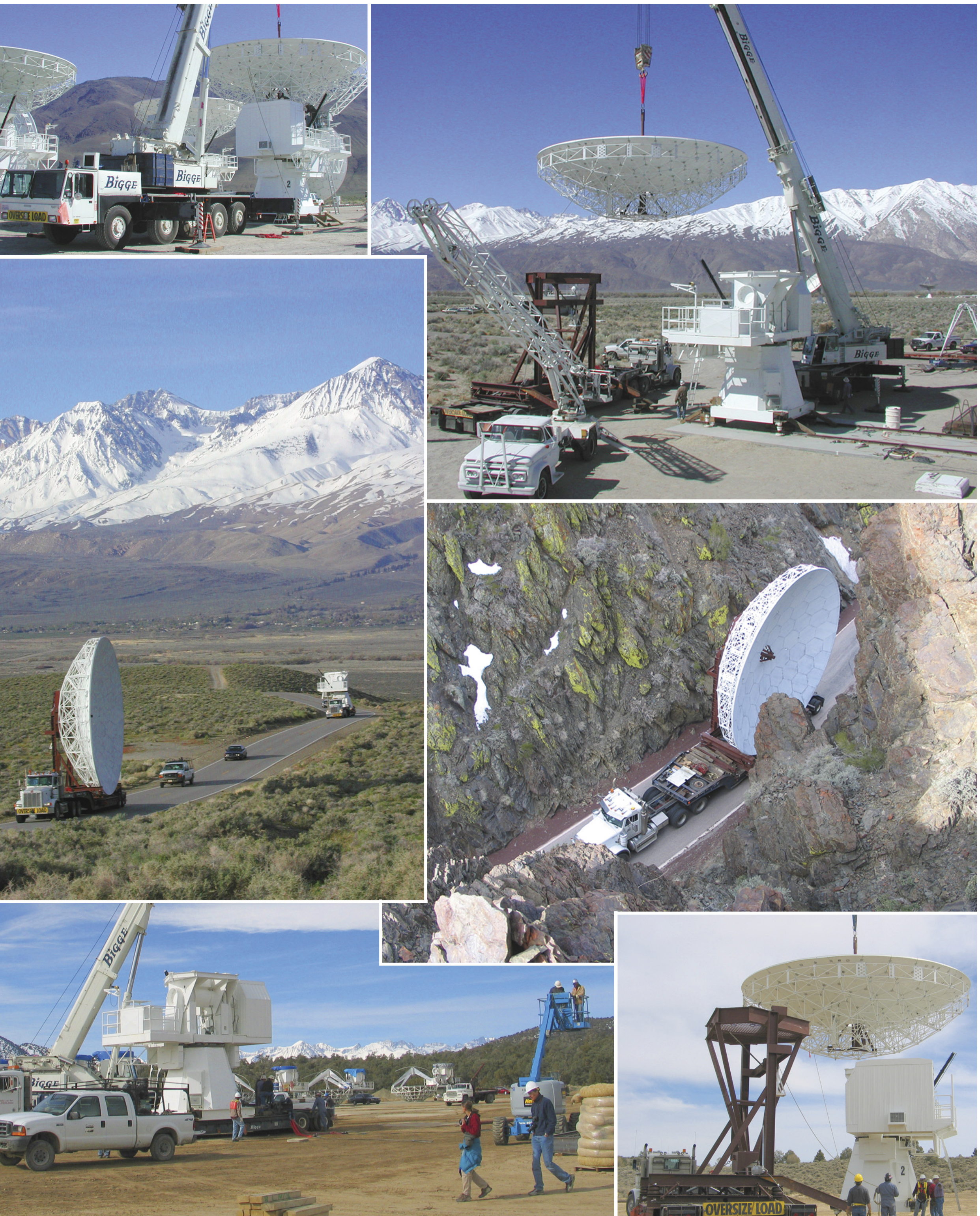
California Institute of Technology

E&S

ENGINEERING AND SCIENCE

Volume LXVIII,
Number 3,
2005

In This Issue

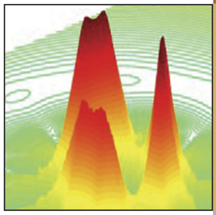


If you think packing and moving a china hutch is a chore, just be glad that your dishes aren't 10 meters in diameter! It took the staff of Caltech's Owens Valley Radio Observatory and a crew from Bigge Crane and Rigging months to prepare and dismantle the observatory's six millimeter-wave radio telescopes (top row), truck them a dozen miles or so across the desert and into the mountains (middle), and reassemble them at Cedar Flats (bottom). Water molecules absorb millimeter waves, and at 7,300 feet, nearly twice the elevation of the telescopes' former home, the air is drier and the "seeing" much improved. For more on the move, see the inside back cover.

California Institute of Technology

E&S ENGINEERING AND SCIENCE

Volume LXVIII, Number 3, 2005



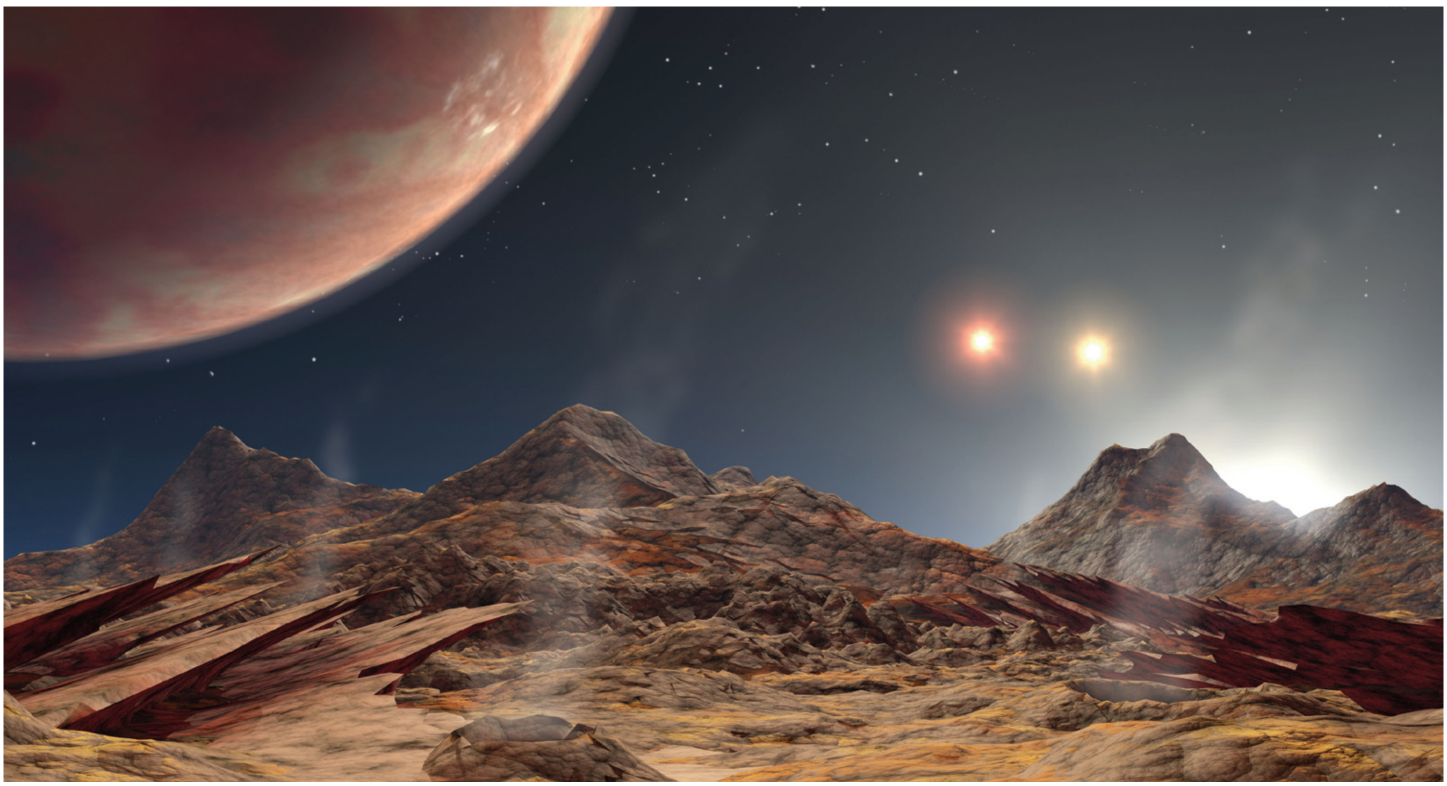
Departments

On the cover: The 200-inch Hale Telescope at Caltech's Palomar Observatory has remained at the forefront of astronomy for an unprecedented six decades by continuously pioneering the most advanced technologies of the day. Now it's a laser guide star, seen here shooting up the side of the telescope and out into the night sky. For more on how this will allow the Hale to take pictures that will rival the Hubble Space Telescope for sharpness, 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, 8-9, 11-13 – Scott Kardel; inside front cover – Doug Bock, Markus Raschke; 2 – NASA/JPL-Caltech; 4-5 – NASA/JPL-Caltech / U. of Maryland; 14, 16, 17 – Jay Winkler, Doug Cummings; 17, 20, 21, 22 – Jennifer Lee; 26, 27, 34-35, 39-42 – Doug Cummings; 43 – Elizabeth Horowitz, Lee Salem/California Science Center; 44 – Peter Mendenhall, Mark Konishi, Bob Paz; inside back cover – Dick Plambeck, Markus Raschke

Visit us on line at **http://pr.caltech.edu/periodicals/EandS/**



Our understanding of how planets form has been upended by postdoc Maciej Konacki, who's found a Jupiter-sized planet (in the upper left corner, shown here from the vantage point of a hypothetical moon) under three suns. The first planet ever discovered in a system where the companion star is neither distant nor small, it orbits the main star of a close triple, HD 188753, at about one-tenth the distance between our sun and Mercury. The secondary and tertiary stars form a tight binary of 1.63 solar masses, and orbit the 1.06 solar-mass primary about where Saturn does in our system. Since Konacki's planet should have formed somewhere around or beyond where our asteroid belt is—a zone that should have been swept clean by the double star—how it managed to coalesce is a mystery. But the fact that it did is good news for planet hunters, as binary and multiple stars outnumber single ones in our neighborhood by some 20 percent. Konacki calls this new class of planets Tatooines after Luke Skywalker's home world, which orbits a close binary. HD 188753 is about 149 light-years from Earth in the constellation Cygnus. Konacki used Caltech's 10-meter Keck I telescope, and the work appears in the July 14 issue of *Nature*.

PICTURE CREDITS: 2 – NASA/JPL-Caltech; 4-5 – NASA/JPL-Caltech / U. of Maryland

LIGO Rides Out Katrina

The Laser Interferometer Gravitational-Wave Observatory (LIGO) escaped serious hurricane damage to its Livingston, Louisiana installation (called LLO), some 50 miles west of the path of Katrina's eye. On August 30, Michael Zucker, head of the Livingston observatory (there is a twin facility in Hanford, Washington) reported via an e-mail from MIT, Caltech's partner on the project, that "site power is back on and the vacuum system is in good shape." However, "the internet connection was severed by falling trees, so there's no point trying to connect to LLO computers or sending e-mail to LLO personnel just yet. Nonessential personnel are asked to remain home; we will keep everyone posted as recovery progresses and will let you know as soon as operations resume." □—*DS*

Powering the Planet

With (pre-hurricane-Katrina) gasoline prices hovering at $3 per gallon, few Americans need convincing that another energy crisis is imminent. And this time it may be for keeps. Such people as Caltech Vice Provost David Goodstein argue that global oil production will peak in the next decade or so and then inexorably decline. There's talk of moving to a "hydrogen economy," but how to make the hydrogen? The best and cheapest methods currently available involve burning coal or natural gas, which means more greenhouse gases and more pollution; using natural gas would also merely replace our dependence on foreign oil with a dependence on foreign gas.

"Clearly, one clean way to get hydrogen is by splitting water with sunlight," says Harry Gray, Caltech's Beckman Professor of Chemistry. Gray leads a group of Caltech and MIT chemists in a National Science Foundation-funded initiative, called "Powering the Planet," to pursue cheap, clean, and efficient ways to store solar energy. "Presently, this country spends more money in 10 minutes at the gas pump than it puts into a year of solar-energy research," says Nate Lewis (BS, MS '77), the Argyros Professor and professor of chemistry. "But the sun provides more energy to the planet in an hour than all the fossil energy consumed worldwide in a year."

But the sun sets every night, and energy demand continues day and night, summer and winter, rain or shine. And electricity can't really be stored in bulk—how many D batteries would it take to run the Empire State Building overnight?—while hydrogen can. Which gets us back to the question of how to make hydrogen.

Your junior-high chemistry lab broke water into hydrogen and oxygen by electrolysis, using a platinum catalyst. And platinum has been selling all year for more than $800 per ounce. So the Caltech group is starting by looking for a cheaper catalyst. In an upcoming article in *Chemical Communications*, Associate Professor of Chemistry Jonas Peters and his colleagues describe a cobalt catalyst. "This is a good first example for us," says Peters. "A key goal is to try to replace platinum, which is extremely expensive, with something like cobalt or, even better, iron or nickel. We have to find a way to make solar-derived fuel cheaply if we are to enable widespread use of solar energy as society's main power source."

The Caltech chemists also hope to fit out a local school to run entirely on solar energy. The initial conversion would likely be done with existing solar panels, but the idea is to use the school as a fairly large-scale testing facility. "We'd build it so that we could troubleshoot solar converters we're working on," explains Gray.

The ultimate goal is a "dream machine with no wires in it," Gray says. "We visualize a solar machine with boundary layers, where water comes in, hydrogen goes out one side, and oxygen goes out the other." Such a machine will require a number of breakthroughs, but as Lewis says, "If somebody doesn't figure this out, and fast, we're toast, both literally and practically, due to a growing dependence on foreign oil combined with the increasing projections of global warming."

The "Powering the Planet" initiative is one of three new "chemical bonding centers" announced by the National Science Foundation on August 11. (The other two are at Columbia and UC Irvine.) The initiative has been funded at $1.5 million for three years, with the possibility of $2 to $3 million per year thereafter if the work appears promising. In addition to Gray, Lewis, and Peters, the initiative includes chemists Jay Winkler (PhD '84) and Bruce Brunschwig, both of Caltech's Beckman Institute, and MIT's Dan Nocera (PhD '84) and Kit Cummins.

The other authors of Peters' paper are Lewis, Brunschwig, postdoc Xile Hu, and undergrad Brandi Cossairt. □—*RT*

For the Record

The picture credits in the last issue of *Engineering & Science* accidentally omitted Shaun Healy, the cartographic deity of Geology and Planetary Sciences, who edited the fault map of Sumatra for us and helped prepare it for publication. Without his expert assistance, *E&S*'s first centerfold would not have been possible. □—*DS*

Can B Cells Be A Students?

Caltech president, Nobel laureate, and professor of biology David Baltimore and Pamela Bjorkman, the Delbrück Professor of Biology and an investigator with the Howard Hughes Medical Institute, have received a five-year, $14 million grant to try what Baltimore and postdoc Lili Yang (PhD '04) have dubbed "instructive immunotherapy." Proposed as an alternative to vaccines, the method would insert antibody-producing genes into the hematopoietic stem cells that live in our bone marrow. These cells produce billions of blood cells daily, including B cells. B cells, a type of white blood cell, develop into antibody-producing plasma cells, so programming them to recognize a disease that has defied vaccination—such as HIV, which Baltimore and Bjorkman will tackle as a test case—could confer lifelong immunity.

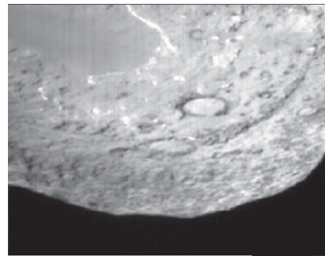
The grant, one of 43 totaling $437 million, was announced on June 27 by the Grand Challenges in Global Health initiative. The initiative, bankrolled chiefly by the Bill and Melinda Gates Foundation, funds the creation of "deliverable technologies"—effective, inexpensive to make, easy to distribute, and simple to use—for developing countries. □—*DS*

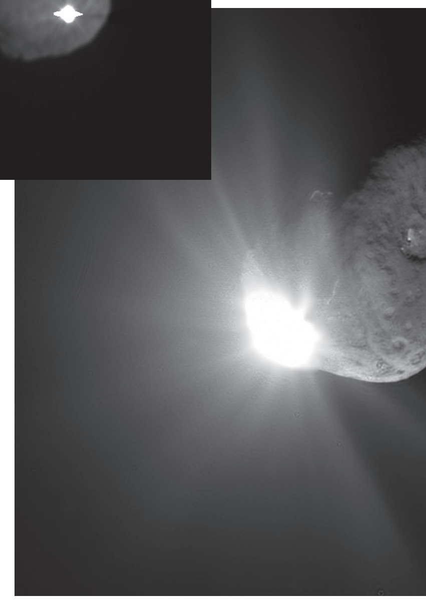
Ultrafast in 4-D

Nobel Laureate Ahmed Zewail, the Pauling Professor of Chemical Physics and professor of physics, has received an $18 million grant from the Gordon and Betty Moore Foundation to create the Ultrafast Science and Technology (UST) Center. The center will focus on a new scientific discipline that Zewail has dubbed "physical biology."

Because life processes are so complex, understanding them completely requires that *all* the atoms in a biological structure be observed over time as they go about their business. The UST Center will develop the science and technology for imaging biological and molecular structures in space and time using diffraction, spectroscopy, and microscopy in order to address the fundamental physics of molecular and biological behavior at varying levels, from the atom to the cell.

"All existing methods have focused on either the spatial *or* the temporal resolution," said Zewail, "but in complex systems, including biological systems, the combined resolutions are essential for a unified picture. The UST Center will be a nucleus for interactions between faculty and research assistants from the different disciplines of physics, chemistry, and biology. As unique techniques of "seeing" are developed by Zewail and colleagues, said Tom Tombrello, Kenan Professor and chair of the Division of Physics, Mathematics and Astronomy, "We shall soon be in a position to see the molecules of life in action." □—*RT*



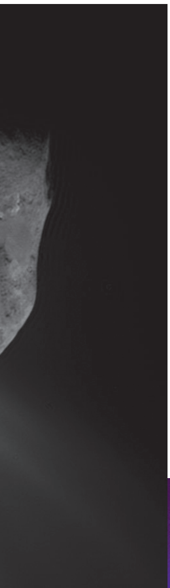


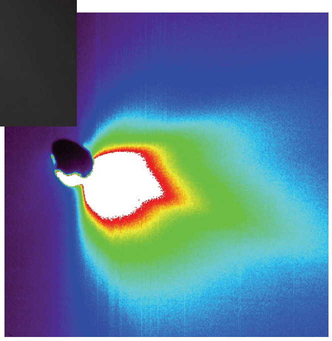
From above to far right: 1. A shot from the probe's targeting camera 90 seconds before the 10-kilometer-per-second impact. 2. The mother ship's camera registers the hit—the nascent debris plume is illuminated by sunlight, and may even have been heated to incandescence. 3. Sixty-seven seconds later, the highly reflective plume has lit up the whole soot-black nucleus, which is some six kilometers across. 4. A backward glance about 50 minutes later shows the growing plume's brightness in false color; the crater, estimated to be 100 to 300 meters in diameter, is on the comet's far side.

Comet Kablooie

Deep Impact, the spacecraft emphatically *not* named after the comet-crash movie, crashed into its comet for real at 10:52 p.m. PDT on July 3. The preholiday fireworks display astonished scientists by being easily visible to the naked eye here on Earth. The plume was bigger and much more reflective than expected, indicating that the comet is covered with a thick layer of very fine dust—"more like talcum powder than beach sand," says Principal Investigator Michael A'Hearn of the University of Maryland, College Park, "and definitely not an ice cube." No large chunks of debris were seen, meaning that the comet probably does not have an icy crust.

The 372-kilogram, copper-clad (to prevent spectral contamination; copper is not found in comets), washing-machine-sized impactor had been released from its mother





ship at 11:07 p.m. PDT July 2, and then steered itself independently into Comet Tempel 1's path, correcting its course three times in the process. The mother ship's sensors saw water, carbon dioxide, and unidentified hydrocarbons in the plume.

A whole fleet of spacecraft and innumerable telescopes have also been watching the show. The first slew of papers will be published in a September issue of *Science*.

The University of Maryland is in charge of the overall mission science; the spacecraft is being flown and managed by JPL, and was built by Ball Aerospace & Technologies Corp. in Boulder, Colorado. □—*DS*

The Dean, Remembered

Saul Bellow died on April 5 at age 89. This photo was taken 25 years earlier, during his stay at Caltech.

In January 1980 my husband, Dan Kevles, then Caltech's Executive Officer for the Humanities, was asked by Roger Noll, the Chair of the Humanities and Social Sciences Division, to arrange "something" for the spouse of a Sherman Fairchild Fellow in Mathematics. Alexandra Ionescu Tulcea was about to arrive from Northwestern University with her husband, a recent Nobel laureate in literature. Could Dan work out a plan with Saul Bellow?

So it came to pass that Dan met Saul and took him for a drive in our 1967 Jaguar sedan, a car that was even then almost a classic. Though dilapidated, at least it ran, which the '56 Jaguar drophead convertible Dan was restoring in our garage did not.

Dan and Saul agreed that Saul would offer a series of seminars with these ground rules—no assignments, no agenda, just literary discussions for the Caltech community. These would meet Wednesday afternoons and Dan would escort him to the auditorium of the new Beckman Laboratory, across from Baxter Hall, where Dan had his office, and where an office was assigned to Saul.

The term "seminar" suggests an intimate and informal discussion, but these meetings were neither. Saul Bellow's fame then was akin to Richard Feynman's after the *Challenger* hearings, so it was not surprising that the auditorium was filled from the first meeting to the last. Postwar readers loved the American voice of his novels *The Adventures of Augie March* and *Henderson The Rain King*; and *Humboldt's Gift* had won a Pulitzer Prize in 1976, the year of his Nobel.

Wednesdays that spring I attended his seminars. The regulars, besides me and Dan, included faculty, students, and some of Caltech's contingent of writers. Saul always took questions, some of which must have taxed his patience. I remember him responding to "Just how do you start writing every day?" by explaining that first he checked his typewriter to see that all the letters of the alphabet were still there. On a more serious note, he told us that he reread all of Shakespeare every year or two.

When not lecturing or working on his next book, Saul seems to have wandered around the campus talking and listening to scientists, who might have sounded different to him from his humanist colleagues on the Committee on Social Thought at the University of Chicago. At Caltech he got to know at least one of our most idiosyncratic scientific characters, apparently providing himself with background for his work-in-progress. He even took time to offer valuable advice to me about my as-yet-unfinished historical novel.

As the Bellows' stay drew to a close, I decided to have a dinner party to thank him for his help and to meet Alexandra. Besides us, the guest list included astronomer Marshall Cohen and his wife, Shirley, who then taught mathematics at John Muir High School in Pasadena, and philosophy professor Will Jones and his wife, Molly Mason Jones, a child psychologist then at Pomona College. Fifteen minutes before the guests were expected, the first course caught fire at almost the exact moment that the doorbell rang. The Bellows were early. I can still hear Dan telling me, "These are your guests, go take care of them. I'll put out the fire."

The near-disaster notwithstanding, the rest of the evening must have been successful, because no one wanted to break up the party. Marshall suggested that the group should reconvene during the week for a visit to

Palomar. We jumped at the idea, and Marshall promised to see about making arrangements at the telescope and to try to get an Institute car.

For the trip to the observatory, six of us (the Joneses did not come) met again at my home in southwest Pasadena, and piled into the limo in mid-afternoon. The plan was to stop en route for a picnic supper and arrive at the observatory as it grew dark. As the weather wavered between drizzle and overcast, we decided against the picnic but did stop to stretch our legs at the Pala Mission, a regular stop on the way up the mountain.

It was raining when we reached the observatory, and Marshall explained that they would not open the dome unless the rain stopped. Disappointed, we found an office inside where we ate our "picnic." Then we scattered to explore the cavernous space beneath the dome. But soon, to my surprise, I heard a grinding noise and looked up to see the dome parting. As I stared, it opened with deliberate speed and the stars—seemingly closer than they would have appeared were I standing outside in the woods—glowed in the clear sky. We were all excited by our change of fortune and sought each other to share the moment.

Saul . . . was sitting in the gondola that was rising slowly above us along the inner surface of the dome, heading towards the prime-focus cage at the top. He had "seized the day" (although it was night) the instant he learned that the dome would open. Later, on the ride down the mountain, he was silent—struck mute by the experience, perhaps, or fixing the impression in his mind.

But Saul was not there—he was sitting in the gondola that was rising slowly above us along the inner surface of the dome, heading towards the prime-focus cage at the top. He had "seized the day" (although it was night) the instant he learned that the dome would open. Later, on the ride down the mountain, he was silent—struck mute by the experience, perhaps, or fixing the impression in his mind. I wouldn't know until later, in 1982, after he published his ninth novel, *The Dean's December*.

Although the first page carries the usual disclaimer about the book's fictional nature, it was obvious to me that Bellow had drawn on some of the people, places, and situations he had encountered that spring in Southern California. Though it takes place in Bucharest and Chicago, *The Dean's December* is in a number of ways a Caltech novel.

The protagonist is a journalist (not a novelist), the Dean of a Chicago university. He is married to a Romanian astronomer (not a mathematician). No mirror of the Bellows, but a good facsimile. As I turned the pages I encountered Clair Patterson, Caltech's great geochemist, in the character of Beech, a scientist obsessed, as Patterson was, with waking up Congress and the citizenry to the dangers of lead—from automobile emissions and paint—to the vulnerable brains of children. As Saul has Beech say: "Millions of tons of intractable lead residues [are] poisoning the children of the poor. . . . It's the growing children who assimilate the lead fastest. The calcium takes it up. And if you watch the behavior of those kids with a clinical eye, you see the classic symptoms of chronic lead insult. . . . Crime and social disorganization in inner city populations can all be traced to the effects of lead. It comes down to the nerves, to brain damage."

Bellow hadn't made any effort to mask Patterson. He even credits Beech, like Patterson, with having used radioactivity to "measure the age of the planet." I wasn't surprised that Bellow was impressed by Patterson's theories. His proselytizing helped to create the Clean Air Act of 1970 and ultimately brought about the removal of lead from gasoline. Bellow's Dean is not convinced, but he listens, as Bellow clearly did.

In the character Varennes, the public defender, I recognized some qualities of my husband, Dan: "healthy, a normal person, with a preference for decent liberal thought . . . his hobby was fixing up classic cars." I recalled how Saul had shuddered every time he entered our quasi-wreck.

On the last pages of the book, I found myself, once again, on the road to Palomar. This time I was with the Dean and his wife, Minna, who had arranged time on the two-hundred–inch. On the drive they stopped at the mission and looked at some handicrafts. This time there was no doubt that the dome would open; Saul had given them beautiful weather—and why not? This was his world.

The Dean ascends with Minna and a resident astronomer in a small elevator that swings in a curve as it moves upward. "If you came for a look at astral space it was appropriate that you should have a taste of the cold *out there*, its power to cancel everything merely human . . . Segments of the curved surface opened quickly and let in the sky—first a clear piercing slice. All at once there was only the lift, moving along the arch. The interior was abolished altogether—no interior—nothing but the open, freezing heavens. If this present motion were to go on, you would travel straight out. You would go up into the stars."

In this description I found the clue to why Saul had been so quiet on our real ride home. He wasn't simply fixing the experience in his memory, he was still in the grip of his ascent. In fact, *The Dean's December* ends with the following words:

"The young man pressed the switch for the descent. 'Never saw the sky like this, did you?'

'No. I was told how cold it would be. It *is* damn cold.'

'Does that really get you, do you really mind it all that much?'

They were traveling slowly in the hooked path of their beam towards the big circle of the floor.

'The cold? Yes. But I almost think I mind coming down more.'"

It is hard to imagine that Bellow ever would have written that passage had he not visited Caltech and Palomar. □—*BK*

Bettyann Holtzmann Kevles is the author of Almost Heaven: Women on the Frontier of Space *and* Naked to the Bone: Medical Imaging in the Twentieth Century*, as well as other books. Her husband, Daniel J. Kevles, the Koepfli Professor of the Humanities, Emeritus, taught at Caltech from 1964 to 2001.*

All It Needs Is a Divining Rod

JPL's Mars Reconnaissance Orbiter lifted off from Cape Canaveral at 4:43 a.m. Friday, August 12, after two postponements, and is slated to arrive at the Red Planet on March 10, 2006. Six months of aerobraking will follow—to an orbit 20 percent tighter than those of our current eyes there—before the spacecraft gets down to the business of following the water. The orbiter carries three cameras, including the largest telescopic camera to ever orbit another planet, capable of seeing dishwasher-sized rocks; a visible/infrared imaging spectrometer that can identify minerals, particularly those revealing a sodden past, in swatches the size of the grassy portion of a softball infield; an atmospheric profiler; and a ground-penetrating radar from the Italian Space Agency that can look up to a kilometer deep for large deposits of frozen or liquid water.

In order to keep up with this flood of information, the orbiter's communications systems can transmit 10 times as much data per minute as any previous Mars mission. This will come in handy when the orbiter begins additional duty as a relay station for the Phoenix lander, set to touch down in the north polar region in May 2008, and the Mars Science Laboratory rover, arriving in October 2010. The Mars Reconnaissance Orbiter was built by Lockheed Martin Space Systems of Denver, Colorado. □—*DS*

Fish Heads, Fish Heads Eat Them Up, Yum!

Can't stomach Elvis's fried peanut butter 'n 'nanner sandwiches? It could all be in your head—it appears that it may be possible to dislike a food without even being able to recognize its taste, as two different regions of the brain seem to be responsible for the two processes. In the June issue of *Nature Neuroscience*, Caltech professor of psychology and neuroscience Ralph Adolphs and his colleagues at the University of Iowa report on a patient who is unable to name even familiar foods by taste or by smell, and shows remarkably little preference in his choice of food and drink.

The 72-year-old man, known as "B," had had a brain infection that destroyed his amygdala, hippocampus, the nearby temporal cortices, and the insula, and damaged several other structures. As a result, he has a memory span of about 40 seconds, somewhat similar to that of the protagonist in the film *Memento*. B is also unable to recognize familiar people and many objects, although his vision and his use of language are unaffected.

B, several other subjects with brain damage, and several normal subjects were all offered salty and sweet drinks. Everyone drank the sweet drinks and said they enjoyed them, and all—with the notable exception of B—said they found the saline drink disgusting. B drank the saline solution with a pleased expression, saying it "tasted like pop." However, when he was asked to sip both a salty and a sweet drink and to continue drinking the one he preferred, he chose the sweet one.

It appears that B, like most people, has some fundamental preference for sweet drinks over salty ones even if he is unaware of the identity of either, but that he can only exercise this preference when he can compare them within the 40-second span of his memory. In other words, the sensation of taste and the innate preference are separate processes whose divorce is revealed by B's memory loss.

Of course "our likes and dislikes in taste stem from both innate and cultural causes," Adolphs remarks. "You may like sushi or bitter melon or certain smelly cheeses, whereas other people turn away from these foods in distaste."

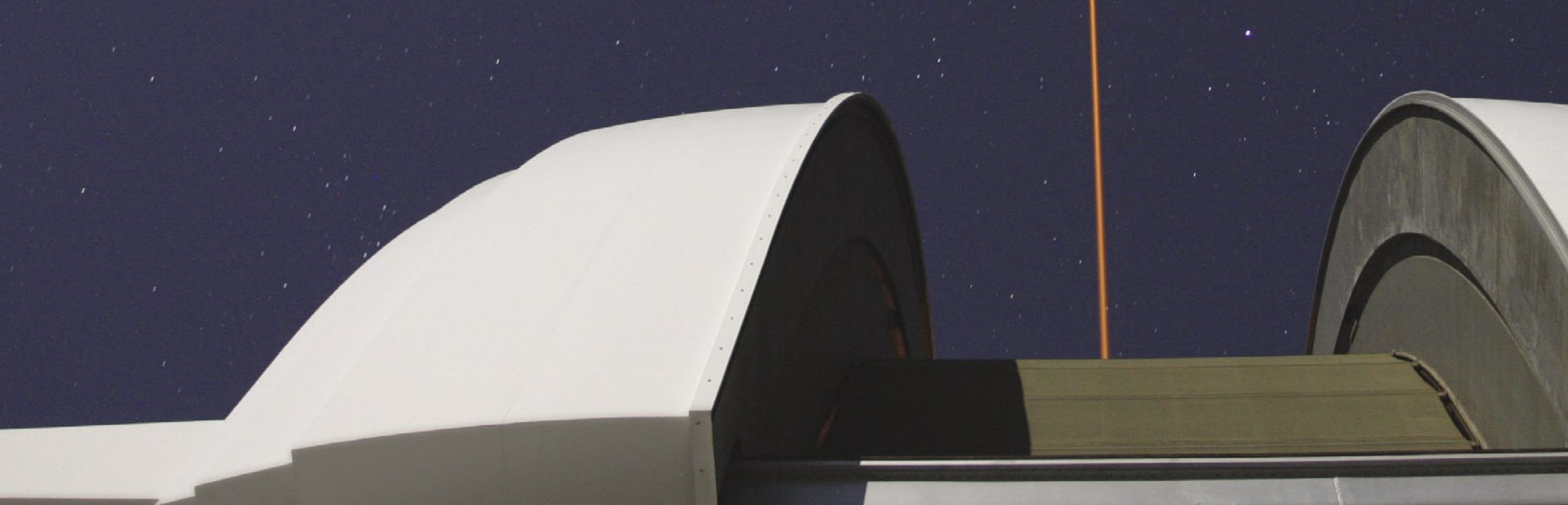
The paper's coauthors are Daniel Tranel, Michael Koenigs, and Antonio R. Damasio, all of the University of Iowa's Department of Neurology and Neuroscience. □—*RT*

Xena, Warrior Planet

Associate Professor of Planetary Astronomy Michael Brown and colleagues have discovered a planet larger than Pluto in the outlying regions of the solar system. The planet is a typical member of the Kuiper belt, but its sheer size means that it can only be classified as a planet, Brown says. Currently about 97 times Earth's distance from the sun, it becomes the farthest-known object in the solar system, and the third brightest of the Kuiper-belt objects. "It is visible in the early-morning sky, in the constellation Cetus," says Brown, who made the discovery with colleagues Chad Trujillo, of the Gemini Observatory, and David Rabinowitz, of Yale University, on January 8.

Brown and Trujillo first photographed the new planet with the 48-inch Samuel Oschin Telescope at Palomar Observatory on October 31, 2003. However, the object was so far away that its motion was not detected until the data was reanalyzed last January. The planet's size is inferred from its brightness, and "if it reflected 100 percent of the light reaching it, it would be as big as Pluto," says Brown. This is unlikely, however, so he estimates that it's probably one and a half times Pluto's size.

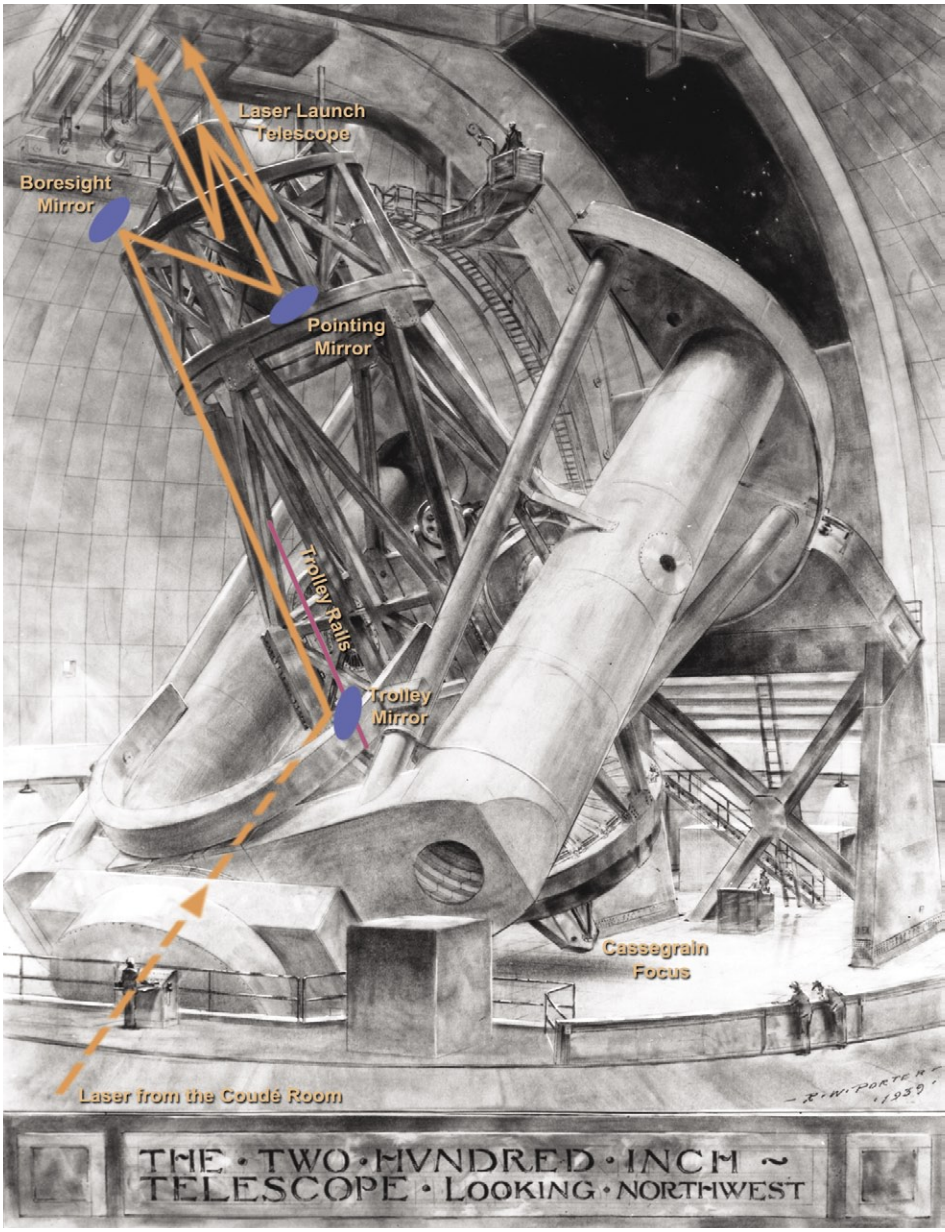
A name has been proposed to the International Astronomical Union, but pending approval Brown *et. al.* have been calling their find Xena, in a nod to the Planet X beloved by science-fiction writers. □—*RT*



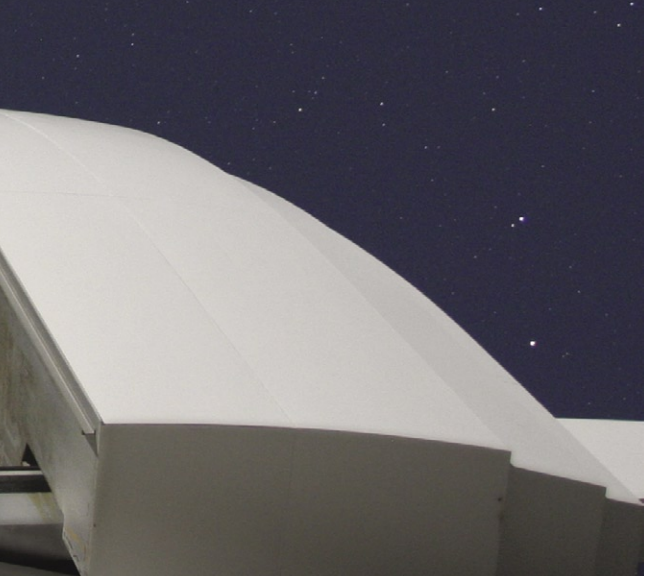
Untwinkle, Untwinkle, Laser Star

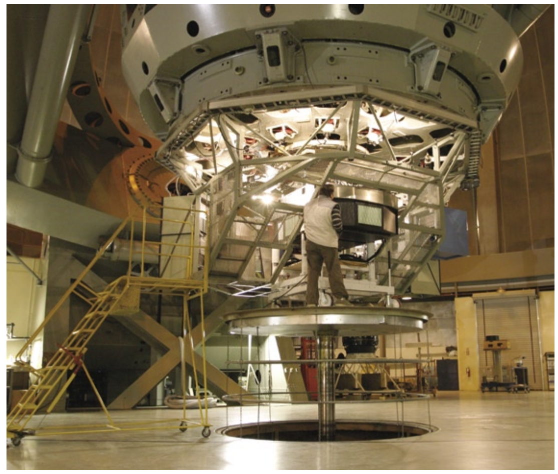
by Scott Kardel

Scott Kardel is the public affairs coordinator at Caltech's Palomar Observatory.



Above: Like the Luxor Las Vegas (although perhaps more Mayanesque in this perspective), the Hale sends a beacon into the night sky. Right: A schematic of the laser guide-star system, superimposed on one of a series of drawings made by Russell W. Porter. (The adaptive-optics mirror and the wave-front sensor live at the Cassegrain focus.) Astonishingly, this set of magnificent pencil sketches, which took a dozen years to draw, were prepared from blueprints before the telescope was even built.





PHARO being installed for an observing run by Steve Kunsman and Karl Dunscombe (hidden behind camera), members of the Palomar day crew.

Imagine what the lives of astronomers would be like if they were doomed to live at the bottom of the ocean. Even if the water were crystal clear, as they gazed up through it in an attempt to see beyond their world, the ocean's currents and ripples would greatly distort their view. In rare moments the water might briefly settle enough to see clearly, but the overall situation would be dismal at best. In fact, we live under an ocean of moving air. This ocean, our atmosphere, has its own currents and ripples that, among other things, make the stars twinkle. Even the best telescopes' images are somewhat blurred, leaving some objects and details forever hidden in the fuzz.

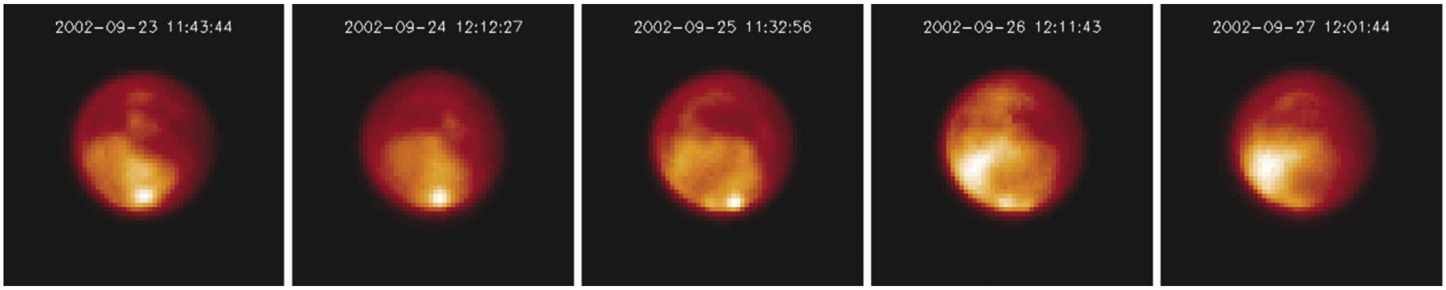
In an attempt to defeat these distortions, astronomers have been putting telescopes above as much of the atmosphere as possible—on high mountains and even in space. Spaceborne telescopes have many advantages over their ground-based counterparts. From their lofty vantage point it is never cloudy, city lights do not brighten the sky, the stars do not appear to twinkle, and all types of light are accessible. (Our ocean of air absorbs many wavelengths of interest to astronomers—the ultraviolet, the far-infrared, and the microwave, to name a few.) However, it is far easier and much less expensive to build and service telescopes here on Earth.

Now there's a way to produce spacelike clarity from Earth-based telescopes. In 1991, the U.S. military declassified much of its research on a technique known as adaptive optics. Adaptive-optics systems make real-time corrections that undo the distortions of the atmosphere, providing almost spacelike sharpness from the ground.

A team of astronomers from Caltech, led by Richard Dekany (BS '89), and JPL, led by Mitchell Troy, started developing an adaptive-optics system for the Palomar Observatory's venerable 200-inch Hale Telescope about a decade ago. The system has been in wide use since 1999. When it is operating, incoming light passes through the telescope's normal optical path to the Cassegrain focus—the only place on the telescope that can hold something as massive as the adaptive-optics equipment. The system uses a device called a wave-front sensor to measure the changing, wavering shape of a bright star, called a guide star, that lies in the telescope's field of view. A computer then rapidly calculates what undistortions would be needed to make the star a pinpoint of light again. To make these corrections, the computer directs 241 actuators that push and pull on the back side of a flexible, 6-inch mirror to adjust the reflective surface on the front. The corrections take place faster than the atmosphere changes—up to 2,000 times a second, making this the world's fastest such system. The result is almost like getting a new pair of glasses—suddenly the universe comes into sharper focus. These images are currently recorded by the Palomar High Angular Resolution Observer (PHARO), a camera sensitive to the near-infrared, developed by a team from Cornell University; plans are in the works to build a spectrograph as well, which would give detailed information on such things as the chemical composition and velocity of the target.

Palomar's astronomers have used the adaptive-optics system for a variety of projects over the last few years. Within our own solar system, astronomers including Don Banfield (MS '90, PhD '94), Phil Nicholson (PhD '79), and Barney Conrath, all of Cornell, have made long-term weather observations of the distant gaseous worlds Uranus and Neptune as they slowly move through their seasons. The system even has enough resolution to accurately measure the composition of icy

A false-color image of Neptune, taken by Antonin Bouchez with the Hale's adaptive optics.



This series of pictures, shot variously by Troy, Dekany, JPL's Christophe Dumas, postdoc Maciej Konacki, then-postdoc Chad Trujillo, Bouchez, and grad student Stan Metchev, run from September 23 to November 18, 2004, during which Titan rotated 184 degrees. Careful analysis shows that some of the bright regions are methane clouds that come and go, while others are surface features that rotate with the planet.

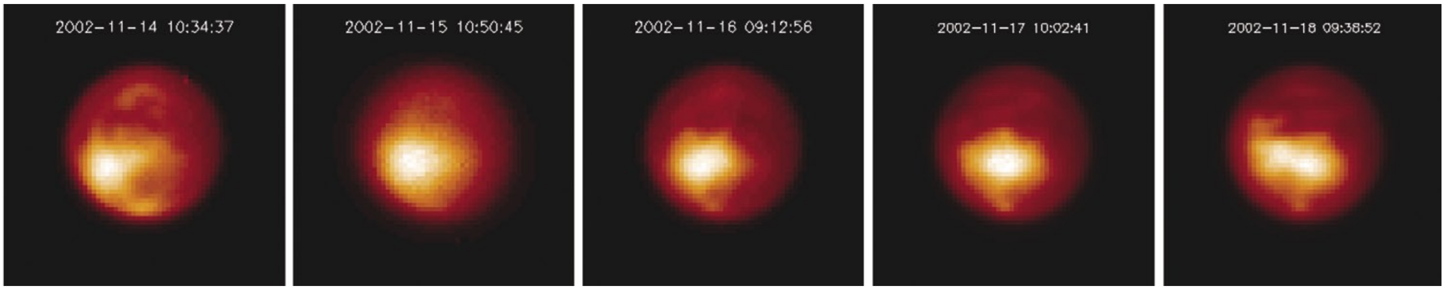
Pluto and its moon, Charon. In a case of being at the right place at the right time, grad student Antonin Bouchez (PhD '04), now Caltech's Adaptive Optics Lead, watched Saturn's moon Titan occult, or pass directly in front of, a pair of stars, and in the process discovered new details in the structure of Titan's stratosphere, including strong, jet-stream-like winds at mid to high northern latitudes. (Movies of the occultation are available at http://www.gps.caltech.edu/~antonin/occultation.) Meanwhile, Cornell's Jean-Luc Margot is studying binary asteroids, pairs of asteroids that orbit each other tightly, to determine their compositions and their orbits about each other. And Palomar astronomers had balcony seats for the crash of JPL's Deep Impact probe with comet Tempel 1. In fact, because they were watching the event live rather than waiting for a downlink, they knew the mission had been a success before its own controllers did!

Guide stars of sufficient brightness are few and far between, and since the guide star and the object of the astronomer's desire have to be in the telescope's field of view at the same time, the technique can only be used over about 1 percent of the sky.

Beyond the solar system, astronomers have used the Hale's adaptive optics to study the intricacies of star formation and to search the area immediately around young stars for planetary or brown-dwarf companions. The key to such work is the ability to resolve fine details, especially in the quest for brown dwarves. Brown dwarves, which usually have masses between 10 and 75 times the mass of Jupiter, are too small to undergo nuclear fusion, like a star does, yet too large to be considered planets. Astronomers generally try to find brown dwarves by photographing them directly—a tricky proposition because they're tiny and very faint compared to their big, bright companion stars. But a special camera called a coronagraph, which blocks out most of the star's light with a small disc, allows the brown dwarf's light to emerge from the glare. (Incidentally, the first brown dwarf was discovered using Palomar's 60-inch telescope, which was armed with a primitive adaptive-optics system built into its coronagraph—see *E&S* 1996, No. 1.) Assistant Professor of Astronomy Lynne Hillenbrand and grad student Stan Metchev have searched some nearby stars for hidden brown-dwarf companions and found only one, which was actually overlooked in their Palomar images and noticed later at Caltech's 10-meter Keck II telescope, also sporting an adaptive-optics system. (The Palomar hunt *did* bag three low-mass stellar companions—0.13 to 0.2 solar masses, as opposed to the brown dwarf's 0.06.) Joe Carson, then with Cornell, now with JPL, also tried a brown-dwarf survey, and of the 80 young nearby stars he examined he didn't find any! This seems to confirm the notion, advanced in the late 1990s, that brown dwarves don't form too close to sun-like parents.

But a major breakthrough would be needed to make adaptive optics really useful for all astronomers. Guide stars of sufficient brightness are few and far between, and since the guide star and the object of the astronomer's desire have to be in the telescope's field of view at the same time, the technique can only be used over about 1 percent of the sky.

The obvious solution is to create your own guide stars and place them wherever you want them—and as silly as that may sound, that is exactly what astronomers at a handful of observatories are now doing. This involves shining a narrow sodium-laser beam up through the atmosphere. (The beam is the same yellow color produced by the low-pressure sodium streetlights that are recommended for minimizing glare and maintaining dark, astronomy-friendly skies.) At an altitude of about 100 kilometers, the beam interacts with a small amount of naturally occurring sodium gas, making it glow.



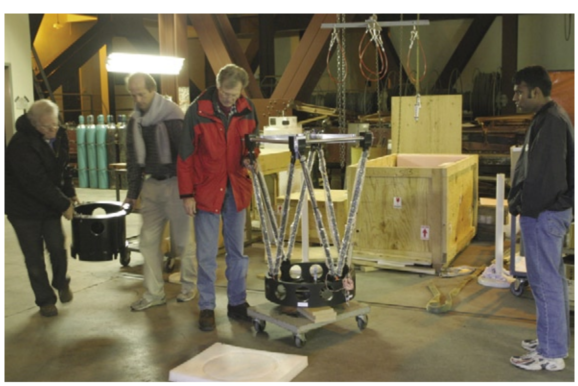
This glowing gas serves as the artificial guide star. The outgoing laser beam is too faint to be seen, except by observers very close to the telescope, and the guide star is even fainter. It can't be seen with the unaided eye, yet it is bright enough to allow astronomers to make their adaptive-optics corrections.

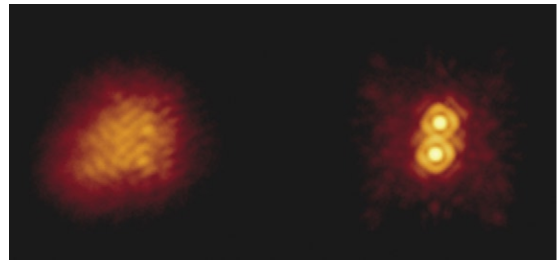
Planning work on the Hale's laser guide-star system began several years ago. Converting any telescope to make use of so much new technology is a challenge, and several large pieces of equipment had to be designed and built for the project.

The heart of the system is the sum-frequency laser. Built by the University of Chicago's Ed Kibblewhite, the laser has a unique design that consists of two pulsed, diode-pumped, infrared lasers enclosed in a temperature-controlled box the size of a phone booth. The two invisible beams are mixed to produce a pulsed, visible beam at a wavelength of 589 nanometers, or billionths of a meter—the same wavelength emitted by sodium atoms. The pulsing helps avoid backward scattering of the laser light, allowing a smaller guide star to be produced. The laser is housed in a large room, known as the Coudé room, located just south of the telescope's mounting.

The beam travels out of the Coudé room to the side of the telescope, where it is met by a set of motorized mirrors that are controlled in real time to keep the beam accurately aligned. These mirrors direct the beam up the side of the telescope and are attached to another new piece of equipment—a

Right: Ed Kibblewhite and his sum-frequency laser. Far right: The laser trolley and its track were hoisted into place with the five-ton traveling crane on the underside of the dome. The trolley is the flat box at the top of the track, which dangles along the left edge of the picture. Below: Observatory Superintendent Bob Thicksten (far left) and Del Johnson carry a component of the Laser-Launch Telescope, the rest of which sits on a dolly between Member of the Professional Staff Hal Petrie (BS '68) and Viswa Velur.





IW Tau, a known binary star, as seen with (far right) and without the adaptive optics. The stars are 0.3 arc seconds apart. The images were taken by JPL's Charles Beichman, a senior faculty associate in astronomy at Caltech, and Angelle Tanner, a JPL postdoc.

"laser trolley" that rides on a track installed along the barrel of the telescope itself. This was no mean feat, as the track and trolley assembly weighs 800 pounds. But the telescope and its mounting weigh some 530 tons—many of its larger parts had to be built in shipyards, which were the only facilities capable of handling pieces of steel of such size; this also accounts for the Hale's battleship-gray paint scheme—so the extra weight wasn't an issue. What did take a little doing, however, was rebalancing the barrel by carefully adding 800 pounds of counter-weights to the other side.

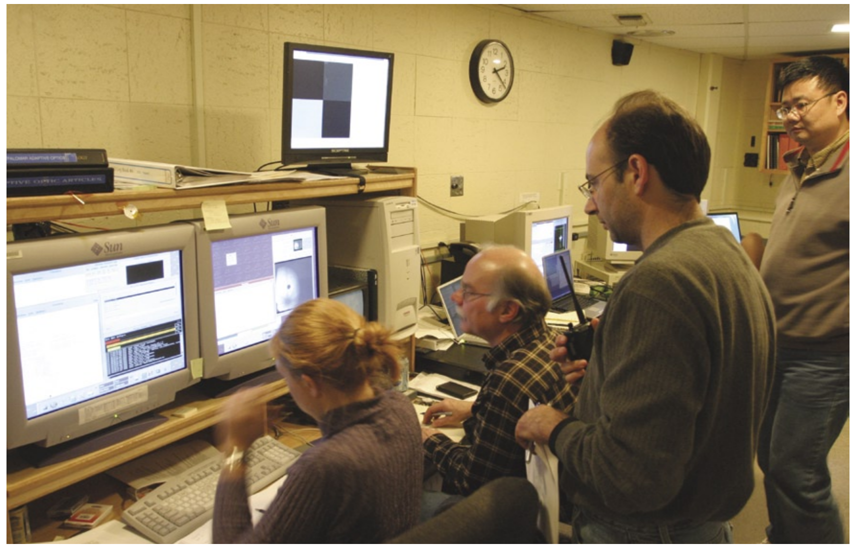
From the top of the barrel, the trolley shunts the beam to the telescope's center axis, where the third major component, the Laser-Launch Telescope, or LLT, sits high atop the Hale in the prime-focus cage—the same location where years ago astronomers would sit taking pictures throughout the night. The LLT widens the laser beam and sends it skyward toward the intended target. Each component attached to the telescope is computer-controlled to maintain its alignment against the shifting pull of gravity as the telescope tracks objects across the sky.

Not a scene from *The Ring*, but a Palomar staff member testing the new infrared camera. It was October, however.

As you might imagine in this post-9/11 era, it is not a good idea for astronomers to start shooting lasers into the night sky whenever and wherever they please. Last January a New Jersey man got into trouble with the law for aiming a five-milliwatt green laser—popular with amateur astronomers for pointing out objects in the sky—at a passing airplane. While the four-watt laser at Palomar still isn't powerful enough to shoot planes out of the sky, it could certainly play havoc with a pilot's night vision, so proper precautions must be taken. Each and every night the laser is to be used, clearance must first be granted by the Federal Aviation Administration (FAA), which will attempt to steer pilots away from Palomar. Because some air traffic might still veer into the target area, the FAA requires that radio-wielding spotters be posted outside the big dome to keep a constant lookout for aircraft. If one is seen on a course that might take it too close to the path of the beam, word is called in and the beam is safely shuttered. (An all-sky camera and a radar system may eventually replace the need for humans to stand out there in the sometimes freezing darkness.) A heat-sensitive infrared camera is also being used, because not all aircraft have their lights turned on. And nightly clearance must also be granted by the U.S. Army Space and Missile Defense Command, the folks who monitor satellites in Earth orbit. While the odds of one crossing the laser's path are remote, we don't want to "light up" any of our satellites, or those of other nations.

When all was ready and the proper clearances obtained, the laser emitted its first light at the telescope in October 2004. Three consecutive nights of precious engineering time—nights devoted to maintenance, repairs, and upgrades instead of astronomy—were granted to get the system up and running, and Palomar's day crew frantically worked alongside staff from JPL and campus to get ready. The first two nights were plagued with fog and alignment problems. The third night saw the proper confluence of good weather and engineer-

From left: JPL's Jennifer Roberts (seated), Chris Shelton, BS '66 (seated), Mitchell Troy, and Fang Shi in the Hale's data room early in the morning of April 27, 2005. Palomar's first laser-created guide star is visible (as a negative image) in the monitor just above Roberts' head.



ing, and the laser painted the sky for the first time. After 55 years of collecting light from the universe, the Hale Telescope finally sent some back!

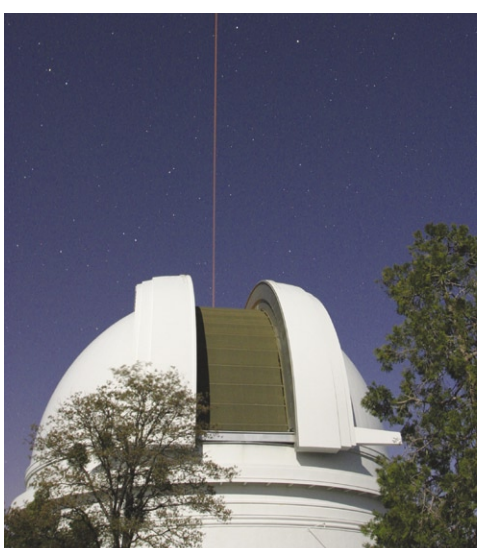
Alas, the astronomers were unable to verify that an artificial star had been born. That feat had to wait until the next window of engineering time, which was dogged by the bad weather of a wetter than normal spring. Almost all of the time in the three nights granted in March was lost to rain and fog. April's nights started much like those in March, with fog ruining the first two attempts, but as they say, "the third time's the charm." On April 26, 2005, on the third night of the third engineering run, Palomar astronomers confirmed for the first time that they had created an artificial star.

The engineering work has not yet advanced enough to turn the system loose for research. So far, the laser has only been pointed straight up. Some final bugs have to be worked out in the beam-transfer equipment before the system can move around the sky, and the team still has to lock the adaptive optics onto the laser guide star. Both of these challenges should be overcome before the end of this year.

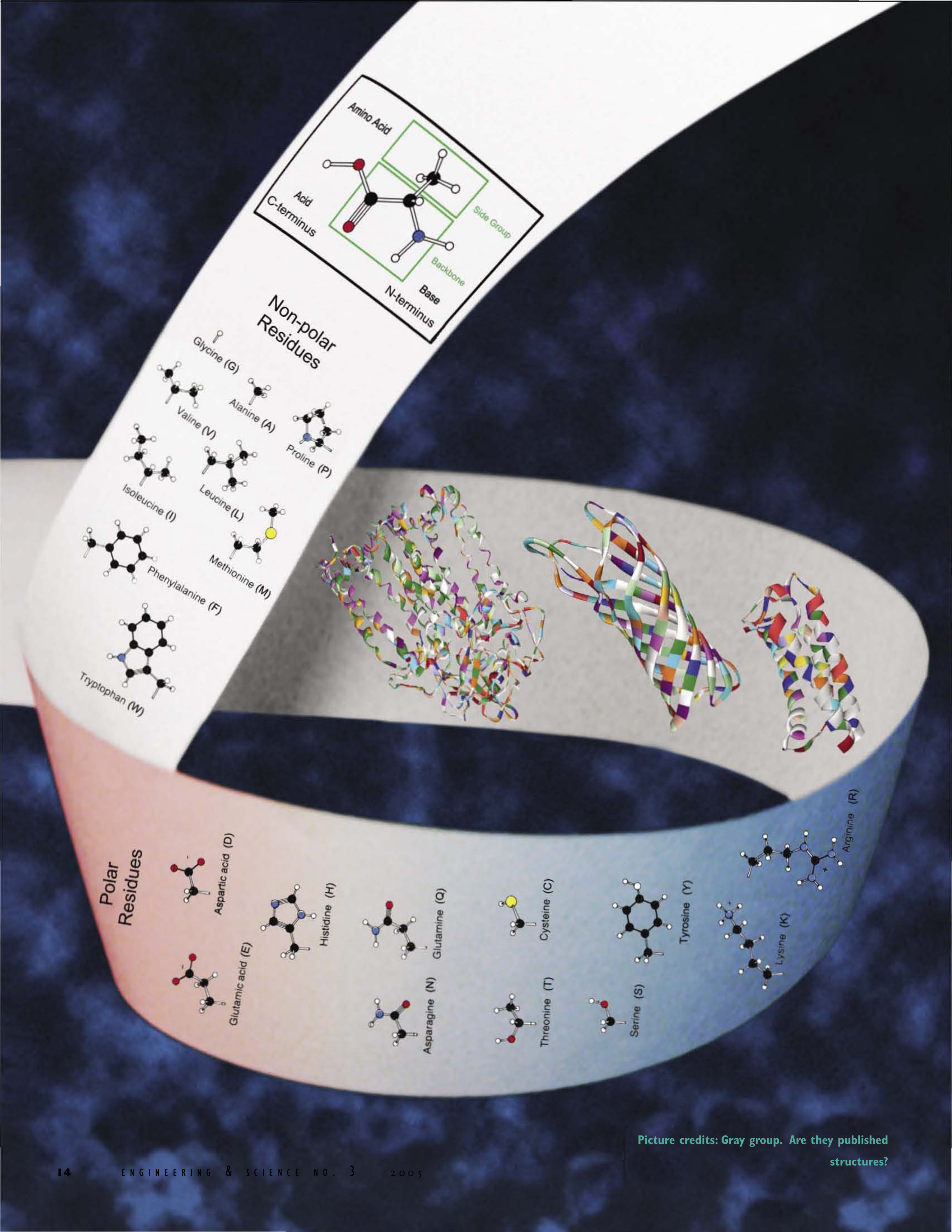
When the system is fully operational, it will place the Hale in elite company, along with the Shane three-meter telescope at the University of California's Lick Observatory and the Keck II, as only the third in the world to deploy a laser guide-star system. This, along with some expected upgrades to the camera and deformable mirror, should allow the earthbound Hale to produce visible-light images that will routinely surpass the sharpness of those obtained from the Hubble Space Telescope—and just in time, as NASA has put on hold a proposed 2006 shuttle mission to service the Hubble that would have extended its life to at least 2011.

Besides promising an exciting time for Palomar astronomers, the system's technical achievements move astronomy further down the path toward future large telescopes such as the Thirty Meter Telescope (TMT). Because of its immense aperture size, different parts of the TMT's giant segmented mirror will see different areas of turbulence in the atmosphere, so a star's look will depend on what region of the mirror it's in. As a result, giant telescopes may be required to use adaptive optics and artificial guide stars all the time. The Hale's adaptive-optics system will be a critical demonstration of many of the key technologies that will be used on the TMT.

Currently in the design phase, the TMT will eventually deliver images at visible and infrared wavelengths 12 times sharper than the Hubble's. The TMT is a collaboration between Caltech and the Associated Universities for Research in Astronomy, the Association of Canadian Universities for Research in Astronomy, and the University of California, and is projected to see its first light in 2015. When that time arrives, it will be a safe bet to say that the road to the TMT will have been paved by the adaptive-optics research under way at Palomar. □



PICTURE CREDITS:
8-9, 11-13 – Scott Kardel



Picture credits: Gray group. Are they published structures?

Misfolded Proteins and Parkinson's Disease

by Jay Winkler

Amino acids share a common backbone. To this is attached a side group, or residue, which can be as simple as the single hydrogen atom in glycine. The other atoms are carbon (black), nitrogen (blue), oxygen (red), and sulfur (yellow). Amino acids link up when the acid carbon (the C-terminus) and the base nitrogen (the N-terminus) react, ejecting a water molecule in the process. A complex interplay of forces between the residues—nonpolar and polar, acidic and basic—creates such shapes as this bundle of α-helices, the barrel made of a rolled-up β-sheet, and eventually such complex structures as this photosynthetic reaction site from the bacterium *Rhodobacter sphaeroides*. (The colors in those structures stand for the various amino acids.)

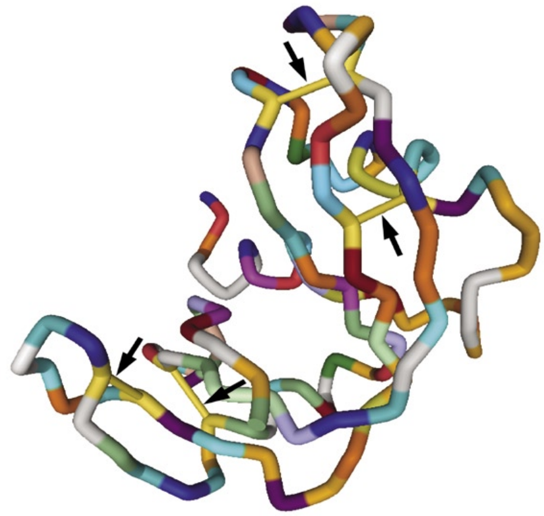
Proteins need to be folded into their correct shapes in order to do their jobs. The folding process is very complex, and there are innumerable ways in which it can go wrong, yet cells do it with a pretty high degree of reliability. How they do so is a very hot field of research, as you might imagine. Here at the Beckman Institute Laser Resource Center we've been developing methods for studying misfolded proteins, and we're very interested in one protein in particular, α-synuclein, that has a direct relationship to Parkinson's disease. But before we start talking about misfolding, we need to talk a little bit about proteins in general, and why proper folding is so important.

The story starts with DNA, which most people know from *CSI* and Court TV—very few molecules get their own shows, much less an entire cable channel. DNA carries genetic information from one generation to the next, and from one cell to another. It carries that information encoded in a sequence of four organic bases, or "letters," arranged like rungs on a ladder that's twisted into the familiar double helix. The code contains "words," each three letters long, standing for the 20 naturally occurring amino acids from which proteins are made. In general, information flows from DNA to RNA—a molecule much like DNA, but single-stranded. The words that go into an RNA molecule are determined by the sequence of letters in the DNA, and the cell uses the information in the RNA to make the thousands of different proteins each cell contains.

Proteins called enzymes catalyze most of the cell's really important chemical reactions, and an enzyme's function is determined by its three-dimensional structure. That structure comes from the amino acids, which a cellular machine called a ribosome—itself an assembly of proteins—strings together in the order prescribed by the RNA. The amino acids have a common backbone that allows them to link to other amino acids, but they all have different shapes—some are small, some are big and bulky; some have floppy side chains, some are rigid. They have different chemical properties as well—some are acidic, some basic; some are polar, some aren't; some have bonding sites, some don't. A complex interplay of forces between these shapes and properties makes the protein fold up in a unique way that is determined by the amino-acid sequence. Enzymes called chaperones often assist the process, but not always. Small proteins in particular can fold completely unaided.

There are roughly 600 general classes of protein structures, and a few fundamental motifs. One common motif is a coil called an α-helix. These coils can form bundles, which can also be helical. Helices are often used as a sort of scaffolding to hold other parts of the protein in position. Another common motif has several protein strands lining up to form a β-pleated sheet. (A single strand in this configuration is called, not surprisingly, a β-strand or β-ribbon.) The sheets often help define the shapes of reactive sites, and they can even wrap around and form barrels. Really complex structures occur when you build an enzyme to be inserted into a membrane that separates different compartments within the cell, or separates the cell from the outside world. Many different proteins are anchored to the membrane, and some actually penetrate it. Typically you find helices spanning the membrane to act as anchors, and then on the inside or on the outside you find a complex structure that includes β-sheets, α-helices, and other things.

In 1972, Christian Anfinsen of the National Institutes of Health won one-half of the Nobel Prize in Chemistry for showing that all the information needed to fold a protein correctly is contained in its sequence of amino acids, which has in turn been coded by the DNA. The other half of the prize was shared by Stanford Moore and William Stein of Rockefeller University, who proved that a protein's catalytic activity is determined by the details of its three-dimensional structure. All



The folded structure of ribonuclease, shown shorn of its side chains for clarity. Again, the colors correspond to the different amino acids. The arrows point to the four disulfide bonds.

three men did their work on a protein called ribonuclease.

Ribonuclease has four cross-linkings, called disulfide bonds, linking two cysteines (a sulfur-containing amino acid) each in widely separated places on the amino-acid chain. In the 1950s, Anfinsen found that he could treat ribonuclease with two chemicals that disrupted its structure entirely. One of them, mercaptoethanol, broke the disulfide linkages and the other, urea, disrupted everything else, leaving a random coil. The amino acids were still in their proper sequence, but the enzyme was no longer active. He then found that if he removed the mercaptoethanol, he could regenerate crosslinks between the cysteines—but the links were random, not the four unique ones that were found in the proper structure, and the protein did not regain its activity. However, if he simultaneously removed the mercaptoethanol and urea slowly, the protein would reform its native structure, and its original enzymatic activity would be regenerated.

You really need to think in terms of a landscape in which high-energy conformations are hills, low-energy ones are valleys, and the conformation of the protein at any given moment is tracked by a boulder that always wants to roll downhill.

This showed that the native fold must be the most stable form thermodynamically. Anfinsen didn't add any energy-producing molecules, or any chaperones. The molecule found the correct structure on its own, so that structure must be the most stable configuration under physiological conditions.

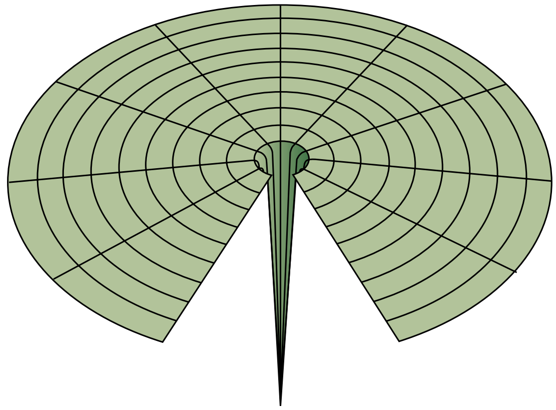
So, how *do* you get from a protein in total disorder to this end point? In the mid '60s, Cyrus Levinthal, then at MIT, proposed a thought experiment. Assume you have a protein with 100 amino acids in it. That's small, but a reasonable starting point. And say that each amino acid can assume just two conformations, a vastly simplifying assumption. We know from physical-chemistry experiments that these conformations interconvert on the scale of a picosecond, or 10^{-12} seconds. So two conformations per amino acid times 100 amino acids gives 2^{100}, or approximately 10^{30}, total conformations, and if it takes a picosecond to make each change, that suggests that the time to sample all possible conformations will be 10^{18} seconds, or some 10 billion years. The problem with that is that the age of the universe is only about 12 billion years, so this can't be the way to fold proteins.

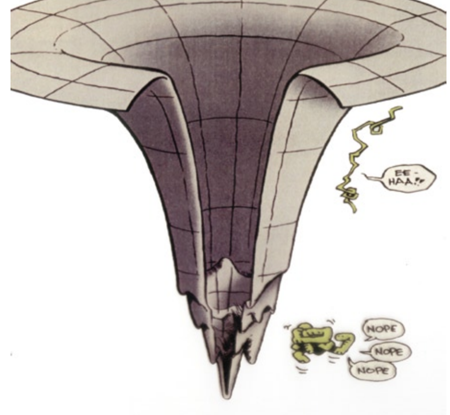
Levinthal knew this was a straw man. Instead of talking about conformations and interconversion rates, you really need to think in terms of a landscape in which high-energy conformations are hills, low-energy ones are valleys, and the conformation of the protein at any given moment is tracked by a boulder that always wants to roll downhill. Levinthal assumed that all the "wrong" conformations were equally probable, which meant that they all had the same energy. In that case, the landscape would look like a putting green—a very small hole somewhere on a huge, flat surface. The chances of the ball dropping into the cup just by rolling at random over the green are exceedingly small, and that's why it would take forever to fold the protein.

More recent theoretical work by a number of people, including José Onuchic (PhD '87) and Peter Wolynes at UC San Diego, suggests that the energy landscape is more like a funnel. For a lot of the really extended, unfolded conformations, rotating part of the molecule around one bond doesn't change the energy very much. So those conformations are equally probable, and the surface way out there is pretty flat. But as you start forming one or two of the weak interactions that are present in the native structure, you stabilize that conformation a little bit. This stability lowers its energy, and that puts you on the lip of the funnel. From there, you can follow a trajectory that is much faster than

If all the wrongly folded conformations had the same stability, the energy landscape would look like a putting green (right). But the three-dimensional structure gets more stable as various parts of it find the correct conformation, making the surface look more like a funnel (far right).

Adapted from Dill and Chan, "From Levinthal to Pathways to Funnels," *Nature Structural Biology*, Volume 4, No. 1, January 1997.

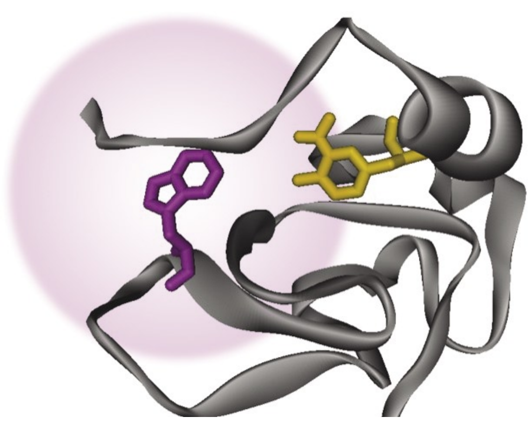




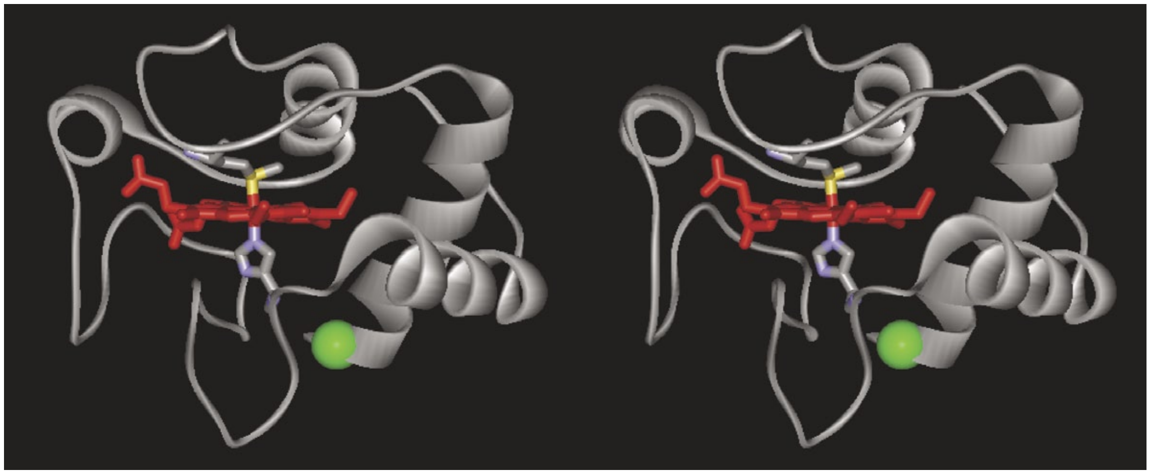
randomly searching every different conformation. Moreover, you don't have to follow a single pathway. There are many possible routes downhill—you don't need one unique set of events to occur in the proper order for each and every molecule. Mind you, there are still ways to go wrong; there are little traps near the bottom of the funnel, local minima, where you could get stuck. So you may have to do some corrections, but you've solved the big problem—once the slope starts to drive you toward the native structure, you need only search through a relatively limited number of configurations.

Here at the laser lab, we decided to try to develop a method for watching the protein as it's folding. All the structures I've shown you were determined by X-ray crystallography, which requires that you prepare a single crystal of the protein—a regular, repeating lattice of protein molecules—which is a notoriously difficult feat, even for a properly folded protein. You then shoot X-rays at the crystal, which diffracts them at various angles and intensities, and by working backward from the diffraction pattern you can deduce the arrangement of atoms that produced it. But a moving, refolding protein doesn't have a regular, repeating lattice. So we use a spectroscopic technique called fluorescence energy transfer, which tells us about the distance between two amino acids of our choice. There may be hundreds of amino acids in the protein and we can only look at two of them at a time, so we don't get anywhere near the amount of information that we do from X-ray crystallography. But if we look at enough different pairings, we can start putting together a picture of what the disordered protein looks like and how it reorders itself as it folds up.

To do energy transfer, we need an energy donor and an energy acceptor. The amino acid tryptophan makes a good donor—when excited with ultraviolet light, one of its electrons jumps to a higher energy state. Within about 10 nanoseconds, or billionths of a second, the molecule reradiates that energy, or fluoresces, at a slightly different wavelength. So if we have an acceptor molecule such as nitrotyrosine, a slightly modified amino acid that has an excited state at a similar energy, the reradiated energy can be transferred to the nitrotyrosine. The rate of energy transfer varies as one over the sixth power of the distance, so if we can measure how fast the energy is transferred from donor to acceptor, we can calculate how far apart they are. We use a fast light detector called a streak camera to measure how the tryptophan's fluorescence decays with time. And we can use molecules in solution—we don't need crystals. Even better, we can collect a sequence of measurements on the

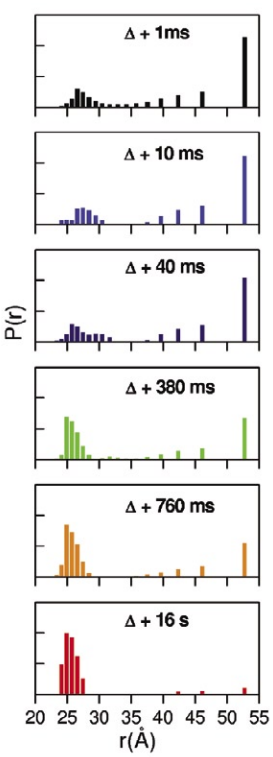


In fluorescence energy transfer, a donor molecule such as tryptophan (purple) radiates energy that is absorbed by an acceptor molecule such as nitrotyrosine (yellow). By measuring how fast this happens, you can tell how far apart they are. Here, the donor and acceptor are attached to a generic protein molecule.



Above: This stereoscopic image shows the three-dimensional structure of cytochrome C. To get the 3-D effect, hold the page about six inches in front of your face, so that one image fills the visual field of each eye. Relax and let your eyes cross slightly, and the 3-D image should pop into view. Cytochrome C has four α-helices. The heme acceptor sits in the center of the molecule and is colored red. The green sphere is the dye-labeled cysteine that acts as the donor.

Below: In this set of plots of cytochrome C refolding itself, r(Å) is the distance between the donor and the acceptor in Ångstroms, or ten-billionths of a meter. (Most atoms are a couple of Ångstroms in diameter.) The probability of finding the donor-acceptor pair at any given distance is P(r). The topmost plot is one millisecond (thousandth of a second) after the denaturant is removed; the bottom plot is 16 seconds after.



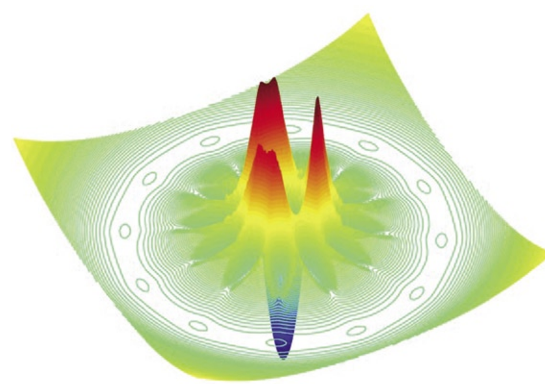
Reprinted in part with permission from Lyubovitsky *et. al.*, *Journal of the American Chemical Society*, 2002, 124, 5481–5485. Copyright 2002, American Chemical Society.

same molecules over time. And the best part is that we can use standard molecular-biology techniques to insert our donor and acceptor anywhere we please—with some caveats—in the amino-acid chain.

Now, a nicely folded protein with a single distance between the donor and acceptor would give a single energy-transfer rate. But a disordered protein has a whole distribution of distances, and we can watch how the distribution changes as the protein refolds. Julia Lyubovitsky (PhD '03) first did this with a protein called cytochrome C, but she didn't use nitrotyrosine and tryptophan. For the energy acceptor she used a part of the protein called a heme, which is very much like the iron-containing molecule in hemoglobin. The heme is bound to the protein by a histidine at position 18. She then reacted the cysteine at position 102 with a dye molecule that acts as the donor. (Remember, the number refers to the amino acid's position counting from the N-terminus.)

First, Julia unfolded the protein by adding guanidine hydrochloride, a denaturant similar to urea, to disrupt the three-dimensional structure. Then she did a set of initial measurements of the donor-acceptor distance distribution. Next, she quickly removed the denaturant in a fast-mixing experiment—basically, diluting it away by adding a buffer solution—and measured the distance distribution as it changed over time. Cytochrome C takes several seconds to completely refold, although some early events happen in tens of milliseconds. A time-lapse plot of the probability of finding a given donor-acceptor distance shows that there's a broad distribution of distances initially, and that the mean distance is relatively large. The heme and the cysteine are 84 amino acids apart, counting along the backbone, so if the protein is completely unfolded they can get pretty far from each other. But the mean distance gets shorter and the distribution of distances tightens up as the protein finds its way to the correct fold. At the end, you have a nice, narrow peak, with just a few molecules that didn't get it right.

Julia used this information to map the energy surface, and discovered that lots of extended, long-



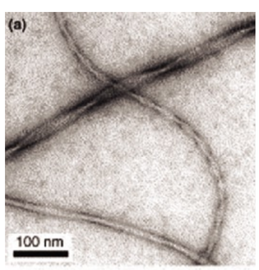
Reprinted in part with permission from Lyubovitsky *et. al.*, *Journal of the American Chemical Society*, 2002, 124, 5481–5485. Copyright 2002, American Chemical Society.

Cytochrome C's energy landscape has a broad, flat plain ringing the outskirts where many different conformations can interconvert freely. The deep funnel (blue) in the middle has the correct fold at its bottom. It is guarded by a ring of mountains, but the passes between them aren't very high and are easily traversed with the energy available to the protein at room temperature. The box canyons on the mountains' flanks are topologically frustrated energy traps, but they're shallow and easy to get out of unassisted.

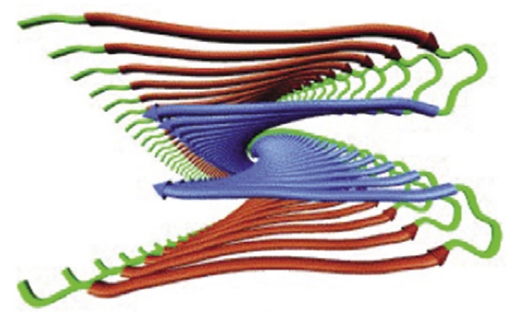
distance structures remained throughout the course of refolding. In other words, once she removed the denaturant, the protein didn't first wad itself up and then wriggle around to try to find the native structure. Instead, about half the molecules stayed well extended while the others collapsed down. Interchange between the extended and collapsed conformations proceeded on time scales of roughly a hundred microseconds. The nearly equal populations of the two conformations indicate that the extended structures lying out toward the edge of the energy surface are not substantially less stable than the collapsed structures.

And this is good, if you think about it, because very often you can get a nonproductive collapse. If the protein winds up with one part of its chain on the wrong side of another, you're stuck. The chains can't pass through one another, so you'd have to break one in order to get to the correct fold. This is called topological frustration. If these wrong structures are really stable and have deep energy traps, you'll have a lot of problems trying to fold the protein. But if these topologically frustrated structures tend to unfold, the protein can go back out to the rim, race around a bit, and hope to recollapse on a more productive route. If the traps aren't very deep, there are many chances to unfold and try again. We think this is an important insight into how proteins avoid getting misfolded. Postdoc Kate Pletneva is developing a more detailed picture of the cytochrome C folding landscape, using six different versions of the dye-labeled protein.

So far I've talked about how things go right, but diseases happen when things go wrong. A protein could misfold because of a mutation in its amino



Above: An electron microscope image of Alzheimer's-type amyloid fibrils, with the twist clearly visible. The scale bar is 100 nanometers, or billionths of a meter, and the fibrils are typically 0.1 to 10 microns (millionths of a meter) long. Above, right: A schematic view of the twist, in which each blue arrow represents a β-sheet. From R. Tycko, *Current Opinion in Structural Biology*, 14, 96-103 © 2004, with permission from Elsevier.



R. Tycko, *Current Opinion in Structural Biology*, 14, 96-103 © 2004, with permission from Elsevier.

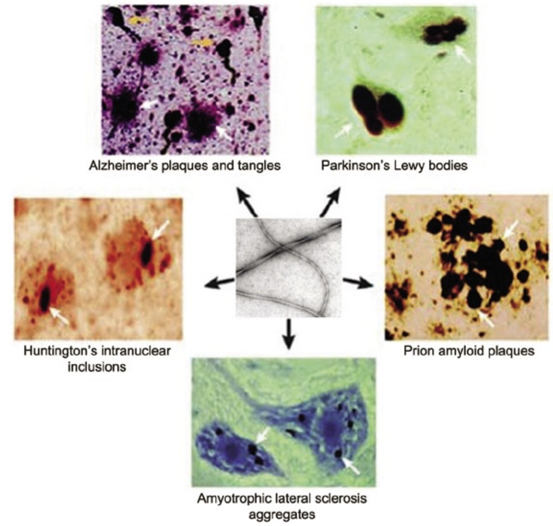
Each β-sheet consists of two amyloid molecules, each of which in turn forms two β-ribbons. The four-stranded β-sheets then stack as shown here (for clarity, only the amino acids at positions 9-40 have been included), with the fibril's long axis coming out of the page toward you.

acid sequence, or environmental stresses might lead it to partially unfold and then set it on a misfolding path.

There's a large and growing list of neurodegenerative diseases that are characterized by insoluble deposits of misfolded proteins. With a few exceptions, proteins that work inside a cell need to be soluble, but the deposits are basically rock-solid masses—tangled, insoluble fibrils of the misfolded protein that trap a bunch of other stuff in with them. Besides Parkinson's disease, brain-tissue samples from Alzheimer's disease; Huntington's disease; amyotrophic lateral sclerosis, better known as ALS or Lou Gehrig's disease; and prion diseases all show fibrils that look pretty much the same, but in each case it's a different protein. In Parkinson's disease, the protein is α-synuclein. In Alzheimer's, it's a relatively short β-amyloid peptide of 42 amino acids. In Huntington's, it's a protein called huntingtin. In ALS, superoxide dismutase is involved. And in prion diseases—which include mad cow and its human analog, Creutzfeldt-Jakob disease or CJD—it's the prions, which are infectious protein particles. In each case, the details are different. In some diseases, the masses form between cells. In others they form within cells. They look somewhat different, and have different names—in Parkinson's, for example, they're called Lewy bodies; in Alzheimer's they're called plaques.

Regardless of what the protein is, all of these misfolds have a similar structure in which the strands, instead of forming helices or whatever, lay out in β-sheets. The sheets lie parallel, stacked perpendicularly to the fibril's long axis, with a little bit of a twist as you go along the fibril. But the sequence of amino acids determines the proper fold, so how can this be? Well, a few years ago Chris Dobson at Cambridge University found that by using the right solvent and temperature conditions, he could pick just about any protein and induce it to form this structure. All the sequence information seems to become unimportant, because these structures

Postmortem brain-tissue samples from several different diseases show dark masses (white arrows) of misfolded proteins. From Claudio Soto, ***Nature Reviews Neuroscience***, 2003, 4, 49–60, with permission from Nature Publishing Group.



arise not from the side chains of the amino acids, but from their backbone, which is the same for all of them. Anfinsen's experiment said that the properly folded structure was the most stable, but these aggregates can be even more stable because they're insoluble. It's a one-way ticket.

We've been studying α-synuclein, which is associated with Parkinson's disease. According to an article in the July 2005 issue of *Scientific American* ["New Movement in Parkinson's" by Andres Lozano and Suneil Kalia], Parkinson's afflicts at least four million people worldwide, including as many as one million Americans, and about half of its victims begin to display symptoms before age 60. Parkinson's disease results from the loss of nerve cells, or neurons, in a small part of the brain called the substantia nigra. These cells produce dopamine, a neurotransmitter associated with movement. As they die, your dopamine level drops, and that leads to the tremors, dyskinesia (jerky, uncontrollable twisting or flailing motions of the limbs), and "freezing" that are characteristic of the disease. There is no known way to prevent Parkinson's, or stop (or even slow) its progression, but its symptoms can be greatly reduced by drugs and other therapies, including the implantation of a pacemaker-like device that delivers electrical stimulation to cells deep in the brain that control movement.

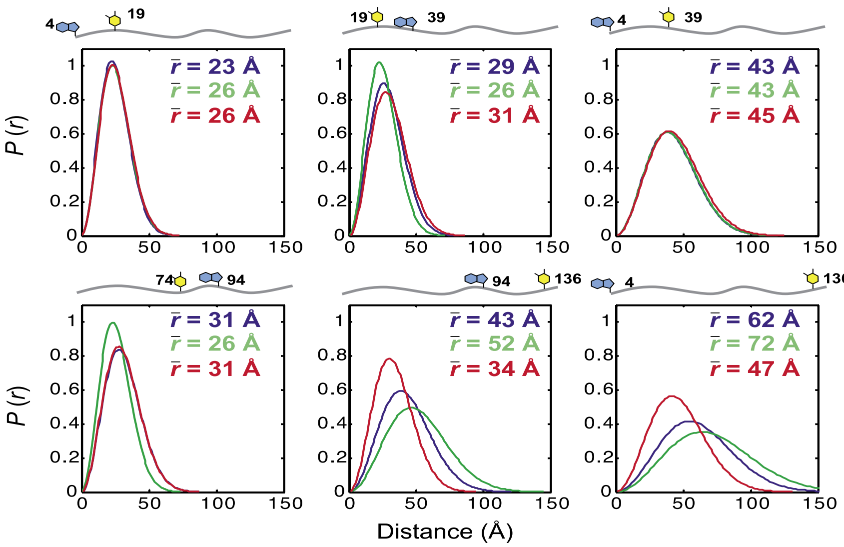
IMAGE NOT AVAILABLE

The substantia nigra is a small region deep in the brain. Named for its black color, the region contains dopamine-producing neurons. As these neurons die, the color fades.

Interestingly, there's a synthetic analog of heroin called China White that, within days of use, sometimes induces irreversible symptoms that are virtually identical to Parkinson's, including the development of Lewy bodies. J. William Langston of the Parkinson's Institute in Sunnyvale, California, studied these so-called "frozen addicts" in the early '80s, and discovered that the culprit was an impurity called MPTP, for 1-methyl-4-phenyl-1, 2, 5, 6-tetrahydropyridine. MPTP is now used in laboratory studies on mice and rats, which don't normally develop Parkinson's disease—possibly because they don't live long enough. But you give them MPTP, and they accumulate α-synuclein deposits, and in some cases develop symptoms resembling Parkinson's.

As I said, the Lewy bodies are primarily composed of α-synuclein. Alpha-synuclein is a small protein, only 140 amino acids long, and is widely found throughout normal brain tissue. Its function is not yet known, but the speculation includes such divergent roles as helping the right synapses form during learning, aiding in membrane formation, and moving fatty molecules called lipids around. It's found in the cytosol, the liquid inside the neuron, but it's also associated with the membranes of synaptic vesicles, which are the sacks that store neurotransmitters.

Oddly, α-synuclein doesn't appear to have a well-defined structure. If you dissolve it in a solution containing membranes or membrane mimics, it'll cling to them and start to form some α-helices, but it never assumes a single, discrete conformation. But if you take a solution of α-synuclein and let it sit at 37 degrees Celsius or so for several days, it will form fibril deposits completely on its own, in



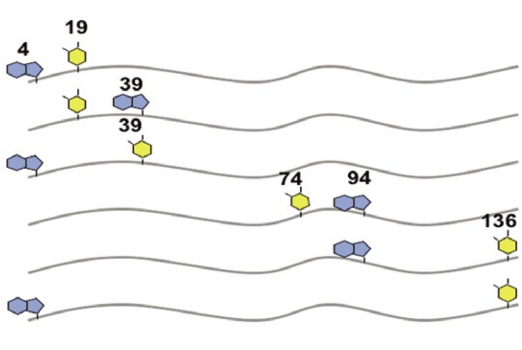
The data for each donor-acceptor pair shows the probability of finding a given donor-acceptor distance *P*(*r*) versus the distance in Ångstroms under three sets of conditions. The blue is normal physiological conditions, the green is after adding a membrane mimic, and the red is after adding acid. The colored numbers give the mean donor-acceptor distance in each case.

the absence of any cellular machinery.

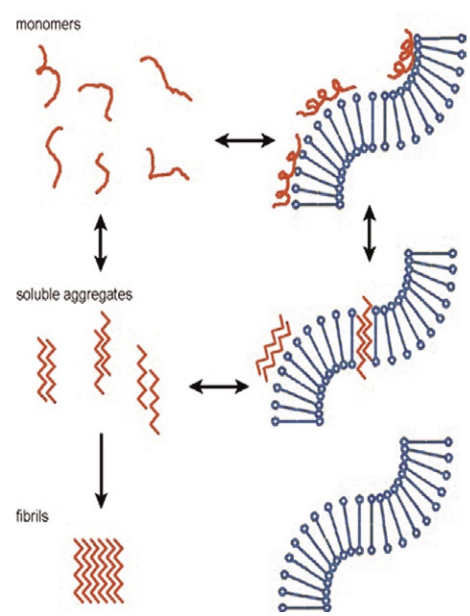
Because of this lack of structure, we thought α-synuclein would be an ideal candidate for our fluorescence energy-transfer methods. Beckman Senior Research Fellow Jennifer Lee (PhD '02) used the tryptophan donor and the nitrotyrosine acceptor, placing donor-acceptor pairs in the protein's N-terminal region, the central region, and the C-terminal region, as shown below. She also put the donor at the N-terminus and the acceptor at the C-terminus to see how close the two ends got to each other. And she made two more pairs by putting the donor and acceptor, both of which have big, bulky ring systems, at various spots where there already were big, bulky ring systems, on the logic that this would cause the least distortion in the structure. Then she measured the energy-transfer kinetics for each of the six pairs, and mapped out the distributions of donor-acceptor distances.

The donor-acceptor distance-distribution curves under various conditions are shown above. By themselves they don't offer much information, but they do give us some constraints. We're working with Vijay Pande, a computational chemist up at Stanford, to plug these distributions into his molecular-dynamics software to try to get a feel for the families of structures that may exist in solution. The blue curves in the figure are for the molecule at the level of acidity found in our cells, that is, at pH 7.4. I'll get back to the green and red curves momentarily.

It's known that α-synuclein associates with membranes, and it's been suggested by, among others, USC's Ralf Langen (PhD '95) that the α-helices I mentioned earlier allow the protein to lie down on the membrane's surface. But as the protein molecules start to aggregate into twos and threes, the helices uncoil and the protein's structure becomes more like β-ribbons. This has caused some people, notably Peter Lansbury at Harvard and Brigham



Six different versions of α-synuclein were made, each with the donor (blue) and acceptor (yellow) at different sites.



Right, top: The helices of individual α-synuclein molecules (red) may allow the molecules to adhere to membrane surfaces (blue). Middle: But as the molecules start to aggregate in twos and threes, they may begin to form β-ribbons that may penetrate the membrane, causing the cell to spring a leak. Bottom: The ribbons eventually form fibrils, keeping them from doing further damage.

1 10 20 30 40 50 60
MDVFMKGLSKAKEGVVAAAEKTKQGVAEAAGKTKEGVLYVGSKTKEGVVHGVATVAEKTKEQVTNVGG

The amino-acid sequence for α-synuclein, using the one-letter codes shown on page 14. The two underlined regions form the two helices, and are largely made up of an almost-identical repeating unit shown in red. (After T. S. Ulmer *et al.*, *Journal of Biological Chemistry*, 2005.)

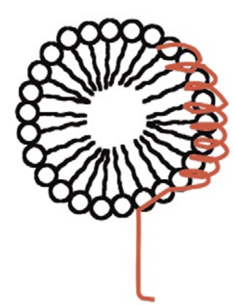
and Women's Hospital, to think that the β structures form a pore, possibly like the β-barrel I described earlier, that penetrates the membrane and leads to leakage and eventually cell death. In that case, forming the insoluble fibrils may actually be a protective mechanism. This really points out how little we know—even though the fibrils are a hallmark of the disease, they may not be the problem. It could be that their precursors are really what's killing the cell, and the fibrils are the cell's attempt at self-defense. It's hard to find out what's really going on, because working with cultures of nerve cells is a very tricky business. You just look at them cross-eyed and they'll die on you.

NMR data suggest that one membrane-bound structure may have two α-helices, with a small flexible region in between. (Whether these helices actually lie flat along the membrane or are embedded into it isn't known.) The green curves in Jennifer's data show what happened when she added sodium dodecyl sulfate (SDS) micelles, a membrane analog, to the solution. A molecule of SDS, known to the nonchemist as "soap," has a negatively charged head and a long, oily tail. Above a certain concentration, the molecules form little spheres, called micelles, with all the heads on the outside and the tails in the interior. Micelles make good stand-ins for biological membranes. Jennifer found that the N-terminal region stayed the same or even shortened up a bit, perhaps showing more helical character; while the C-terminal region seemed to stretch out. This is probably an electrostatic effect, as the outside surface of the micelle and the C-terminus of the protein both have negative charges that would tend to repel each other.

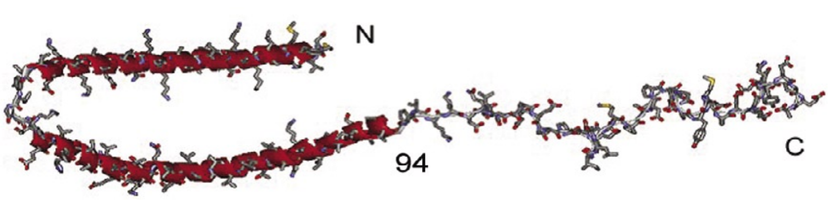
We don't really know that the amino-acid backbone bends to put the two helices side by side, the way they've been drawn, but we plan to find out. Jennifer is going to put a donor at the N-terminus and an acceptor at the C-end of the second helix, at roughly position 94. If this partially straightened paper-clip-like structure is correct, we should see a short distance. NMR tends to show the most stable structures, but it also points to places where we should put donors and acceptors. So combining these techniques is potentially very useful.

It's been found that the insoluble aggregates form faster under acidic conditions, so Jennifer also did a set of studies at pH 4.4. The red lines in the plot on the opposite page show that there's not too much change until the C-terminal region, where you see much shorter distances. This shortening, again, is probably primarily electrostatic in nature. As we acidify the solution, the negatively charged and weakly acidic carboxylic acid group on the C-terminus accepts a positively charged hydrogen ion from the solution and becomes electrically neutral. The C-termini are now more inclined to snuggle up, rather than being repelled by one another. We don't yet understand how the conformations we find in solution relate to the propensity for fibril formation—as you can see, the relationship is not straightforward. (Jennifer's samples did not make fibrils, as she was working at low protein concentrations where they don't form.)

While Parkinson's is usually caused by a mix of genetic and environmental factors, about 5 percent of the cases are strictly genetic, says *Scientific American*. There are several different mutations that can cause Parkinson's, at least two of which occur in α-synuclein. If your DNA replaces the amino acid named alanine at position 30 with a proline, or the alanine at position 53 with threonine, you will develop the disease while you're still in your 30s. Jennifer looked at how the shape of



An α-synuclein molecule can coil up and lie down on an SDS micelle the way it does on a membrane.



This structure of α-synuclein bound to a membrane mimic was determined by NMR spectroscopy. (After T. S. Ulmer *et al.*, *Journal of Biological Chemistry*, 2005.)

70 80 90 100 110 120 130 140
AVVTGVTAVAQKTVEGAGSIAAATGFVKKDQLGKNEEGAPQEGILEDMPVDPDNEAYEMPSEEGYQDYEPEA

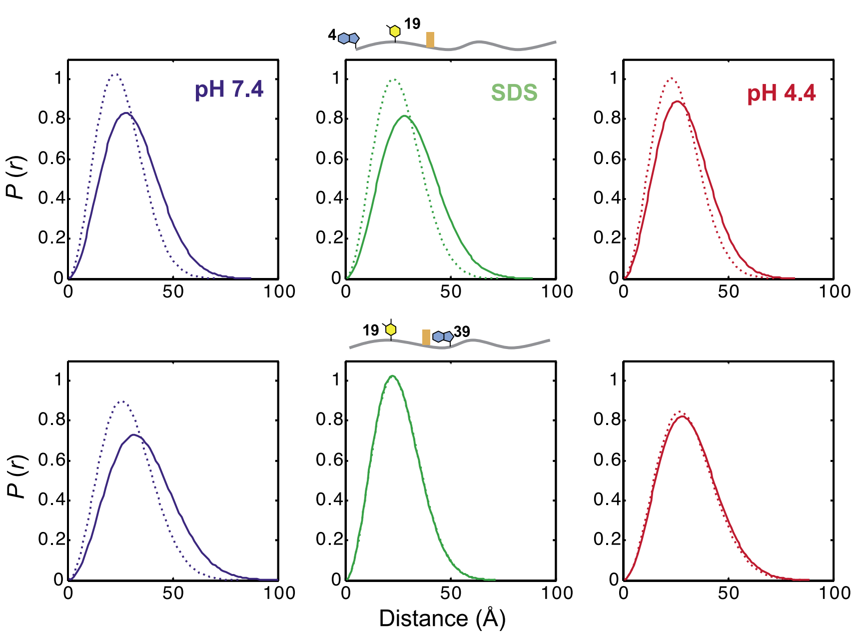
the molecule changed when she made the alanine-proline mutation, placing a donor-acceptor pair on the N-terminal side of the mutation, and a donor-acceptor pair to span the mutation site. She looked at the distance distribution at physiological pH, in the presence of SDS micelles, and under acid conditions. In all three cases, she found elongation at the N-terminal region when she introduced the mutation. Interestingly, however, when the donor-acceptor pair spans the mutation, you only see significant lengthening at normal pH, pH 7.4; you don't see a substantial change in structure in the presence of SDS micelles or at acid pH. We still don't understand the molecular basis for this change. We do know that it's not electrostatic, but we need more data to figure out what's going on.

We're now bringing fluorescence energy transfer to bear on the aggregation of α-synuclein into fibrils. I mentioned that the toxic form may actually be the fibrils' soluble precursors, and we think our method will give us some insights into them. We'll put a small concentration of our protein in a solution of the regular protein, and we hope to see structural changes as the protein starts to aggregate before the solids start forming.

While we've been concentrating on α-synuclein, and we hope to make a contribution to untangling the role that misfolded proteins play in these debilitating neurological diseases, you can see that fluorescence energy transfer is a very general technique. You can look at protein structures in solution, and you can follow what happens when the protein interacts with other molecules—signaling molecules, drugs, environmental agents—under various conditions. It's really a very basic, powerful tool for molecular biology, with applications to essentially any protein system or cellular process. □

Jay Winkler received a BS in chemistry from Stanford University in 1978. He received his PhD in chemistry from Caltech in 1983, working with Beckman Professor of Chemistry Harry B. Gray on, among other things, electron transfer in ruthenium-modified cytochrome C. After a two-year postdoc with Norman Sutin and Tom Netzel at Brookhaven National Laboratory, he received an appointment as a staff scientist there and resumed studying electron-transfer reactions in various proteins. In 1990, he returned to Caltech as a Member of the Beckman Institute and Director of the Beckman Institute Laser Resource Center.

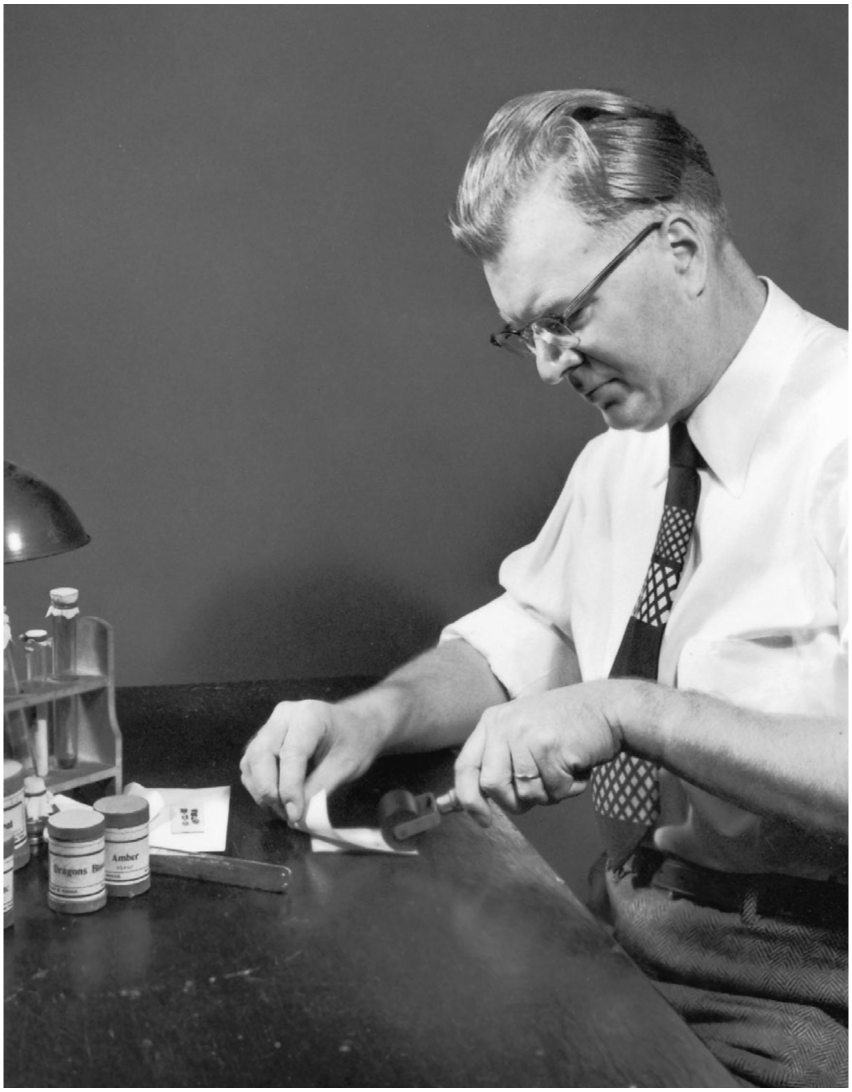
PICTURE CREDITS: 14, 16, 17 – Jay Winkler, Doug Cummings; 17, 20, 21, 22 – Jennifer Lee



Swapping the alanine at position 30 (orange block) with a proline causes early-onset Parkinson's. Shown here are distance-distribution data from the N-terminus (top row) and spanning the mutation site (bottom row). The dotted line is for normal α-synuclein, and the solid line is the mutant version.

Copies in Seconds

by David Owen



In 1962, Chester Carlson (BS '30) reenacts making the world's first photocopy. (The "dragon's blood" in the vial is a resin, not an alchemical ingredient.) Photo courtesy of the Xerox Corporation.

When Chester Carlson, working in the patent office at P. R. Mallory, needed a copy of a drawing in a patent application, his only option was to have a photographic copy made by an outside company that owned a Photostat or Rectigraph machine. "Their representative would come in, pick up the drawing, take it to their plant, make a copy, bring it back," he recalled later. "It might be a wait of half a day or even twenty-four hours to get it back." This was a costly nuisance, and it meant that what we now think of as a mindless clerical task was then an ongoing corporate operation involving outside vendors, billing, record keeping, and executive supervision. "So I recognized a very great need for a machine that could be right in an office," he continued, "where you could bring a document to it, push it in a slot, push a button, and get a copy out."

As Carlson began to consider how such a machine might work, he naturally thought first of photography. But he realized quickly that photography had distressingly many inherent limitations. Reducing the size of a bulky Photostat machine might be possible, but a smaller machine would still require coated papers and messy chemicals—the two main reasons making Photostats was expensive and inconvenient. Photography, furthermore, was already so well understood that it was unlikely to yield an important discovery to a lone inventor like Carlson. People had been using cameras for more than a century, and the laboratories at Eastman Kodak were filled with well-financed researchers, yet no one, so far, had come up with a method of making photographic prints on ordinary paper. Carlson reasoned that silver halide photography almost certainly did not hold the solution to the copying problem—and that if it did somehow hold the solution, he himself would be highly unlikely to find it.

Having eliminated conventional photography as a field of investigation, Carlson next considered the possibility of making copies chemically—perhaps by using a mild solvent to partially dissolve the text or image of an existing document, so that an impression of it could be made by pressing a blank piece of paper against it, as with a copying press. But there are hopelessly many different writing and printing media—water-based inks, oil-based inks, graphite, charcoal, crayon, and others—and Carlson knew that no single solvent would work with all of them. Besides, even if a single practicable solvent could be found, using it would unavoidably harm the original document, and the reproduced image would be reversed, like a reflection in a mirror. Chemistry alone, he decided, could not provide the answer.

If ordinary photography was messy, and chemical processes ruined originals, what was left? "The only thing common with the different inks, pencils, and papers is that they reflect light in different ways from the image areas and from the background areas," he said later. We easily distinguish text from the paper it's printed on, because the ink absorbs most of the light that strikes it (and therefore appears black), while the paper reflects the light (and therefore appears white). A nondestructive copying process, Carlson reasoned, would almost certainly have to take advantage of this contrast—just as conventional photography does. But how? Were silver halides the only materials that changed when exposed to light? Carlson went back to the library and soon found a book called *Photoelectric Phenomena,* which had been published a few years before.

Photoelectricity is so hard to understand that Albert Einstein won the Nobel Prize in 1921 for having explained it in 1905. (Incidentally, Einstein, like Carlson, was a physicist who worked in a patent office.) To simplify a great deal, a photoelectric material is one that sheds electrons when light shines on it. The phenomenon was first noticed in 1887 by the German physicist Heinrich Hertz (whose name is preserved in the standard scientific term for "one cycle per second"). Hertz observed that the sparks thrown off by an induction coil in his laboratory got smaller when he darkened the room (as he had done in the hope of seeing the sparks better). Einstein's explanation, which became part of the basis of quantum mechanics, was that when light, behaving like a stream of particles, collides with electrons on the surface of a photoelectric material, it knocks significant numbers of the electrons loose and thereby stimulates increased electrical activity: bigger sparks. A related phenomenon is photoconductivity, which Carlson read about in the same book. A photoconductive material is one whose ability to transmit electricity increases when it is illuminated. This happens because light, behaving like a stream of particles, jostles the electrons on the material's surface and thereby increases the material's ability to conduct a charge.

"I thought that if a layer of photoconductive material could be placed in contact with a sheet of paper that had been wetted with a chemical, the paper would change color if electricity flowed through the sheet," Carlson said later. Working in the kitchen of his apartment, he saturated a sheet of ordinary paper with a solution of potassium iodide and starch, placed the treated paper on a copper plate coated with cuprous oxide (a photoconductor), placed a printed document on top of the treated paper, and shone a bright light through the back of the document. As he explained on another occasion, he was hoping that the sheet of paper "would be darkened by the photoelectric currents that I thought would be produced during exposure," and that an image of the printed document would form on the treated paper. But nothing happened.

"That led me to take a somewhat deeper look into the needs of the process," he recalled in 1964; "e.g., I recognized that photoelectric currents are bound to be rather small, but, on the other hand, electrochemical effects which I was trying to use require rather large currents to cause any substantial darkening of a layer."

Furthermore, a current large enough to darken paper would also most likely be large enough to set it on fire, among other undesirable results. He concluded that his idea was "even less satisfactory than the known photographic methods that were then used," and turned his attention from amperage to voltage. "With high voltage, the current could be small but still the energy could be high," he realized. "This led me to the idea of electrostatics."

Electrical phenomena are conventionally divided into two broad and confusingly overlapping categories: current electricity and static electricity. Current electricity is what makes electric appliances work; it consists of continuously flowing electrical charges. Static electricity is what causes your hair to stand up when you run a plastic comb through it; it consists of opposite electrical charges that are separated or imbalanced (and that produce transitory electric currents—sparks, lightning—when the voltage is sufficient to ionize the air separating them). Scientists have been known to come to blows over these definitions. For the purposes of understanding xerography, it's enough to say that the most important difference has to do with amperage, which can be thought of as analogous to volume in the flow of water, and voltage, which can be thought of as analogous to water pressure. Generally speaking, an electric current involves relatively high amperage at relatively low voltage, while electrostatic phenomena involve high voltage at low amperage. (The electric current you experience when you stick a butter knife into a wall receptacle is just 110 volts, but it's more than enough amps to

Carlson realized that if he could devise a copying process based on voltage rather than amperage, he might be able to build a machine that would neither set paper on fire nor electrocute its operator.

PICTURE CREDITS: 26, 27 – Doug Cummings

The creative spark: Static electricity allows you to play with very high voltages but very small currents—this plasma ball has a couple of thousand volts running through it, but only about one amp.

kill you; the harmless electrostatic shock you receive when you shuffle across the carpet and touch a metal doorknob is many thousands of volts but virtually zero amps.)

Carlson realized that if he could devise a copying process based on voltage rather than amperage, he might be able to build a machine that would neither set paper on fire nor electrocute its operator.

Carlson returned to the library. And there, while working his way through a pile of foreign technical journals, he came across a brief article by a Hungarian physicist named Paul Selenyi. Selenyi had been trying to devise a way of transmitting and printing facsimiles of graphic images, such as news photographs. His method, which he had tried with some success, involved using a directed beam of ions to lay down a patterned electrostatic charge on the outside of a rotating drum that was covered with an insulating material—something like the way a cathode ray tube creates a picture on a television screen, by scanning a beam of electrons repeatedly across it one line at a time, or like the way an ink-jet printer sprays ink in an intelligible pattern onto a sheet of paper.

"He had developed, essentially, a triode in air," Carlson said later. "It embodied a heated cathode enclosed in a metal cup which had a small hole in it. Then there was a drum coated with hard rubber or some kind of insulating varnish that rotated very close to that hole. The heated cathode created ions within the metal cup and the metal let varying proportions of ions through a little opening. They were deposited on the rotating, insulating drum by a bias field that was applied. Then, after the image had been scanned, he simply dusted the drum with a fine powder and the image became visible." The powder stuck to the ions on the insulating surface of the drum in the way that beach sand sticks to wet spots on a bathing suit. A transmitted photographic image that Selenyi had generated in this manner was reproduced in the journal; it was grainy, and the scanning lines were quite noticeable, but the image was reasonably distinct.

Using finely divided powders to make visible images of electrostatic charges was an old idea in physics; it had first been done in 1777, when George Christoph Lichtenberg, a German professor, noticed that house dust adhered to an electrostatically charged piece of amber in a distinctive arrangement, which later became known as a "Lichtenberg figure." Carlson knew about Lichtenberg figures, and Selenyi's work reminded him of them. Suddenly, he saw that he might be able to make copies by employing a similar phenomenon in combination with photoconductivity. Instead of trying to use light to generate an electric current in a sheet of paper placed on top of a photocon-

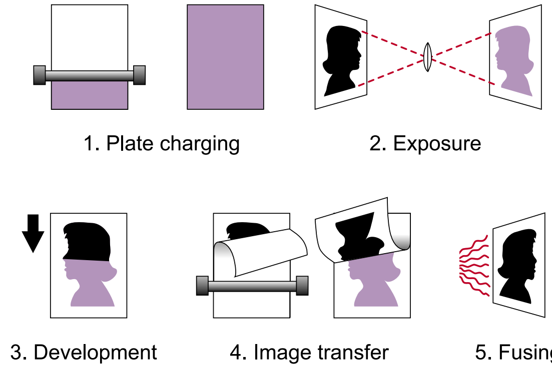
Carlson's senior picture in the *Big T*, the Caltech yearbook. Carlson, who grew up in the San Bernardino area, entered Caltech after graduating from Riverside Junior College in 1928. Upon receiving his BS in physics, he took an engineering job at Bell Labs and moved to Manhattan. He soon transferred to the Lab's patent office, from which he was fired in 1933. He married Elsa von Mallon in 1934 before taking up the quest for xerography in earnest in 1937; the strain contributed to their divorce in 1945.

ductor, as he had done in his kitchen experiments, he would use light to remove electrostatic charges from the nonimage areas of a uniformly ionized photoconductor. Then he would make the pattern visible by dusting it with powder, and transfer the powder to a sheet of untreated paper.

Photoconductivity was the key. Carlson knew he needed to find a material that would act as an electrical conductor in the light and as an electrical insulator in the dark. If a grounded metal plate coated with a thin film of such a material could, in the dark, be given a uniform electrostatic charge—perhaps by using an electrostatic generator to spray ions onto its surface—then exposing the plate to light should cause the charge to drain away. And if that light could be shone on the charged plate not uniformly but in the image of a printed page, then the charge should drain away only from the illuminated parts of the plate (the parts corresponding to the reflective white background of the page) and persist in the parts that remained dark (the ones corresponding to the black ink). Dusting the entire plate with an oppositely charged powder should then make the latent image visible, because the powder would adhere only to the places where charges remained. That powder would form a mirror image of the original page and could then be transferred to a sheet of paper: a copy.

Carlson's knowledge of electrostatics had arisen partly from personal experience. Back in his physics class at Riverside Junior College, a student had asked the teacher one day whether static electricity had any commercial use, and the teacher had said that it did not. "But at that time I was working for a cement plant," Carlson recalled later, "and I could think of one commercial use for it—in separating dust from the flue gases and separating smoke from the air." The plant where Carlson worked had been sued by neighboring orange growers, whose trees became coated with the fine white dust that billowed from the plant's smokestacks. The plant had been able to eliminate the problem and satisfy the growers by installing two sets of electrodes in the flues—one to give escaping dust particles an electrostatic charge and the other, of the opposite polarity, to pull the charged particles out of the air. The copying process that Carlson had now conceived would operate in a similar manner—except that the electrostatic charges he had in mind would be used not simply to attract dust randomly but to form it into a comprehensible pattern.

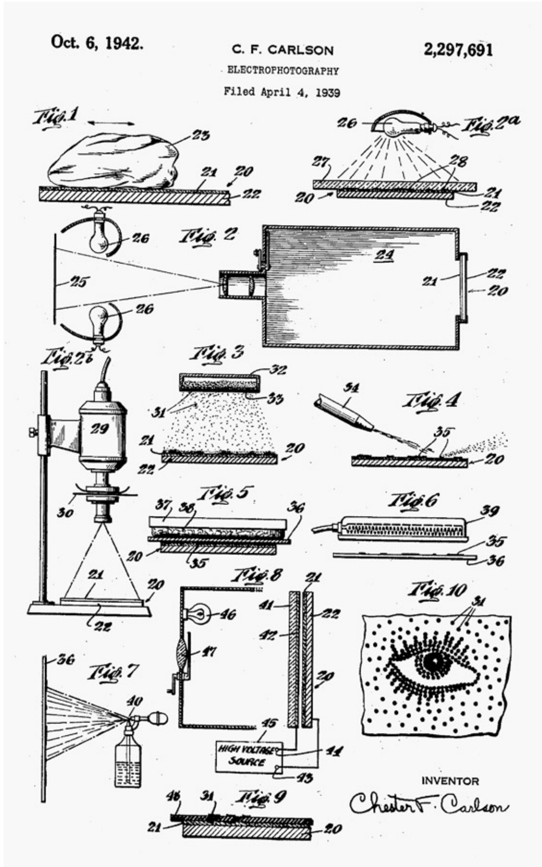
Few big inventions truly have a single inventor; most technological revolutions are essentially collective efforts, arising in several minds and in several places at more or less the same time, generated as much by cultural pressures as by spontaneous individual insight. If Gutenberg hadn't thought of movable type in the early 1400s, someone else would have, because other advances in printing technology, along with an accelerating increase in the demand for books, had made a breakthrough of some kind inevitable. Carlson, in contrast, was genuinely alone. He always credited Selenyi with having inspired him, but Selenyi never saw the connections that Carlson did. As a matter of fact, in the years following Carlson's discovery, the few people who came up with truly similar ideas were able to do so only after studying Carlson's patent specifications, and their innovations were merely variations on themes he had long since defined. Carlson alone thought of a way to make copies easily and quickly on plain paper; no one yet has come up with a better way of doing it.



How xerography works: A specially prepared plate is charged with static electricity (purple). The charge drains away wherever light hits the plate; dark areas remain charged. A black powder of opposite charge will stick only to those areas, and when a piece of paper is pressed against the plate the powder (and the image) is transferred. Heat treatment binds the powder to the paper.

"Xerography had practically no foundation in previous scientific work," Dr. Harold E. Clark, a Xerox physicist, told John Brooks in 1967. "Chet put together a rather odd lot of phenomena, each of which was obscure in itself and none of which had previously been related in anyone's thinking." Carlson himself believed that his lonely upbringing had contributed to his success: spending so much time in his own company had given him an acquired immunity to conventional thinking. "The result was the biggest thing in imaging since the coming of photography itself," Clark continued. "Furthermore, he did it entirely without the help of a favorable scientific climate. As you know, there are dozens of instances of simultaneous discovery down through scientific history, but no one came anywhere near being simultaneous with Chet. I'm as amazed by his discovery now as I was when I first heard of it."

Carlson at first called his idea "electron photography," and then he decided upon "electrophotography." As soon as the elements had come together in his mind, the process seemed so intuitively obvious to him that he worried some other researcher would follow the same line of reasoning and beat him to market with a functioning product. He



Pages from Carlson's second (left) and third (opposite page) electrophotography patent applications. Courtesy of the United States Patent Office.

called his old roommate Dumond—who had been fired from his job at the *Daily News* and was now managing a small investment fund for some midwestern businessmen—and asked him to meet him at a local Automat. (Carlson had recently served as the best man at Dumond's wedding and, as a prank, had hidden a wound alarm clock in the newlyweds' honeymoon luggage.) Over coffee, Carlson described the idea behind electron photography and then asked Dumond to sign and date a document stating that Carlson had explained the process to him and that he understood it. Carlson wanted this affidavit as proof of his priority, in the event that someone else should think of a similar idea while he was working on a patent application. Dumond happily complied. Carlson also asked his employer to grant him permission to apply in his own name for a patent for an "improvement in photography"—which, he explained, was unrelated to his work at the company—and Mr. Mallory himself approved his request (in a letter headed "Dear Carlson").

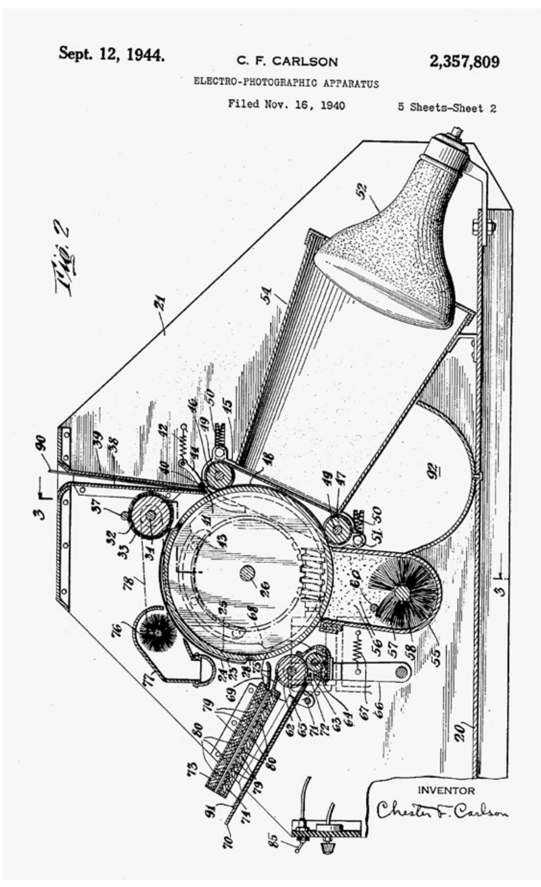
With these documents in hand, Carlson went to work on his patent application, a task for which his job, his legal studies, and his methodical temperament suited him perfectly. He filed his first application in the fall of 1937 and followed it a little over a year later with an improved and expanded version. That expanded patent, which was issued in the fall of 1942, has been regarded ever since as a model in the genre: Carlson knew how to protect an invention. In just a dozen pages and a few simple drawings, he lucidly anticipated and described virtually every aspect of what would ultimately become known as xerography.

Confident that he had now done everything he could to protect himself from competing inventors and manufacturers, Carlson set out to establish that his idea would actually work. In this, he was far less successful. He was positive, he said many years later, that he had truly solved the copying problem, and he was equally confident that his invention would one day be a commercial success. But his efforts to prove the practicality of his idea—to actually make a copy of something—were painfully unproductive. He could see the process in his mind, and he could understand how its elements fit together. But he couldn't make it work.

One of his difficulties was the manual ineptitude that he had noted in his college diary (and which had contributed to his decision to transfer out of his experimental job at Bell Labs). Another was the circumstances under which he was trying to work. Since January 1938, he and Elsa had been living with Elsa's parents in a small house in Jackson Heights. He conducted his experiments in the house's old coal cellar when he could, but there were times when he needed running water and an open flame, and that meant he had to share the kitchen with his wife, who resented the intrusion. He stocked a single shelf with a modest selection of experimental supplies: a jar of chemically pure crystalline sulfur (a photoconductor), which he had bought at a chemical supply house called Eimer & Amend; a few business-card-size zinc engraver's plates; and a miscellaneous collection of parts from which he hoped to fashion an electrostatic generator. He concentrated at first on coating one of the plates with sulfur, by sprinkling crystals on the zinc and using a pair of pliers to hold the plate over one of the burners on the kitchen stove. He found that if he held the plate at the right distance

The usual result of these efforts was not a uniformly coated plate but a sulfur fire, which filled the kitchen with acrid fumes and made the entire building smell like rotten eggs. These accidents annoyed his wife and drew bitter complaints from his mother-in-law. "My experiments became very unpopular around the house," he told an interviewer later.

from the flame and kept it moving, the crystals would eventually liquefy and spread across the plate—although the usual result of these efforts was not a uniformly coated plate but a sulfur fire, which filled the kitchen with acrid fumes and made the entire building smell like rotten eggs. These accidents annoyed his wife and drew bitter complaints from his mother-in-law. "My experiments became very unpopular around the house," he told an interviewer later.



His attempts to make a suitable developing powder were unpopular as well. "I decided that the way to do it was to spray-dry a solution of a dyed resin in a highly volatile solvent in a spray booth or chamber and collect the deposit," he recalled later. "Well, in an apartment I didn't have a very convenient spray chamber, so I decided to use the bathtub. I got an air brush, which is a form of spray gun, and I produced a solution of resin and dye and acetone, and I pulled the shower curtains around the tub, and I sprayed the solution into the space above the tub, and it settled down and I swept it up. Unfortunately, the tub was not very clean after that."

Carlson eventually realized that his apartment made a poor laboratory and that he needed help with his experiments. In the fall of 1938, nearly a year after filing his first patent application, he rented a room on the second floor of a house owned by his in-laws, at 32-05 Thirty-seventh Street in Astoria, Queens. The room had once been the kitchen of an apartment, which was now occupied by a beauty parlor, and there was a bar downstairs. But the room contained a sink and a gas connection, the house was a fifteen-minute walk from home, and the rent (payable to his mother-in-law) was just $15 a month.

Next, he set out to find an assistant. He returned to the library and searched through the classified advertisements in the back pages of scientific magazines. The American economy had been paralyzed for most of a decade, and many scientists were unemployed, but few of them, apparently, saw any point in advertising for work. Carlson could find only one ad that seemed promising. It was in a magazine called *Electronics,* and it had been placed by an Austrian physicist named Otto Kornei, who had recently immigrated to the United States and had had no luck in finding work. Kornei had decided, in desperation, to spend the last of his minimal savings in publicly seeking a job. Carlson's response was the only one he received.

The first xerographic image, now at the Smithsonian. (Courtesy of Xerox Corporation.)

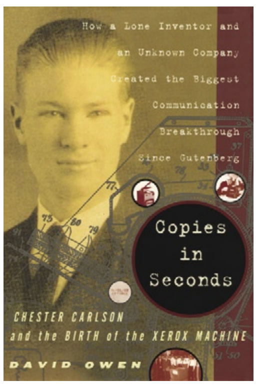
Carlson's own finances in 1938 were far from robust. His final salary at Bell Labs, in 1933, after a companywide wage cut, had been $100 a month. He was making roughly three times that much at Mallory, and he was earning regular raises, but he could not afford extravagances. His budget in 1935 had added up to a little over $230 a month, including $45 for rent, $20 for entertainment for himself and Elsa, and $50 for groceries. Now he was bearing the additional expense of law school. The salary that Carlson offered to Kornei was small in absolute terms—just $90 a month for a period of six months, plus an expense budget of roughly thirty cents a day—but it represented a major portion of his resources. Elsa was already annoyed by his copying obsession; she can't have been pleased that he had now decided to devote more than a third of his gross income to pursuing it.

Kornei was scarcely more enthusiastic. He was a skilled experimental scientist, and he had spent the previous two years, in Vienna, working as an electrical engineer. In a better economy, he would have had his choice of good jobs at big companies. Instead, he found himself being interviewed for a virtually imaginary position by a man who not only wasn't a research scientist but held a mundane job in a corporate back office. The offered salary was low even by the standards of the Depression, and Carlson's so-called laboratory looked more like a janitor's closet—which, in fact, it had once been. Carlson, furthermore, was not a salesman. He was thirty-one years old but looked and acted older, and he dressed like an actuary. He showed Kornei his patent application and gave him a lucid explanation of his idea, but he was too reticent to be able to convey more than a fraction of the excitement he felt about electrophotography, much less to inspire someone else to share it. Carlson augmented the offered salary by promising Kornei 20 percent of the first $10,000 in Carlson's net proceeds from the invention, and 10 percent after that. Kornei agreed to the terms but viewed the offered royalty less as a deal-clinching inducement than as additional evidence that his employer was living a fantasy.

Nevertheless, Kornei turned out to be an ideal assistant. He went to work on October 6, 1938, and in just a few days he made more concrete progress with electrophotography than Carlson himself had managed in more than a year of fumbling experimentation. Coating a zinc plate with a thin, uniform layer of sulfur—a task that had virtually defeated Carlson—turned out to be easy for Kornei. He also showed Carlson that there was no need to build or purchase an electrostatic generator, since they could create a sufficient electrical charge by rubbing the coated plate with a pocket handkerchief or a scrap of fur. And almost immediately he had some limited success in partially discharging coated plates by exposing portions of them to sunlight. That experience persuaded him that he needed a stronger and more reliable light source than the sun shining through the window, and he told Carlson on October 19 that they needed to invest in a Mazda No. 2 Photoflood lamp. Carlson agreed.

The following Saturday, Carlson visited the lab, as he did each weekend. Kornei had already coated a zinc plate with sulfur, and he had ground down the surface with emery paper and polished it with precipitated chalk. He had also purchased a small quantity of lycopodium powder—the extraordinarily fine yellow spores of a plant known as club moss or Christmas tree fern, and the same substance Paul Selenyi had used to develop his facsimile images. (Lycopodium powder is so fine that it is used as a dusting agent in a variety of scientific experiments, and is so water-repellent that it was once sold as baby powder. If you sprinkle lycopodium powder on water, it will float on the surface indefinitely; if you then stick your hand into the water through the film of powder, the lycopodium will coat your hand like a glove and keep your skin dry. It's also explosively flammable and was the key ingredient of early flashbulbs.)

Kornei arranged these materials on a table. "He pulled down the window shade and charged the sulphur surface in the darkened room by rubbing it with a cotton handkerchief," Carlson wrote later. "Then he laid a transparent celluloid ruler having black scale markings on the charged plate and turned on an incandescent lamp (photo flood lamp) for about 10 seconds." The lamp was positioned about a foot above the ruler and the charged plate. "He then turned off the lamp and carefully removed the ruler. Nothing was visible on the plate in the subdued light of the room, but an electrostatic image was there. He sprinkled a little lycopodium powder from a cloth-covered test tube onto the sulphur surface then gently blew away the loose powder. There, adhering to the plate, was a perfect image of the scale of the celluloid ruler, every line and inch number standing out sharply as little ridges of powder."



Carlson raised the shade and held the plate to the light. "The powder image was adhering to the plate by virtue of relatively small, but nevertheless real, electrostatic forces," he wrote. "Kornei then drew his finger over the surface of the plate wiping away the powder image." Kornei took a glass microscope slide and, using India ink, wrote the place and date on it: "10-22-38 ASTORIA." He then closed the shade again, rubbed the sulfur-coated plate with his handkerchief, placed the inscribed slide on the charged surface (as he had previously done with the ruler), turned the flood lamp back on for another ten seconds, and dusted the plate with lycopodium powder. "The letters came out clearly," Carlson wrote, "proving that the plate could be re-used without difficulty."

They repeated the experiment several times, to convince themselves that it worked, then walked to Carlson's apartment and got some waxed paper. Back in the lab, using Kornei's slide once more, they went through the steps again. This time, though, they didn't wipe away the developed image from the surface of the sulfur-coated plate. Instead, Carlson cut out a small rectangle of waxed paper and pressed it against the image, so that most of the lycopodium powder stuck to it. He then placed a warm metal plate against the back of the waxed paper, softening the wax so that the powder became embedded in it. Carlson was now holding the world's first xerographic copy. (You can see it today at the Smithsonian Institution.) He gazed at the paper for a long time, and held it up to the window. Then he took his assistant to lunch.

Carlson felt elated. And, indeed, the sudden appearance of a reproduced image on a photoconductive plate seems almost magical. Charging and exposing a plate makes no change in its appearance, yet if you then sprinkle powder over the surface and blow, an exact facsimile of the original image appears all at once, just as if it had been printed there. In two weeks of experimentation, Kornei had fully justified Carlson's confidence in the process he had conceived. Electrophotography worked, and it worked exactly as he had predicted it would. All that remained to do was to refine the basic process and incorporate it into a functioning office machine. ☐

This, of course, was not as easy as it sounds—the XeroX 914, the first plain-paper copier for office use, didn't come out until 1960. For the full story of Carlson's rags-to-riches life, and the 20-year struggle to build a commercially viable product after meeting what he called "an enthusiastic lack of interest" from two dozen companies including Eastman Kodak, GE, IBM, and RCA, read the book. Copies in Seconds *is available in bookstores, or it can be ordered directly from the publisher, Simon and Schuster.*

David Owen is a staff writer at The New Yorker.

The Price is Right Mysterious

by R. Preston McAfee

I want to start out with an insight so obvious that you'll probably think, "Everyone knows that." Only everyone doesn't. The insight is this: If you offer discounts to your rival's customers, it will cause your rival to fight to hold onto his customers, and he will do this by cutting prices. He will then take some of your customers away from you. In the end, you'll get some of his customers, he'll get some of yours, and you'll both be selling at lower prices. If, on the other hand, you reward loyalty by offering a better deal to customers that have been with you for a while, you make your customers expensive to poach. Your rivals are discouraged from poaching them, and tend to respond in kind.

This is a pretty trite insight, but some cell-phone companies have gotten it dramatically wrong, and it's cost them billions of dollars. Both Verizon Wireless and T-Mobile offer discounts to new customers that are not available to their old customers. If you go to their websites to sign up for a phone plan, you're told "Prices exclusive to T-Mobile.com and valid only with new service activation" and "All phone prices are offered only with activation of a new line of service with Verizon Wireless, under the terms and conditions of selected service plan." The obvious thing this does is to encourage their own customers to leave, if for nothing else than to get the other companies' discounts. Cingular is neutral; if you're a customer and your contract has expired, you qualify for every discount offered. Sprint is the only cell-phone company that gets it right. If you've been with them for 18 months, you get a discount on a new phone that no one else is offered. This is good business.

Here's another obvious insight along the same lines: If you reward your sales force on quantity, such as giving them a commission per unit sold, it encourages the sales force to cut prices wherever they can in order to sell more units, and they don't bear the costs of this price-cutting. If, instead, you reward the sales force on net profits, or even on revenue, you reduce the incentive to cut prices. There are always going to be some price-sensitive customers for whom you eventually have to lower the price, but you should do that by reducing the quality in some way (and we'll talk more about that), or by offering them a bundle of products that makes it hard to compare their deal with any alternative deal. This makes it easier to sustain different prices for different customers so that you can continue to charge your better customers (the ones with the highest willingness to pay) higher prices.

There's a simple formula that characterizes the price that maximizes the profits of a monopoly:

$$\frac{p-m}{p} = \frac{1}{\varepsilon}.$$

This says that the proportion of the price charged, p, that is the markup over the marginal cost, m, equals one over the elasticity of demand, ε. The last two terms are explained in the sidebar.

A monopoly should therefore charge higher prices to customers with inelastic demand, and lower prices (a lower markup over marginal cost) to customers with elastic demand.

The formula works even for companies facing competing products, provided the elasticity is understood to reflect demand for the company's own product and not market demand. Demand for a company's product is more elastic than market demand. For example, if Exxon increases its gasoline price by 10 percent and the other companies do not, it might experience a 40 percent reduction in sales, for an elasticity of 4. In contrast, if all the companies raise their prices by 10 percent, their sales would generally fall only by about 4 percent, for an elasticity of market demand of 0.4. In this case, the market demand is very inelastic, while the demand facing one firm is quite elastic, because an increase in price by one firm drives some customers to switch to competing firms.

The formula can be rearranged as:

$$p = \frac{\varepsilon}{\varepsilon - 1} m,$$

and this version has been widely used—or rather, abused—to justify a "constant percentage markup" policy. After all, that's what it says: Price should be a constant number, elasticity over elasticity minus one, times the marginal cost. But the formula doesn't justify that way of thinking, since the elasticity of demand, and hence the constant number, depends on the type of customer. The marginal cost should be marked up according to customer's elasticity, with markups higher for inelastic customers—and we'll talk about who they are below—and less high for elastic ones.

How can companies go about doing that? One way is to have different charges depending on who the customers are, such as the discounts offered by movie theaters to senior citizens and students, both relatively elastic types of customer. For another example, try logging into Amazon with your own identity and asking for a price on something. Then clear your cookies (so Amazon cannot access your personal information and purchasing history) and search again anonymously for the same item. Sometimes you will be quoted a different price, because when Amazon looks at your past spending pattern, and sees that you have not always gone for the lowest price, they will treat you as a poor searcher—a more inelastic customer—and make you a less attractive price offer.

This is known as direct price discrimination, and you can expect to see more of it in the future. Direct price discrimination means charging different customers different prices for the same good. Most companies prefer to call it value-based pricing, since discrimination sounds unappealing.

Marginal Cost

The marginal cost (m) is the cost to a company of producing one additional unit. If I ordinarily run a fast-food restaurant serving a thousand meals per day, my marginal cost would be the cost of an additional meal per day, or, alternatively, the savings of producing one meal less. For an integrated circuit manufacturer with a $3 billion factory, the marginal cost of a $100 chip might be 25 cents—the cost of the additional labor and materials required to produce an extra chip—until the capacity of the plant is reached, at which point the next chip, which requires building another factory, has a marginal cost of $3 billion.

Elasticity of Demand

The elasticity of demand, ε, is the percentage decrease in quantity sold (Q) associated with a one-percent increase in price (p):

$$\varepsilon = -\frac{\%\Delta Q}{\%\Delta p},$$

and it measures the responsiveness of customers to price changes, that is, their price sensitivity. If customers are very price sensitive, the elasticity of demand will be a large number, and a price cut will produce a large increase in sales. A price increase, on the other hand, will cause a large decrease in sales.

A problem with direct price discrimination is resale among customers, or arbitrage. Customers who can buy something at a lower price may sell the goods to others; Americans who travel to Mexico or Canada to buy prescription drugs are a good example of this. But there's another way to charge different prices to different people that doesn't involve having to observe customer's spending records, and that prevents arbitrage—indirect price discrimination.

Direct price discrimination means charging different customers different prices for the same good. Most companies prefer to call it value-based pricing, since discrimination sounds unappealing.

Indirect price discrimination enlists the help of the customer in the effort to charge customers a different price. Take coupons, for example. Coupons are available to anyone willing to spend time reading the newspaper coupon flyers or the coupon books found at the entrance to many grocery stores, cutting out the coupons, and remembering to give them to the cashier at the checkout (something I always forget to do). Coupons can save 50 cents or $1 off a $3 item, which is a pretty big percentage price cut, yet many shoppers do not use them. So coupons are one way of enlisting the customer in the effort to charge more elastic customers lower prices, while getting other customers—those who place a high value on their time and don't want the work involved in clipping coupons—to volunteer to pay the higher price. The success of coupons relies on the fact that price-sensitive customers are more likely to use coupons than less price-sensitive customers, because lower wages tend to induce price sensitivity and make the time spent on coupons worthwhile.

A quantity discount is analogous. Suppose a company takes 48 rolls of paper towels, wraps them up together in plastic, and charges half the price per roll than for one individual roll. People with small apartments and people with small cars won't buy the 48-roll bundle, and more price-sensitive families with seven children constantly spilling things will. Since large families also tend to be more price-sensitive, it's a good deal for the manufacturer, because it achieves the price discrimination of offering a discount to the more price-sensitive customer.

For a remarkable example of indirect price discrimination, go to the Dell website. The first thing you are asked is what type of customer you are. It gives you four choices: You can be a medium to large business, a home, a small business, or a government agency. A few months ago, I searched for the price of a 512-megabyte memory module, part number A0193405, under each of these headings, clearing my cookies in between my choices. I was quoted $289.99 for a large business, $266.21 for a government agency, $275.49 for a home, and $246.49 for a small business. (At the time of writing, the prices are $334.99 for medium and large businesses and government, and $267.99

Grocery store customers who don't use coupons are inadvertently volunteering to pay higher prices.

for home and small business.) Dell didn't verify what sort of purchaser I was. In fact, they don't care. As a Dell spokesperson said, "Each segment sets its own prices and the customer is free to pick the one that's cheapest." So this is an example of using information provided by the customer to discriminate for or against them. As mentioned above, this is known as "value-based pricing," but where's the value for the large business that paid $43.59 more than a small business? I suspect few large companies are using coupons, either, so they're paying more in two different ways.

Another example of price discrimination occurs when you book a hotel room. If you call a hotel to ask for a room and they quote you a price, ask them if they have a better rate—the answer is almost always yes. These hotels discriminate between customers purely on the basis of whether or not they know to ask.

Companies can also charge more price-sensitive customers less by offering them less, such as giving them a lower-quality product. And an easy way of lowering the quality is to damage the goods. IBM came up with an interesting way to do this. In 1989, Hewlett-Packard came out with the first consumer-oriented laser printer, affordable for small businesses and home use, which printed at five pages per minute. IBM's LaserPrinter printed 10 pages a minute and was almost twice as expensive as the new HP. The problem for IBM was that although it had the better product, many of their customers didn't need the speed, especially when not having it cut the price of the printer in half. IBM was going to lose a huge portion of their market unless they reduced the price of the Laserprinter, but at the same time they didn't want to lose those profitable customers willing to pay extra for the faster speed. So they launched a "new" printer, the LaserPrinter E, a 5-page-a-minute printer that sold at about the same price as the HP printer. It was, in fact, the regular LaserPrinter, but with seven chips added. These chips introduced "wait" states into the processing of the pages. Printing instructions came down the line, reached one of the chips, the chip received the instruction, ticked the clock for a few milliseconds, and then passed the instruction on. That's all the chip did. And that's all the six other chips did as well. IBM had taken a fully functional 10-page-a-minute laser printer and added chips to slow it down so that they could charge just slightly more than half the price for it. It's analogous to a refrigerator salesman who takes a ball-peen hammer and whacks a part of his inventory, then sells those units as "warehouse damaged" at a reduced price.

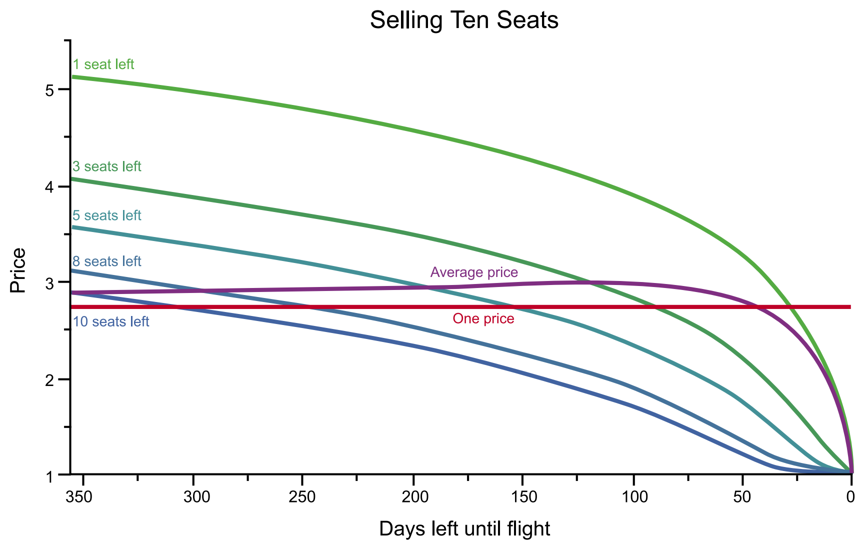
There are many other examples of manufacturers intentionally damaging a portion of their production. The Intel 486SX processor was just the regular 486 processor with the math coprocessor disabled, and was sold for about two-thirds the price. The Sony MiniDisc comes in two sizes, a 60-minute version and a 74-minute version.

At the top is the expensive way to commute from Austin, Texas, to work in Los Angeles from Monday to Thursday and get back home to Texas for the weekend. By buying the tickets another way, below, it's much cheaper, because both tickets involve Saturday-night stayovers.

They're exactly the same except that the 60-minute version has a software instruction that prevents writing on a portion of the disc, cutting its length by 14 minutes. If you buy an inexpensive DVD player from a company that also makes expensive ones, such as Sony, and pop off the top of the remote, you'll often find hidden buttons that provide functionality not accessible on your unit because you didn't pay enough for it. The DVD player and remote possess the functionality, but the company has hidden it from you, so they can sell the player for less.

The airline industry offers some extreme examples of price discrimination. In the process of moving to Caltech in early 2004, I had to commute from Austin, Texas, for several months, flying out to Los Angeles every Monday morning and returning to Austin on Thursday evening. There were two ways to book the trips. The straightforward way was to buy a return ticket from Austin to L.A. on Monday, returning Thursday, and another return ticket to L.A. the next Monday, returning the following Thursday. If I did that, a pair of trips would cost me $2,200. When I booked the tickets another way, buying one round-trip from Austin to L.A., leaving Monday and returning the

Airlines practice dynamic price discrimination, also known as yield management, by placing a different value on each airline seat depending on how many seats are left to sell. This graph shows the standard textbook model of how it works when there are 10 or fewer seats left to sell from a year before the departure date to day 0.



Thursday a week later, and also buying a second round-trip from L.A. to Austin, leaving L.A. on the first Thursday and returning the next Monday, it cost me $420, less than a fifth of the previous price. The gap between those numbers has narrowed since then, but the cost of a return ticket is still much lower if there's a Saturday night stayover. This stayover requirement is exactly the same thing as damaging the goods. The restriction doesn't save the airline any money, because exactly the same seats are being occupied, but it deters some of the business travelers who don't want to spend the weekend away from their families, which allows the airline to charge them more.

If you call a hotel to ask for a room and they quote you a price, ask them if they have a better rate—the answer is almost always yes.

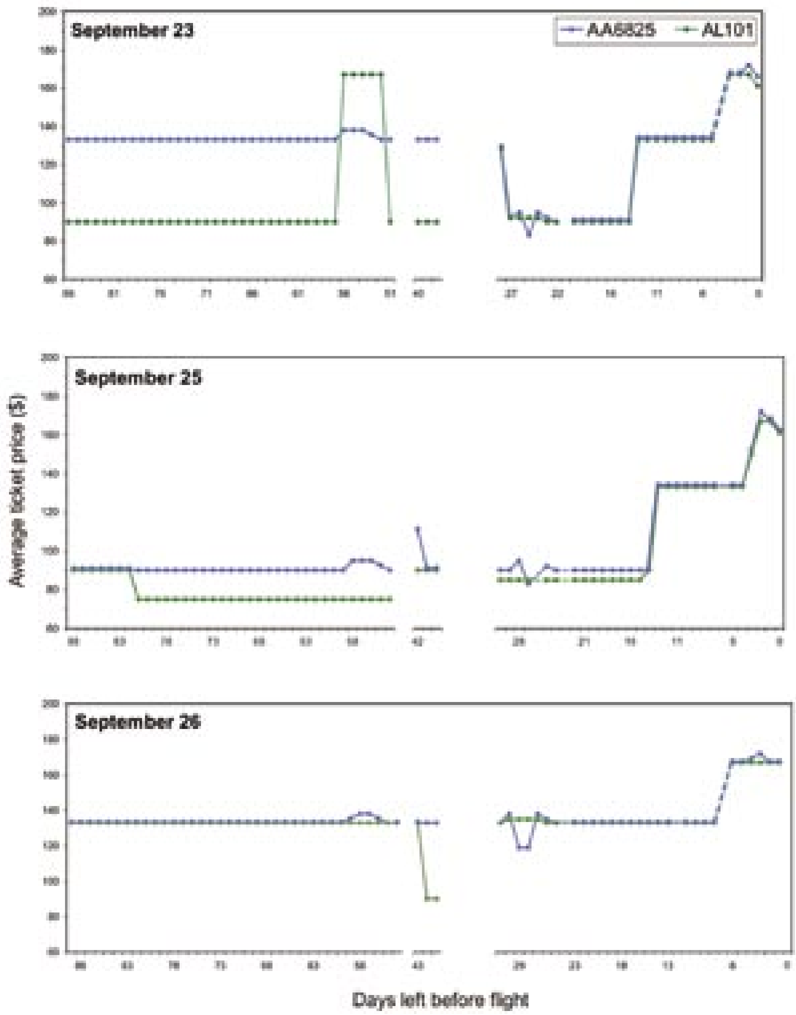
Why do airlines have such complex pricing systems? When American Airlines owned the yield-management company Sabre Corporation, one estimate said that yield management, which is the technical term for dynamic price discrimination, was worth $500 million a year to the airline in added revenue. That was more than 5 percent of American Airline's revenue at the time, so I was intrigued to find out how such an obviously valuable system worked. I began by reading the literature, and that's when I noticed that many of the academics writing papers on yield management tended to disappear from the pages of the journals. It seemed like a John Grisham novel—was American Airlines murdering these people? They weren't. The professors wound up working for the Sabre Corporation and no longer published their work.

A simple example of yield management is when airlines set aside a number of seats in case some really high-value people, usually business people, need them at the last minute and are prepared to pay a very high price. This means that even when there is a lot of tourist demand, the airline doesn't have to turn away passengers willing to pay a large premium. On the negative side, if those last-minute, full-fare-paying passengers fail to materialize, tourists who would have filled those seats have been turned away.

The graph above shows how the ticket price for 10 seats or fewer varies from a year before takeoff to the day of departure. When there are 10 seats left, the price falls along the dark-blue curve, but if two more seats are sold, the price jumps up to another curve associated with having eight seats left. Then if at some point three more seats are sold, the price jumps up to the curve for five seats, and so on. The airline has a different price path for every possible number of seats. As time goes by, all prices tend to fall, because the closer it gets to the departure date, the lower the value to the airline of having a lot of unsold seats.

If there are a lot of seats to sell (and planes are getting bigger all the time—the new Airbus A380 will seat 800), the price will be pretty close to the average price most of the time—this proximity to the average is a consequence of the statistical fact known as the law of large numbers. An implication is that most of the value associated with charging different prices based on the number of available seats occurs with the last 15 or 20 seats. The graph only shows ten seats, but there are similar calculations for 200 seats or more. For most of the time and most of the seats, prices will be pretty steady, and that means the airlines don't do much better than if they'd just picked the average price and stuck with it until they sold all the seats (the red line). Or, put another way, an airline doesn't gain very much with this system if it has 100 or more seats per plane to sell.

So theoretical models of yield management fail to explain how American can make $500 million a



The average daily price of a single ticket from Oakland, California, to Portland, Oregon, was tracked over 86 days for American Airlines AA6825 (blue) and Alaska Air AL101 (green) for three different departure dates in September 2004. It's a mystery why there's such a variation in price between the two airlines, especially on September 23, because AA6825 and AL101 are actually the same flight. (The reason there are gaps in the graphs is that undergrad Vera te Velde's information-gathering efforts were misinterpreted by the Institute as a "denial of service" attack, and her computer connection was temporarily shut down—twice.)

year with the Sabre system. I'm currently working with Caltech undergraduate Vera te Velde to test the standard textbook model of yield management against what is happening in the airline industry, and I can give you a quick summary of what we've learned so far: Everything we knew is wrong.

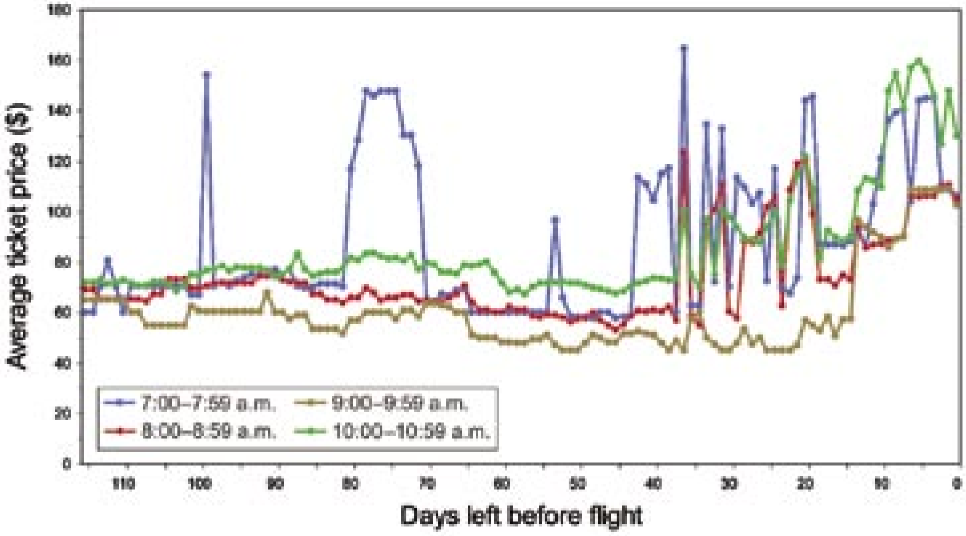
For many months we've been collecting data on ticket prices on a very fine grid, the way financial data is collected, by checking the prices quoted on Orbitz several times a day. The top graph on the left shows the results of tracking two scheduled flights from Oakland to Portland that were close alternatives—that is, flying between the same airports, at about the same time—American Airlines flight AA6825 and Alaska Air flight AL101. The first noticeable feature of this graph is that, for the first 30 days, AA6825 costs about $50 more than AL101. Then at some point, for reasons I don't know, Alaska almost doubles its price and American's price goes up by $5. After a few days American's price comes down followed by Alaska's, and both trade at their former level until 28 days before departure, when Alaska's price jumps up steeply, and American's comes down a bit, so that, on day 27, they both trade at the same price. After that they both drop down a lot and remain in lockstep until departure, apart from an odd downward blip by American on day 25.

The next graph tracks prices for the same flights leaving two days later, on September 25. This time, American Airlines starts by pricing at the Alaska level, then Alaska drops for a while, comes back up, goes down by a much smaller amount, and then they continue in lockstep until the end.

The third graph is for the same two flights departing September 26. Prices are steady and in lockstep for much longer, but again, there's the same puzzling American Airlines $5 blip between 60 and 56 days before takeoff that we saw in the other two graphs. (Even two months later, American still had that same blip. Other blips in the graphs aren't repeated.)

I said these two flights were close matches, but they're a little more than that—they're the same airplane. This flight is operated by Alaska but code-shared with American. Orbitz is quite open about this, offering a choice of flying for $90 on Alaska 101, or for $135 on American Airlines 6825, and it clearly indicates the flight is code-shared with Alaska 101. Why are people choosing American? To earn frequent-flyer miles? But these companies also share their frequent-flyer program, and the miles earned on either flight can be applied to either airline. So it's a mystery to me why, in the first graph, American is selling the same seats, on the same airplane, for 30 days at a price $50 higher than Alaska.

Most existing economic analyses of airlines, and all antitrust analyses for evaluating airline mergers, are based on the assumption that airports in the same city, different times of flight, and different airlines can be considered close substitutes,



The graph shows the average ticket prices of flights departing from Oakland to Portland between 7 and 7:59 a.m., 8 and 8:59 a.m., 9 and 9:59 a.m., and 10 and 10:59 a.m., plotted against days before takeoff. There was no correlation between the prices quoted for the different time slots except in the two weeks before departure. This is a time when all tickets tend to become more expensive, because the airlines can charge more for unplanned travel. (Unplanned travel is often by business people.)

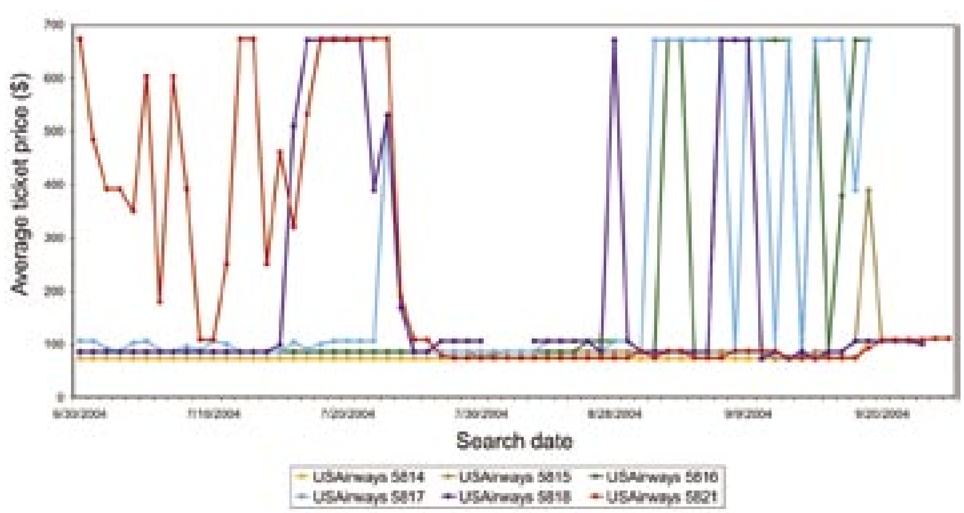
meaning customers view them as good alternatives. Vera and I found that this wasn't the case at all. For example, when we charted the ticket prices of flights taking off between 7 and 7:59 a.m., 8 and 8:59 a.m., 9 and 9:59 a.m., and 10 and 10:59 a.m. on the same route between Oakland and Portland (above) we saw some correlation in the last month prior to takeoff—when all prices moved up—but before that the prices were not closely correlated, as good substitutes must be.

These price fluctuations are not just in economy flights, we're finding the same thing on first-class, one-way, full-fare, refundable tickets—the most expensive way to fly. In the graph below, we plotted the average price of a first-class ticket from Los Angeles International Airport (LAX) to Las Vegas on US Airways, as quoted on Orbitz, at five different departure times on September 23, and at 8:10 a.m. on September 25. It's just a short hop from LAX to Vegas, but depending on the day of booking, and the time of the flight, a ticket could cost either $680 or $90. Before I started this research, I would have guessed that first-class fares were pretty steady, and I would have been wrong.

Most of the assumptions people make about airline pricing don't seem to be borne out by our data (which is the first of its kind), and it's possible that there may be randomization built into airline pricing. Vera and I are currently testing that theory.

My main advice for buying airline tickets is to always book more than a month in advance, as prices rise in the last month—especially during the last two weeks, when our data show that they go up by $70 on average. Flexibility in the time of day in which you travel and the airport from which you fly can be worth 50 percent. And finally, even if you're committed to flying on a particular flight with a particular airline, it still pays to search if you've got two months before the flight takes off. Check the price every day, and if it falls by 20 percent, book it. A saving of 20 percent simply by monitoring the price on Orbitz for two weeks is an enormous return on invested time.

Some unlucky high-rollers heading for Las Vegas from Los Angeles on September 23 and 25 with US Airways might have paid almost $700 for their first-class seat while the person next to them had paid only $90. Ticket prices for the flights monitored here even changed dramatically several times a day. Because the graph shows average daily prices, a plot of $400 may well reflect a price of $700 for half the day, and $100 for the other half.



If Airlines Sold Paint

Buying paint from a hardware store

Customer: Hi, how much is your interior flat latex paint in Bone White?
Clerk: We have a medium quality, which is $16 a gallon, and premium, which is $22 a gallon. How many gallons would you like?
Customer: I'll take five gallons of the medium quality, please.
Clerk: That will be $80 plus tax.

Buying paint from an airline

Customer: Hi, how much is your paint?
Clerk: Well, sir, that all depends.
Customer: Depends on what?
Clerk: Actually, a lot of things.
Customer: How about giving me an average price?
Clerk: Wow, that's too hard a question. The lowest price is $9 a gallon, and we have 150 prices up to $200 a gallon.
Customer: What's the difference in the paint?
Clerk: Oh, there isn't any difference; it's all the same paint.
Customer: Well then, I'd like some of that $9 paint.
Clerk: Well, first I need to ask you a few questions. When do you intend to use it?
Customer: I want to paint tomorrow, on my day off.
Clerk: Sir, the paint for tomorrow is the $200 paint.
Customer: What? When would I have to paint in order to get the $9 version?
Clerk: That would be in three weeks, but you will also have to agree to start painting before Friday of that week and continue painting until at least Sunday.
Customer: You've got to be kidding!
Clerk: Sir, we don't kid around here. Of course, I'll have to check to see if we have any of that paint available before I can sell it to you.
Customer: What do you mean check to see if you can sell it to me? You have shelves full of the stuff; I can see it right there.
Clerk: Just because you can see it doesn't mean that we have it. It may be the same paint, but we sell only a certain number of gallons on any given weekend. Oh, and by the way, the price just went to $12.
Customer: What! You mean the price went up while we were talking?
Clerk: Yes sir. You see, we change prices and rules thousands of times a day, and since you haven't actually walked out of the store with your paint yet, we just decided to change. Unless you want the same thing to happen again, I would suggest that you get on with your purchase. How many gallons do you want?
Customer: I don't know exactly. Maybe five gallons. Maybe I should buy six gallons just to make sure I have enough.
Clerk: Oh no, sir, you can't do that. If you buy the paint and then don't use it, you will be liable for penalties and possible confiscation of the paint you already have.
Customer: What?
Clerk: That's right. We can sell you enough paint to do your kitchen, bathroom, hall, and north bedroom, but if you stop painting before you do the bedroom, you will be in violation of our tariffs.
Customer: But what does it matter to you whether I use all the paint? I already paid you for it!
Clerk: Sir, there's no point in getting upset; that's just the way it is. We make plans based upon the idea that you will use all the paint, and when you don't, it just causes us all sorts of problems.
Customer: This is crazy! I suppose something terrible will happen if I don't keep painting until after Saturday night?
Clerk: Yes, sir, it will.
Customer: Well, that does it! I'm going somewhere else to buy my paint.
Clerk: That won't do you any good, sir. We all have the same rules.

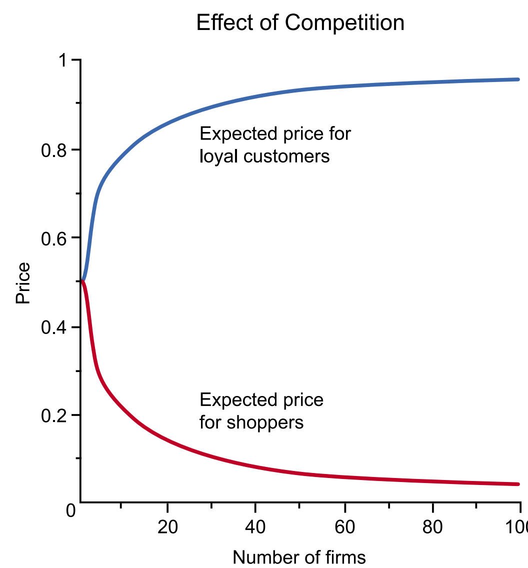
Written by Alan H. Hess, President of Hess Corporate Travel, and reproduced here by permission, this piece was originally published in *Travel Weekly*, October 1998.

Cheerful newspaper flyers announcing items on sale are actually weapons in a sophisticated price war.

An area of pricing where we already see randomization is that of sale items in grocery stores presented in those garish advertisements that have probably annoyed you when they fall out of the newspaper and scatter all over the floor. These flyers indicate that something quite mysterious is happening to prices. For example, a 12-pack of diet Coke can go from $4.99 down to $2.50, and then back up to $4.99 the week after. Bounty paper towels at $2.89 go down to $1.19, then back up to $2.89, and Smuckers grape jelly, normally $2.49, can be on sale for 98 cents. These are very dramatic price changes. In most cases no coupons are required, and the flyers document a temporary sale price. Consider the Smuckers jelly. What is mysterious about this sale is that the manufacturing costs didn't change, the set of jelly manufacturers didn't change, there was no grape shortage or glut, and the demand didn't change. But the price changed a lot. It's puzzling. Maybe it's not on the quantum-theory scale of puzzling, but it probably has more important effects on the pocketbooks of most Americans than the quantum theory does. So why does the price fluctuate? The answer turns out to be very simple: *It has to*. There are no stable prices once the products of different grocery stores are advertised on the same day. Let me explain.

Two types of people shop in grocery stores. One type, whom I'll call loyal customers, go to one store and don't shop around. They may or may not buy a product, depending on its price, but they are not shopping around. The other type shops in different stores for bargains. I'll call these customers "shoppers." A grocery store that's a penny cheaper than its rivals picks up most of the shoppers. So if an item is priced at 98 cents, a rival store will either want to price the item at 97 cents to pick up those shoppers, or it will not even try to compete for the shoppers and just charge its loyal customers $2.50. One thing a rival store won't do is match the price; it'll either want a much higher price, or it'll undercut slightly. In the kind of world that has shoppers and loyal customers, a store's prices mustn't be predictable, because rival stores can exploit predictability. Companies must randomize their sale prices, and the products they put on sale, to stop them being predicted by their rivals.

The only thing that's stable is the statistical distribution of prices, which economists call an equilibrium price dispersion. Conceptually, an equilibrium price dispersion is analogous to how children play the game Rock, Paper, Scissors. In



Loyal customers—those who don't shop around for the best buys—are affected by competition among grocery firms in a much less favorable way than shoppers who look for bargains. As more and more firms compete for the bargain hunters, prices come down (red curve). But lower prices reduce profits, so stores begin to opt out of the price war and rely on recouping lost income from their loyal customers—by charging them more (blue curve).

When stores compete for an ever-increasing proportion of bargain-hunting shoppers as opposed to loyal customers, prices for bargain hunters drop (red curve). For loyal customers, however, prices stay much higher (blue curve) until the last loyal customer becomes a shopper. Then prices plunge to the same level as the shoppers pay.

this game, two children choose one of three items simultaneously, and if each chooses the same item, the game is a tie. If they choose different items, paper beats rock, rock beats scissors, and scissors beat paper. The only stable play of this game is an even split among the three items, because any other play can be exploited by rivals. In an episode of *The Simpsons* in which Lisa and Bart played this game, Lisa guessed that Bart would always play rock, which could smash things, so she played paper and won every time. Unpredictable sales have an effect similar to random play in Rock, Paper, Scissors. The distributional strategy of sales prevents rivals from exploiting the store's pattern of pricing and leads them to also choose randomized prices. Another aspect of equilibrium price dispersion is that the profits are always the same, no matter what prices are charged in any particular week.

There are no stable prices once the products of different grocery stores are advertised on the same day.

What's the effect of competition in a market with both loyal customers and shoppers? The graph on the facing page shows that when more and more stores compete for customers, it gets progressively harder for any one of them to win the competition for the shoppers, even with substantial price cutting, so as the number of stores grows, most of them stop competing for shoppers except on rare occasions. This means that loyal customers get soaked most of the time, because they're more likely to be shopping in a store that didn't bother to try to win the shoppers in that particular week. Shoppers, on the other hand, continue to do better than the loyal customers because there are still a lot of stores competing for their business. So competition is good for shoppers, and bad for loyal customers. If you're a loyal customer, you really want to do away with all the competitors to your store except one. You want one rival to remain, because if your store had the monopoly, it could charge whatever price it wanted.

The effect of shoppers on other buyers is shown by the graph above. As the proportion of shoppers increases, competing for them becomes more attractive to the grocery stores, and prices fall for both types of customers, but in different ways. Prices for shoppers fall smoothly down to the competitive level, which is reached when everybody is a shopper. Prices for loyal customers stay high until the last loyal customer is gone. Another way of putting this observation is that if most people are shoppers, a single loyal customer does a huge amount of damage to any other loyal customer. Loyal customers damage shoppers as well, but they harm their own kind much more.

Grocery-shopping models predict that prices are unpredictable and should vary from week to week, often by as much as 50 percent. Items on sale should be things price-sensitive customers care about, but price-insensitive customers don't—which is why you don't often see expensive olives on these sales flyers, but see milk, paper towels, and whole chickens instead. There's also a negative correlation of price over time: If prices are low one week, shoppers stock up, so the next week there are fewer shoppers buying, leading to higher average prices. When the shoppers' inventories run down, they're back in the market again, leading to more competition among the firms for the shoppers, and an increased likelihood that prices will be low.

So what can we learn from the economic analysis of pricing? My best advice to consumers is to search for the best prices, both because the savings can be significant and because the search for good deals contributes to making markets more competitive. Prices for goods as disparate as airline tickets, diet Coke, and gasoline vary a great deal, both geographically and temporally, and the savings from shopping around can be significant.

It pays to shop around for gas, as some pumps can be significantly cheaper. These prices were photographed at lunchtime on August 5, at gas stations a short distance from Caltech.

Gasoline is an interesting example because prices vary significantly over short distances. Part of that difference is due to the mistaken impression that the quality varies across brands, when in fact air-quality regulation standardizes the product to the point where the tiger in that tank is merely marketing hype. Drivers who don't shop around should not complain about the price—not shopping encourages gasoline companies to use high prices.

Pricing is a central aspect of a firm's profitability, yet by and large much of American industry just uses a straight markup on the cost of producing the item. These companies also make the organizational mistake of giving the job of pricing to the marketing department. Marketing departments tend to focus on increasing demand and pay little attention to the science of pricing. Pricing should not be an afterthought of a marketing department, but involve a separate division within a company.

In summary, the economic analysis of pricing offers a variety of lessons for businesses, which may have a substantial impact on the bottom line. Companies should reward loyalty. It took the cell-phone companies a long time to understand this and only Sprint is currently getting it right. If a company is selling goods that expire or go bad, like airline seats, hotel rooms, restaurant meals, or fresh fruit, yield management can increase profits by a couple of percent. It also often pays to sell the same goods at different prices, especially by producing them in different qualities, or by deliberately damaging a portion of the output; in some cases customers will pay more simply out of ignorance. Quantity discounts, even for dissimilar items bundled together, can be an effective means of price discriminating.

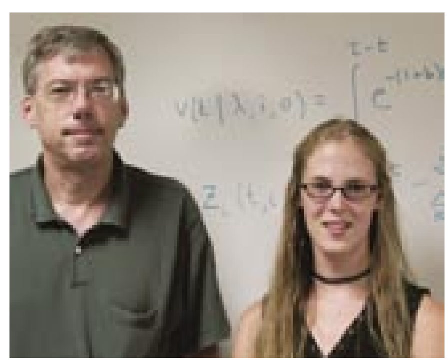
It pays, however, for the business to think about the basis for price discrimination: What causes some buyers to be price sensitive, and how can a price cut be targeted only to that group? Then pricing can be optimized for various groups, a process that has important implications for marketing channels, promotional vehicles like introductory offers, record-keeping, product design, and packaging.

I'll close with the example of a South Carolina retailer who offered an innovative twist in quantity discounts by advertising "Shoe: buy one, get one free." □

R. Preston McAfee joined Caltech in January 2004 as the J. Stanley Johnson Professor of Business Economics and Management. A recognized expert in industrial organization and auctions, he has advised the U.S. government on matters such as collusion, price-fixing, electricity pricing, bidding, procurement, and sales of government property. He was the codesigner of an auction for the FCC to sell off radio frequencies for digital cell phones and pagers, which netted the federal government $17 billion, and has since advised on similar auctions in Mexico, Canada, and New Zealand. As an expert witness for the Federal Trade Commission and the Antitrust Division of the Department of Justice, he analyzed the mergers of Exxon and Mobil, BP and ARCO, and Oracle and PeopleSoft.

McAfee holds a BA in economics ('76) from the University of Florida, plus master's degrees in both mathematics and economics ('78) and a PhD in economics ('80) from Purdue. He taught at the University of Western Ontario from 1981 until 1990, then moved to the University of Texas at Austin to become the Baker Professor of Political Economy and then, in 1997, the Murray S. Johnson Professor of Economics. He first taught at Caltech as a visiting professor from 1988 until 1990, and has also taught at MIT and the University of Chicago.

This article is based on a talk given on the 68th Annual Seminar Day in May, arranged by the Caltech Alumni Association. If you would like to learn more, check out McAfee's book, Competitive Solutions: The Strategist's Toolkit, *and his* Introduction to Economic Analysis, *an open-source text available to all at http://www.introecon.com.*



Above: Preston McAfee has been working with Vera te Velde, a junior majoring in math and economics, to study pricing in industries such as the airlines. This is Vera's second Summer Undergraduate Research Fellowship (SURF) with Preston. Last summer, her data-mining program collected over 12 million different data points.

Norman Horowitz 1915 — 2005

Professor of Biology, Emeritus Norman Horowitz, a geneticist who made key contributions to the understanding of how genes code for proteins and how evolution works at the molecular level, and who designed an instrument for the two Viking missions to Mars to search for signs of life, died on June 1 at his home in Pasadena. He was 90.

A native of Pittsburgh, Horowitz earned his bachelor's degree at the University of Pittsburgh in 1936 and his doctorate at Caltech in 1939. After a postdoctoral appointment at Stanford with George Beadle, Horowitz returned to Caltech when Beadle moved to the Institute in 1946, and was on the faculty of the biology division for the remainder of his career. He was division chair from 1977 to 1980, and became professor emeritus in 1982.

A memorial service has been scheduled for September 12 at 2:00 p.m. in Dabney Lounge and Gardens, and will be covered in a subsequent issue of *E&S*. □

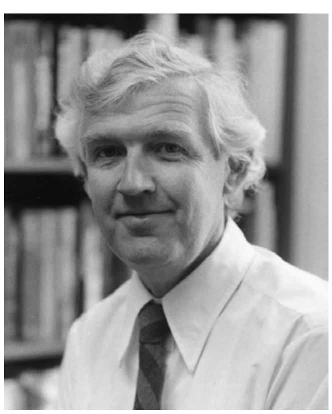
Ronald F. Scott 1929 — 2005

Ronald Fraser Scott, the Hayman Professor of Engineering, Emeritus, died August 16 at his home in Altadena after a long battle with cancer. He was 76.

Scott was an international leader in the field of soil mechanics, particularly in relation to landslides and other soil failures. Born in London and raised in Scotland, he earned his bachelor's degree from the University of Glasgow and his master's and doctorate degrees from MIT. He joined the Caltech faculty in 1958 as an assistant professor, and rose through the ranks to become the Hayman Professor. He retired from active faculty duties in 1998.

Scott worked on various NASA missions, including the Surveyor unmanned and Apollo manned missions to the moon and the Viking spacecraft that landed on Mars in 1976. He designed the soil scoop that fed Norman Horowitz's instrument.

As a memorial service is being planned, *E&S* will carry a full obituary at a later date. □



Konishi Wins Neuroscience Prize

Bing Professor of Behavioral Biology Masakazu "Mark" Konishi and his former postdoctoral researcher Eric Knudsen, now chair of the neurobiology department at Stanford University, have been awarded this year's Peter Gruber Foundation Neuroscience Prize for their work on the brain mechanisms of sound localization in barn owls. They will receive a gold medal and a $200,000 unrestricted cash award at the annual meeting of the Society for Neuroscience in November.

Konishi has worked extensively on the auditory systems of barn owls and songbirds for two decades. In a remarkable collaboration, Konishi and Knudsen established that owls—who can home in on mice on the ground in total darkness—have "space-specific" neurons that respond to sounds coming from particular directions and form a topographic map of auditory space in the midbrain. They also worked out how this auditory map is calibrated with the neighboring visual map.

The citation praises their research as a "paradigm for the precise organization of a sensory system and its ability to adapt to environmental experiences," and adds that their "mentorship and care of their disciples have made them models for scientists all over the world." □

Kip Thorne (center), the Feynman Professor of Theoretical Physics, has been named California Scientist of the Year by the California Science Center in Los Angeles. He was honored for "being one of the world's leading experts on the astrophysical implications of Einstein's general theory of relativity, and for having trained a generation of scientists." The award was presented at the Center's Discovery Ball by former California governor George Deukmejian, left. Jeffrey Rudolph, President of the Science Center, is on the right.

PICTURE CREDITS:
43 – Elizabeth Horowitz, Lee Salem/California Science Center;
44 – Peter Mendenhall, Mark Konishi, Bob Paz

New Division Chair for E&AS

David Rutledge, a leading researcher in the wireless telecommunication revolution, became chair of the Division of Engineering and Applied Science on September 1, He replaces Richard Murray, Rutledge is currently the Kiyo and Eiko Tomiyasu Professor of Electrical Engineering.

He earned his bachelor's degree at Williams College, his master of arts degree from the University of Cambridge, and his doctorate from UC Berkeley. Rutledge joined the Caltech faculty as an assistant professor in 1980, and rose through the faculty ranks to become the holder of the Tomiyasu chair in 2001. He also served as executive officer for electrical engineering from 1999 to 2002.

Rutledge's research group is currently involved in building circuits and antennas for numerous electronic applications. His work on microwave circuits has been important for various advances in wireless communications and useful for applications such as radar, remote sensing, and satellite broadcasting.

He is also director of the Lee Center for Advanced Networking, which aims at creating a reliable and robust global communication system. □—*RT*

Other Honors and Awards

Emmanuel Candes, associate professor of applied and computational mathematics, received the James H. Wilkinson Prize in Numerical Analysis and Scientific Computing at the Society for Industrial and Applied Mathematics annual meeting held in New Orleans. The honor recognizes Candes's "outstanding theoretical and practical contributions to computational harmonic analysis and image processing." **Shri Kulkarni**, MacArthur Professor of Astronomy and Planetary Science, has been chosen as the Biermann Lecturer for 2005. The Biermann Lectureship is considered the highest visiting position of the Max Planck Institute for Astronomy in Garching near Munich, Germany. **Jerrold Marsden**, Braun Professor of Engineering and Control and Dynamical Systems, gave this year's John von Neumann Lecture at the Society for Industrial and Applied Mathematics annual meeting. Marsden was chosen for his fundamental contributions to geometric mechanics based on symmetry. **George Rossman**, professor of mineralogy and divisional academic officer for geological and planetary sciences has been awarded the 2005 Friedrich Becke Medal of the Austrian Mineralogical Society for his "outstanding contributions in the fields of mineralogy, petrology, and geochemistry." □

THE ROAD TO CARMA

Above: Barely a year after site development, the CARMA array telescopes and buildings are all in place at Cedar Flat. In mid-August, signals from three telescopes were successfully combined. Right: One of the OVRO telescopes negotiates "The Eye of the Needle" on Highway 168.

there's only **one.caltech**
THE CAMPAIGN

For more information about supporting CARMA, please contact:

Caltech Associates
Mail Code 5-32
Pasadena, CA 91125
626-395-3919
associates@caltech.edu

In May 2004, Inyo National Forest Supervisor Jeff Bailey signed the special use permit allowing construction of the Combined Array for Research in Millimeter-wave Astronomy (CARMA) at Cedar Flat, in California's Inyo Mountains. CARMA relocates Caltech's Owens Valley Radio Observatory (OVRO) millimeter-wave array and the Berkeley-Illinois-Maryland Association (BIMA) array to a site with improved atmospheric transparency. The project will create a frontline instrument for future studies of the formation of planets, stars, and galaxies, and of the large-scale structure of the universe.

Site clearing and construction began immediately. The first convoy of three trucks carrying pedestals from the six-meter BIMA telescopes left Hat Creek for Cedar Flat on September 30, 2004, and were quickly followed by the six remaining pedestals and all nine reflectors; the move of the six 10-meter OVRO telescopes followed between March and June 2005. By August all 15 telescopes had been reassembled at their new home.

The project's $15 million cost is being divided equally among Caltech, BIMA's universities (UC Berkeley, the University of Illinois, and the University of Maryland), and the National Science Foundation, which has supported OVRO and BIMA operations and upgrades for more than 20 years and will continue to provide similar support for CARMA. Thanks to funding from the Norris Foundation and the Gordon and Betty Moore Foundation, Caltech had already raised $4 million toward the project by the beginning of 2005. Soon after, the Caltech Associates set their sights on raising the final $1 million of Caltech's funding commitment.

The Associates hosted a special fund-raising field trip to the CARMA site in June. The overnight trip gave participants a firsthand view of the control room, machine shop, dorm rooms, and (of course) the telescopes, thanks to private tours led by Anneila Sargent (MS '67, PhD '77), OVRO/CARMA director and Rosen Professor of Astronomy; Geoff Blake (PhD '86), OVRO deputy director and professor of cosmochemistry and planetary sciences and professor of chemistry; and CARMA project manager Douglas Bock. In an enthusiastic response, one donor quickly made a $100,000 contribution. To date, the Associates have raised $283,000 toward their $1 million goal.

As the project nears "first light," expected late this fall, CARMA scientists and staff are testing the system as each component comes on line, and are working hard to construct more antenna pads, complete the basic array infrastructure, upgrade the system electronics, and implement the site's computing systems. The CARMA team anticipates full operation in late spring 2006. ☐—*Vannessa Dodson*

Engineering & Science

California Institute of Technology
Pasadena, California 91125