through either a window or a grism (a combination of a grating and a prism), which are mounted on a wheel. The wheel can rotate so that we can get either an image (through the window) or spectrum (through the grism) of every object in the field of view.

GALEX has a dichroic beam splitter, which can send the far ultraviolet signal to one detector and the near ultraviolet (which is slightly redder) to a separate detector. These detectors are not silicon or semiconductors; they're actually imaging photomultiplier tubes with millions of glass microtubes that count the individual photons. This is the largest version of this detector ever flown in space (six times larger than those on the Hubble Space Telescope), and the beamsplitter and grism are also the first of their kind. They all worked as expected, which is really amazing. *Popular Science* magazine named it one of the innovations of the year (along with the Spitzer Space Telescope).

The satellite was launched in April 2003 by a Pegasus rocket, carried aloft on an L-1011 that dropped the Pegasus at 40,000 feet, 100 miles east of the Kennedy Space Center. The launch vehicle



In the optical (above; DSS), NGC 1512 doesn't appear to have the spiral arms filled with young stars that emerge in the ultraviolet (left). Blue stars are those seen in the far ultraviolet, and red, the near ultraviolet.

drops for 5 seconds—a very long 5 seconds—then the booster is lit, and it flies aerodynamically for a few tens of seconds and then flies ballistically. The satellite orbits 700 kilometers above the Earth, completing one orbit every 98 minutes. We spend two-thirds of each orbit (about an hour) in the day with the solar panels pointed toward the sun, and then we slew over to the target of interest for that particular orbit and spend about half an hour on the night side, observing. Then we slew the solar panels back to the sun on the day side. We can't observe during the day because the ultraviolet background from Earth's tenuous outer atmosphere is so large.

We have now been observing galaxies for more than a year. Above are images of galaxy NGC 1512. In the optical image you can see that most of the light is in the center, but in the ultraviolet you see a lot of star formation going on in the spiral arms, swirling way outside the inner body of the galaxy. Blue represents the far ultraviolet and the red, the near ultraviolet. These spiral waves are probably caused by a companion galaxy, which you can see at the lower right. The companion is orbiting around the main galaxy, generating density waves, which are one way to trigger star formation. If you've ever driven on Los Angeles freeways (especially the 405), you've encountered density waves—patterns that persist long after the trigger for the pattern is gone. For example, a traffic accident can jam up the freeway for hours after the cars have been towed away. This is exactly what's happening in spiral arms. Different radii of the galaxy rotate at different rates, causing the beautiful spiral pattern. And because most of the star-forming clouds wind up in the spiral arms, the clouds collide with one another and become denser still. Ultimately the most dense bits will collapse into stars.

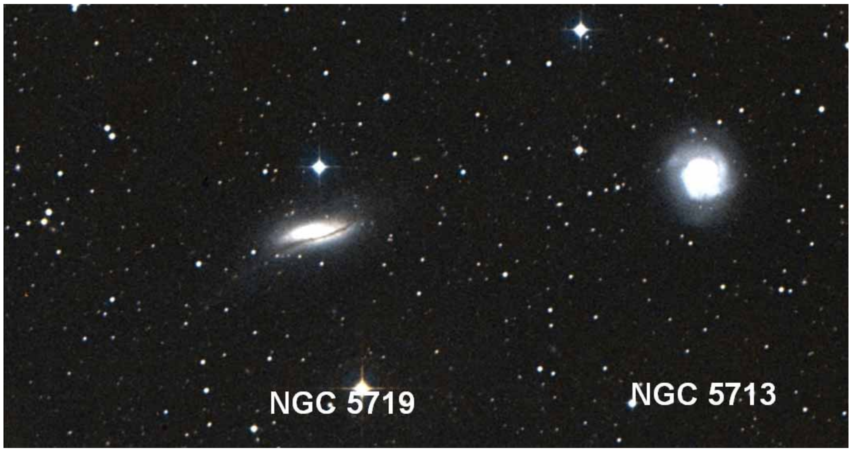
Some galaxies, such as M 33 at right, don't have prominent spiral density waves, and we see only a kind of random, raggedy spiral pattern. This is

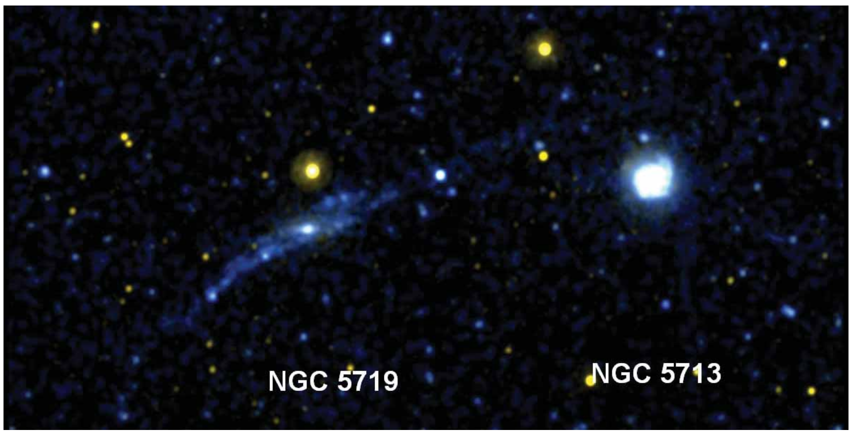
The messy spiral of M 33 (below) is the result of turbulence.

GALEX is not a JPL spacecraft; it's a *Caltech* spacecraft, the Institute's first space mission. Chris Martin, professor of physics and the project's principal investigator, is responsible directly to NASA, and not through the usual prime contract under which Caltech operates JPL for NASA. Still, it made a lot of sense to call on the Jet Propulsion Lab for its expertise in managing space missions and developing science instruments. Jim Fanson (MS '82, PhD '87), a JPL employee, was appointed project manager. He brought a small team down the hill from the Lab, and they set up the project office on the fourth floor of Downs, where Martin's team also resides. The combined group included Frank Surber, project engineer; Amit Sen, instrument manager; Peter Friedman, project scientist; David Schiminovich, science operations and data analysis manager; and Kerry Erickson, mission manager. Work began in December 1997, and the satellite was launched in April 2003.

The project is a NASA Small Explorer mission, which means not only small in size, but also small in cost. GALEX cost less than $100 million (and $24 million of that was for the Pegasus rocket). Being able to do work at the campus or JPL, whichever was best suited to the particular task, gave the team added flexibility to keep costs low. Most of the major procurements, including the spacecraft bus made by Orbital Sciences Corporation in Virginia, were made from Caltech. Most of the telescope, on the other hand, was built at JPL.

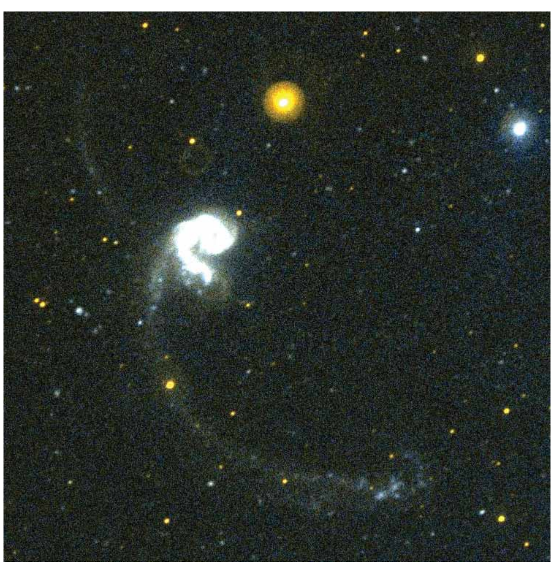
Besides Caltech and JPL, GALEX involved an international team of investigators, which gave the project crew a whole education in export-control requirements. French scientists at the Laboratoire d'Astronomie Spatiale in Marseilles were in charge of the optical design, and they also produced the grism, a critical optical component for which they had unique technology in France. Korean investigators from Yonsei University in Seoul performed software development for mission planning and science operations. In the United States, investigators at Johns Hopkins University, which houses the archive for the Sloan Digital Sky Survey, have responsibility for the GALEX catalog, whose sources will be matched with Sloan sources. At UC Berkeley, Ossie Siegmund and Pat Jelinsky built the UV detectors, the largest of their kind ever flown in space. —*Ed.*





Left: Two galaxies that look independent in the optical (top) are exposed in the ultraviolet (bottom) as having a relationship, as the blue band of new stars in NGC 5719 reaches out toward NGC 5713.

Below: The two Antennae galaxies are colliding and forming stars at a rapid rate, making them extremely bright in the ultraviolet. Tails full of new stars have also resulted from this interaction, and at the end of the lower tail, a new galaxy can be seen evolving.

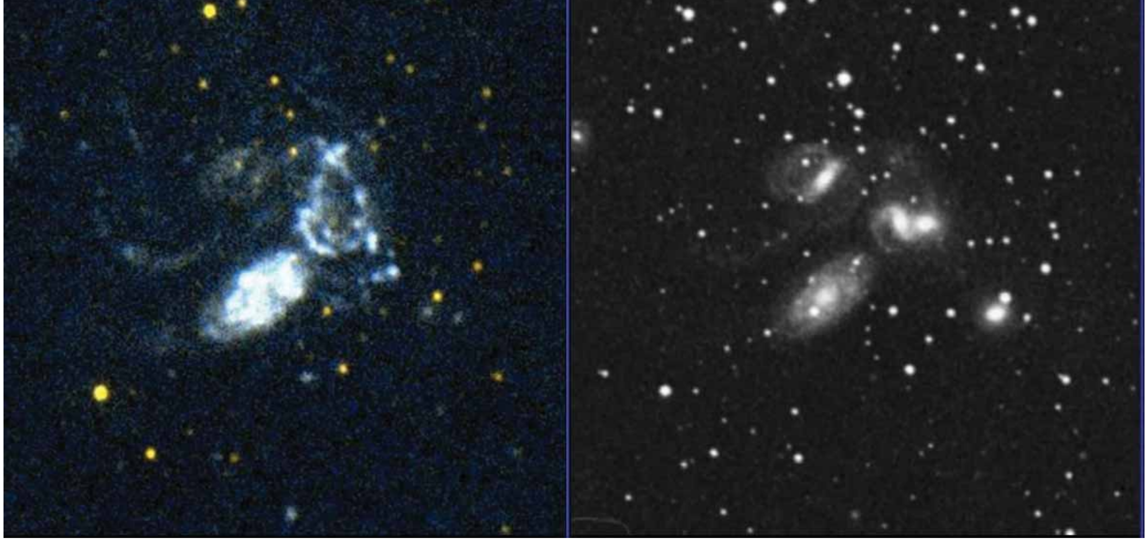


mainly due to the fact that the differential rotation is shearing the star formation regions around. This kind of patchy distribution is actually consistent with turbulence—it's essentially noise that has many different size scales. Energy is being dumped into the gas at various scales, and that energy ultimately results in the collapse of the gas and formation of stars.

At left are a couple of galaxies that in the optical do not appear to be interacting. But seen in the ultraviolet, one galaxy (NGC 5719) is elongated and stretched out—almost bridging the other galaxy (NGC 5713). And in fact, if you look at where the gas is, clearly the interaction between these two galaxies has pulled the gas out of 5719. As the gas is pulled out, it becomes unstable and collapses into new stars. It may even be forming a new galaxy—the little clump at the far left end.

An example of a much later phase in such an encounter is the Antennae galaxies (below, left), in which two disks are colliding. It's very bright in the center, where the disks are colliding, which shows that star formation is occurring at at least a factor of 10 more efficiently than it does in a normal spiral galaxy. We believe this is happening because the two disks are bringing their gas reservoirs together, increasing the density very rapidly. The tails are the remnants of this interaction, which has been going on for about 300 million years. In this ultraviolet image you can see the star formation going on in these tails. Out at the end of the tail at lower right, you can see a lump that may be a new galaxy being born before our eyes. In this lump, or dwarf galaxy, we can use the ultraviolet color as a clock to date the age of the star formation; we know that it is much younger than the interaction, proving that the action of pulling the gas out actually forms new stars.

In the nearby galaxy group known as Stephan's Quintet, you can see four galaxies and an interloper that's not really part of the system. Even



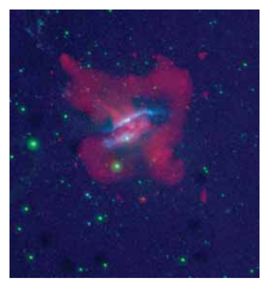
The misnamed Stephan's Quintet looks more like a quartet plus a soloist at visible wavelengths (right; DSS), but in the ultraviolet (left), where all the interaction can be seen, the four galaxies seem to be merging into one.

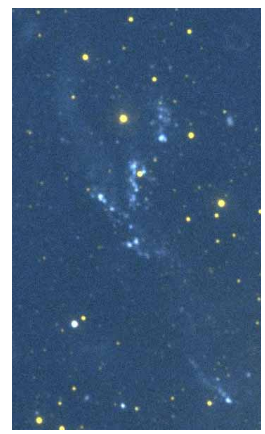
though there's lots of interaction going on and it's a very close group, in the optical version you can see that these are four distinct objects. But when you look at it in the ultraviolet, it looks completely different. That's because you're not looking at four galaxies anymore; you're looking at a picture of what the interaction has done to form stars in the last 100 million years. This has nothing to do with the original galaxies. It has to do with how the gas has been pulled out of them and made unstable, forming new stars in the process. Stephan's Quintet is not only an interesting object in *today's* universe; the process of galaxies merging together and forming new, larger galaxies was probably happening in the very early universe also, so this is a way of studying the early universe in our local environment, where the observations are much easier.

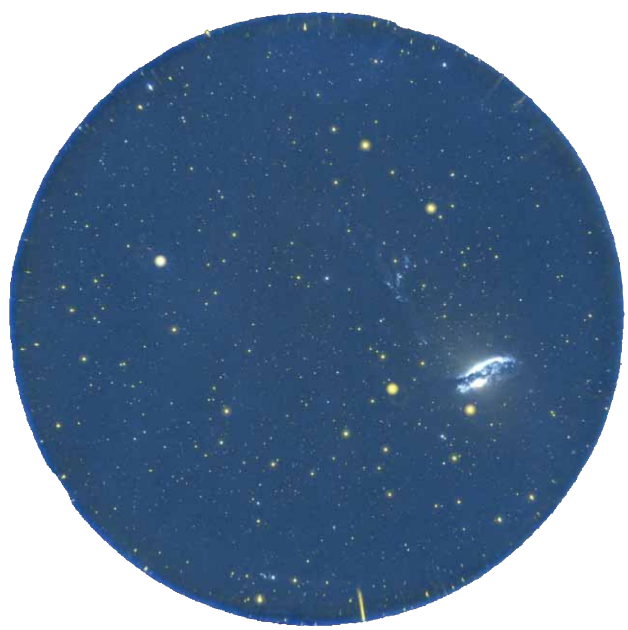
There are still other ways to trigger star formation. The galaxy at right, Centaurus A, has a massive black hole in the center that produces a very energetic jet, traced by red X-ray contours in the picture. When the jet comes out and strikes the cloud of gas (which you can't see here), it causes dense gas to form, which ultimately collapses into new star-formation regions. And if you blow that up (far right), you see all sorts of star formation going on due to this interaction. This is unusual in our local universe, but in the distant universe, it may perhaps be a much more common mechanism. Many galaxies in the early universe were forming stars at a prodigious rate. These so-called starburst galaxies produced massive winds of energetic plasma, which they ejected. Because most of the gas in their environs had not yet been converted into stars, there would be a lot of it, and getting struck by the plasma winds would trigger an explosion of star formation.

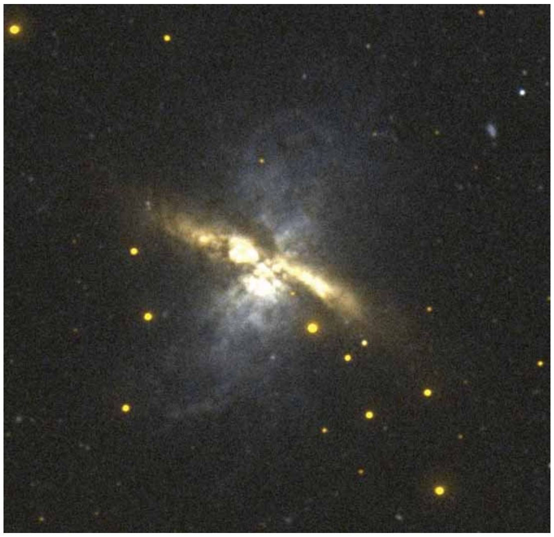
One problem we have in measuring galaxies in the ultraviolet is that dust absorbs the light from some of the stars, and in some dusty regions GALEX can't see anything at those wavelengths.

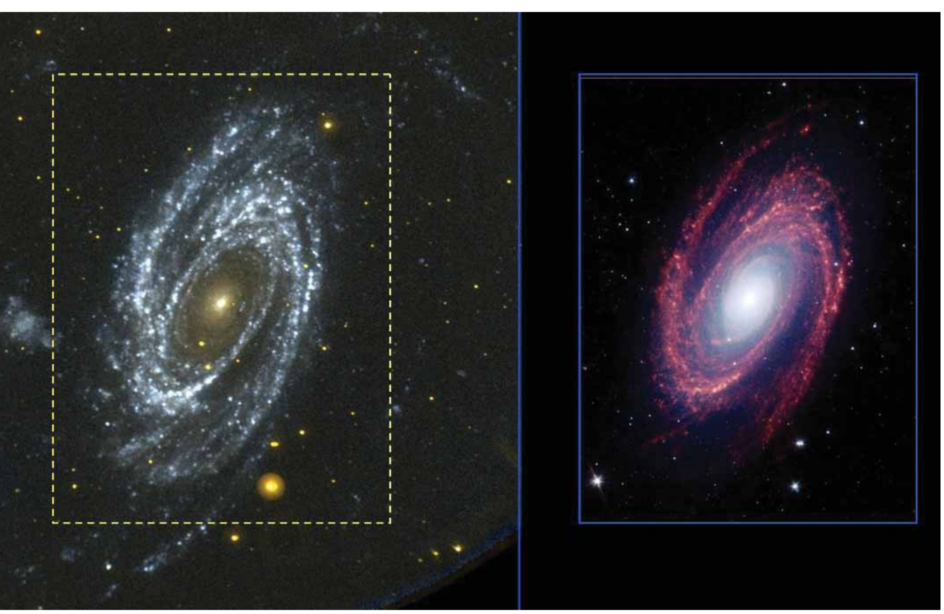
Below: The active galaxy Centaurus A is seen in GALEX's field of view (bottom). And, in a close-up (below, right) of the region to the upper left of the galaxy, new stars are forming. X-ray emission (below, left) of the jet of energetic particles from the galaxy center is traced by NASA's Chandra observatory (red is X-rays, blue is far ultraviolet, and green is near ultraviolet).











Right: Supernova explosions from young stars are causing the starburst galaxy M 82 to eject great, glowing gusts of dust, which are so bright in the ultraviolet because they're reflecting light from the violent activity in the center. Below: Comparing the GALEX image of M 81 (left) with the mid-infrared image from the Spitzer Space Telescope shows up stellar nurseries, where the ultraviolet is being absorbed and reradiated in the infrared.

I like to make an analogy between that and reprocessing perfectly good, healthy grapes (purple, or ultraviolet) into unhealthy wine (red, or infrared). Dust absorbs the ultraviolet radiation from the massive stars and reradiates it in the infrared. We're trying to understand this effect, because it's a way of tracing metals in galaxies. Dust is formed from heavy elements, and we want to trace the evolution of this dust over cosmic time as more and more heavy elements are being formed.

Of the two famous galaxies Messier 81 and 82 (see cover), M 81 is a classic, grand-design spiral galaxy, and M 82 is a starburst galaxy, with exploding winds of gas coming out the two axes of the disk. There's an interaction going on between these two galaxies. When we first observed M 82 in the ultraviolet, we were astonished to see how bright these two cones of ejected material are. Based on our analysis, we believe now that what we're seeing is dust that is being ejected out of the starburst galaxy by these winds. The dust is scattering the starburst light in the center. So in this case, dust isn't absorbing light but reflecting it, just as clouds on Earth can both absorb and reflect light. Stars are being formed, a process possibly promoted by the interaction between these two galaxies.

We have an extensive plan to do joint observations of M 81 with the Spitzer Space Telescope, which is observing in the mid and far infrared [*E&S*, 2003, No. 4]. The mid-infrared image of M 81 traces a molecular material which we believe is associated with dust. It's interesting to compare it with the image obtained in the far ultraviolet. You can see that there's a sort of global correlation, but there are regions where you see only infrared, which are probably very new molecular regions, where the ultraviolet is being absorbed and reradiated entirely in the infrared. And then there are regions where you see only ultraviolet, in which the molecules have been disrupted by the action of the massive stars. The massive stars have winds and produce supernova explosions, which are very important mechanisms for adjusting the local rate of star formation. If you form too many stars, they will blow the gas out of the galaxy and stop the star formation. It's a form of negative feedback.

Stars are simple. You can label them with a number for their mass and pretty much predict what they're going to do. But galaxies are complicated with a lot of bells and whistles. In order to try to understand them in a controlled experiment, you need a million galaxies, out of which you can find two sets of maybe a hundred each that are exactly the same except for one variable. Then you can make a controlled comparison between those two. So we're performing an all-sky survey to collect millions of galaxies in the local universe as well as deep surveys of representative pieces of the distant universe, totaling 100 degrees square, also with millions of galaxies. We'll end up with a huge sample of these distant galaxies to compare with younger, closer galaxies.

Using these two surveys, we now have our first measurement of the star-formation history of the universe. We can compare it to previous measurements, which are all over the place, partly because these earlier measurements use diverse techniques. We've used a consistent technique (measuring the ultraviolet to get the star-formation rate) to go all the way from the local universe out to the distant universe to measure the star-formation history. Our early results seem to be telling us that star formation was much more vigorous in the past—in other words, that galaxies formed most of their stars early in their lives, chiefly in the first third. This means that something has changed very radically about star formation since that time, making it much less prevalent today. It could be something as simple as the gas running out. Or it could be something subtle: that all the gas that could fall to the center of galaxies and form stars has been used up, but the spinning gas, which can't fall easily because of angular momentum, is still forming stars, although much more slowly. The interesting thing is that the history we have measured completely disagrees with some of the most recent models. These first results are based on only 1,000 galaxies, so we are looking forward to using 100 times as many to measure not only the average star-formation history, but also to ask how the star-formation history depends on other properties of a galaxy, such as its mass, its morphological type, and its neighborhood. One of the most interesting questions is how star formation depends on the number of galaxies in a region of space.

Whenever you do a survey in a new part of the spectrum, you find all sorts of new and interesting things. We are finding them, and we're not even looking, since our small science team is focusing on one topic: galaxy evolution and star formation. But we have discovered remnants from the explosion of a peculiar binary system with a white dwarf star that may have occurred 2,000 years ago. This is the first direct evidence connecting this kind of system with explosions called novae. We have also discovered evidence that exploding stars produce shock waves in the gas in the interstellar medium, suggested by remarkable cirrus-cloud-like structures never before seen in the ultraviolet. And we have seen flare stars that change brightness by factors of more than a thousand during a single observation. We have found many other interesting things, and we have only just begun to survey the sky. As our own team and other astronomers explore the data, we look forward to many discoveries in the future. □

Chris Martin has been professor of physics since 1993. He earned a BA in physics from Oberlin College in 1978 and a PhD in physics from UC Berkeley in 1986. After leaving for the East Coast to be assistant, then associate, professor at Columbia University from 1987 to 1993, he returned to the West Coast to join the Caltech faculty. This article is adapted from his Seminar Day talk in May.

Think building a small, relatively cheap spacecraft is a snap? Read on before you decide to try it. Every mission involves a few unexpected problems, but Project Manager Jim Fanson believes GALEX had more than its share of bolts from the blue. He has a few favorites:

When the new type of gyroscope to orient and point the spacecraft turned up as the subject of a patent-infringement suit against the manufacturer, a mad scramble ensued to find a replacement. First the team switched to a gyro that had just been launched on another satellite, FUSE (Far-Ultraviolet Spectroscopic Explorer). Then that one began failing in orbit. Up against the wall, Fanson's group launched a dragnet to find existing gyros to beg, borrow, or cannibalize, and found one (of the type used on Cassini) sitting on a shelf at the Goddard Space Flight Center. Its solid-state resonators, however, had been contaminated by helium gas, and a new set of resonators had to be built. With a heroic effort, they were ready in time.

Then there was the radio, necessary to receive data from the spacecraft. Just before the radio was completed by the low bidder (a company in England), Fanson received a phone call that they were going out of business and being liquidated. "If we wanted any of our hardware," recalls Fanson, "we nearly had to show up in a back alley in the dead of night." The radio was duly collected and flown back to the U.S., where the team tried to figure out how to finish the critical tuning of its radio frequency circuits. The experts at JPL said this had to be done by the engineer who designed it. "And this is when we entered something of a logic-free zone," says Fanson, in trying to get the design engineer involved. The State Department lumps spacecraft in the same category as munitions, and licenses are required before spacecraft hardware can be shipped to a foreign company. The project had *had* a license, but because the company had gone bankrupt, it was no longer valid. "So even though the radio was originally built by this guy, we couldn't send it back to him to work on," Fanson explained.

Another dragnet, this time for an existing radio. They found one in a finished spacecraft, sitting in cold storage because of payload problems. "We joked about going in late one night, opening it up, and making off with the radio," says Fanson. Ultimately, they did get permission to take it, but because the donor spacecraft was an earth-science mission and GALEX is a space-science mission (which are assigned to different sections of the electromagnetic spectrum), bureaucratic somersaults had to be turned to get permission to operate "out of band." Then they had to build all new ground receiving equipment to accommodate the different frequency and data rate.

And then there's the grism—large, fragile, and difficult to make, etched out of a single calcium fluoride crystal. A firm outside Paris was doing the etching using machines bolted to the basement foundation for stability. The firm's address was "rue du Canal." (You know what's coming, don't you?) Yes, the storm of the century roared through Europe in December 1999, dumping vast amounts of rain on Paris; the "canal" overflowed its banks, of course, flooding the adjacent basement, and the grism was a goner. At least it was the spare. The GALEX crew coped by babying the one they had left and sparing it any unnecessary handling and testing.

But there's always a silver lining. Fanson figures he got "two or three projects' worth of experience out of this mission. Just about everything that could go wrong did go wrong. It had great training value." —*Ed.*

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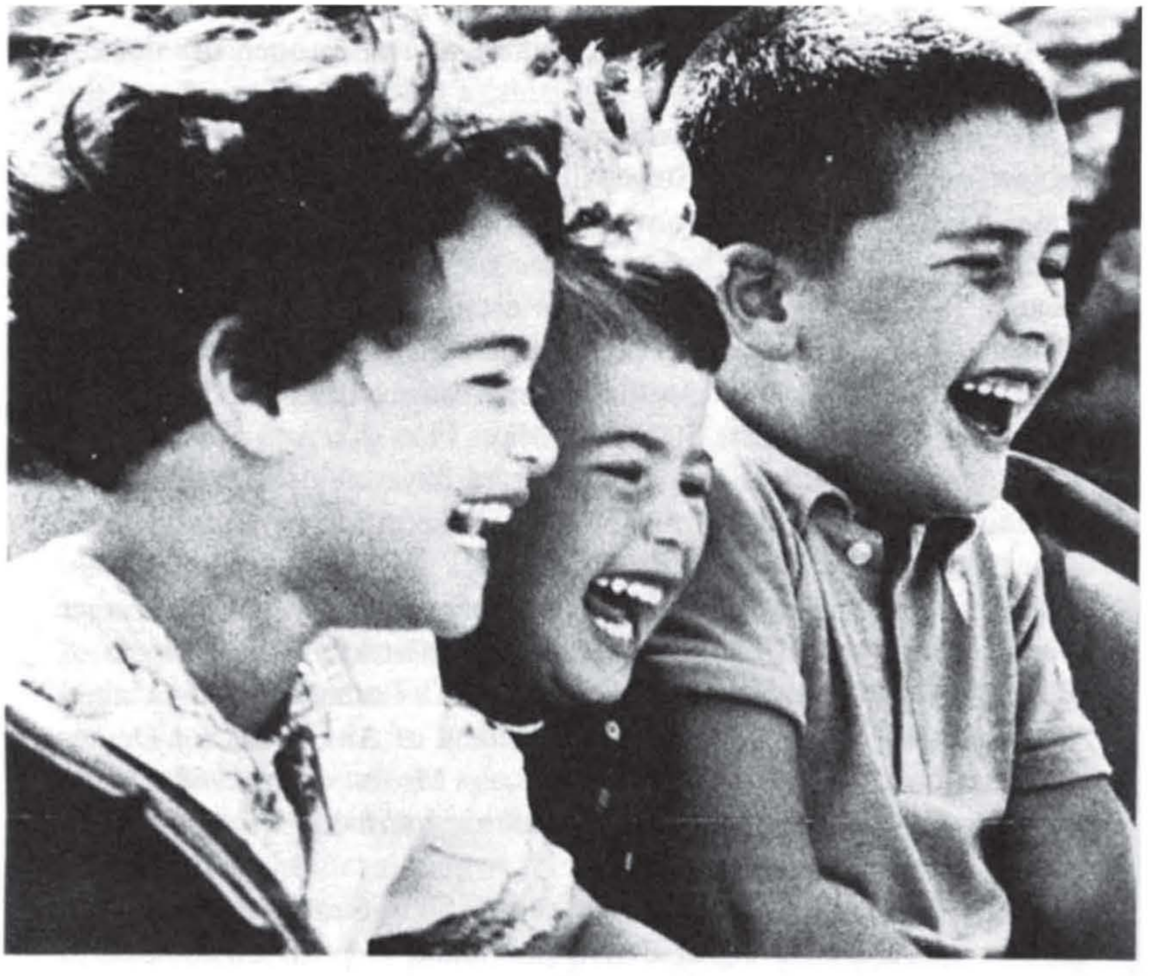

Your children's teeth contain Strontium-90

All children's teeth now contain radioactive Strontium-90 from nuclear weapons tests.

Radioactive Strontium is a potential cause of leukemia, as pointed out in the United Nations report on radiation. Early signs of leukemia appear in the mouth, and dentists are familiar with them.

Scientists can tell how much radioactive Strontium-90 is in children's bones by measuring the radioactive material in their teeth. A recent analysis of baby teeth shows a 16-fold increase in Strontium-90 over the past five years.* Unlike baby teeth, however, the permanent teeth and bones retain Strontium-90 throughout their existence.

As dentists, we deplore the buildup of radioactive Strontium-90 in children's teeth and bones. It is a measure of the sickness of our times. Even if nuclear weapons tests cease today, the accumulation of Strontium-90 will continue for years.

We oppose nuclear weapons testing by all nations not only because of the contamination of bones and teeth of our children and patients, but because it is a direct stimulus to the runaway arms race. The testing race only multiplies mistrust and tension, and increases the chances of nuclear war.

Therefore, as dentists, our responsibility to promote life and health compels us to make this public appeal to all governments to cease nuclear weapons tests and to develop those international agreements which would eliminate the nuclear arms race.

*Committee for Nuclear Information St. Louis Baby Tooth Survey

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18 – U.S. Army, National Atomic Museum; 27 – Bob Paz

Biology and "The Bomb"

by Jennifer Caron

"We have made a thing," J. Robert Oppenheimer told a joint meeting of the American Philosophical Society and the National Academy of Sciences three months after the bombings of Hiroshima and Nagasaki, "a most terrible weapon, that has altered abruptly and profoundly the nature of the world. We have made a thing that by all the standards of the world we grew up in is an evil thing. And by so doing . . . we have raised again the question of whether science is good for man." Among the men who participated in the development of the atomic bomb were Caltech faculty members, as well as scientists who would come to Caltech after the war.

Physicists Robert Christy, Richard Feynman, and Robert Bacher worked on the Manhattan Project. Feynman worked on bomb theory and Christy helped design the trigger mechanism. Bacher was at various times in charge of the nuclear physics division and the bomb division. Physicists Thomas Lauritsen [BS '36, PhD '39] and Jesse DuMond [BS '16, PhD '29] and electrical engineer Robert Langmuir [PhD '43] worked for the Office of Scientific Research and Defense; geochemist Harrison Brown worked on the isolation of plutonium at the Oak Ridge National Laboratory.

After the war, Brown returned to the University of Chicago and served as executive vice chairman of Einstein's Emergency Committee of Atomic Scientists, working to educate the public about the threat of nuclear weapons. Within a year he published a 160-page book arguing for international control of nuclear power, *Must Destruction Be Our Destiny?* Brown came to Caltech in 1951; because of his growing activism he was given a joint appointment as professor of geochemistry and of science and government in 1967. Chemist Linus Pauling [PhD '25], though he was not involved in the bomb project, also served on Einstein's Emergency Committee.

Christy, Brown, and Pauling all opposed the further development of nuclear weapons. But despite their efforts, and those of like-minded people, the hydrogen bomb was developed under the leadership of Edward Teller and the Atomic Energy Commission (AEC). At least three members of the Caltech faculty had AEC connections. President Lee DuBridge served on its General Advisory Committee, Provost Bacher served on the commission, and George Beadle, chairman of the Division of Biology, served as a science consultant.

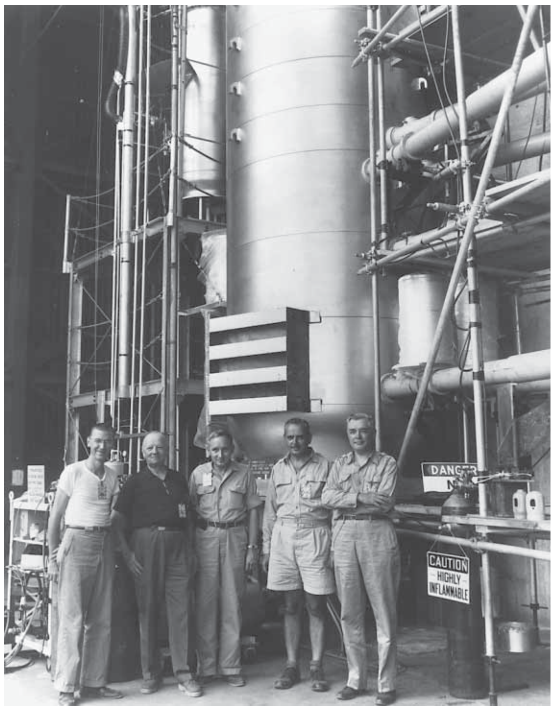
The first hydrogen-fusion device, Mike, was secretly detonated at Eniwetok atoll on November 1, 1952, destroying the mile-wide island of Elugelab and leaving a crater in the ocean floor. The public was told nothing of the power released—only that the AEC had successfully detonated a fusion device in the Pacific.

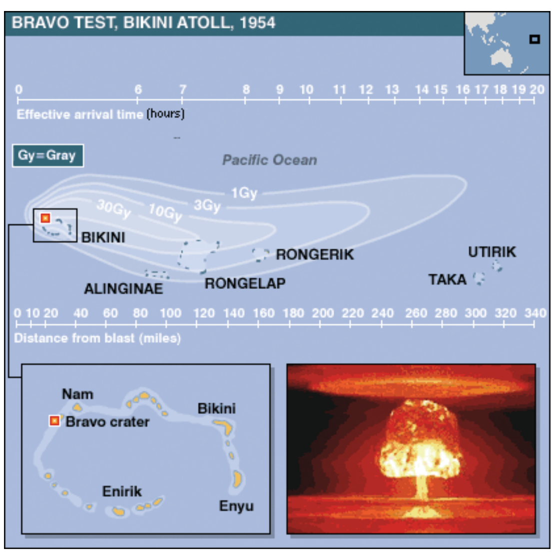
The AEC planned to secretly test six hydrogen bombs in March and April of 1954. The might of Bravo, the first one, surprised everyone, including the scientists and engineers who built it. The first news of these tests to reach the American press was a brief notice that residents of the Marshall Islands had been evacuated due to radioactive fallout. Two weeks later a Japanese tuna boat, the *Lucky Dragon*, which had been about 85 miles downwind, returned to its home port of Yaizu with its crew of 23 suffering from severe radiation sickness. Panic spread from Japan to the United States.

The H-bomb made it possible to obliterate even the largest cities with a single weapon, and, with a large number of such bombs, to end human life on Earth. Such potential for catastrophe was beyond the grasp of most people. So, in an attempt to communicate the dangers of nuclear war, the *Bulletin of the Atomic Scientists* had earlier created the "Doomsday Clock." When first published in 1947, it read seven minutes to midnight. After the Soviet Union detonated their first atomic bomb in 1949 it was moved to three minutes. In 1953, after both the United States and the Soviet

Strontium belongs to the same chemical family as calcium, and like calcium, it concentrates in the teeth and bones, especially of growing children. Strontium-90, or Sr-90, has a half-life of 29 years, meaning that half of it will have decayed during that time. Until it does, however, it exposes the body to beta rays from within, damaging cellular DNA. In 1957, Caltech geneticist Edward Lewis published a calculation of radiation-induced leukemia risks to humans that included Sr-90 as an example. His work was exploited by organizations like SANE, which ran this full-page ad in the *New York Times* on April 7, 1963.

Mike, the first fusion "device," created a mushroom cloud (above) that rose to 135,000 feet—the top of the stratosphere—in five minutes and lofted 80 million tons of freshly radioactive soil into the air. Mike wasn't exactly portable (right)—it was about 20 feet tall and weighed 82 tons, including 12 tons of cryogenic apparatus to keep its deuterium fuel liquid. The first "real" bomb, Bravo, used solid lithium deuteride, making it a manageable 15 × $4\frac{1}{2}$-foot cylinder. Unexpectedly large amounts of tritium produced by the fast-neutron fission of lithium-7 more than doubled Bravo's predicted yield—to 15 megatons, some 1,000 times the power of the Hiroshima blast. The inhabited atolls downwind (below right) were blanketed with a layer of ash-like fallout up to two inches deep. (The gray is a unit of absorbed radiation dosage.)





Courtesy of www.bikiniatoll.com

Union exploded their first hydrogen-fusion devices, the hands read two minutes to midnight, the closest to Armageddon they have ever been.

While atomic bombs created local fallout for a short time, H-bombs sent radioactive debris into the stratosphere. From there it spread over the globe, descending to Earth for up to two years afterward. On March 31, 1954, nearly a month after Bravo, the chairman of the AEC, Admiral Lewis Strauss, stated that nuclear tests had resulted in a small increase in radiation in some places in the United States. He claimed that this increase was "far below the levels which could be harmful in any way to human beings."

Strauss assumed that, as in the case of many chemical toxins, there existed a threshold dose below which radiation did no harm and that the low dose to which the public was exposed did not exceed this threshold. The threshold assumption was widely held—in fact, shoe stores of the day routinely contained X-ray boxes so that patrons could see the bones in their feet.

Only a select community of biologists understood that the United States and Soviet governments were killing people without realizing it. In the late 1920s, geneticist Hermann Muller had discovered that high-energy radiation caused genetic mutations in fruit flies at a rate proportional to the dosage received. (He won the Nobel Prize for this in 1946.) After the H-bomb tests became public knowledge, he felt morally obligated to warn policymakers and the public about the risk of mutations in the germ line—the reproductive cells in the testes and ovaries—from radioactive fallout.

Muller and Caltech genetics professor Alfred Sturtevant had been graduate students of Thomas Hunt Morgan—founder of Caltech's biology division—at Columbia University. Both Muller and Sturtevant were alarmed by the AEC's assurances that no harm was occurring. In his September 1954 presidential address to the Pacific Division of the American Association for the Advancement of Science (AAAS), Sturtevant enumerated five conclusions that had "now been so widely confirmed that we may confidently assert that they apply to all higher organisms, including man." These were that high-energy irradiation produced mutations at a rate that was directly proportional to dosage, that the existence of a threshold dosage was extremely unlikely, that the effects of successive exposures were cumulative, that children born with a mutation would carry it permanently, and that the overwhelming majority of mutations were deleterious.

At the close of his speech Sturtevant made it clear that he was not taking a political stand. He said, "I do not wish to be understood as arguing that the benefits ultimately to be derived from atomic explosions are outweighed by the biological damage they do. It may be that the possible gains are worth the calculated risk."

Sturtevant as he appeared on the January 1955 cover of *E&S*. Morgan, Muller, Sturtevant, and Lewis all used fruit flies as their experimental organism of choice.

Data on genetic effects takes generations to acquire—a matter of days for fruit flies, but decades for human beings. Clearly some other way was needed to estimate the risks of radiation exposure. In January 1955, Sturtevant published an article in *E&S* titled "The Genetic Effects of High Energy Irradiation of Human Populations." He concluded, "No scientist interested in exact quantitative results would touch the subject, were it not that its social significance leaves us no alternative. We must, like it or not, try to get some sort of idea as to how much, of what, is happening to how many people."

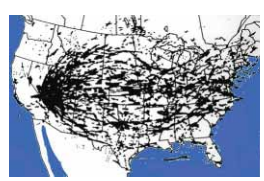
A study of American radiologists published in 1950 had shown that they died of leukemia at a rate 10 times that of nonradiologist MDs. Beadle realized that radiation-induced cancers would be visible in the present generation, making them more available to quantitative analysis than genetic damage to the germ line. In July 1955 he sent a memo headed "Possible Direct Effects on Man of Low Level Exposures to Ionizing Radiation" to the biology faculty. Citing the radiologist study, he questioned the assumption that low-dose exposures were "of negligible importance." Furthermore, he suggested that natural background radiation might cause some leukemias. He identified two ways of pursuing human risk estimates: First, doing further research on those occupationally exposed; and second, studying people exposed to different levels of natural radiation, including increased solar radiation in high-altitude communities. Also, he speculated that the observed increase in cancer rates in the U.S. might be due, at least in part, to heavy cigarette smoking and the increased use of synthetic organic compounds, some of which Sturtevant had pointed out might be carcinogenic.

Edward Lewis was one of the younger members of the biology faculty. After studying with Sturtevant, he had received his PhD from Caltech in 1942. The war under way, Lewis then went through Caltech's meteorology program and became the weather officer for the G2 (intelligence) section of the Tenth Army. He arrived at Okinawa shortly after U.S. troops landed, and stayed on the command ship there until the end of World War II. Returning to Caltech as an instructor in 1946, by 1955 he had worked his way up to associate professor. He responded to Beadle's memo with his own "Memorandum on Fallout," which he circulated to Caltech's geneticists and to Bacher, the division chairman for physics, math, and astronomy, in late November. Sharing the goal of quantitative risk estimates, Lewis summarized the available literature on the biological effects of high-energy radiation and argued the necessity of more accurate measurements of radioactive fallout.

The memorandum went on to say, "It is unlikely that direct radiation effects will show the simple linear relationship to dosage that the genetic effect shows and that the direct effects will be as independent of the time over which the dosage is administered as the genetic effects are. Nevertheless for discussion purposes it may be useful to inquire what the rate of leukemia per R unit [Roentgen] per given population would be if the relationship to dosage is linear and if all forms are considered radiation induced." He concluded that when it became possible to estimate the exposures of survivors from Hiroshima and Nagasaki, and when data on their leukemia rates became available, it would be possible to make "the beginnings of estimates of the direct effects of radiation."

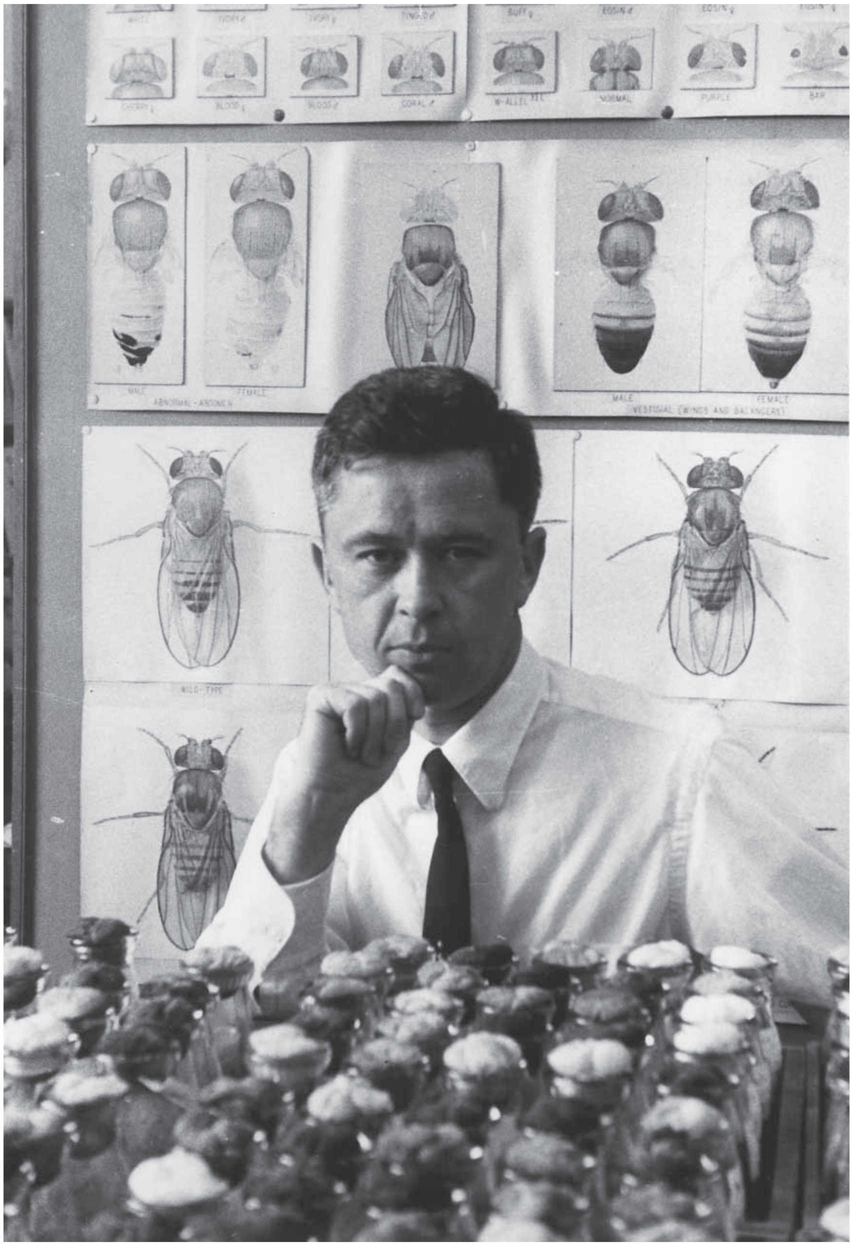
Two days after Lewis's memo, the *New York Times* reported that the Atomic Bomb Casualty Commission had discovered increased incidences of leukemia and cataracts among their study group of 30,000 bomb survivors; however, while it had been feared that the radiation might create previously unknown diseases, none were found. Beadle used his AEC connections to get Lewis the commission's unpublished data.

Lewis told me that several forces motivated him to pursue this research. Over lunch at the Athenaeum—Caltech's faculty club—with members of the physics faculty, he had learned that some of them "were unaware of the possibility that ionizing radiation even at low levels could induce cancer." He was also concerned about the communities around the Nevada Test Site—even the Geiger counter on the roof of Kerckhoff, Caltech's biology building, was recording increased radioac-



After *Under the Cloud*, Richard L. Miller

Fallout from the Nevada Test Site was carried eastward across the entire United States by the prevailing high-altitude winds.



Above: Lewis's fly work was *E&S*'s cover story in November 1957.

Above, right: Beadle in 1950 in a three-acre field in nearby Temple City, where Caltech geneticists grew corn from seeds irradiated by nuclear tests. Beadle would share the Nobel Prize in 1958 for his part in the discovery that genes act by regulating specific chemical events.

tivity after some of the tests. And of course the curiosity that drove his lifelong career in science also played a role: Muller had proposed the somatic-mutation theory of carcinogenesis in 1937, but it had never been further researched. (Somatic cells are all the cells in the body that aren't germ cells.) Fallout presented an opportunity to examine this theory in the light of human data.

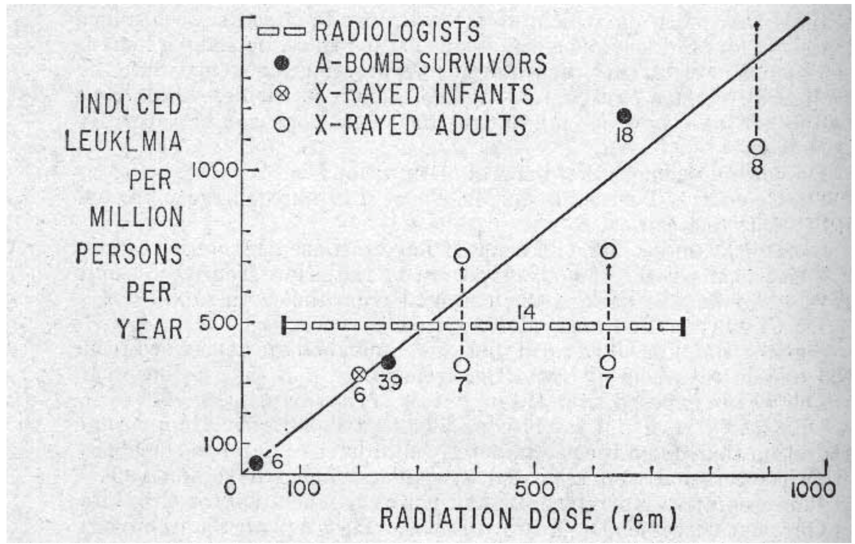
Nationally, 1956 was an exciting year in the debate over nuclear testing. In April, AEC commissioner Thomas Murray called for a unilateral moratorium; he was endorsed by Democratic presidential candidate Adlai Stevenson. In June, the National Academy of Sciences (NAS) issued a report that offered mixed messages on the dangers of radioactive fallout. The AEC was quick to reassure the public.

In the September 1 issue of the *Lancet*, Alice Stewart, M.D., and her coworkers published a study that found that a single, low-dose, obstetric X-ray doubled a child's chances of dying from leukemia or other cancers.

In early October Beadle, Lauritsen, Brown, physicist Matthew Sands, and Sturtevant met over lunch at the Athenaeum. According to Lauritsen they agreed that "a useful purpose could be served by an intelligent statement emphasizing the need for public discussion." This statement was framed by Brown, Lauritsen, Sands, and Christy. On October 14, bearing the signatures of 10 Caltech physicists who had participated in building the original atomic bombs, the statement supporting Stevenson and the cessation of nuclear-weapons testing was published as an advertisement (paid for by the physicists) in the *Los Angeles Times*. The biological effects were among the reasons advanced.

The following day, both DuBridge and Albert Ruddock, chairman of Caltech's Board of Trustees, responded publicly to the ad. DuBridge wrote, "I regret that a partisan stand on the continuation of H-bomb tests has been made by a scientific group because there is no disagreement among American citizens on their desire for peace and for avoidance of nuclear war through enforceable international agreements. . . . The question of the best diplomatic methods of achieving these agreements is not a subject on which scientists are especially competent to render advice. The principal technical question involved in the present debate is whether large-scale tests are an important part of our weapons-research program. Those in responsible charge of that program assure us that they are and that their discontinuance, therefore, should follow and not precede enforceable international

Lewis compiled data from four classes of people exposed to high-energy radiation. "X-Rayed Infants" had been treated for an enlarged thymus—a gland in the neck that is part of the immune system—and "X-Rayed Adults" were patients with ankylosing spondylitis, a crippling, arthritis-like disease. The number below each circle is the number of excess leukemia cases in each population, all of which Lewis assumed to have been radiation-induced. The radiologists were plotted as an elongated bar because the dosages they received were unknown, but the important thing is that a straight line can be drawn through the data points.



agreements. In my own official government contacts I have become convinced that this is the case." Ruddock criticized the ad as "clearly political in character" and warned that it "must not be taken to represent any official position by the Institute, its officers, Trustees, or faculty as a whole." Institute leaders had, for years, provided advice and aid to the government on matters of national defense and disarmament "without the slightest reference to political motivation," he said, and "the Institute stands squarely behind the policies of its government."

Harrison Brown's involvement went beyond drafting the statement. As author Robert Divine explains in his history of the national fallout debate, *Blowing on the Wind*, it was Brown who first encouraged Stevenson to take on the test-ban issue. Brown spent the weekend that the ad was published at Stevenson's Illinois farm working on the candidate's first test-ban speech.

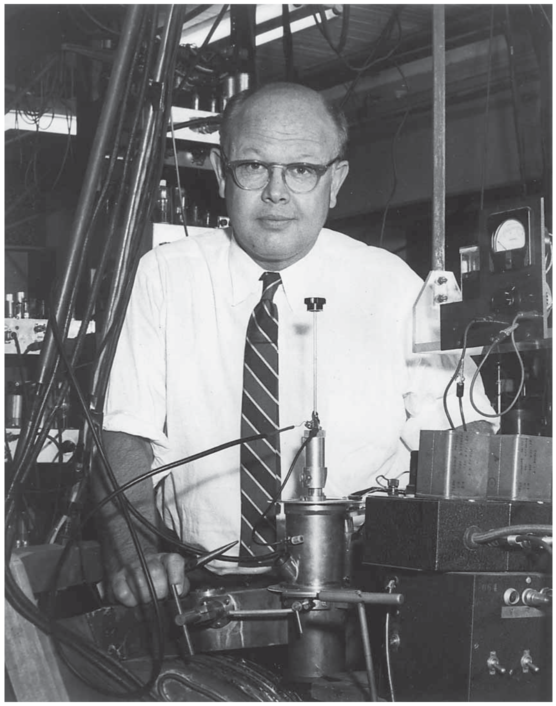
Chemistry professor Linus Pauling had become an opponent of nuclear-weapons development shortly after the war. By 1956 he was a well-known advocate for ending nuclear testing and for international control of nuclear power. At the end of October he wrote to Beadle and carbon-copied Lewis and Sturtevant about a case that a reporter in Nevada had called him about. A seven-year-old boy had died of leukemia in a small town an hour and a half from the Nevada Test Site. The boy and his family had been exposed to fallout intense enough to result in eye irritation, which AEC doctors had told them not to worry about. Pauling informed the reporter "that there was no way of saying what had caused the leukemia" but agreed that the circumstances were suspicious.

Meanwhile, the *Washington Post* ran an article headed "Tenfold Rise in A-Tests Seen as Safe." This prompted a rebuttal from Sturtevant, run as a letter to the editor on October 26, in which he explained that he was on the NAS committee that had been falsely credited with this conclusion. Furthermore, he said, the AEC's Willard Libby, who was known for downplaying radiation risks, had recently indicated that the strontium-90 danger was greater than previously reported, so that the committee's findings would need "revision upward." (Libby would win the 1960 Nobel Prize in chemistry for the invention of carbon-14 dating.)

Radioactive strontium-90, or Sr-90, is chemically similar to calcium and gets absorbed into the teeth and bones. Not found in nature, it is a byproduct of uranium and plutonium fission—which can be used alone in an atomic bomb, or to trigger the fusion reactions in a hydrogen bomb. It was primarily ingested by eating fallout-dusted crops or the products of the animals that ate them, but could also be absorbed by drinking contaminated water or, in some cases, by inhalation. Once in the bones, it irradiated the body from within, causing leukemia, a cancer of the white blood cells (white blood cells are produced in the bone marrow), as well as other cancers.

Meanwhile, Lewis had been analyzing the AEC data. On November 30, he circulated a draft of a paper, titled "Leukemia and Ionizing Radiation," to several Caltech faculty members, including Pauling and Brown. The covering note concluded, "Comments and especially criticisms are earnestly solicited." DuBridge was convinced that Lewis did not know what he was talking about and sent him to see "a radiologist friend," whom Lewis remembers as "unbelievably ignorant" of the genetic and somatic effects that radiation might cause.

Lewis used data from four independent populations—atomic bomb survivors, ankylosing spondylitis and thymic-enlargement patients (both of whom had been treated with X-rays), and occupationally exposed radiologists—to demonstrate the linear relationship between dosage and leukemia, and argued that this implied that the leukemias resulted from a somatic-cell gene mutation. Furthermore, since the data showed no sign



Fowler in his lab in 1956. He would win the Nobel Prize in 1983 for showing how stars transmute hydrogen and helium into the rest of the periodic table.

of a threshold dose below which mutations did not occur—even at doses as low as 25 R—he concluded that there was no evidence supporting the existence of a threshold for leukemia induction. He estimated that the probability of radiation-induced leukemia was 2×10^{-6} per individual per rad (or rem) per year. This means that a person exposed to one rad and then living for another 60 years without additional exposure would have a total risk of 12 in 100,000, or 12×10^{-5}. (For an explanation of rads, rems, and Roentgens, see the table on page 24.)

Added to the paper's final version was an application of this estimate to strontium-90 exposure, for which Lauritsen and fellow physics professor William "Willy" Fowler [PhD '36] helped Lewis calculate the cumulative doses one would receive as the Sr-90 decayed into radioactive yttrium-90 and thence into stable zirconium-90. Lewis predicted that the AEC's recommended "safe" limit for the public—one-tenth the Maximum Permissible Concentration for workers with radioisotopes—"would be expected to increase the present incidence of leukemia in the United States by about 5 to 10 percent."

Brown was an editor for the *Saturday Review*, a prestigious weekly magazine. The chief editor was Norman Cousins, a national leader in the test-ban movement. Through these men Lewis's manuscript, or a summary thereof, reached Albert Schweitzer, the Nobel Peace laureate for 1952, at his bush hospital in French Equatorial Africa around March 1957.

On April 24, 1957, Dr. Schweitzer issued his "Declaration of Conscience" under the auspices of the Nobel Committee. In it, he called the effects of radioactive fallout "the greatest and most terrible danger" and concluded that nuclear testing is wrong because the whole world pays the costs in health and lives for the military security of a few nations. Furthermore, he argued, people have a "right to know" what is being done to them and to their world.

The following day, Libby wrote an open letter to Schweitzer, in the form of an AEC press release that was widely reprinted, arguing that the proper standard of concern was "detectable effects." He contended that the risks were "extremely small compared with other risks which persons everywhere take as a normal part of their lives." He claimed that the risk of cancer from fallout was less than that from wearing a luminous-dial wristwatch (the hands and numerals were painted with radium to make them glow in the dark) and that "living in a brick house . . . in certain parts of the world, increase[s] radiation exposure many times over that from test fallout." Libby dismissed the moral argument out of hand and concluded, "We accept risk as payment for our pleasures, our comforts, and our material progress. Here the choice seems much clearer—the terrible risk of abandoning the defense effort which is so essential under present conditions to the survival of the free world against the small controlled risk from weapons testing."

On May 1, Pauling gave a speech on the molecular structure of abnormal hemoglobin to the Chicago Section of the American Chemical Society. When the talk ended, a small group surrounded him asking about the effects of fallout. He estimated that 1,000 people would die of leukemia due to the upcoming British test of their first H-bomb. A reporter was in the group and the estimate ended up in the newspaper. Again Libby replied the next day. It seems that they were on a first-name basis, because Libby wrote, "Dear Linus . . . I am very interested in the details of your calculation of this number. I suppose that we probably know more about radioactive fallout

IMAGE NOT LICENSED FOR WEB USE

Edward Clark/*Life*/Getty Images

Congress's fallout hearings got extensive press coverage, including a six-page photo essay titled "A Searching Inquiry into Nuclear Perils" in the June 10, 1957 issue of *Life* magazine. This picture was captioned, "Worried senators, hearing testimony from scientists, are John W. Bricker of Ohio, John Pastore of Rhode Island and Clinton Anderson of New Mexico. Anderson closely questioned witnesses, once corrected a scientist's arithmetic." Another shot showed Lewis in front of a calculation-filled blackboard.

than you do, but I am quite certain that none of us here knows as much about leukemia, so I would like very much to see your calculation."

In a letter that was cc'd to Brown, Beadle, and Lewis, Pauling explained that he had derived the number from Lewis's still-unpublished paper. Lewis had estimated that a dose of radiation from Sr-90 of 0.002 R per year could give an individual a 5:1,000,000 risk of leukemia. Pauling assumed that this dose would be generated for the world's population of 2.5 billion if 50 megatons' worth of fission products were uniformly distributed over the globe. The upcoming test was to be approximately five megatons, yielding his result of 1,000 leukemia deaths.

Privately, Lewis took issue with Pauling's extrapolation to the whole world's population. It was known that fallout was not uniformly distributed—the stratospheric wind called the jet stream brought the vast majority of it to the northern hemisphere and concentrated it along the 40th parallel. Lewis had been careful and conservative in generating his risk estimates; Pauling was being far less careful in his use of them. It is important to understand that Pauling and Brown were motivated not only on health grounds, but also because they believed that ending testing would be a first step to disarmament. In contrast, Lewis and Sturtevant simply wanted the risks to public health acknowledged, and decisions made on the best available information.

On May 15 the British went ahead, against much public opposition, with the H-bomb test at Christmas Island. The same day, Pauling initiated the "Scientists' Bomb-test Appeal," gathering signatures from scientists all over the country.

Fallout was in the news. The Special Subcommittee on Radiation of the congressional Joint Committee on Atomic Energy scheduled hearings on "The Nature of Radioactive Fallout and Its Effects on Man" for June. Beadle and Brown pushed Lewis to publish, which, he told me, made the writing rushed.

"Leukemia and Ionizing Radiation" was the lead article in *Science* on May 17, 1957. In his front-page commentary, "Loaded Dice," editor Graham DuShane put Lewis's contribution in political and historical perspective. He reminded readers of Schweitzer's declaration, Libby's reassurances, Pauling's estimate, and the Earl of Home's response that "we have no information that any deaths have been caused by the Russian and American explosions during 1956–1957." DuShane acknowledged that the issue had become a political debate, greatly complicating efforts at dispassionate scientific discussion, and wrote, "Thanks to Lewis . . . we are approaching the point at which it will be possible to make the phrase 'calculated risk' mean something a good deal more precise than the 'best guess.' . . . It is apparent that the atomic dice are loaded. The percentages are against us and we ought not play unless we must to assure other victories."

A week after the publication of Lewis's paper (and following months of negotiations with the Soviet, British, and French governments), President Eisenhower approved a temporary test ban. On the same day Brown published "What Is a 'Small Risk'?" in the *Saturday Review*, in which he stated that the risk of increased incidence of leukemia from low doses of radiation "was uncovered by a lone geneticist, Professor E. B. Lewis."

Congress invited Lewis to testify. When he arrived in Washington, he visited DuShane at *Science*'s editorial offices, where DuShane said that he had received a "very strong letter from DuBridge protesting the 'Loaded Dice' editorial." (Unfortunately, DuShane could not find the letter while Lewis was there, and it does not appear to have been archived.) As Lewis left the building, several AEC officials entered, apparently to pressure DuShane further. These pressures did not reach Lewis directly; he assured me that the AEC never interfered with his work and that he was not bothered by the House Un-American Activities Committee.

Lewis testified on June 3, the same day that Pauling presented his "Appeal" to Eisenhower. Having been asked to confine his testimony to leukemia and radiation, Lewis explained that "I do not wish to imply that I think that leukemia is the most important effect of radiation on man," and that the genetic, i.e. germ-line effects, or other malignant diseases, might be more important. He had simply chosen leukemia because good data were available. He then explained the threshold-versus-linear controversy and argued for the linear view.

In his testimony, Lewis used the conservative estimate that Americans were being exposed to 0.001 R, one milliroentgen, of radiation per year from fallout. From this he derived a long-term estimate of 10 leukemia deaths per year, though he explained, "We have not had this exposure long enough to make it 10 per year as yet . . . I do not think it would be higher than 1 to 3 deaths per year at the present time from the fallout that has accumulated so far. In terms of our population [172 million] that is a very minute fraction of the population—an exceedingly minute fraction—but, after all, it does correspond to somebody."

Finally, Lewis evaluated the AEC's safety standard for the general public of 100 "sunshine units," the AEC-named unit for one picocurie of radioactivity from Sr-90 per gram of calcium (as, for example, in the body). The AEC asserted that this dose would not affect the public. Using the linearity hypothesis, Lewis calculated that this dose would cause between 500 and 1,000 cases of leukemia in the U.S. each year, and noted that constant exposure to even one "sunshine unit" would lead to five to 10 cases annually.

Later that afternoon, Lewis participated in a "roundtable discussion" before the committee, centered around the linear-vs-threshold debate. Dr. Jacob Furth, president of the American Association for Cancer Research, who had been studying leukemia for nearly 30 years, posited that there must exist a "reparative force" that would "counteract the effect of very low level radiation." While linearity could not be ruled out as a possibility, he did not consider complete linearity to be "a reasonable probability."

Dr. Hardin Jones of the University of California Radiation Laboratory (now part of Lawrence Berkeley National Laboratory) homed in on the conflict, noting that "part of the difference is in the way people look at small quantities. In very small doses, you get very small effects. It is very easy to say that very small effects are zero, and then you have the threshold concept. If very small effects are just that—'very small'—then you do not have a threshold phenomenon." That day Lewis was given the last word. The danger, as he saw it, came "in legislating a dose that is said to be permissible for the public." Echoing Sturtevant from three years earlier, Lewis argued that, whatever the standards were, "the percentage or the number who are expected to be damaged should be stated, instead of implying that there is no danger from fallout or that the permissible dose will cause no damage."

Three days later, Lewis's work was debated in another roundtable, where Dr. Shields Warren proved to be one of his main adversaries. Warren had been director of the AEC's Division of Biology and Medicine from 1947 to 1952, and was now on the AEC's Advisory Committee and a physician-

"For three days the scientists testified," *Life* reported, "interspersing their well-ordered presentations with a brain-taxing assortment of figures measured in unfamiliar units like milliroentgens and microcuries. (At one point, Senator Anderson was moved to ask plaintively, 'Can you keep it to pecks, quarts, and bushels?')" Those units might not help today's reader, but perhaps this glossary will.

Unit	Measures	Definition	Conversions
Curie (Ci)	Radioactivity	1 curie = 37,000,000 atomic nucleus disintegrations per second (dps)	1 microcurie = 10^{-6} Ci = 3.7×10^4 dps 1 picocurie = 10^{-12} Ci = 0.037 dps = 2.2 disintegrations per minute
Rad	Absorbed dose	1 rad = 100 ergs of energy absorbed per gram of irradiated material	1 gray (Gy) = 100 rads = 1 joule per kilogram
Rem, for Roentgen equivalent man	Biological effect	1 rem = the dose equivalent* that gives the biological effect of 1 Roentgen' s worth of X-rays	1 sievert (Sv) = 100 rem
Roentgen (R)	Exposure	1 Roentgen of X- or gamma rays produces 1 electrostatic unit's worth of ions in 1 kilogram of dry air	
Sunshine Unit	Sr-90 concentration	1 sunshine unit = 1 picocurie' s worth of Sr-90 per gram of calcium (the average adult contains 1 kilogram of calcium)	

*Dose equivalent = absorbed dose × quality factor, which depends on the type of radiation. For X-rays, gamma rays, and beta rays (electrons), the quality factor is 1. For alpha rays, it is 10. Alpha rays are helium nuclei, which can be stopped by a sheet of paper and therefore do not contribute significantly to fallout exposure. Thus, for our purposes, a rad and a rem are essentially equivalent.

pathologist at New Deaconess Hospital in Boston. When Warren said, "I am not at all satisfied that strontium-90 will cause any additional cases of leukemia," Senators John Bricker (R-Ohio) and Clinton Anderson (D-New Mexico) put him in a corner. Anderson reminded him of Lewis's assertion that background radiation was responsible for some fraction of leukemia cases. Warren replied that he knew of no way to prove that assertion. When pushed, he conceded that it was "a fair and reasonable assumption," but added, "I do not think we are warranted in accepting it as an established fact." Bricker noted that Lewis's assumption was an educated guess. Anderson followed, "When you say, also, that one microcurie or one-tenth of a microcurie is a safe background, that is also an educated guess, is it not?" Warren's first reply was no, but then he conceded, "I feel—well, yes it is an educated guess." This was one of many occasions when those defending nuclear testing demanded a higher level of evidence from people advising caution than they required of themselves.

Later that month, Beadle published a letter in *Science* saying that, when speaking as regular citizens, scientists should "make it clear that they are speaking not as experts but are expressing private opinions." This made the biologists unique: At no point did Beadle, Lewis, or Sturtevant make known the personal beliefs that, as engaged and thoughtful men, they surely held. Rather, they always confined their public statements to their field of expertise. For example, on June 21 Lewis gave a summary of his paper at the New York organizing meeting for what became the Committee for a Sane Nuclear Policy (SANE). Both Brown and DuShane attended the meeting. When the group decided that ending nuclear testing was their goal and that the biological effects were a major argument for this, Lewis declined to sign the ad they ran in the *New York Times*, nor did he participate in the group beyond making his presentation.

"I do not think it would be higher than 1 to 3 deaths per year at the present time. . . . That is a very minute fraction of the population—an exceedingly minute fraction—but, after all, it does correspond to somebody."

On October 4, Sputnik was launched, intensifying America's Cold War fears of the Soviet Union.

On January 13, 1958, Pauling presented the "Scientists' Test Ban Petition," signed by over 9,000 scientists internationally, to the United Nations. In May 1958 he published his book, *No More War!*, which included a chapter called "Radiation and Disease" that relied heavily on Lewis's paper.

After the hearings, Lewis was asked to serve on the National Advisory Committee on Radiation, which reported to the Surgeon General under the umbrella of the Public Health Service; it had no statutory authority, but brought together scientists from outside the radiation establishment. It included physicians, public-health officials, geneticists, a scientist from the AEC's Brookhaven National Laboratory, and Lauriston Taylor of the National Bureau of Standards and the National Council on Radiation Protection. Arnold Beckman [PhD '28], president of Beckman Instruments, represented the radiation-instruments industry; according to Lewis, he never said a word. The first meeting was held in Washington, D.C., on March 13, 1958.

In August, A. W. Kimball published a paper in the *Journal of the National Cancer Institute* criticizing Lewis's work. Kimball was a statistician at Oak Ridge National Laboratory, where uranium was processed for atomic bombs. He attempted to create doubt about Lewis's methodology, but found only one error—the confidence limits that Lewis believed were 95 percent were actually 90 percent. This insignificant error had unknowingly been carried over from a published table that Lewis had used in his calculations. The following month Austin Brues, director of the biological and medical research division of the Argonne National Laboratory, which was in charge of the peaceful development of atomic power, published a review article in *Science*. Brues sought to cast doubt on the linearity hypothesis by reinterpreting the available data and looking at other mechanisms that could be responsible for cancer. Lewis did not respond to either paper—he was doing research, teaching genetics, managing Caltech's *Drosophila* collection, working on the Surgeon General's committee, and helping raise three sons at home. The journals wanted responses right away and he was too busy—and exhausted, he told me, from all the attention.

In March 1959, a year after its formation, the Surgeon General's committee suggested that the "ultimate authority" for protecting the public from nuclear radiation be removed from the AEC. The committee called giving the AEC the dual responsibilities of regulating and promoting nuclear power "unwise"—promotion was clearly winning at the expense of public health. Eisenhower agreed, and that August he created the Federal Radiation Council to set safety standards and oversee public-health protection.

In addition to his genetics research, Lewis continued to study the effects of fallout. In June 1959, fearing that the article might meet review problems in *Science*, he published "Thyroid Radiation Doses from Fallout" in the *Proceedings of the National Academy of Sciences*. Sturtevant sponsored the paper on Lewis's behalf; at the time a member of the Academy could submit a paper without further review. In it, Lewis showed that iodine-131, in fresh milk from cows grazed in contami-

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SANE ran this full-page ad in the *New York Times* on July 5, 1962.

nated pastures, exposed the thyroid glands of infants and young children to radiation levels approximately equal to that of the natural background, in effect doubling their dose. (The thyroid concentrates iodine, especially in children.) This hazard had previously been overlooked, largely because I-131 has a half-life of only eight days. Just as had Lewis's work on Sr-90, this work provided fuel for SANE's campaign.

The Joint Committee on Atomic Energy held another round of hearings in May 1959, this time on "Fallout from Nuclear Weapons Tests." Representative Chester "Chet" Holifield (D-California) convened the hearings, but unlike the 1957 hearings, which he also organized, these were designed to show the public that fear of fallout was unfounded. Like the AEC, Holifield argued that winning the arms race was worth the small risks of nuclear testing. Lewis was not invited to appear, but presented his findings on both radioiodine and leukemia in a written statement. This time the hearings did not make front-page headlines. The panel concluded that the Sr-90 hazard was slight by comparison to other, normal radiation exposure, but nonetheless present.

Throughout this time diplomats, pushed by public fear of fallout and the more overwhelming, but less discussed, possibility of nuclear war, worked nonstop to find ways to limit the nuclear threat. Soviet officials repeatedly called for a halt in testing, but they refused to consider on-site inspections or other enforcement methods. Thankfully, from 1959 until the Soviet Union detonated an H-bomb on September 1, 1961, the U.S. and the U.S.S.R. voluntarily ceased atmospheric testing. During this time, both the Public Heath Service and the AEC reported that Sr-90 concentrations in American milk dropped rapidly, and the fallout scare subsided. On September 15, the U.S. also resumed testing—but underground, for the first time ever, to avoid generating atmospheric fallout.

Five days later, President Kennedy approved the Federal Radiation Council's proposal to change the guidelines for population exposure to strontium-89, strontium-90, iodine-131, and radium-226. The AEC subsequently modified its regulations. Atmospheric testing, however, was not yet over—on April 25, 1962, the United States resumed it in the Pacific.

On August 5, 1963, more than a decade after the first thermonuclear explosion, the nuclear powers of that time—the United States, Great Britain, and the Soviet Union—signed the Limited Test Ban Treaty banning nuclear tests in the oceans, in the atmosphere, and in outer space. This treaty went into effect on October 10, at which time the Nobel Committee announced that it would award the held-over 1962 Peace Prize to Linus Pauling for his continuous efforts, beginning in 1946, to end nuclear-weapons tests and

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Pauling, who had won the Nobel Prize in 1954 for his work on the chemical bond, was invited to dinner with President Kennedy at the White House with other Nobelists on April 29, 1962. He took the opportunity to picket his host the preceding day, joining a demonstration protesting the American resumption of nuclear testing.

"against all warfare as a means of solving international conflicts."

Many outspoken activists who had clear political agendas could not, at the same time, speak with the authority of science on related issues. One of Pauling's most powerful tactics was to employ Lewis's risk estimates to show the costs in human lives. Similarly, SANE used the health effects of fallout as their central argument. These activists relied heavily on the credibility of Lewis and other scientists who were careful to limit their statements to their areas of expertise and to remain as much outside the political quagmire as possible. Without both the sensational and the scientific, the movement to end nuclear testing would have been either without a widely heard voice or without authority. □

Jennifer Caron (BS '03, Science, Ethics, and Society) wrote her senior thesis on Lewis's role in the national fallout debate. She will be attending the Johns Hopkins School of Nursing this fall.

For further reading, see :

Blowing on the Wind: The Nuclear Test Ban Debate, 1954–1960*, Robert Divine, Oxford University Press, 1978;*

Genes, Development and Cancer: The Life and Work of Edward B. Lewis*, edited with commentary by Howard Lipshitz, Kluwer Academic Publishers, 2004;*

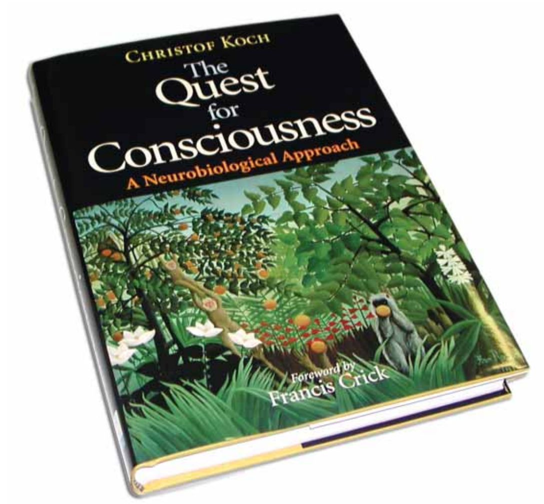
Under the Cloud: The Decades of Nuclear Testing*, Richard Miller, Two-Sixty Press, 1986; and*

"Edward Lewis and Radioactive Fallout: The Impact of Caltech Biologists on the Debate over Nuclear Weapons Testing in the 1950s and 1960s," *Jennifer Caron, 2003, http://resolver.caltech.edu/CaltechETD:etd-03292004-111416*

Lewis shared the 1995 Nobel Prize with Christiane Nüsslein-Volhard and Eric Wieschaus for the discovery of "master" genes that control other genes in early embryonic development. These genes, in turn, control other genes that control still more genes, allowing the creation of limbs and even entire body segments to be directed by a handful of genes being turned on in the proper order. Using X-rays to manipulate the genes of the bithorax complex, Lewis created a mutant fruit fly (above) with an extra set of wings. A bithorax fly of real fruit (or at least, vegetable matter) decorated a cake (below) at a campus celebration in his honor.

On July 21, as *E&S* was going to press, Ed Lewis died after a long battle with cancer. He was 86. An obituary will appear in a subsequent issue.

The Quest for Consciousness: A Neurobiological Approach
by Christof Koch
Roberts & Company Publishers, 2004
429 pages, $45



This book stems from a 16-year collaboration between Christof Koch, the Troendle Professor of Cognitive and Behavioral Biology and professor of computation and neural systems and Nobel Laureate Francis Crick, of the Salk Institute in La Jolla, to find a neurological explanation for consciousness—one of the last major unsolved problems of science. Most of the book deals with Koch's research on vision and perception, but the lively, informal style and thorough glossary make it accessible for anyone who has ever thought about thinking. What follows is the final chapter, which has been written in the form of a fictitious interview.

Interviewer: *Let's start at the beginning. What is the overall strategy that you are pursuing in tackling this problem?*

Christof Koch: First, I take consciousness seriously, as a brute fact that needs to be explained. The first-person perspective, feelings, qualia, awareness, phenomenal experiences—call it what you want—are real phenomena that arise out of certain privileged brain processes. They make up the landscape of conscious life: the deep red of a sunset over the Pacific Ocean, the fragrance of a rose, the searing anger that wells up at seeing an abused dog, the memory of the exploding space shuttle *Challenger* on live TV. Science's ability to comprehend the universe will be limited unless and until it can explain how certain physical systems can be sufficient for such subjective states.

Second, I argue for putting aside, for now, the difficult problems that philosophers debate—in particular the question of why is it that it feels like something to see, hear, or to be me—and concentrate on a scientific exploration of the molecular and neuronal correlates of consciousness (NCC). The question I focus on is, What are the minimal neuronal mechanisms jointly sufficient for a specific conscious percept? Given the amazing technologies that brain scientists have at their disposal—engineering the mammalian genome, simultaneously recording from hundreds of neurons in a monkey, imaging the living human brain—the search for the neuronal correlates of consciousness, the NCC, is tractable, clearly defined, and will yield to a concerted scientific attack.

Qualia. The elemental feelings and sensations making up conscious experience, such as seeing a face or hearing a tone.

Percept. An impression of an object obtained by use of the senses.

Do you mean to imply that discovering the NCC will solve the mystery of consciousness?

No, no, no! Ultimately, what is needed is a principled account explaining why and under what circumstances certain types of very complex biological entities have subjective experiences and why these experiences appear the way they do. The past two thousand years are littered with attempts to solve these mysteries, so they truly are hard problems.

Remember how much the elucidation of the double-helical structure of DNA revealed about molecular replication? The two complementary chains of sugar, phosphate, and amine bases, linked by weak hydrogen bonds, immediately suggested a mechanism whereby genetic information could be represented, copied, and passed on to the next generation. The architecture of the DNA molecule led to an understanding of heredity that was simply beyond the capabilities of the previous generations of chemists and biologists. By analogy, knowing where the neurons that mediate a specific conscious percept are located, where they project to and receive input from, their firing pattern, their developmental pedigree from birth to adulthood, and so on, might provide a similar breakthrough on the way to a complete theory of consciousness.

A fond dream.

Perhaps so, but there is no credible alternative to understanding consciousness by searching for the NCC. Experience has shown that logical argumentation and introspection, the preferred methods of scholars throughout all but the past two centuries, are simply not powerful enough to crack this problem. You can't reason your way to an explanation of consciousness. Brains are too complicated, and are conditioned on too many random events and accidents of evolutionary history, for such armchair methods to successfully illuminate the truth. Instead, you have to find out the facts. How specific is the tapestry woven by axons among neurons? Does synchronized firing play a critical role in the genesis of consciousness? How crucial are the feedback pathways crisscrossing cortex and thalamus? Are there special neuronal cell types that underlie the NCC?

What, then, is the role of philosophers in your quest for a scientific theory of consciousness?

Historically, philosophy does not have an impressive track record of answering questions about the natural world in a decisive manner, whether it's the origin and evolution of the cosmos, the origin of life, the nature of the mind, or the nature-versus-nurture debate. This failure is rarely talked about in polite, academic company. Philosophers, however, excel at asking conceptual questions from a point of view that scientists don't usually consider. Notions of the Hard versus the Easy Problem of consciousness, phenomenal versus access consciousness, the content of consciousness versus consciousness as such, the unity of consciousness, the causal conditions for consciousness to occur, and so on, are fascinating issues that scientists should ponder more often. So, listen to the questions posed by philosophers but don't be distracted by their answers. A case in point is the philosopher's zombie.

Zombies? Cursed, dead people walking around with outstretched arms?

Well, no. People like you and me but with no conscious feelings at all. David Chalmers and other philosophers use these soulless, fictitious creatures to argue that consciousness does not follow from the physical laws of the universe; that knowing about physics, biology, and psychology won't help one iota in understanding how and why experience enters the universe. Something more is required.

This radical, imaginary zombie doesn't strike me as a very useful concept; but there is a more modest and restricted version. Therefore, Francis and I co-opted this catchy term for the set of rapid, stereotyped sensory-motor behaviors that are insufficient, by themselves, for conscious sensations. The classic example is motor control. When you want to run along a trail, you "just do it." Proprioceptive sensors, neurons, and the muscular-skeletal system take care of the rest, and you're on your way. Try to introspect and you'll be confronted with a blank wall. Consciousness has no access to the amazingly complex sequence of computations and actions that underlie such a seemingly simple behavior.

So zombie behaviors are reflexes, only more complex?

Yes. Think of them as cortical reflexes. Reaching for a glass of water by extending your arm and automatically opening the hand to grasp it constitutes a zombie action that requires visual input to control the arm and hand. You carry out thousands of these actions daily. You can "see" the glass, of course, but only because neural activity in a different system is responsible for the conscious percept.

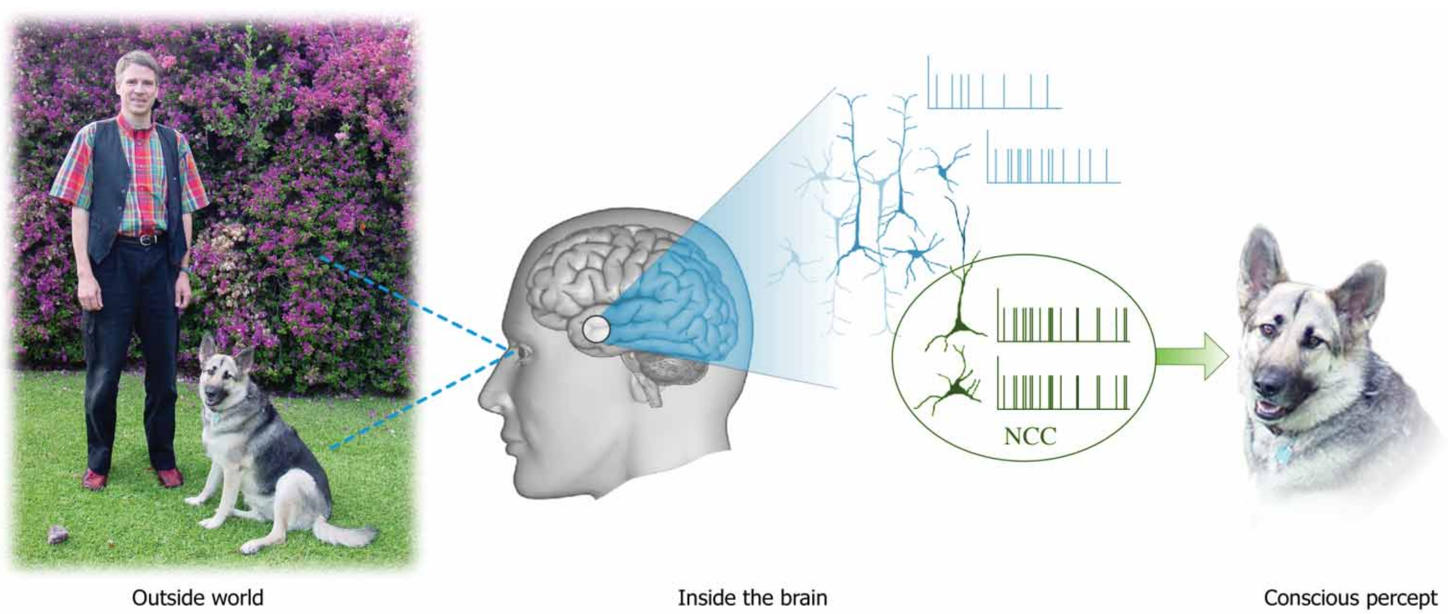
You imply that unconscious, zombie systems co-exist with conscious ones in normal, healthy folks.

Exactly. A disconcertingly large fraction of your everyday behavior is zombie-like: You drive to work on autopilot, move your eyes, brush your teeth, tie your shoelaces, greet your colleagues in the hall, and perform all the other myriad chores that constitute daily life. Any sufficiently well-rehearsed activity, such as rock climbing, dancing, martial arts, or tennis is best performed without conscious, deliberate thought. Reflecting too much about any one action will interfere with its seamless execution.

Why, then, is consciousness necessary at all? Why couldn't I be a zombie?

Well, I know of no logical reason why you couldn't, although life would be pretty boring without any sensations (of course, you wouldn't feel any ennui as a zombie). However, evolution took a different turn on this planet.

Some simple creatures may be nothing but bundles of zombie agents. Thus, it might not feel like anything to be a snail or a roundworm. If,



On seeing Koch with his dog, below, the viewer is conscious of the dog because of a number of neural events and mechanisms (center), in this case synchronized action potentials (depicted by the bars) in some pyramidal neurons in the cortex. The *minimal* neuronal mechanisms sufficient for this percept, the neuronal correlates of consciousness (NCC), are those within the ellipse.

however, you happen to be an organism with plenty of input sensors and output effectors, say, a mammal, devoting a zombie system to each and every possible input-output combination became too expensive. It would have taken up too much room in the skull. Instead, evolution chose a different path, evolving a powerful and flexible system whose primary responsibility is to deal with the unexpected and to plan for the future. The NCC represent selected aspects of the environment—the ones you are currently aware of—in a compact manner. This information is made accessible to the planning stages of the brain, with the help of some form of immediate memory.

In computer lingo, the current content of awareness corresponds to the state of cache memory on the CPU. As your stream of consciousness flitters from a visual percept to a memory to a voice out there, the content of the cache fluctuates, too.

Given the close evolutionary kinship among mammals, and the structural similarity of their brains, I assume that monkeys, dogs, and cats can be aware of what they see, hear, or smell.

I see. The function of consciousness, therefore, is to handle those special situations for which no automatic procedures are available. Sounds reasonable. But why should this go hand-in-hand with subjective feelings?

Aye, there's the rub. Right now, there are no set answers. Or, to be more precise, there is a cacophony of answers, none of them persuasive or widely accepted. Francis and I suspect that meaning plays a critical role.

As in the meaning of a word?

No, not in any linguistic sense. The objects I feel, see, or hear out there in the world are not meaningless symbols but come with rich associations. The bluish tinge of a fine porcelain cup brings back childhood memories. I know I can grab the cup and pour tea into it. If it falls to the ground it will shatter. These associations don't have to be made explicit. They are built up from countless sensory-motor interactions with the world over a lifetime of experiences. This elusive meaning corresponds to the sum total of all synaptic interactions of the neurons representing the porcelain cup with neurons expressing other concepts and memories. All the vast information is symbolized, in a shorthand way, by the qualia associated with the percept of the cup. That's what you experience.

Leaving that aside for now, what is so important in this field, which has been plagued by hundreds of years of unsubstantiated speculations, is that our framework leads to tests for consciousness. Zombie agents operate in the here and now, so they have no need for short-term memory. You see an outstretched hand, so you reach out and shake it with your own hand. A zombie could not handle a delay between the sight of the hand and the motor action; it didn't evolve to deal with that. The more powerful, albeit slower, consciousness system would have to take over.

These different behaviors can be shaped into a simple operationalized test for consciousness in animals, babies, or patients that can't easily communicate their experiences. Force the organism to make a choice, such as inhibiting an instinctual behavior, following a delay of a few seconds. If the creature can do so without extensive learning, it must make use of a planning module that, at least in humans, is closely linked to consciousness. If the NCC underlying this action is destroyed (or rendered inoperable for some time) by some external means, the delayed response shouldn't happen anymore.

This is hardly very rigorous.

At this point in the game it is too early for formal definitions. Think back to the 1950s. How far would molecular biologists have gotten if they had worried about what exactly they meant by a gene? Even today, this is no easy matter. Think of it as a sort of Turing test except it is not meant for intelligence but for consciousness. It is good enough to be applied to sleepwalkers, monkeys, mice, and flies, and that's what counts.

Wait. Are you saying that insects may be conscious?

Many scholars believe that consciousness requires language and a representation of the self as a basis for introspection. While there is no doubt that humans can recursively think about themselves, this is just the latest elaboration of a more basic biological phenomenon that evolved a long time ago.

Consciousness can be associated with quite elemental feelings. You see purple or have pain. Why should these sensations require language or a highly developed notion of the self? Even severely autistic children or patients with massive self-delusions and depersonalization syndromes don't lack basic perceptual awareness—the ability to see, hear, or smell the world.

The pre-linguistic origin of perceptual consciousness, the type of consciousness I study, raises the question of how far down the evolutionary ladder it extends. At what point in time did the *Ur*-NCC first appear? Given the close evolutionary kinship among mammals, and the structural similarity of their brains, I assume that monkeys, dogs, and cats can be aware of what they see, hear, or smell.

The Turing test was proposed in 1950 by mathematician Alan Turing as a way of testing the intelligence of a machine. If, after carrying out an extended online conversation on a variety of arbitrary topics, you can't tell whether you've been interacting with a human or a machine, the machine should be considered intelligent.

What about mice, the most popular mammal in biological and medical laboratories?

Given the comparative ease of manipulating the mouse genome, of inserting new genes or knocking out existing ones, applying the anti-zombie delay test to mice in some practical manner would give molecular neuroscientists a powerful model to study the basis of the NCC. My laboratory and others are developing such a mouse model of attention and awareness using classical Pavlovian conditioning.

Wait. Why did you say "awareness" instead of "consciousness"? Do they refer to different concepts?

No. It is more of a social convention. Consciousness—the C word—evokes powerful aversive reactions in some colleagues; so you're better off with some other word in grant applications and journal submissions. "Awareness" usually slips under the radar.

Continuing with animal consciousness, why stop at mice or, indeed, at mammals? Why be a cortical chauvinist? Do we really know that the cerebral cortex and its satellites are necessary for perceptual consciousness? Why not squids? Or bees? Endowed with one million neurons, bees can perform complicated actions, including amazing feats of visual pattern matching. For all I know, a hundred thousand neurons may be sufficient to see, to smell, and to feel pain! Maybe even fruit flies are conscious, to a very limited extent. Today we just don't know.

Sounds like unsubstantiated speculations to me.

For now, yes. But behavioral and physiological experiments bring these speculations into the realm of the empirical. And this is new. We were not in a position to think about such litmus tests until recently.

Could these tests be applied to machines to assess whether they are conscious?

I'm not only a member of the biology faculty at Caltech, but also a professor in the Division of Engineering and Applied Science, so I do think about artificial consciousness, based on an analogy to neurobiology. Any organism capable of behaviors that go beyond the instinctual and that has some way to express the meaning of symbols is a candidate for sentience.

The Internet taken as a whole is a tantalizing example of an emergent system with millions of computers acting as nodes in a distributed, but highly interconnected network. While there are file swapping programs that link large numbers of computers, or algorithms that solve mathematically intractable problems by distributing them over thousands of machines, these assemblies bear little relationship to the coalitions of neurons that excite and inhibit each other in the brain. There are no collective behaviors of the entire World Wide Web to speak of. I've never witnessed the

Why be a cortical chauvinist? Do we really know that the cerebral cortex and its satellites are necessary for perceptual consciousness?

spontaneous appearance of any purposeful, large-scale action not designed into the software. It doesn't make any sense to speak of the conscious Web unless it displays such behaviors on its own—by directing electrical power allocation, controlling airline traffic, or manipulating financial markets in a manner unintended by its makers. With the emergence of autonomous computer viruses and worms, this may change in the future, though.

What about a robot endowed with reflex-like behaviors—to avoid running into obstacles, to prevent its battery from draining, to communicate with other robots, and so on—in addition to a general planning module. Could that be conscious?

Well, suppose the planner was powerful enough to represent the machine's current sensory environment, including its own body and some of the information retrieved from its memory banks that is germane to the present situation, so that it would be capable of independent and purposeful behaviors. Assume, moreover, that your robot could learn to relate sensory events to positive and negative goal states so as to guide its behavior. A high ambient temperature, for example, might cause a drop in the machine's supply voltage—something it would want to avoid at all costs. An elevated temperature wouldn't be an abstract number anymore but would be intimately connected to the organism's well-being. Such a robot *might* have some level of proto-consciousness.

That seems like quite a primitive notion of meaning.

Sure, but I doubt that at your birth you were conscious of much more than pain and pleasure. There are other sources of meaning, though. Imagine that the robot establishes sensory-motor representations by some unsupervised learning algorithm. It would stumble and fumble its way around the world and would learn, by trial and error, that its actions lead to predictable consequences. At the same time, more abstract representations could be built up by comparing information from two or more sensory modalities (e.g., that moving lips and particular staccato sound patterns often go together). The more explicit representations there are, the more meaningful any one concept is.

To establish these meanings, it would be easiest if the machine designers could replicate the developmental phases of childhood for the robot.

Just like HAL, the paranoid computer in the movie 2001*! But you haven't answered my earlier question yet. Would your delay test distinguish a truly conscious machine from a fake that is just pretending to be conscious?*

Just because this exercise distinguishes reflexive systems from conscious ones in biological organisms doesn't imply that it will do the same for machines.

It makes sense to grant at least some animal species sentience due to their evolutionary, behavioral, and structural similarity to humans, based on an argument of the form "since I am conscious, the more similar other organisms are to me, the more likely they are to have feelings." This argument loses its power, though, in the face of the radically different design, origin, and form of machines.

Let's leave this topic and look back to your earlier ideas about the neuronal correlates of consciousness. What did you and Francis propose?

In our first publication on the topic in 1990, we put forth the idea that one form of consciousness involves dynamic binding of neural activity across multiple cortical areas.

Wait, wait. What's binding?

Think of a red Ferrari zooming past. This triggers nervous activity at myriad locations throughout the brain, yet you see a single red object in the shape of a car, moving in a certain direction, and emitting a lot of noise. The integrated percept has to combine the activity of neurons that encode for the motion with neurons that represent red and others that encode the shape and the sounds. At the same time, you notice a pedestrian with a dog walking past. This also has to be expressed neuronally without confusing it with the representation for the Ferrari.

At the time of our 1990 paper, two German groups, led by Wolf Singer and Reinhardt Eckhorn, respectively, had discovered that neurons in the cat visual cortex, under certain conditions, would synchronize their discharge patterns. Often, this would occur periodically, giving rise to the famous 40 Hertz (Hz) oscillations. We argued that this was one of the neuronal signatures of consciousness.

What does the evidence look like now?

The neuroscience community remains deeply divided on the topic of oscillations and synchronization. A scientific journal will publish evidence in favor of their functional relevance, while a contribution in the following issue pooh-poohs the entire concept. Unlike cold fusion, which has no credible evidence in its favor, the basic existence of neuronal oscillations in the 20 to 70 Hz frequency range and synchronized discharges is accepted. There is a great deal more, however, that remains contentious. Our reading of the data is that synchronized and oscillatory firing helps one coalition—representing one percept—overcome the others in the competition for dominance. Such a mechanism might be particularly important during attentional biasing. We no longer believe that 40 Hz oscillations are necessary for consciousness to occur.

This uncertainty is symptomatic of the inadequacy of existing tools to probe the neuronal networks that underlie the mind. In a cortex of billions of cells, state-of-the-art electrophysiological techniques can listen to the pulses emanating from a hundred neurons. That's a dilution of one out of one hundred million. What is needed is the record of the simultaneous activity of ten thousand or one hundred thousand brain cells.

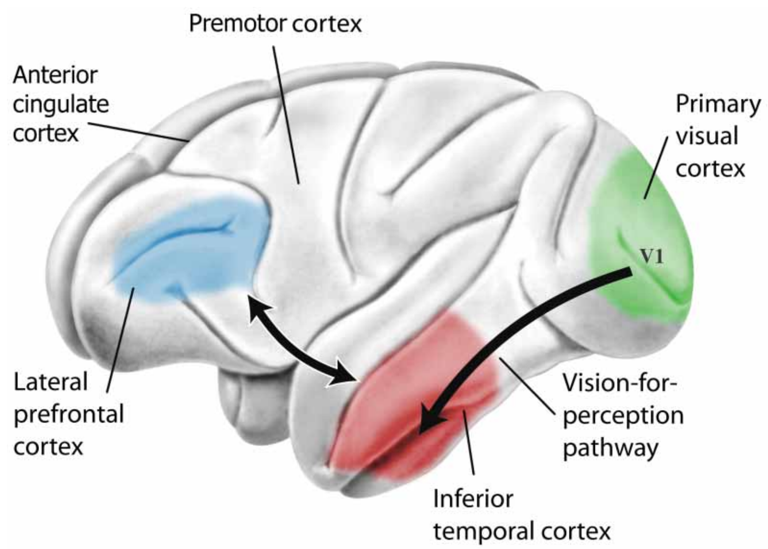
So, if the NCC are based on a coalition of cells, their existence could easily be missed among the din of those billions of neurons chattering to each other.

Precisely. It's like trying to learn something meaningful about an upcoming presidential election by recording the everyday conversations of two or three randomly chosen people.

I see. Let's move on to your next step.

This came in 1995 and pertained to the function of consciousness, which we had ignored up to that point. We hypothesized that a major function of consciousness was to plan for the future, allowing the organism to rapidly deal with many contingencies. This, by itself, was not so different from what other scholars had proposed. We took this argument a step further and asked about its neuroanatomical consequences. Because the planning parts of the brain are located in the frontal lobe, the NCC must have direct access to these brain regions. It turns out that in the monkey, none of the neurons within the primary visual cortex, V1, at the back of the brain, send their output to the front of the brain. We therefore concluded that V1 neurons are not sufficient for visual perception, that visual consciousness requires higher cortical regions.

That's not to say that an intact V1 isn't necessary for seeing. Just as the neural activity in your eyes does not correspond to visual perception—since otherwise you would see a gray disk of nothingness at the blind spot where the optic nerve leaves the eye and no photoreceptors exist—V1 activity is necessary but insufficient for sight. V1 is probably not necessary for visual imagery or for experiencing visual dreams.



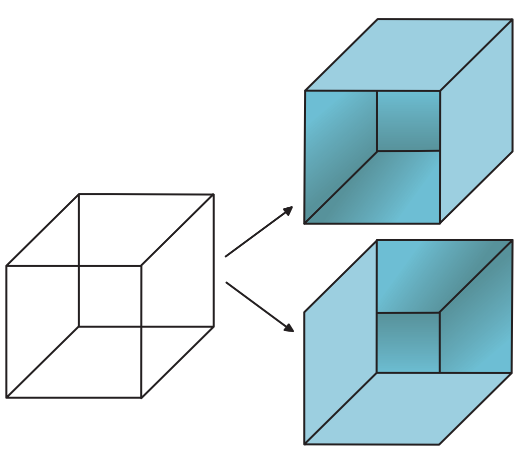
Above: The neuronal correlates of visual consciousness are likely to be based on nerve cells in the inferior temporal cortex and the frontal lobes, but not on neurons in the primary visual cortex at the back of the brain. Below: Your mind can see the Necker cube in two different ways, and can flip easily from one to the other. But you can never see both at the same time.

I don't see why you make such a big deal out of this. So what if the NCC aren't in V1?

Well, if true—and the current evidence is quite encouraging—our hypothesis represents a modest but measurable step forward. This is emboldening because it demonstrates that, with the right approach, science can make progress in uncovering the material basis of consciousness. Our hypothesis also implies that not all cortical activity is expressed consciously.

So where, among the vast fields of the cortex, are the NCC?

Look within the "vision-for-perception" pathway if you're concerned with visual consciousness. Coalitions of neurons in and around the inferior temporal cortex, supported by feedback activity from cells in the cingulate and frontal cortices, are essential. By way of this reverberatory feedback activity, the coalition can win out over its competitors. The echoes of this conflict can be picked up by EEG or functional brain imaging.



Ongoing electrophysiological explorations of these brain regions continue apace. A popular strategy exploits visual illusions in which the relationship between an image and its associated percept is not one-to-one. Although the input is continuously present, sometimes you see it one way and sometimes in another. Such bistable percepts—the Necker cube is the classical example—are used to track the footprints of consciousness among the different neuronal cell types in the forebrain.

Why invoke a loop from the sensory regions of the cortex to the more frontal ones?

As I just mentioned, this is one of the pivotal roles of consciousness in the life of an organism—to plan for multicontingency situations that can't be dealt with by the nonconscious sensory-motor agents. It is probably the projections to and from the frontal lobes, responsible for planning, thought, and reasoning and the seat of the self, that create the powerful feeling that there is a homunculus inside my head, the true "me." The little person—the original meaning of the term homunculus—is part of the front of the cortex observing the back. Or, in anatomical terms, the anterior cingulate, prefrontal, and premotor cortices are receiving a strong, driving synaptic input from the back of the cortex.

But who is, in turn, inside the homunculus's head? Don't you end up with an infinite loop?

Not if the homunculus is, itself, unconscious or has a reduced functional role compared to that of the conscious mind.

Can the homunculus freely initiate actions?

You must sharply distinguish the perception of will from the force of will. See, I can raise my hand and I certainly feel that I am willing this action. Nobody told me to and I didn't even think about this until a few seconds ago. Perception of control, of authorship—the sense that I am in charge—is essential to my survival, enabling my brain to label these actions as mine (this perception of authorship will have its own NCC, of course). The neuropsychologist Daniel Wegner points out that the belief "I can initiate actions" is a form of optimism. It lets me accomplish things with confidence and exuberance that a pessimist might never attempt.

But was your raised hand completely determined by prior events or was it freely willed?

You mean, do the laws of physics leave room for a will that is free in the metaphysical sense? Everybody has opinions on this age-old problem, but there are no generally accepted answers. I do know of many instances of a dissociation between an individual's action and her intentions. You can observe these slip-ups in your own life. When "you want" to climb above a ledge, for example, but your body doesn't follow because it's too scared. Or, when running in the mountains and your will slackens but your legs just keep on going. There are many extreme forms of dissociations between action and the experience of willing an action, including hypnosis, table turning, automatic writing, facilitated communications, spirit possession, deindividuation in crowds, and clinical dissociative identity disorders. But whether raising my hand was truly free, as free as Siegfried's destruction of the world order of the gods in Wagner's *Der Ring des Nibelungen*, I doubt it.

From your answer I gather, in any case, that you think your quest for the NCC can be divorced from the question of free will.

Yes. Whether or not free will exists, you still have to explain the puzzle of experience, of sensation.

What will be the consequences of discovering the NCC?

The most obvious ones will be of a practical nature, such as techniques to track the status of the NCC. Such a conscious-ometer will enable medical personnel to monitor the presence of consciousness in premature babies and young infants, in patients whose minds are afflicted with severe autism, or senile dementia, and in patients who are too injured to speak or even to signal. It will permit anesthesiologists to better practice their craft. Understanding the brain basis of consciousness will allow scientists to determine which species are sentient. Do all primates experience the sights and sounds of the world? All mammals? All multicellular organisms? This discovery should profoundly affect the animal rights debate.

Such a conscious-ometer will enable medical personnel to monitor the presence of consciousness in premature babies and young infants, in patients whose minds are afflicted with severe autism, or senile dementia, and in patients who are too injured to speak or even to signal.

How so?

Species without NCC can be thought of as bundles of stereotyped sensory-motor loops, without subjective experience, zombies. Such organisms could be accorded less protection than animals that do show NCCs under some conditions.

So, you would not want to experiment with animals that can feel pain?

In the ideal world, no. However, one of my daughters died 8 weeks after birth from sudden infant death syndrome; my father wasted away over a period of twelve years from Parkinson's disease compounded at the end by Alzheimer's disease; and a good friend killed herself in the throes of a florid episode of schizophrenia. Eliminating these and other neuronal maladies afflicting humanity requires animal experimentation—carried out with care and compassion and, whenever possible, with the animal's cooperation (as in the vast bulk of the monkey research described in this book).

What about implications for ethics and religion?

What matters from a metaphysical point of view is whether neuroscience can successfully move beyond correlation to causation. Science seeks a causal chain of events that leads from neural activity to subjective percept; a theory that accounts for *what organisms* under *what conditions* generate subjective feelings, *what purpose* these serve, and *how* they come about.

If such a theory can be formulated—a big if—without resorting to new ontological entities that can't be objectively defined and measured, then the scientific endeavor, dating back to the Renaissance, will have risen to its last great challenge. Humanity will have a closed-form, quantitative account of how mind arises out of matter. This is bound to have significant consequences for ethics, including a new conception of humans that might radically contradict the traditional images that men and women have made of themselves throughout the ages and cultures.

Not everybody will be enthralled by this. Many will argue that this success marks the nadir of science's relentless, dehumanizing drive to deprive the universe of meaning and significance.

But why? Why should knowledge lessen my appreciation of the world around me? I am in awe that everything I see, smell, taste, or touch is made out of 92 elements, including you, me, this book, the air we breathe, the earth we stand on, the stars in the sky. And these elements can be arranged in a periodic kingdom. This, in turn, rests on an even more fundamental triad of protons, neutrons, and electrons. What secret form of cabalistic knowledge provides greater satisfaction? And none of this intellectual understanding lessens my love of life and the people, dogs, nature, books, and music around me by one bit.

What about religion? Most people on the planet believe in some sort of immortal soul that lives on after the body has died. What do you have to say to them?

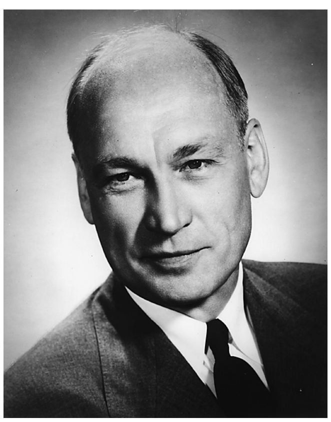
Well, many of these beliefs can't be reconciled with our current scientific world view. What is clear is that every conscious act or intention has some physical correlate. With the end of life, consciousness ceases, for without brain, there is no mind. Still, these irrevocable facts do not exclude some beliefs about the soul, resurrection, and God.

Now that your five-year-ordeal of writing this book is over and your children have left for college, what are you going to do?

As Maurice Herzog famously pealed at the end of *Annapurna*, his account of the first ascent of the eponymous Himalayan mountain, "There are other Annapurnas in the lives of men." □

An accomplished pianist, Beckman formed his own dance band in high school. He also accompanied the silent movies at the local theater. After being discharged from the Marines in 1919, he headed west for the summer as an itinerant movie-house pianist before entering college.

Arnold O. Beckman
1900 – 2004



Beckman in an undated photo, circa 1945.

Inventor and philanthropist Arnold Orville Beckman, PhD '28, founder and president of Beckman Instruments, Inc., and chairman emeritus of Caltech's board of trustees, died in his sleep on May 18 at Scripps Hospital in La Jolla after a long illness. He was 104.

Born on April 10, 1900, in rural Illinois, Beckman's life paralleled and helped catalyze the transformation of the United States from an agrarian society to an industrial one. Running water and residential electricity did not arrive in his boyhood town of Cullom until his early teens.

A mechanically inclined son of a blacksmith, at age nine Beckman stumbled across a chemistry textbook in the attic and began doing the experiments. For his tenth birthday his father gave him the use of a backyard shed that promptly became his laboratory. His high-school dream career was to be a freelance chemist—have beakers, will travel. He would later recall, "I visualized having a trunk with apparatus—test tubes and chemicals—that I could take anywhere and analyze anything."

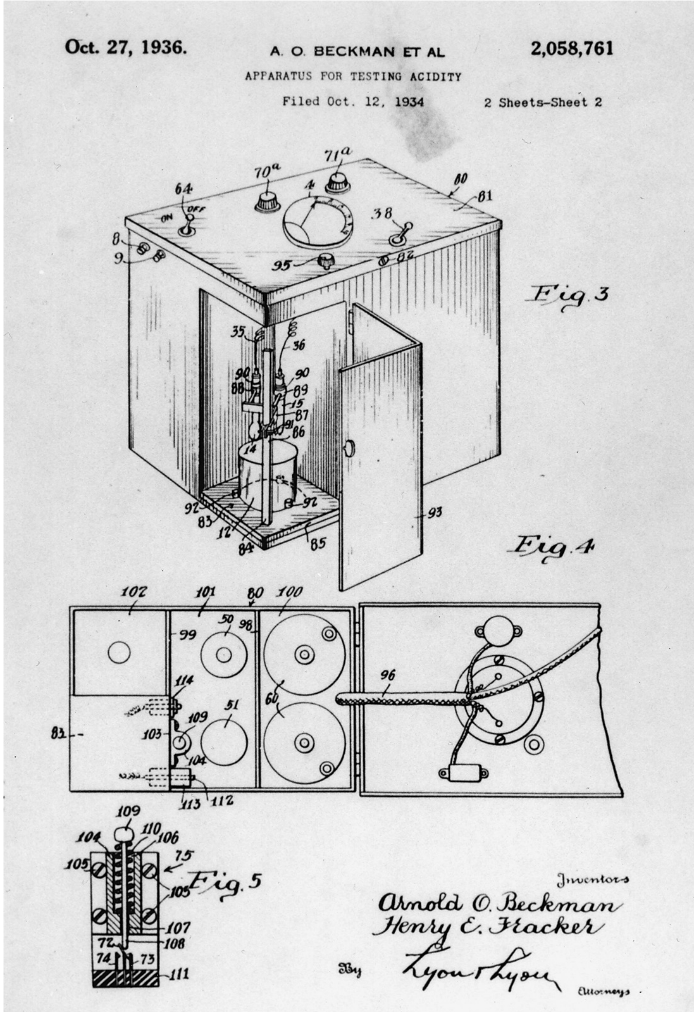
In August 1918 Beckman joined the Marines, missing being shipped off to fight Leon Trotsky's Red Army by one place in line at the Brooklyn Navy Yard. Thus he wound up eating Thanksgiving dinner at the Greenpoint YMCA, where 17-year-old Mabel Meinzer helped serve his table. It was love at first sight (they would be married nearly 64 years), but despite a voluminous correspondence, they would not get engaged until April 1923.

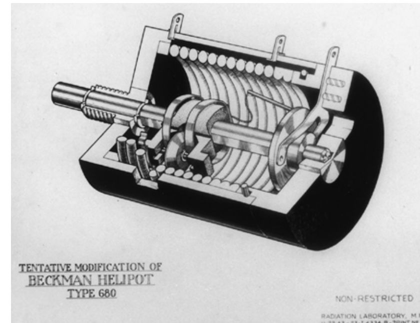
Instead, Beckman entered the University of Illinois, from which he earned a BS in chemical engineering in 1922 and an MS in physical chemistry in 1923. There he learned about electrochemistry and the new ionic theory that was redefining acidity, and mastered the art of glassblowing for experimental apparatus. He was accepted to the doctoral programs at the University of Chicago, MIT, and Caltech, opting for the "fabled country of California, land of milk and honey and oranges." But by now Mabel was an executive secretary at the Equitable Life Assurance Company in New York, and he left Caltech after a year to get a job near her.

This proved to be at Western Electric's Engineering Department, which was in the process of transforming itself into Bell Laboratories, the premiere corporate research entity in the world in its day. There Beckman helped develop quality-assurance procedures for the manufacture of Audion vacuum tubes, which were used to amplify weak electrical impulses for transcontinental telephone calls, and learned about circuit design. "If I'd never gone to Bell Labs, I might not have developed any interest in electronics," he said.

Arnold married Mabel on June 10, 1925, and in 1926 the newlyweds returned to Pasadena after a six-week cross-country journey by Model T, which he had modified for better hill climbing. In the days before fuel pumps, the gasoline couldn't make it uphill from the tank to the engine on steep slopes. Most motorists dealt with this by driving up such grades in reverse, but Beckman fitted his gas cap with a bicycle-tire valve, allowing him to pressurize the tank with a hand pump when needed.

Now reenrolled at Caltech, Beckman did his PhD work on ultraviolet photolysis, applying the newfangled quantum theory to chemical reactions; he was asked to stay on as an instructor. The following year he and his thesis advisor, Roscoe





A drawing (left) from the patent application for the pH meter. Beckman held 14 patents, including the shockproof potentiometer (right).

Dickinson (PhD '20), built an instrument to determine the energy of ultraviolet light by shining it on a thermocouple, which turns heat into electricity, connected to a galvanometer. By the early '30s Beckman, now an assistant professor, had become the go-to guy when the department's instrument builder, Fred Henson, was overbooked. At least partially in self-defense, he began teaching a course in laboratory glassblowing. He fielded off-campus requests as well, leading him to set up a side business (with the blessing of Robert Millikan, Caltech's president, who had directed most of the inquirers to him in the first place) as a "scientific consultant."

One client, National Postal Meter, needed a nonclogging ink. Beckman found a workable formulation, but it was based on butyric acid—the active ingredient in stinky feet—and no ink company would touch it. So he decided to make it himself, in the back of a garage on an alley behind Colorado Boulevard that he rented from Henson. Hiring two Techers, Robert Barton (PhD '33) and Henry Fracker (BS '30), and incorporating as National Inking Appliance Company, the firm also test-marketed his invention to reink typewriter ribbons. This was not a success, as "the last things that secretaries wanted to do was get their fingers dirty with ink to save the boss a 75-cent ribbon."

Meanwhile, Sunkist, which handled more than three-quarters of California's citrus crop, had a problem of its own. Lemons that weren't top grade were juiced to make pectin (for jellies), citric acid, or other things, with the juice's acidity determining how it was processed. But the sulfur-dioxide preservative added to the juice bleached the litmus paper whose color change was usually used to measure acidity, and poisoned the hydrogen electrodes used in the favored high-precision electrochemical method of the day. An alternative, the so-called glass electrode, was immune to SO_2 but was big, with thin, fragile walls. To make matters worse, it gave a very weak signal, meaning you needed an ultrasensitive galvanometer that was itself vulnerable to the slightest jarring. And with either electrode, the whole temperamental setup, including rheostat, rectifier, and reference cell, sprawled across several square feet of benchtop.

So chemist Glen Joseph took a day trip from the lemon lab in Ontario, some 30 miles east of Pasadena, to pick the brains of his old classmate from the University of Illinois. Beckman realized that an amplifier would allow a small, stout glass electrode, which would give out an extremely tiny signal, to be hooked to a rugged but insensitive ammeter, and that the vacuum tubes he had worked with at Bell Labs were just the ticket. He built a gadget the size of a flour canister that used a second vacuum tube to crank up the output from the first one to give a REALLY BIG signal, just to be sure. It worked so well that Joseph never got to use it, as everyone else in the lab kept borrowing it.

The acidimeter, or pH meter, was the first instrument to package the chemist in the box. No more assembling complex apparatus and then spending months trying to figure out its idiosyncrasies. Now you just opened a door, stuck in your sample, and read off the result.

In 1935, Beckman's rechristened National Technical Laboratories (NTL) began selling the acidimeter through scientific-supply catalogs for $195—roughly a month's salary for a junior professor—in competition with 10-cent vials of litmus paper. But the unassembled components for a build-it-yourself electrochemical setup cost about $500, so the acidimeter was really half the price and none of the headaches.

Like IBM's prediction in the early '50s that the world market for mainframe computers would never exceed six, "the most optimistic estimate I got was . . . 600 over a 10-year period [would] saturate the market," Beckman would say. But in the first three months, NTL sold 87. A move to bigger quarters—a former dry-cleaning shop three blocks away owned by chemistry professor Ernest Swift (MS '20, PhD '24) that actually fronted on Colorado Boulevard—quickly followed.

In 1939, Beckman left Caltech to run NTL full-time, and in 1940 the company moved into a brand-new 12,000-square-foot plant in South Pasadena.

Beckman clowns with the commemorative plastic brain given to him at a construction-site ceremony for the Beckman Behavioral Biology building on May 8, 1972. He has an appreciative audience in Mabel Beckman, lower right, and Caltech president Harold Brown, center. The fence hides the two-story-deep foundation excavation; Beckman Auditorium is in the background.

That same year, work began on an ultraviolet/visible spectrophotometer inspired by a Coleman Instruments (now PerkinElmer) model that itself used a slightly modified version of NTL's pH meter for data readout. Beckman, his chief design engineer, Howard Cary (BS '30), and the NTL team redesigned the instrument from scratch. They used a quartz prism for wavelength selection rather than the usual glass one after discovering that glass doesn't transmit ultraviolet light well. (This is why you can't get a suntan behind a picture window.) They blew their own ultraviolet lamps and photocells, and put the readout dial on the faceplate rather than leaving the user to wire the spectrophotometer up to a separate pH meter. Again, all the expertise was in the box, and with the twist of a knob you could read out the entire chemical fingerprint of a sample, identifying its components—a set of measurements that might have previously taken hours or even days. Or, by parking on a single characteristic wavelength, you could continuously measure the amount of the substance absorbing it. More than 21,000 Model DU spectrophotometers would be sold from April 1942 until the machine was discontinued in 1964, and a few of them are still in use today.

During World War II, DUs and infrared spectrophotometers, which NTL built in secret for the government's synthetic-rubber project, played vital roles in the production of war materiel ranging from penicillin and Vitamin A (essential to night vision) to aviation gasoline and TNT.

While at a secret meeting in Detroit with members of the Office of Rubber Reserve, Beckman got a phone call from a man named Rosenberg who refused to identify himself further but wanted Beckman to fly to Cambridge, Massachusetts, right away. Paul Rosenberg proved to be a professor of physics at MIT's highly secret Radiation Laboratory, where a British invention called radar was being perfected. (The Lab was headed by physicist Lee DuBridge, who would later become Caltech's president.) Many components in a radar set need to be precisely tuned, and Rosenberg had discovered that the potentiometers used for the fine calibration of Beckman's pH meters were a factor of 10 better than anything else available. A potentiometer is a variable resistor—as you turn the knob, an electrical contact slides along a C-shaped resistive element, and the farther along the C it travels, the higher the resistance.

The NTL design got its extraordinary sensitivity by using a helical resistive element. "Thus a 10-turn coil would provide 3,600 degrees of rotation, whereas a single-turn potentiometer provided less than 360 degrees." Rosenberg wanted to know if the Helipot, as it was called, could be made to military specs. Beckman said sure, only to soon discover a fatal flaw—any sudden jolt would knock the spring-loaded contact off the coil, causing the radar to lose lock and need retuning. Especially in a rumbling propeller-driven airplane, it was "absolutely worthless. . . . I began getting calls from the military, particularly from the Navy: "Where are the Helipots? We have ships ready to go. . . . One sleepless night I conceived of a design using a solid rotor in a groove; the contact would slide up and down in the groove so it couldn't get displaced." Tens of millions of these Helipots have been sold since, with no end in sight.

Beckman wound up providing a second secret device for the Navy as well—oxygen monitors for use on submarines, built to a design by chemistry professor Linus Pauling (PhD '25). These became standard equipment in hospitals in 1955, when doctors at Johns Hopkins discovered that an outbreak of blindness in premature babies was being caused by excessive oxygen—over 40 percent, versus air's 21 percent—in their incubators.

Air-quality issues of another sort began surfacing as the Los Angeles basin industrialized during the war—smog. From 1948 to 1952, Beckman served as the scientific consultant to the newly formed Los Angeles County Air Pollution Control District. It was widely assumed that sulfur dioxide from coal-fired power plants, oil refineries, and factories was to blame. But Beckman, who knew SO_2 when he smelled it, was not persuaded. And Arie Haagen-Smit, another Caltech chemistry professor, had been doing studies that implicated ozone. So Beckman designed a program to collect air samples basinwide, from which Haagen-Smit extracted a few drops of "smelly brown stuff." After identifying the material as a mix of toxic, highly reactive organic peroxides, Haagen-Smit was able to trace them back to their source: a complex web of reactions between auto exhaust, sunlight, nitrogen oxides, and ozone. Beckman then helped develop the county's pollution-control regulations and smog-alert procedures. (And, incidentally, started a new line of business, up to and including mobile air-quality labs.)

As scientists returned to civilian work, the pace of research and development quickened, and Beckman Instruments (NTL changed its name when it went public in 1950) became a fixture in every lab. The company began acquiring other firms with compatible products, such as centrifuges and biomedical instruments, and continued to develop its own wares at a breakneck pace. In some years in the early '60s, Beckman Instruments launched an average of one new product a week.

Beckman retained close ties to Caltech, being elected to the Board of Trustees in 1953, and becoming its chair in 1964—the first alumnus to hold that position, which he did until 1974, when he was voted a Life Trustee.

He stepped down as president of Beckman Instruments at 65, "the age of statutory senility," staying on as chairman of the board while he and Mabel embarked on an ambitious campaign to give away their entire fortune to causes they believed in—in particular, basic scientific research. By the time of Mabel's death in 1989, they had donated $200 million; to date, the Beckmans and their foundation have distributed some $400 million. Major gifts to Caltech include the Beckman Auditorium, the Mabel and Arnold Beckman Laboratories of Behavioral Biology, the Arnold and Mabel Beckman Laboratory of Chemical Synthesis, and the Beckman Institute. In recognition of these and numerous other contributions, in 1981 Caltech's trustees and other donors established the Arnold O. Beckman Professorship in Chemistry, held by longtime friend and founding director of the Beckman Institute Harry Gray.

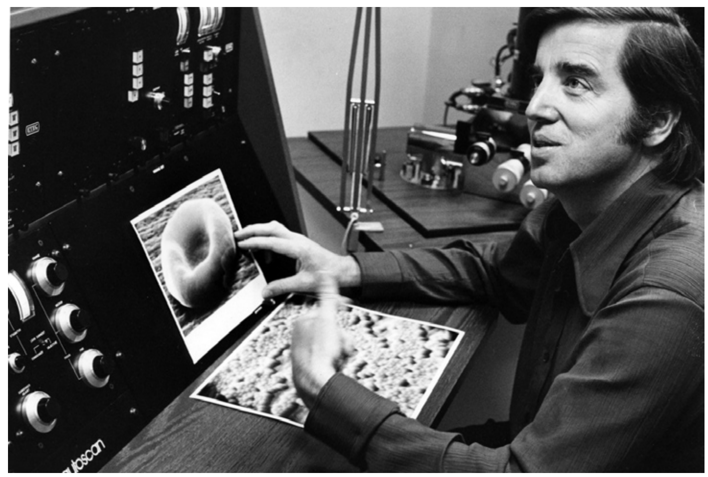
Other notable gifts include $40 million to fund an interdisciplinary research institute at the University of Illinois; $20 million to create a conference center in Irvine, California, for the National Academy of Sciences; and $14.5 million to improve K-6 science education in Orange County, California, where the Beckmans had lived since the early '60s.

Besides honors and awards too numerous to mention, Beckman was named to the National Inventors Hall of Fame in 1987. He received the National Medal of Technology in 1988 and the National Medal of Science in 1989.

He is survived by his children, G. Patricia Beckman of Corona del Mar, and Arnold S. Beckman of Asotin, Washington. □—*DS*

Beckman's quotes published here are drawn from past E&S *articles and from* Arnold O. Beckman: One Hundred Years of Excellence *by Arnold Thackray and Minor Myers, jr., Chemical Heritage Foundation, 2000.*

William Dreyer
1928 – 2004



Bill Dreyer, in 1973, analyzes two scanning electron micrographs: of a normal blood cell and of polymeric spheres coated with antibodies that will react only with specific substances on the blood cell's surface. Dreyer was trying to develop molecules that would attack certain types of cancer cells, work that grew out of his research on normal cells' surface recognition codes.

Dr. William J. Dreyer, professor of biology since 1963, died April 23 after a long illness. He was 75.

A native of Kalamazoo, Michigan, Dreyer earned his bachelor's degree at Reed College and his doctorate in biochemistry at the University of Washington in 1956. After his graduation he worked for six years as a research biochemist at the National Heart Institute and National Institute of Arthritis and Metabolic Disease before joining the faculty at Caltech, where he remained the rest of his life.

Dreyer was perhaps best known for his suggestion in the 1960s that genes could be "reshuffled" to provide additional information for the formation of proteins. At first a controversial idea, the theory later came into prominence after it was experimentally demonstrated by others, including Leroy Hood, who at one time was Dreyer's student.

At a Society for Biomolecular Screening conference held in 2003, Hood credited Dreyer for mentoring his early career, teaching him the art of conceptual thinking, and providing him with "a wonderful introduction to the exhilaration of rapidly paced molecular immunology." Hood added that Dreyer always emphasized two principles: "Always practice biology at the leading edge," and "If you really want to change biology, develop a new technology for pushing back the frontiers of biological knowledge."

Dreyer also investigated fundamental questions related to how embryos develop, and he made significant contributions to the field of biological instrumentation.

He was the author of numerous journal articles and also held a number of patents—including one for an immunological reagant and radioimmunoassay, and two for polyacrylate beads that he developed with two colleagues.

Dreyer had been an avid pilot since 1960 and often flew to Baja California, various archaeological sites in the western United States, and to remote regions in British Columbia. He once said that his taste for flying his Cessna P210 at altitudes of 15,000 feet—high for a small privately owned prop plane but low for commercial aircraft—was "an allegory for my tastes in scientific research. I like to work where research isn't too competitive and crowded—to move beyond the current mob scene, even if the place where I end up is lonely."

Dreyer is remembered by his many former students as having taught them to look at data with a fresh eye, rather than through the filter of current scientific dogma, and for having infected them with his love of science.

He is survived by his wife and colleague, Dr. Janet Roman, and three daughters. □

Quarterback and captain-elect Sharp catches a pass for the 1933 *Big T*.

Robert Phillip Sharp
1911 – 2004

Robert P. Sharp, the Robert P. Sharp Professor of Geology, Emeritus, died peacefully at his home in Santa Barbara on May 25. He was 92.

The eldest son of Oxnard fruit growers Julian and Alice Sharp, he came to Caltech in 1930 with vague thoughts of becoming a civil engineer, but changed his mind when he took the core geology course in his sophomore year. "I had hardly ever heard the word geology before that time," he later recalled, "but this course hit me just right. Bingo! So I elected to give geology a try." He wasn't sure, though, that he would be able to make a living from it.

Sharp played quarterback for the Caltech football team for three years, thrilled to be able to compete against teams like UCLA at the Coliseum (Caltech didn't win, but gave UCLA a good run for their money) and to have the Rose Bowl as home field. When a 1958 issue of *Sports Illustrated* named him one of 25 "Men of Achievement" who had been undergraduate football stars, he told the reporter, "I think most young scientists need what you get from football—the news that you have got to be determined as hell and that there is a certain poise and aggressiveness that is desirable." He remained physically active all his life, jogging, hiking (preferably to a mountain stream for some trout fishing), and skiing (which he took up at 55).

After a BS in 1934 and an MS in 1935, he moved to Harvard for a doctorate in geology (1938), and found the going easier than the other grad students after "being worked like a dog" at Caltech. While there, he met and married another geologist, Radcliffe graduate student Jean Todd, and they were together for 62 years until Jean's death in 2000. After five years in the geology department of the University of Illinois, he was called to wartime service with the U.S. Army Air Forces from '43 to '45, working in the Arctic, Desert, and Tropic Information Center and rising to the rank of captain. After two years on the faculty of the University of Minnesota, he came back to Caltech in 1947 as a professor of geomorphology and was appointed division chair in 1952, after the untimely death of Professor of Paleontology Chester Stock. He was chair of the Division of Geological Sciences, as it was then called, until 1968, during which time he introduced several new, and groundbreaking, academic programs. (He can also be credited with putting the P into GPS, though the official name change to the Division of Geological and Planetary Sciences didn't happen until 1971.)

"The most important thing he did was to hire real talent in the new areas of geochemistry, planetary sciences, and geophysics," said Lee Silver (PhD '55), Keck Foundation Professor for Resource Geology, Emeritus. "He knew that bringing in chemists and physicists and blending them into the division would make a very rich and productive assembly of faculty, and it quickly became a multidisciplinary division."

"All three of these areas were very mathematical," added Bruce Murray, professor of planetary science and geology, emeritus. "Sharp was not a quantitative man, yet his foresight and ability to push this through were extraordinary."

Unable to find a vertebrate paleontologist to succeed Stock, Sharp decided to give this area of research a lower priority. "Bob sold all the division's vertebrate fossils to the L. A. County Museum of Natural History," recalled Silver, "and used the $100,000 raised to build geochemistry labs. It was the first geology department in the world to go in that direction."

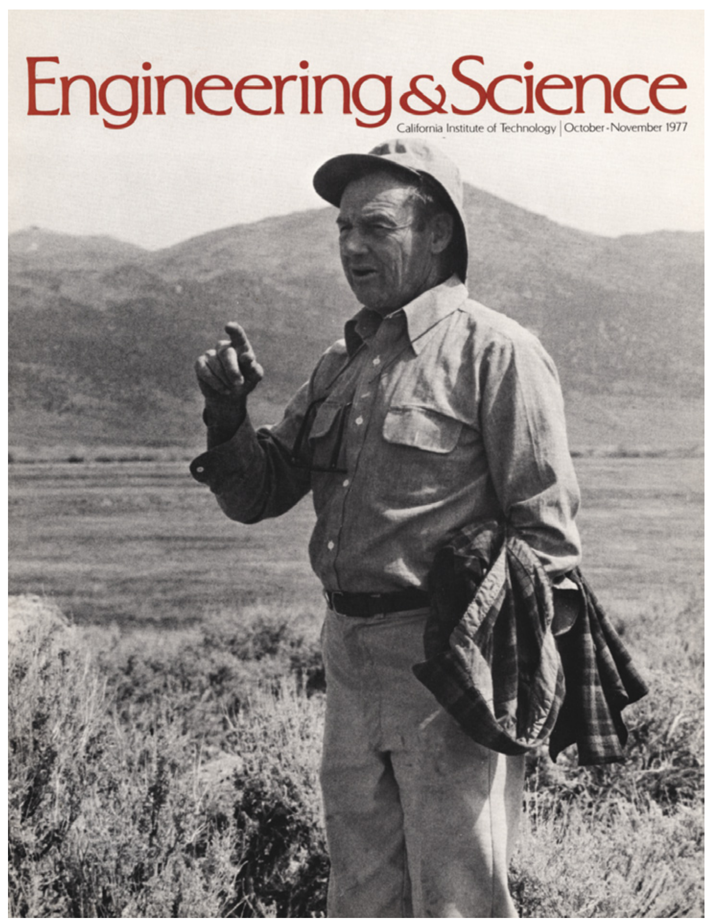
"It was a radical change," said Murray. The skepticism it generated came as a shock to Sharp, who later recalled, "I would go to national geological meetings and geologists would come up and hiss in my face, 'How's the department of geochemistry at Caltech?' I used to say, 'Just be patient and give us time.'"

Of course, he turned out to be right, said Silver. Bringing in geochemists Harrison Brown, Clair Patterson, and Sam Epstein made Caltech the wellspring for the use of isotopes in geology.

To modernize seismology, Sharp recruited geophysicist Frank Press in 1955 and raised the money to move the seismological laboratory from a cramped house in the San Rafael hills to a beautiful mansion on the other side of the road. Later, he used all his persuasive powers to bring the seismo lab downhill onto the campus.

Sharp didn't need to persuade the astronomers to let the geology division move into the field of planetary science in 1963. They were making great discoveries on the new Hale telescope at Palomar, and were quite happy to leave the planets to the geologists. Bruce Murray became Caltech's first faculty member in planetary science (he would later become director of JPL). Murray became, like so many others in the division, a close personal friend, and Sharp was best man at his wedding. Andrew Ingersoll, the Anthony Professor of Planetary Science, who arrived in 1966, still remembers Sharp's welcome: "He said to me 'My job is to give you every opportunity to be as productive as you can,' and I thought, 'Wow! What a great place to come to.' He was a great leader, and supportive of everyone in the division."

The 1965 Mariner IV flyby of Mars gave Sharp the chance to do planetary science as well. Mariner IV was the first spacecraft to carry a digital TV camera, built by physics professor Robert Leighton (BS '41, MS '44, PhD '47) and Murray. They brought in Sharp to help them interpret, "for thousands of home TV viewers" as *E&S* wrote at the time, the first-ever close-up images of the red planet beamed back to Earth. The trio also worked on Mariners



Jean joined Bob on the third Grand Canyon trip to raise money for the division's first endowed chair.

VI, VII, and IX, and "had a ball." In a 1991 *Pasadena Star-News* article, Sharp recalled how one of the Mariner technicians had told him that the latest images from Mars revealed the presence of a lake. Looking at the images, he saw that the rippling features the technician had seen were actually sand dunes. "That was the beauty of it for me," he said. "Astrophysicists, engineers, and computer guys, and they need this dumb ol', dirty fingernail geologist like me!"

As well as running the division, teaching, and fund-raising, Sharp found time for "creative, original research," said Silver. "He was one of the most highly respected geologists in the world." His work included investigations of basin and range structure, continental basin deposits, mountain and continental glaciation, glacial-lake shorelines, frozen ground, erosion surfaces, desert sand dunes, oxygen and hydrogen isotopes in snow and glacier ice, surface forms and processes on Mars, and even the mysterious sliding stones of Death Valley's Racetrack Playa. He preferred "today's geology," things that could be measured, like glaciation and sand dunes. This was a smart combination, remarked Silver, because he could study glaciers in winter and sand dunes closer to home in summer.

Sharp's scientific contributions garnered many honors, including the Geological Society of America's Kirk Bryan Award in 1964 and its highest honor, the Penrose Medal, in 1979. He was elected to the National Academy of Sciences in 1973, and awarded America's highest scientific honor, the National Medal of Science, in 1989. He donated the medal to the division, and it is now on display in the Robert P. Sharp lecture theater.

Sharp's take on teaching made him very popular with students: "I try to tell them something about the environment that creates interest," he told the *Claremont Courier* in 1989. "We don't teach right when we give students a mass of facts and tell them that they may need them later. What we should do is create the interest and then make them do the nasty intellectual exercises later." After just three years at Caltech, he was hailed by *Life* magazine as one of the 10 great U.S. college teachers of 1950. "Sharp's enthusiasm is contagious, and his sophomore geology course is one of the favorites on the Caltech schedule," *Life* wrote, "credited with attracting many unsuspecting students into the lifetime study of geology."

Bill Tivol (BS '62), who today manages the electron microscopy facility in the Broad Center for the Biological Sciences, recalls that when he took the Ge 1 "culture course," Sharp made a bet with the class that if there was a volcanic eruption that year, the students were to buy him a beer, and, if not, he'd buy a beer for each of them. "Not only did he win the bet—and get presented with a beer in class—but he continued to win every year since," said Tivol. "This was his very memorable way to point out that something we think of as rare is really quite a common geological event, globally."

Sharp's former students may also remember their teacher's penchant for punctuality. In a 1973 issue of *Caltech News*, one of them observed, "When he says a caravan will leave the campus for a field trip at 8 a.m., he means 8:00 and not 8:05. He's been known to drive out of the parking lot and leave stragglers standing on the steps." On one memorable occasion, he even set off without a trustee.

In 1978, he became the Robert P. Sharp Professor of Geology. The division's first endowed chair, it was funded in a very imaginative way. Delayed at an airport in Houston by engine trouble, Lee Silver and Gene Shoemaker (BS '47, MS '48) came up with the idea of taking Caltech benefactors on guided raft trips through the Grand Canyon at $50,000 a head ($75,000 for a couple) until they'd raised the necessary $1 million. The idea was enthusiastically embraced by division chair Barclay Kamb (BS '52, PhD '56, the Rawn Professor of Geology and Geophysics, Emeritus) and Sharp, and the four of them led these popular trips (with suitably luxurious campsites and meals) for the next three years. President Marvin Goldberger and his wife, Mildred, went along on the third expedition, and one evening toward the end of the trip, Goldberger announced that all the money had been raised and the new chair would be named in Sharp's honor. Dumbstruck at the time, Sharp later recalled: "It was a beautiful place for the announcement. Right on the river. Beautiful evening. In camp. And a *satellite* went over." He always felt it was one of the nicest things that ever happened to him.

Sharp loved taking people

on field trips, feeling that "you have to bring them into the fold by taking them out to have a look at nature." He felt sorry for the division's secretaries and lab technicians because they were always left behind when the faculty and students went off. So in a gesture typical of his consideration for others, he organized and led an annual staff geological excursion. Every year for seven years he took the division staff on day trips to the San Gabriels, or two-day trips to Owens Valley, and sometimes even three-day trips to Hawaii.

He also started the popular Alumni Association travel program. Arlana Silver, who currently heads the Caltech Associates and worked with Sharp on these programs for many years as associate and then deputy director of the Alumni Association, recalled that he took alumni to places such as Alaska, Hawaii, Yellowstone and Glacier National Parks, and the American Southwest until he was well into his eighties. "Other faculty members have joined in with their own trips now," she said, "but Bob was the one who set the pattern. He had a great rapport with the alumni, and the people who traveled with him once wanted to travel with him again. In fact, so many people wanted to go on each trip that they were commonly wait-listed, and the trips had to be repeated."

Project Pahoehoe, an eight-day spring break to Hawaii for the division's graduating seniors and doctoral candidates, was another of his innovations. It wasn't the traditional kind of spring break on the beach, however. Sharp wanted the students to learn about hot-spot volcanism, and he worked them hard. The project had to be funded from year to year by donations, and he put a lot of effort into raising the money. To ensure it could continue after his death, he established an endowment with his own pledge and those of others. He and his wife, Jean, also gifted a partial remainder interest in their Santa Barbara home to the Institute.

Sharp became a professor emeritus in 1979 but continued to teach a class at Caltech—staying in touch with young people was what kept him going, he said—and to lead field trips. He also wrote popular geology books, including *Geology: Field Guide to Southern California* and his humor-tinged collection of vignettes on sites of geological interest, *Geology Underfoot in Southern California* and *Geology Underfoot in Death Valley and Owens Valley* (both written with Allen Glazner). The latter two are now in their fourth printing, and have a wide and appreciative readership. He had almost finished another *Geology Underfoot* book on Idaho, which will be completed by its two coauthors.

Sharp is survived by two children, Kristin Lytle and Bruce Sharp, two grandchildren, Lenore and Mathew Lytle, and many generations of fond students and colleagues. A memorial service is planned for the fall.

Those wishing to make a contribution to Caltech in his memory should write to Robert P. Sharp Ventures in Earth Sciences Fund, GPS Division, attention Marcia Hudson, Mail Code 170-25, Pasadena, CA 91125, making checks payable to Caltech with a notation earmarking the gift for the memorial fund. □—*BE*

Edward E. Simmons Jr.
1911 – 2004

Edward E. Simmons Jr. (BS '34, MS '36) died May 18 of complications from cancer surgery. He was 93.

In his quasi-medieval garb (which he had adopted as perfectly practical for Southern California), Simmons was a familiar figure around Pasadena, particularly on the Caltech campus, where for decades he attended all seminars and lectures that interested him—and just about everything did. He considered Caltech "a suitable local amusement park."

Simmons was born in Los Angeles and grew up in the Pasadena area, where both he and his brother Robert attended Caltech at the same time. Both were outdoors enthusiasts; Robert, who became known for innovations in surfboard design and construction, died in a surfing accident in the early '40s.

While constructing electrical equipment (in his own garage) for Assistant Professor of Mechanical Engineering Donald S. Clark's Impact Research Lab in 1938, Ed Simmons invented the strain gauge, an instrument consisting of a tiny wire connected to a device that measured the change in electrical resistance when strain stretched the wire. It was simple, elegant, and cheap, and quickly proved indispensable to the wartime aircraft industry. The postage-stamp-sized strain gauge could be plastered all over a prototype airplane wing and is credited by some as the greatest contribution to the efficient structure of American aircraft during World War II. The strain gauge eventually spun off a multi-billion-dollar industry when it also found application in bridges, buildings, machinery, and any kind of structure that undergoes stress. Today it's an essential component of electronic weighing equipment, and in his last years Simmons was fond of presenting bathroom scales to baffled recipients as a reminder of his achievement.

When Caltech claimed the patent, Simmons sued; he fought his case all the way to the California Supreme Court, which finally ruled in his favor in 1949. The case inspired the board of trustees to adopt a resolution requiring of employees a written agreement assigning to Caltech all patents for "inventions made in the line of Institute duty."

In 1944 Simmons was awarded the Edward Longstreth Medal of the Franklin Institute of Philadelphia. At the awards ceremony, he sat next to Harlow Shapley, the famous Harvard astronomer. Shapley was dressed in white tie and tails; Simmons wore his tennis clothes.

At a memorial service on May 24, longtime friends fondly recalled Simmons's unique genius and eccentricity, his passion for experiment, and his love of collecting used equipment (sometimes very large used equipment). Despite his lack of social skills (he couldn't bring himself to shake hands and was unable to recognize differences in emotion in others), he was kind, gentle, and generous. He didn't just think outside the box, said the Rev. Stanley Hirtle. "He *was* outside the box."

Simmons was buried near his parents and siblings at Mountain View Cemetery. ☐ *—JD*

Simmons was a conspicuous presence in the audience of many, if not most, of Caltech's public lectures and seminars. Here, in Baxter Lecture Hall, he's warmly greeted by Russian poet Yevgeny Yevtushenko in March 1992.

Honors and Awards

Jacqueline Barton, the Hanisch Memorial Professor and professor of chemistry, has been awarded a grant of $50,000 for two years by the National Foundation for Cancer Research.

Seymour Benzer, the Boswell Professor of Neuroscience, Emeritus, has been awarded the inaugural 2004 Neuroscience Prize of the Peter Gruber Foundation for his innovative and pioneering contributions to neuroscience.

This year's recipients of the ASCIT Teaching Awards are **Colin Camerer,** the Axline Professor of Business Economics; **K. Mani Chandy**, the Ramo Professor and professor of computer science; **Alan Hajek**, associate professor of philosophy; **Kayoko Hirata**, lecturer in Japanese; and **Feng-Ying Ming**, lecturer in Chinese.

Sunney Chan, the Hoag Professor of Biophysical Chemistry, Emeritus, has received the William C. Rose Award of the American Society for Biochemistry and Molecular Biology/International Union of Biochemistry and Molecular Biology. The award recognizes "his outstanding contributions to biochemical and molecular biological research and his demonstrated commitment to the training of younger scientists."

Mory Gharib, the Liepmann Professor of Aeronautics and Bioengineering, has been selected by the Technion, Israel Institute of Technology, for its 2004–05 Pollak Distinguished Lecturer Award.

Three of the latest Presidential Early Career Awards for Scientists and Engineers have gone to members of the Caltech faculty: **Babak Hassibi,** associate professor of electrical engineering; **Mark Simons,** associate professor of geophysics; and **Brian Stoltz,** assistant professor of chemistry. The award recognizes outstanding young professionals at the outset of their independent research careers.

Peter Goldreich, the DuBridge Professor of Astrophysics and Planetary Physics, Emeritus, has been elected a Foreign Member of the Royal Society, which cited him and his close collaborators for "several seminal contributions to an unparalleled range of topics in planetary science and theoretical astrophysics, including spiral arms in galaxies and planetary rings and the explanation of white dwarf oscillations."

Hiroo Kanamori, the Smits Professor of Geophysics, has been selected as a recipient of the 2004 Japan

Academy Prize, which is awarded "for exceptional works and other scientific achievements."

Michela Muñoz Fernández, a PhD student in electrical engineering, whose research focuses on deep-space optical communications, has received a second Amelia Earhart Fellowship Award from Zonta International.

Wilhelm Schlag, professor of mathematics, and **Kip Thorne,** the Feynman Professor of Theoretical Physics, are this year's recipients of the Graduate Student Council Teaching Awards.

Joann Stock, professor of geology and geophysics, has been selected to be a fellow of the John Simon Guggenheim Memorial Foundation. The fellowship will grant her $30,000 to research the tectonic history of rift basins. She has also been awarded a Fulbright grant to Japan for 2004–05.

Ed Stolper, the Leonhard Professor of Geology and chair of the Division of Geological and Planetary Sciences, has been selected to receive the Geological Society of America's Arthur L. Day Medal. □

Jennings Named Provost

Paul Jennings, professor emeritus in civil engineering and applied mechanics, has been named provost of the Institute. He takes the post on August 1.

Jennings, who has been on the campus as a student, professor, and administrator for 44 years, returns to the provost position after a nine-year hiatus. He served as vice president and provost from 1989 to 1995. Thus, he was the Institute's sixth, and is now its eighth, provost since the post was created in 1962.

"Paul is an exciting choice," said Caltech President David Baltimore. "At a time when so many things are happening on campus—the $1.4 billion capital campaign is in mid-stream, there are a number of building and renovation projects projected, there are budgetary challenges to be met—he brings a wealth of knowledge and experience to the office. He is an effective administrator, a great leader, and an eloquent spokesman. I personally enjoyed very much working with Paul when he filled in as acting vice president for business and finance a few years ago, and I look forward to having the opportunity to work closely with him again."

Jennings is an expert in the design of earthquake-resistant structures and in how the earth moves during a temblor. He played an active role in investigating the effects of damaging earthquakes.

He was chair of the Division of Engineering and Applied Science from 1985 to 1989, served as the acting vice president for business and finance in 1995 and again in 1998–99, and as executive officer for civil engineering and applied mechanics from 1975 to 1980.

Jennings, who is highly regarded within the Caltech community for his energy, enthusiasm, and organizational skills, is also internationally renowned in the seismology and engineering fields. He has been the president of the Seismological Society of America and of the Earthquake Engineering Research Institute. He was a member of the National Science Foundation's advisory committee on earthquake engineering and a chairman of the National Research Council's committee on seismology.

Jennings earned a BS from Colorado State University in 1958, then earned both an MS in 1960 and a PhD in 1963 from Caltech. Staying on at the Institute, he was a research fellow in civil engineering in 1965 and swiftly moved up the academic ladder to become a full professor in 1972. He has been an emeritus professor since 2002. He also served on the teaching staff of the U.S. Air Force Academy from 1963 to 1965.

Jennings replaces Steve Koonin, who served as provost from 1995 until early this year when he stepped down from the administrative role to become chief scientist of BP in London. Koonin is on a leave of absence from his faculty appointment as professor of theoretical physics.

Jennings is a hiker and avid fly fisherman. He and his wife, Missy, live in Pasadena, and he has two grown daughters, Kathryn and Margaret. □

Astronomers One Step Closer to CARMA

The CARMA observatory will eventually resemble the rendering above right, but meanwhile there's a lot of digging to do. Being urged on at the groundbreaking, below, by director Anneila Sargent (in the background) are, from left to right, CARMA board members Richard Barvainis (National Science Foundation), R. James Kirkpatrick (University of Illinois), Thomas Tombrello (Caltech), Stephen Halperin (University of Maryland), and Mark Richards (with son; UC Berkeley).

The chemistry of creation and the complex phenomena that shape our cosmos can be superbly explored at millimeter wavelengths. The relocation and merging of the six 10-meter dishes of Caltech's Owens Valley Radio Observatory (OVRO) millimeter array and the nine six-meter dishes of the Berkeley Illinois Maryland Association (BIMA) millimeter array into one instrument will ensure that Caltech can continue to do innovative astronomy in that portion of the spectrum.

On March 27, the project came one step closer to completion when a small groundbreaking ceremony was held at the planned site for the Combined Array for Research in Millimeter-wave Astronomy (CARMA). The project will move the relatively nearby OVRO array and the BIMA array, now some 300 miles north at Hat Creek, to Cedar Flat in the Inyo Mountains of eastern California. According to Anneila Sargent (MS '67, PhD '77), the Rosen Professor of Astronomy and director of CARMA, a major advantage of relocating the telescopes is the dry air at 7,300 feet, almost twice the altitude of OVRO's and BIMA's present locations.

"More telescopes, innovative technology, and better atmospheric transmission will make CARMA an order of magnitude more powerful than the present arrays," said Sargent.

The facility will be used to observe molecular gas and dust in planets, star-forming clouds, planet-forming disks around other stars, nearby galaxies, and even galaxies so distant that they must have formed soon after the Big Bang.

"These measurements will enable studies that address directly some of the most important questions in astrophysics today, such as how the modern universe and the first stars and galaxies formed and evolved, how stars and planetary systems like our own are formed, and what the chemistry of the interstellar gas can tell us about the origins of life," Sargent explained.

The new array will be operated by the CARMA Association, which comprises the four partner universities—University of California, Berkeley; University of Illinois, Urbana-Champaign; University of Maryland, College Park; and Caltech.

CARMA's total cost of approximately $15 million includes such things as developing roads, running electrical power, constructing buildings and pouring concrete pads, and moving the telescopes from their present locations. Early funding toward Caltech's $5 million portion of the total cost was provided by the Kenneth T. and Eileen L. Norris Foundation; the Institute is still seeking $3.5 million to fulfill its obligation to the CARMA partnership. —*Vannessa Dodson*

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