California Institute of Technology

E&S
Engineering and Science

Volume LXX,
Number 3,
2007

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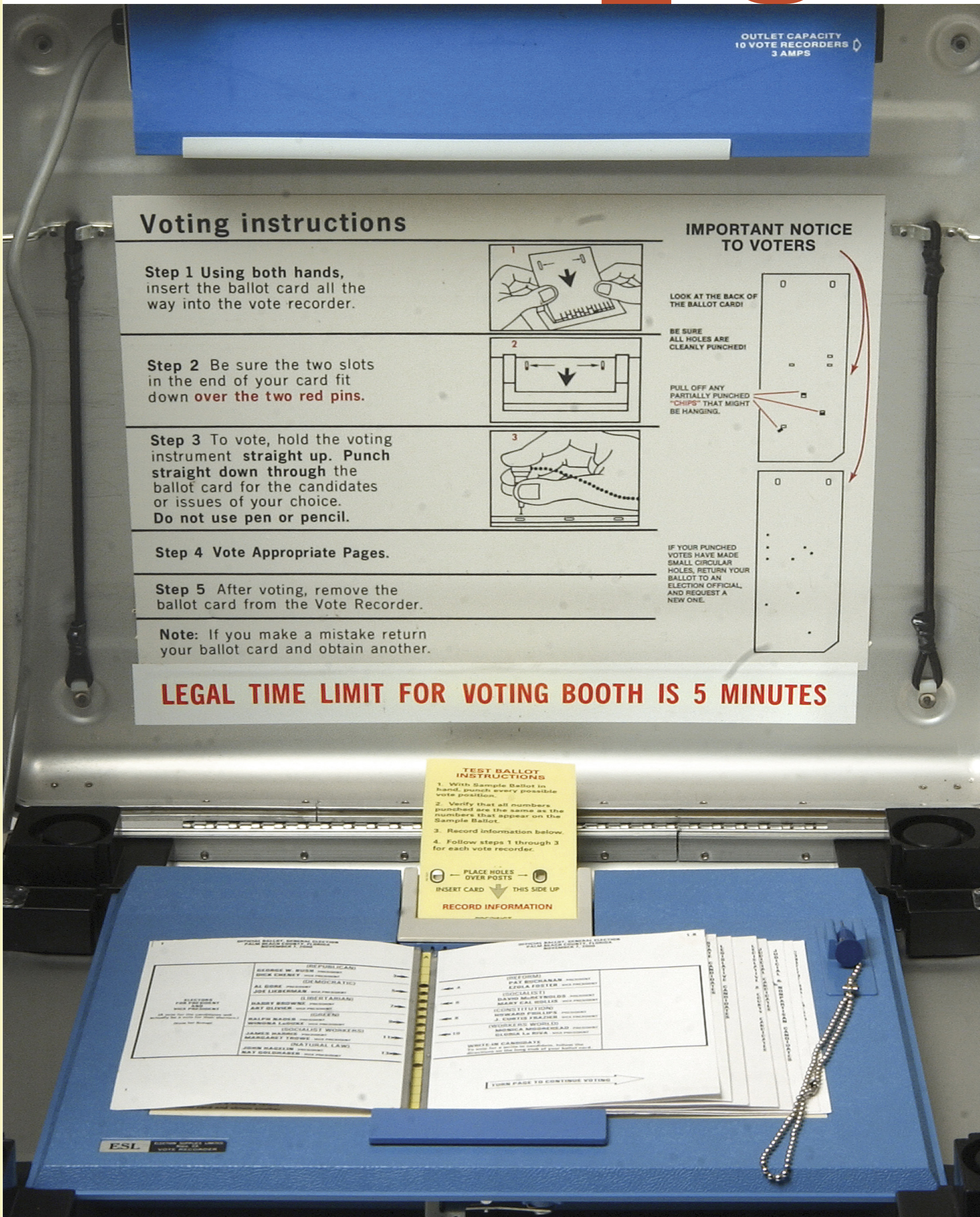
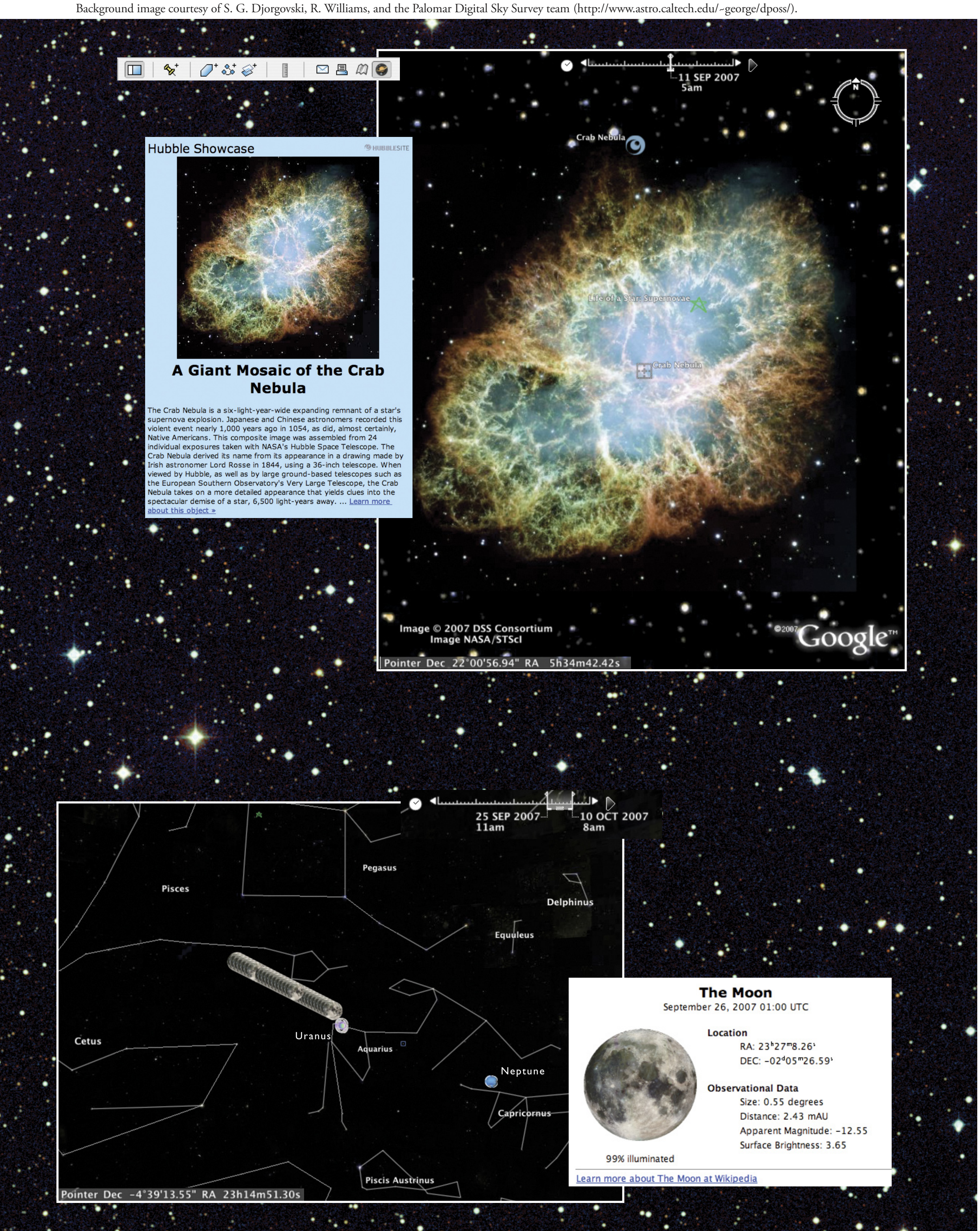


Background image courtesy of S. G. Djorgovski, R. Williams, and the Palomar Digital Sky Survey team (http://www.astro.caltech.edu/~george/dposs/).



The heavens are now available for easy desktop browsing via Sky in Google Earth, introduced on August 22. You can navigate the celestial sphere, and tools including Hubble Showcase and Wikipedia explain what you're seeing. Sky even tracks orbits, as shown with the moon's path at lower left. Sky's northern-hemisphere base-map imagery comes from a survey conducted in the 1980s and '90s with the 48-inch Samuel Oschin Telescope at Caltech's Palomar Observatory. Foreground content comes from sources worldwide, including Caltech and JPL. Many of these partners also provide overlays, or "mashups," showing specific data sets. A Caltech mashup called VOEventNet, available in the Google Earth Gallery, allows users to track fleeting phenomena such as the gamma-ray bursts thought to signal the transformation of dying stars into black holes.

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ENGINEERING AND SCIENCE

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On the cover: Stalin is credited with saying, "Those who cast the votes decide nothing. Those who count the votes decide everything." But what happens when machines count the votes? Punch-card ballot voting machines like this one were at the root of the 2000 presidential election debacle. Will replacing them thanks to the 2002 Help America Vote Act reinstill our faith?

Engineering & Science (ISSN 0013-7812) is published quarterly at the California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125. Annual subscription $20.00 domestic, $30.00 foreign air mail; single copies $5.00. 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, 14, 15 — National Museum of Natural History, Smithsonian Institution; 2, 3 — Doug Smith; 4–5 — NASA/JPL/Caltech; 6 — Ariel Shoresh; 8 — NASA/JPL/MSSS; 9 — NASA/JPL/Cornell; 10, 27, 30, 31 — Bob Paz; 17, 18, 22, 24 — Melissa Slemin; 19, 25, 29, 34, 35, 42 — Doug Cummings; 30, 32 — Caltech Brain Imaging Center; 32 — NASA/JSC; 26, 27, 28, 29 — Shimojo lab; 33, 38, 39 — Caltech Archives; 34, 37, 42 — Seth Shostak; 43 — NASA/STScI/AURA

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Serious Fun at the Outdoor Science Lab

Children's Center staffers Jason Mytar and Monica Wood, and two potential Nobelists in the outdoor lab.

It's not rocket science, but it may lead to rocket scientists. Catering to three- to five-year-olds, the Children's Center at Caltech's Outdoor Science Laboratory was dedicated on May 12. The Children's Center is Caltech's daycare facility, and the lab is the brainchild of director Susan Wood, who came to Caltech from UCLA six years ago and brought a science-based curriculum with her. To the kids, however, the curriculum is hard to distinguish from fun. At that age, "inquiry-based, hands-on educational opportunities," as they tend to be called in the ed biz, consist of such things as a trek across campus to Millikan Pond to see the turtles, which on a recent day the Koalas—the three-year-olds—were doing.

The Koalas were in the midst of a unit called "Dead or Alive," in which their assignment was to figure out how to decide if something is living or nonliving. Observations and hypotheses are noted in their journals, which is to say the budding investigators draw pictures and dictate one-on-one to a grown-up who writes down the words. Sample entries:

"Jason [Mytar], you are alive because you have eyes."

"The strawberry is alive because it is green."

"Q: [to Jason] Are these *Curious George* monkeys? A: Yes. The monkeys are not living because they are in a picture."

"Monkeys. Not living because I don't like monkeys."

Every child gets a turn to speak in the discussion sessions that follow, says Wood—"We teach the value of collaboration"—and the group's collected wisdom is distilled into posters. It's an open-ended conversation, she adds. "I don't want it to be a quiz show—'What color is my blouse?' 'Blue!' 'That's right!'" Another day's discussion might focus on toys with moving parts, or machines in general—if something moves by itself, does that mean it's living? "We will carry this through several months. Kids learn through repetition."

Another experiment involves comparing natural loofahs to the rectangular sponges you get in four-packs. "Water play is very big in the summer, and it gives us the chance to introduce exotic words like 'saturated' into the discussions," says Wood. "We don't expect them to retain every word they hear, but they pick up a lot. We're learning as we go that they are more capable than we expected, and we had very high expectations."

It's Tool Time! Jason Mytar hands out the protective gear as Children's Center director Susan Wood (background, at left) and Anne Chandler, science curriculum coordinator, look on from the shade of the lab.

The four-year-old Raccoons, meanwhile, are learning about energy by estimating how far a paper airplane will go, throwing it, and measuring the result. Another day they'll be putting a thermometer in a shaft of sunlight to see what happens. Their workroom has quantitative tools of all kinds—measuring cups, rulers, a kitchen scale.

The Beavers, age five, have moved on to the six simple machines—the wheel and axle, the wedge, the lever, the inclined plane, the screw, and the pulley. The underlying lessons are about form and function, and about tools in general. The Beavers' journals are full of drawings of machines seen around campus: a telescoping construction crane (pulleys), the ubiquitous electric carts (wheels), a cherry picker trimming tree branches (levers), and even a washing machine full of clothes (gears).

Each day offers a host of activities, including a class on drawing from life. This teaches close observation—really *looking* at things, which is of course the basis of science. Today the Beavers are doing watercolors of a pot of lilies in bloom. A snippet of overheard conversation between the teacher and a student: "What are you going to draw first, the stem or the flower?" "The stem." "Where is the stem?" "This is the stem." Says Wood, "She's making them aware of the details, but she's not telling them what to draw. There's a big difference between this and doing crafts." Mapmaking is big, too. Explains Wood, "A map, like this one of our trip to Millikan Pond, is like a story. It has a beginning, a middle, and an end. It's a lot like reading, and it's a very good activity for our pre-readers."

The Children's Center occupies four 1920s vintage bungalows, two on either side of Chester Avenue on the northern border of campus. The Koalas, Raccoons, and Beavers live in the two houses on the west side of the street. The Outdoor Science Laboratory is nestled between the Beaver house and the Koala/Raccoon house. It is largely shielded from the street by the houses, and has no wall on the yard side "to help facilitate the exploration of nature." Under a rakishly slanted corrugated-steel roof, the central, U-shaped work island has a built-in light table, whiteboards that flip over to reveal overhead mirrors for better views of things on the counters, and portable electrical power from a pair of overhead cable reels. There are even microscopes for looking at bugs and leaves. The walls are lined with cabinets, sinks, and another whiteboard. Construction cost about $200,000, half of which was financed by five years of fund-raisers; the balance came from a grant from the Howard Hughes Medical Institute arranged by Stephen Mayo (PhD '87), the Bren Professor of Biology and Chemistry, whose sons were a Koala and a Beaver last year.

M)Arch. (yes, that's their preferred spelling) of Santa Monica designed the project. The firm was chosen because of their highly collaborative approach—they worked with Wood, the CCC staff, and the CCC board "for many months before the pencil hit the paper," says Wood. The industrial look was chosen, she adds, because it "tells the kids that what we are doing is real, and it's important. And a lot of them have seen labs, so the architects and I went into several labs and took pictures before they began designing." This is in keeping with the center's philosophy. For example, in the make-believe kitchens "the tea sets are all real china—we want to give them as many real things as possible. The message is, we trust them. These things are delicate, and they know that." The outdoor lab stocks tools—real ones, including saws with sharp teeth that really cut. Similarly, the clay-modeling supplies include sculpting tools from an art-supply house instead of the typical assortment of repurposed kitchenware. "Good tools are just easier to use."

The lab won gold in the Spark Design Awards' Architecture and Interiors category. The awards, given annually by Pasadena's Art Center College of Design, are in seven categories ranging from mobility to architecture. The finalists were culled from hundreds of entries worldwide. (Other honorees included a design for a Dutch rental-bike dispenser and an ergonomic chair made from sustainable bamboo.) Juror Robert Hale, a principal at the Rios Clementi Hale Sudios, called the lab "minimal intervention in architecture that achieved maximum results."

The fully accredited Children's Center at Caltech is a private, nonprofit organization that offers childcare to the Caltech/JPL community; it is also open to children from the surrounding area. □—*DS*

Mira, Mira

Truly the fairest one of all, the "comet" above is an aging red-giant star named Mira. Although Mira has been studied for more than 400 years, its tail has just been discovered by Caltech's Galaxy Evolution Explorer (GALEX) spacecraft. Shed from Mira's surface over the last 30,000 years, the tail contains carbon, oxygen, and other elements that will eventually be recycled into new stars and planets—enough material, in this case, to form at least 3,000 Earths or nine Jupiters. Most stars travel at more or less the same speed as the interstellar gas around them, but Mira is hurtling along at a relative velocity of 130 kilometers per second, piling up a "bow shock" whose hot gas mixes with the cooler hydrogen being shed by the star. As this hydrogen swirls away in a turbulent wake, the atoms fluoresce in the ultraviolet. The tail of gas and dust stretches 13 light-years across the sky—for comparison, Proxima Centauri, the nearest star to our sun, is only about four light-years away.

Mira, a pulsating variable star 350 light-years from Earth, will be bright enough to see with the naked eye in mid-November. It lies, appropriately enough, in the tale of Cetus, the whale.

Professor of Physics Christopher Martin, GALEX's principal investigator, is the lead author of a paper announcing the discovery in the August 16 issue of *Nature*. □—*DS*

Flight of the Phoenix

The Phoenix Mars Mission blasted off on August 4 en route to a May 25, 2008, landing on the red planet. The first of NASA's Mars Scout missions, Phoenix is led by the University of Arizona in partnership with JPL and Lockheed Martin Space Systems, which built the spacecraft. Phoenix was so named because it reuses the body of the Mars Surveyor, built for a 2001 mission that was canceled before launch. Phoenix will alight on the plains around Mars's north polar cap. A JPL-built robot arm will sample the soil, and the water ice believed to lie just below it, to see if the site has ever had conditions favorable for microbial life. □—*DS*

Dopamine Economics

From investing in the stock market to trying the new sushi bar down the street, you make decisions every day that balance risks and rewards. Researchers working at the interface of neuroscience and economics—neuroeconomists, as they've dubbed themselves—have been watching brains at work to understand this decision-making process. Two studies involving Caltech neuroeconomists have identified certain regions of the brain that are responsible for interpreting risk as well as reward. These regions are controlled by a neurotransmitter called dopamine, which, among other functions, stimulates the brain's pleasure centers.

While neuroscientists have been studying reward for decades, very little has been known about the brain's internal representation of risk. In economics, one financial "model assumes risk and reward are computed separately and then integrated," says Steven Quartz, associate professor of philosophy. "We looked for biological evidence for this model, such as brain signals that correlated with reward and risk."

Subjects in Quartz's study played a simple game while lying inside a functional Magnetic Resonance Imaging (fMRI) machine, like the ones doctors use to diagnose torn muscles. Here the fMRI allowed the neuroscientists to observe changes in blood flow in the brain, pinpointing regions that became active during the game.

Each round of the game consisted of the subjects being shown two cards, one at a time, on a video screen. The deck consisted of 10 cards, numbered 1 through 10. Before seeing either of the cards, the subjects placed a $1 bet on whether the second card would be higher or lower than the first. "It was kind of mean. Since they didn't have any information, it was a 50-50 gamble on every trial," says Kerstin Preuschoff (PhD '07), a former grad student in Quartz's lab and lead author of the study, which appeared

in the August 3, 2006, issue of *Neuron*. Preuschoff is now a postdoc in the lab of Peter Bossaerts, the Hacker Professor of Economics and Management and professor of finance, and the third author of the study.

The researchers observed what happened after the first card had been seen. "I deliberately used numbered cards, so I knew that they knew what the probabilities of the outcomes were. The idea was for the subjects to experience different probabilities," says Preuschoff. These probabilities, in turn, led to different levels of expected reward and risk. Say you bet your buck that the second card would be higher, and your first draw proved to be the 1. Your sense of expected reward would be at its highest, as any card you could draw next would be a winner. At the same time, your sense of risk would be zilch. But if the first card drawn was a 5, you would have a 50-50 chance of winning, and thus experience maximum risk.

Activity in a dopamine-controlled region called the ventral striatum proved to mirror the levels of both expected reward and risk. Located deep inside the middle of the brain, below the cerebral cortex, the striatum has been associated with movement control (another of dopamine's functions; in fact, dopamine therapy is a treatment for the tremors of Parkinson's disease) and reward-related behaviors for decades. But its involvement in judging risk came as a surprise. "We found two signals in this system—first, an immediate reward signal, and then a delayed risk signal," says Quartz. The risk signal peaked when the second card was shown. Because the subjects weren't warned when the second card would appear, the researchers speculated that the risk signal might also serve as an unconscious alert to anticipate the resolution of the bet.

Besides explaining stock-market strategies, the researchers hope future studies may illuminate gambling addiction and bipolar disorder. People with these illnesses may have distorted perceptions of risk or reward, which leads them to choose risky behaviors.

Meanwhile, Colin Camerer, the Axline Professor of Business Economics, has been collaborating with researchers at Baylor College of Medicine and George Mason University to study a different type of reward. These neuroeconomists found that dopaminergic systems not only respond to rewards people experience directly, but also to rewards that people imagine could have been theirs.

To understand the distinction, imagine you are investing in the stock market. Each month, you invest the same small portion of your paycheck and watch the market's activity. Say the market has skyrocketed for a few months, and you are pondering how much to invest next month. In the past, when you invested a small portion of your paycheck, you got modest rewards. But had you been investing half of your earnings, you would have landed a large windfall. So now you decide to go for it, and put more of your next check into the market.

"The empirical fact is that people will often switch to strategies they never picked before. They couldn't have learned these strategies by reinforcement" from experienced rewards, says Camerer. In these situations, people use imagined rewards, or rewards that could have been theirs, to guide their decision making. This process, called fictive learning, is similar to the emotion of regret. "Regret is essentially the bodily sensation or name we give to fictive learning when there was a better choice than the one we chose."

Subjects in this study played a similar stock-market game while the fMRI scanned their brains. The researchers matched activity patterns in their brains with the "fictive error," which was defined as the difference between the best possible reward and the reward actually experienced.

Camerer and colleagues found that activity in the ventral caudate nucleus mirrored the differences between imagined and experienced rewards. The caudate nucleus is a subdivision of the striatum, the region highlighted in the Quartz study. "Almost everything you would naturally call a reward, or an anticipated reward, seems to activate the striatum," says Camerer. "It's quite interesting because it means that simply imagining something rewarding might turn on the reward signal."

Camerer hopes to expand this research to examine how we learn through observing others' actions. Imitation may be a socially transmitted form of fictive learning. "If I see you do something and I see it makes you smile or see it makes you vomit, then, even though I didn't have to do it myself, I may learn something from your actions," says Camerer.

Although the ability to use imagined rewards has obvious advantages, there could be a dark side. "That same capacity for imagination to activate brain areas as powerfully as actual experiences could lead to paranoia, delusions, and phobias. So, as we come to understand fictive learning better, it may help us to understand these mental states."

The article describing this work appeared in the May 29 issue of *The Proceedings of the National Academy of Sciences*. The other authors of the article were Terry Lohrenz and P. Read Montague of Baylor College of Medicine and Kevin McCabe of George Mason University. □—*MT*

Michael M. Torrice is a chemistry grad student who uses amino acids not found in nature to study how signals cross the synapses between nerve cells. He is working with Dennis Dougherty, the Hoag Professor of Chemistry.

Jackson's lab designers, David Mispagel and Anneline Van Benthem-Weil, recreated in linoleum an infrared laser beaming through a diamond-anvil cell. In the cell (inset sketch), two semi-flawless diamonds squeeze a sample grain of deep-mantle rock while an infrared (IR) laser heats it. With Earth's deep-mantle conditions thus simulated, its material properties can be scrutinized from the relative comfort of the lab.

Getting at the Core

If you want to know what's going on deep inside Earth, step into the brand-new lab of Jennifer Jackson, assistant professor of geophysics in Caltech's Seismological Laboratory. Jackson started at Caltech last December, and just five months later her lab—the Institute's first to use a so-called diamond-anvil cell to study mineral transitions under the intense heat and pressure of core-mantle boundary conditions—was up and running. Hers is one of fewer than a dozen labs in the United States equipped to tackle this kind of research. Her tools: a couple of gem-quality diamonds, a laser, and a speck of super-dense deep-mantle mineral of the perovskite family, made of iron, magnesium, aluminum, and silica.

Jackson has several goals in mind. She'd like to figure out how Earth's metallic core interacts with its rocky mantle, how iron-rich materials melt at high pressures, how seismic waves move under these conditions, and, ultimately, how our planet evolved to its present state. As she describes it: "We're at a middle stage in Earth's evolution, and we're using mineral physics both to understand its present state and to draw a line back to where it started."

Drills can't help Jackson's research because their casing collapses under the pressure as they inch deeper into Earth's crust. The deepest a drill ever penetrated is a mere 12 kilometers—a scratch on the surface considering the core is some 2,900 kilometers deep—and it took 24 years and more than $100 million to accomplish. But squeezed together, diamonds can both exert and withstand extreme conditions, as long as they're slowly coaxed into them. (Unfortunately, they don't survive the return trip—they develop ring fractures on decompression.) Jackson begins with two diamonds, a quarter of a carat each, with their tops and tapered tips ground flat. These gems are Type Ia, meaning they're both natural and semi-flawless, because impurities in synthetic or slightly dirty diamonds obscure the signals from the object of Jackson's study—a perovskite grain sandwiched between the diamonds, squeezed by the gems inside a metal collar. Together these parts comprise the diamond-anvil cell, and you wouldn't want to stick your finger in one of them.

A diamond-anvil cell can exert a pressure up to that inside Earth's core, which is calculated to be 360 gigapascals (GPa)—"approximately one million elephants standing on your head," as Jackson describes it—corresponding to a depth of about 6,400 kilometers. Jackson takes her samples up to 130 GPa for now, to study lower-mantle properties, but she plans to go higher. To better mimic mantle and core conditions, she also beams an infrared laser through the samples to heat them to temperatures near that of the core, which is thought to exceed 6,000 degrees Celsius. The exact figure has an uncertainty of 2,000 degrees, and is a subject of great interest because it carries implications about the true composition of the core, how heat is generated inside it, and when exactly it formed. We still don't know whether Earth retained its original core after the planet formed four and a half billion years ago, or whether Earth completely restratified after the impact that is thought to have ejected the moon and possibly melted the planet some 50 million years later. Figuring out the core's temperature could also yield insight into when Earth's magnetic field developed.

Inside Jackson's lab, the samples are pressurized, heated, or both, in incremental steps. Then she takes them to Chicago, to the Advanced Photon Source at Argonne National Laboratory, a synchrotron source of the world's most brilliant X rays. At the facility she uses X-ray scattering methods to identify the minerals' internal structures and studies how seismic waves disperse through the material under different conditions. Comparing these measurements to observations of how seismic waves travel through the whole planet after an earthquake, scientists have begun to parcel out finer and finer zones deep inside Earth.

As for *The Core*, 2003's Hollywood interpretation of what Jackson studies, she says she appreciates how the movie got people excited about such a recondite topic. But in her version, she wouldn't have put amethyst caves in the upper mantle because, as she points out, "that's clearly not allowed." □—*EN*

Like many who first venture into the blogosphere, Sean Carroll, a senior research associate in theoretical physics at Caltech, wasn't sure where it would take him. But when he wrote his first post on the Preposterous Universe blog on February 29, 2004, he set out on a path that would make him one of the most-read scientist-bloggers around.

More than three years after his first post, Carroll is still going strong. He's since abandoned the Preposterous Universe, and for two years has been writing for Cosmic Variance, a blog he shares with a group of physicists and astronomers, drawing 4,000 visitors a day. Their posts often spark lively discussions, with comments from professional scientists and the general public alike. Carroll, who is the most frequent contributor to the blog, was recently invited to speak about cosmology at YearlyKos, an annual convention of mainly liberal bloggers and like-minded political activists. This year's convention even featured a debate among the Democratic presidential candidates, showing the growing influence of the blogging community.

Although it tends to center on physics and astronomy, Cosmic Variance gives the scientists the opportunity to write about anything they like, whether it be politics or the Harry Potter finale. According to Carroll, part of the purpose of the nonscience posts is to show the human side of science. "We're all very concerned about people in elementary school, and especially girls and groups who don't traditionally become scientists," Carroll says. "We want to show them scientists are human beings, that being a scientist is something they can do someday, and that it's not that scary." Additionally, he says the blog gives the public an inside glimpse of what scientists do and think. Carroll recently wrote a three-part series on how an idea grows into a full-fledged research paper, from scribbling equations over a drink at a bar to finally posting the work to arXiv.org, the online depository for papers in physics, astronomy, mathematics, computer science, and related fields.

At first, Carroll wanted to link to as many physics blogs as possible, but with more than 50 now listed on Cosmic Variance, he says he's since given up. Despite the proliferation of physics blogs, Carroll is not very optimistic about them taking a more prominent role in physics research. From posting papers on arXiv.org to e-mail, the current way in which physicists communicate is already efficient. Blogs, however, could serve as a place for specialists and nonspecialists to interact, chipping away at the barriers separating academia from the general public. Still, most physics blogs are written by students or nonscientists who are interested in physics—and not professional physicists, Carroll says. "I think physicists have been slower to catch onto blogs than people in the social sciences or humanities," he explains. "Physics is more of an esoteric topic where we talk to each other rather than the outside world." For instance, blogging in technical detail about the cosmological effects of Lorentz-violating vector fields—one of Carroll's areas of research—probably has a limited audience. For him, Cosmic Variance's purpose is clear. "We don't have a lot of goals other than us having fun," he says.

One social scientist and blogger is Caltech's Professor of Political Science Michael Alvarez. (A feature article about his work begins on page 12). As part of the Caltech/MIT Voting Technology Project, which he codirects, he started the Election Updates blog. Unlike Cosmic Variance, this blog has a research-oriented purpose of disseminating news and developments among those in the field of voting technology. According to Alvarez, readers include other academics, policy-makers, those who build and develop voting machines, political junkies, and others who may not be in the circle of academic political scientists. "Our role is to push research out into the community, to people who normally won't be exposed to it," he says.

When he started the blog two years ago, a couple of blogs devoted to election politics already existed. But none focused on voting technology, and that's where Election Updates found its niche. The blog, which Alvarez runs with Thad Hall, an assistant professor of political science at the University of Utah, features a small group of contributors. The blog receives about 150 views a day, but when election season comes up, so does the number of hits. The site saw more than 16,000 total visitors last November, when his graduate students and colleagues were constantly updating, he says. "It was almost a full-scale operation."

What's the future of blogs in academia? Alvarez anticipates that soon, the open, online communication afforded by blogging could become a regular part of political-science research. Caltech Library Services already uses blogging technology to disseminate research papers in all fields. Its Open Access Authoring @ Caltech site posts papers written by Caltech researchers that have been published in so-called "open access" journals. These journals don't require a subscription, supporting themselves by other means such as subsidies from institutions or universities or by charging the author a production fee.

Meanwhile, Alvarez wants to take further advantage of this new platform, and in particular, to explore multimedia possibilities. His first post, in fact, was a podcast, an audio recording of his own commentary. He and his colleagues also posted their own YouTube videos of election sites. "There's a lot of interesting things you can do with the technology," he says. "We've only scratched the surface."

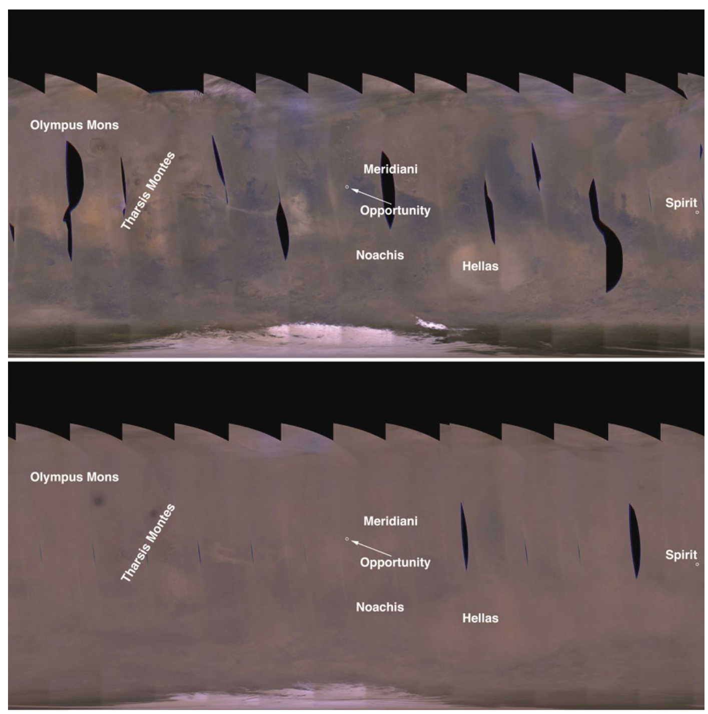
As blogs continue to evolve, so will their roles—whether for disseminating research, bridging the gap between academia and the public, or just for fun. "The power of this is pretty profound," Alvarez says. □—*MW*

Visit Cosmic Variance at http://www.cosmicvariance.com, Election Update at http://electionupdates.caltech.edu/blog.html, and Open Access Authoring @ Caltech at http://oacaltech.blogspot.com. □

Weathering the Storm

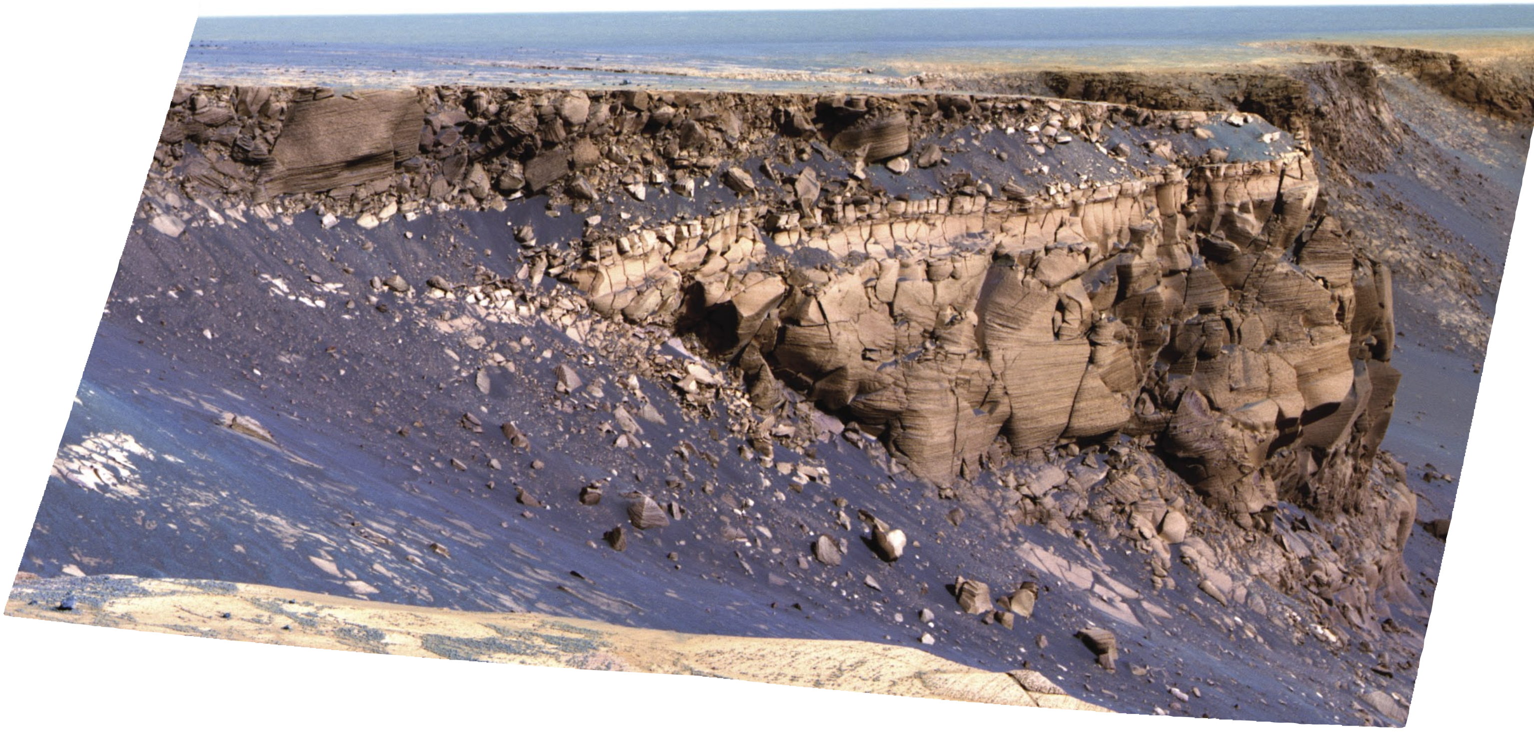
July and August here in Pasadena are usually some of the most predictable days of sunshine the year has to offer. Scientists on the Mars Exploration Rover (MER) team at JPL, however, spent the better part of their summer battling the largest dust storm in the solar system, which enshrouded nearly the entire planet in a dark haze. Project managers were forced to pull back the reins on rovers Opportunity and Spirit and hunker down for the storm.

In the biggest threat to the mission since their landings on Mars three and a half years ago, the twin rovers faced the risk of losing power and shutting down indefinitely. The situation was particularly hazardous for Opportunity, which at the storm's peak was receiving less than 1 percent of the normal amount of sunlight on its solar panels. A heater switch in Opportunity's arm that had been stuck in the "on" position since landing provided an additional energy challenge, draining one-third of the diminished solar-generated electricity. Both rovers parked themselves and went into a low-power mode in order to conserve as much energy as possible. While on standby, communications



Top: Mars as it appeared to the Mars Reconnaissance Orbiter's Mars Color Imager on June 22, 2007. The first in a series of regional dust storms has sprung up, to the west of Opportunity.

Bottom: By July 17, nearly the entire planet was obscured.



opportunities were limited to once every three days, and all but the most basic functions necessary for the rovers' survival were turned off. But the heat generated by the rovers' electronics helps keep the insulated boxes housing them warm, and with much of their circuitry inactive, concern grew that the rovers might not be able to maintain their normal operating temperatures during the cold Martian nights. Damaged circuitry or a depleted battery could have spelled doom for even the most intrepid robotic explorer.

The storm came at an inopportune time. Spirit was poised near a plateau known as Home Plate, ready to study Mars's volcanic history. Opportunity was waiting out the storm at the rim of Victoria Crater, into which it is slated to descend to study the billions of years of geological history chronicled in the walls of the 70-meter-deep crater. Victoria Crater exposes significantly more strata than any other feature studied by the MER team, who are eagerly awaiting the chance to look further into Mars's geological past than ever before.

While the rovers were stymied on the surface, the Mars Reconnaissance Orbiter (MRO) had a field day imaging the storm and its evolution. As Richard Zurek, JPL's project scientist on the MRO mission put it, "When you get lemons you make lemonade, and when you get a dust storm you study the dust storm." Dust storms are common on Mars, but storms of this magnitude only flare up every five or six years, rather like the El Niño cycle here on Earth. With months of data from this storm, the MRO team will be in a position to answer some fundamental questions about Martian weather patterns: What triggers such a global storm? Why do they occur some years and not others? How does dust get distributed over the planet and alter surface features? This in turn will help us interpret the evolution of Mars's surface geology with more confidence.

Zurek is often asked just what it would be like to experience this dust storm. "Visibility is still a few miles," he says, "like a hazy day in L.A., but quite a bit darker. It is significantly cooler during the day since the majority of the sun's energy is absorbed or scattered by the dust, but warmer at night since the remaining heat is trapped, leaving average temperatures essentially unchanged over the course of a martian day."

Both rovers resumed driving and doing science in late August. Spirit climbed onto Home Plate the week after Labor Day. And favorable gusts of wind have removed some dust from Opportunity's solar panels almost as quickly as it settled. As *E&S* went to press, Opportunity was cautiously beginning its descent into Victoria Crater via a scallop on its edge known as Duck Bay. □—*EQ*

Elijah L. Quetin is a graduate student in astronomy, working on galaxy evolution with Richard Ellis, the Steele Family Professor of Astronomy.

This false-color view of Cape St. Vincent, a quarter of the way around Victoria Crater from Duck Bay, shows the band of bright rock just below the rim that is visible all around the crater. The band, thought to be Mars's surface just before the crater was created, will be one of Opportunity's first stops on Duck Bay's much gentler slope.

A Curious Premiere

Coming in October to a PBS station near you is *Curious*, a two-part profile of Caltech and JPL scientists in their own words. Produced by WNET, the program features many names familiar to *E&S* readers—including Nathan Lewis and Mark Davis, who appeared in our last two issues. Check your local listings for air times. □—*DS*

At first, it was just a class project. When seniors Rudy Roy and Ben Sexson took Product Design for the Developing World (E/ME 105), they didn't think their idea of turning bicycles into wheelchairs for the poor and disabled in Guatemala would go beyond the classroom. But during the fall quarter of 2006, as they designed and built a prototype chair, learned how to make a business plan, and held videoconferences with students in Guatemala, the project became a passion. "The problem became personal," Sexson says. "We really wanted to do something good." They carried on with the project after the term ended, and upon graduation teamed up with Charlie Pyott, a student at the Art Center College of Design, to form a new nonprofit organization called Intelligent Mobility International, with Roy as the chief executive officer, Sexson as the chief financial officer, and Pyott as the chief technical officer.

The class, taught by Visiting Professor of Mechanical Engineering Ken Pickar, introduces students to developmental engineering. This emerging field is about finding cheap, technological solutions to some of the most basic needs of the poorest people on the planet. The solutions must also generate income, in the proverbial way of giving a man a fishing pole instead of a fish. The class focuses on rural Guatemala and includes close collaboration with students at Rafael Landivar University to gain crucial insight into the people's culture, daily lives, and needs. Once the students identify a problem, they find a solution, and form a business plan to market and manufacture their product.

Reliable statistics are scarce, but the number of disabled in Guatemala is estimated to be at least in the many tens of thousands, as a result of decades of civil war and violence. Without the means to get around, getting a job or an education is nearly impossible. Imported wheelchairs are too expensive, so Sexson and Roy decided to build them from ready-made bicycle parts. Not only are bicycles—and local bicycle manufacturers—common in Guatemala, but this design uses mountain bikes, resulting in an off-road wheelchair capable of negotiating the rural terrain. These durable wheelchairs could last up to 10 years, Sexson says. A standard chair wouldn't come close.

The key innovation is a standardized and simplified manufacturing process. The team has designed a special workbench on which you place the bicycle. The workbench acts as a template, telling you exactly where and how to take the bicycle apart and to reassemble it into half a wheelchair—each wheelchair is made from two bicycles. Because of the process's ease and efficiency, you don't need a lot of training or education, which is essential because the designers hope to employ the same people the chairs are designed for: the poor and disabled.

Developmental engineering is about developing local economies and empowering people, says Mario Blanco, director of process simulation and design collaboration in the Materials and Process Simulation Center in the Beckman Institute. "That empowerment allows them to get a better life for them-

PICTURE CREDITS: 2, 3 — Doug Smith; 4–5 — NASA/JPL/Caltech; 6 — Ariel Shoresh; 8 — NASA/JPL/MSSS; 9 — NASA/JPL/Cornell; 10

selves," he says. Blanco, who is from Guatemala, has been involved with the course since its inception three years ago.

"Technology for the developing world needs to be designed and built from the ground up," says Blanco. "Because of cost constraints and socio-cultural issues, first-world technology rarely 'trickles down' successfully to the 2.8 billion people living on less than two dollars per day—a level of poverty often referred to as the 'Bottom of the Pyramid.'"

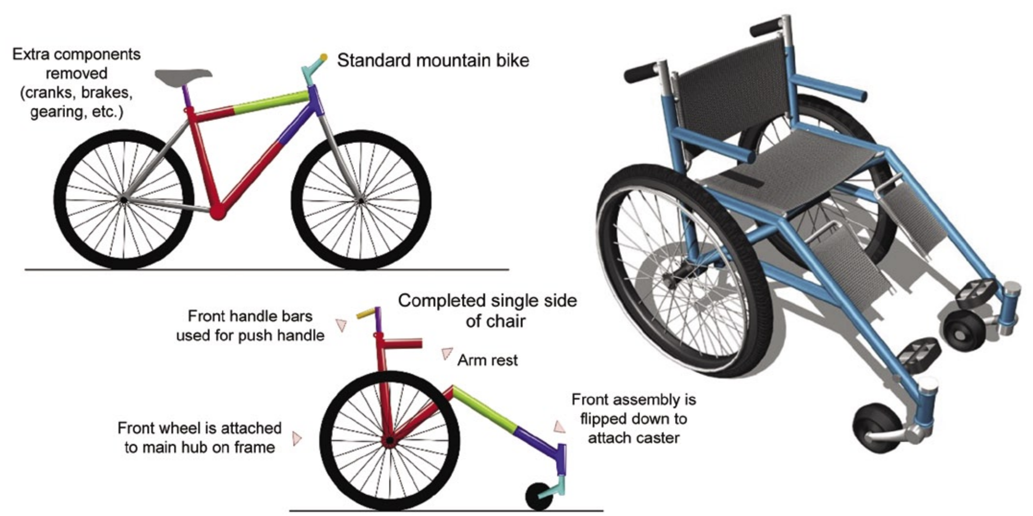
Developing a product cheaply to address the basic needs of the poor may not be as difficult as building robots to send to Mars, Blanco says, "but if you have a problem with tremendous constraints on cost, you make it an impossible problem. Caltech students like to focus on just this kind of problem!"

To solve these impossible problems, this summer Blanco and Pickar helped run the first annual International Development Design Summit at the Massachusetts Institute of Technology. Run by Caltech, MIT, and Olin College, the meeting involved nearly 50 students, engineers, and academics from 15 countries, and from all walks of life, including one participant who had never before left his village in Tanzania. In the same spirit as Pickar's class, the participants divided into teams to design products that address the needs of the developing world. At the end of the month-long summit, in which participants lived, worked, and played together, they produced 10 prototypes. Designs included a refrigerator that keeps food cool using only evaporating water, and a device that tests water safety. By detecting microbes in the water with an incubator, the device would cost less than $50 instead of the thousands needed for a conventional instrument. The goal, of course, is to turn these ideas into real products, much like what Sexson and Roy have been doing with their wheelchairs.

Intelligent Mobility International is still in the research and development stage, but the team continues to push the project forward. They have just started a campus club, Intelligent Mobility, to involve more students. Additionally, they plan to continue their collaboration with the Art Center, to recruit help with design aspects of the project, such as creating a website. "A little bit of work can go a long way," Sexson says. "It doesn't take much to make a big difference. If we keep plodding along and keep moving, we can accomplish something." They hope to finish the third prototype by October, and are talking with Bicicletas Corsario—El Salvador's largest bicycle company, which has branched out to Guatemala—to provide the bicycles. They plan to roll out 500 wheelchairs in the first year of operation. Meanwhile, they hold down other full-time, paying jobs, although they continue to meet a few days a week.

Roy says the experience has shown them what they can achieve as engineers, going beyond academics. "How many times do you get an opportunity in college to make a big impact in the world?" he says. □—*MW*

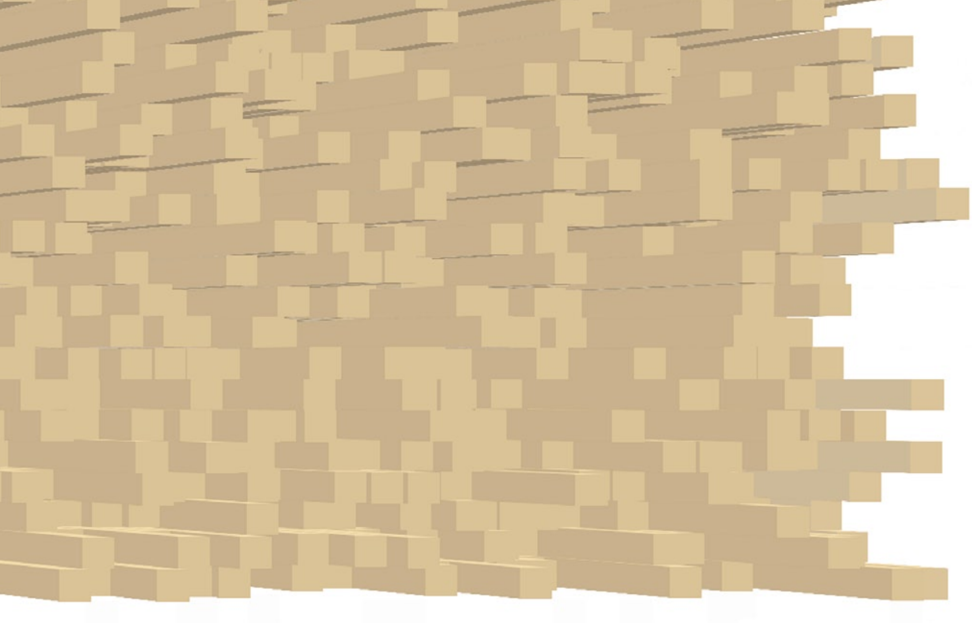
Presto, chair-o: Starting with the far left photo, Ben Sexson (in suit; after all, he is the CFO), and Charlie Pyott steady a mountain bike frame in one of the template's holders as Rudy Roy prepares to make the first saw cut. Then the frame is flipped over to position it in another holder for the second cut, and so on. The graphics at right, drawn by Pyott, continue the transformation.



Rocking the Vote

By Elisabeth Nadin

George Caleb Bingham's 1852 painting *The County Election* shows a typical election-day scene in Missouri. At the time, only white male property owners had the right to vote, and they did so by voice, recorded in public. Alcohol flowed freely, and candidates or their representatives could solicit votes just before they were cast. Today, campaigning is prohibited within 300 feet of a polling place. Painting courtesy of the Saint Louis Art Museum.



"Every vote counts" is a familiar motto, but how true is it? Certainly the 2000 presidential election swung on a handful of votes in Florida. But that handful also spurred nationwide protests as more and more vote-counting errors were uncovered, and people became painfully familiar with absurdities of the system such as hanging and pregnant chads. Even then, however, advances in voting technology were under way. That year saw the first ballots cast online—before the 2000 general election, participants could vote over the Internet in Arizona's Democratic primary and in a straw poll in the Alaskan Republican primary. Soon after, the first online ballots ever counted in a presidential election were cast by 84 citizens overseas in a government-sponsored endeavor to the tune of $6.2 million. If Michael Alvarez, Caltech political science professor and codirector of the Caltech/MIT Voting Technology Project (VTP), has his way, Internet voting will eventually be an option for the rest of us. But there's a big hill to climb before we get there.

The VTP was initiated in December 2000 by former Caltech president David Baltimore and former MIT president Charles Vest "to prevent a recurrence of the problems that threatened the 2000 U.S. Presidential Election." Since then, Alvarez and his VTP colleagues have uncovered significant flaws in our current voting system and, in some of the remedies already being implemented, threats to future elections far greater than hanging chads. Alvarez also thinks that Internet voting holds the best promise for reaching citizens who historically can't or don't vote on Election Day—"I'd love to be able to vote online. I like to vote as simply and quickly as possible. I have a six-year-old, my wife works. Many times we're traveling on election day," he says. But for now, it's simply not an option.

Countries like Switzerland and Estonia are overtaking the United States as we stall on the path toward ubiquitously available online voting. There are several reasons for this, says Alvarez.

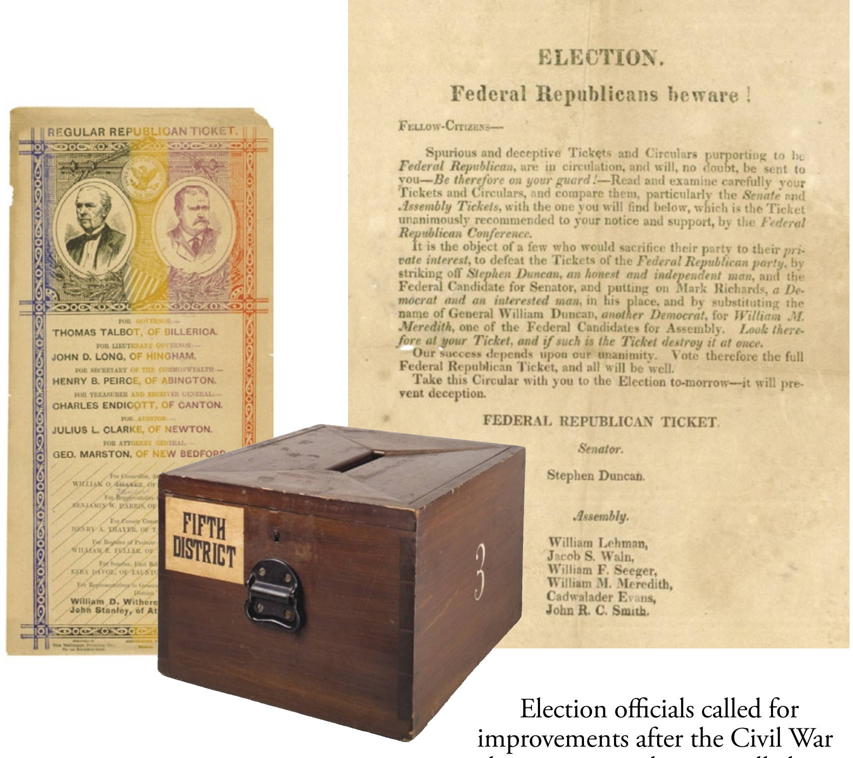
Photo by William L. Bird, courtesy National Museum of American History.

Miscast and miscounted Florida ballots in the 2000 election set off a flurry of protests around the country.

Point, Click, and Vote: The Future of Internet Voting, published by Alvarez and his colleague Thad Hall of the University of Utah shortly before the 2004 election, decries the shabby legacy of voting reform that has culminated in the haphazard introduction of electronic voting machines—which have failed time and again—without any real testing. Instead of continuing in this tradition, Alvarez advocates a rigorous, scientific implementation of Internet voting, just like clinical trials for medical advances. Citizens overseas or college students away from home would form control (traditional vote) and treatment (Internet vote) groups. If these votes were successfully cast and counted, the experiment could be expanded to the scale of statewide elections, with some counties allowing Internet voting and others not. The eventual aim would be, for any citizen who wants it, the option to vote from any computer anywhere.

Among the questions raised in the aftermath of the 2000 election was whether or not our country needs to change the way people vote. Another presidential election is upon us, with primaries even nearer. How effective are the changes that were made? Can we achieve Internet voting? And what, after all, is the most foolproof way to cast a vote?

Voting-related antiquities hint at the fraud that tainted early elections. From left to right: The 1878 official ballot of the Regular Republican Party was boldly colored to distinguish itself; a wooden ballot box from 1870—these often hid compartments stuffed with fake ballots; and a Vermont circular from 1816 that warned of "spurious and deceptive" party tickets.



ELECTION.

Federal Republicans beware !

Fellow-Citizens—

Spurious and deceptive Tickets and Circulars purporting to be *Federal Republican*, are in circulation, and will, no doubt, be sent to you—*Be therefore on your guard!*—Read and examine carefully your Tickets and Circulars, and compare them, particularly the *Senate* and *Assembly Tickets*, with the one you will find below, which is the Ticket unanimously recommended to your notice and support, by the *Federal Republican Conference*.

It is the object of a few who would sacrifice their party to their *private interest*, to defeat the Tickets of the *Federal Republican party*, by striking off *Stephen Duncan, an honest and independent man*, and the Federal Candidate for Senator, and putting on Mark Richards, *a Democrat and an interested man*, in his place, and by substituting the name of General William Duncan, *another Democrat*, for *William M. Meredith*, one of the Federal Candidates for Assembly. *Look therefore at your Ticket, and if such is the Ticket destroy it at once.*

Our success depends upon our unanimity. Vote therefore the full Federal Republican Ticket, and all will be well.

Take this Circular with you to the Election to-morrow—it will prevent deception.

FEDERAL REPUBLICAN TICKET.

Senator.

Stephen Duncan.

Assembly.

William Lehman,
Jacob S. Waln,
William F. Seeger,
William M. Meredith,
Cadwalader Evans,
John R. C. Smith.

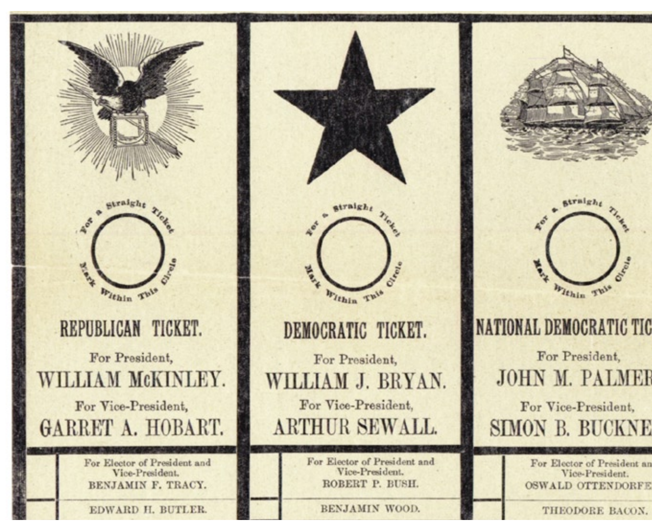
Our Voting History

The first votes in the United States were cast in a fairly crude manner, and as more and more people won the right to vote, systems to accommodate them grew increasingly cumbersome. Indeed, the 200-odd years since the first votes (exclusively by white men who owned property) have been plagued by fraudulent elections and slipshod progress. "At various times, poor people, women, African Americans, and younger Americans have been kept from voting by legal or extralegal measures," says Alvarez. Those early votes were either spoken and recorded in public, or written on paper ballots and slipped into boxes in public. Ballots were printed and distributed by political parties that listed just their own candidates, and had to conform to specifications that varied from state to state. Not only did the color of your ballot immediately give away your vote, but parties often printed fake ballots to trick voters. The potential for confusion and fraud was high.

Election officials called for improvements after the Civil War as the voting population swelled with immigrants and black men, who had won the right to vote (though they and other poor men were often denied this right by restrictions such as taxes and tests). The number and variety of ballots issued by political parties had grown so unmanageable that state governments finally wrested the logistical duties from the competing parties. The blanket ballot was introduced, listing the names of all the candidates, and ballot boxes sported new security features. Voting finally became a private affair with the introduction of the booth, and ballots featuring party symbols meant even illiterate men could vote. But intimidation and manipulation often reigned in the political scene, despite the hiring of poll watchers by political parties.

By the early 1900s, multiple candidates and referenda made for lengthy and complex ballots. The electorate practically doubled in 1920 when women won the right to vote under the 19th Amendment, thus justifying local government investment

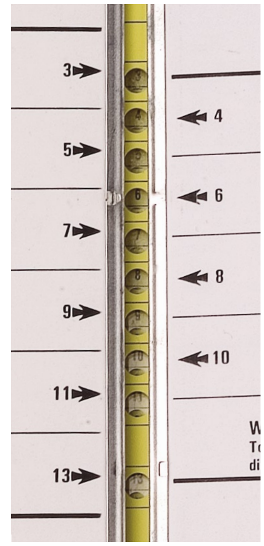
Right: The blanket circular, listing all candidates for office regardless of party, was developed in Australia in the 1850s but only reached the United States in 1888. Voters marked their ballot in the privacy of a booth. Far right: Two election-scene operatives try to rescue their booth from a surprise attack in 1887.



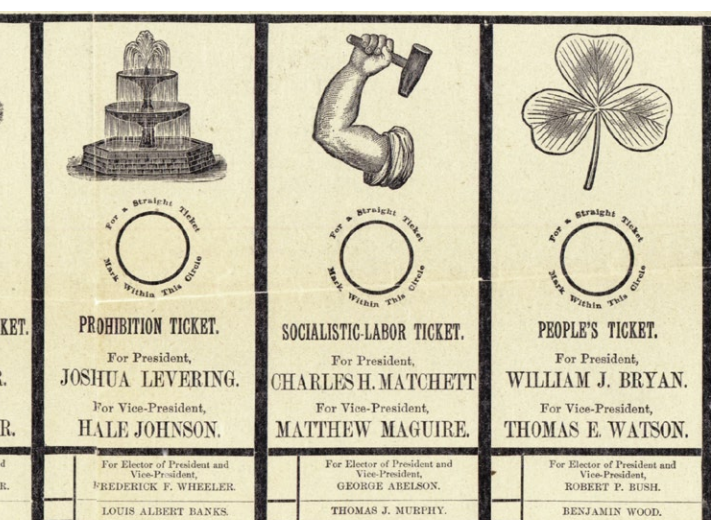
in the new gear-and-lever voting machine. In the mid-1960s, protests against discriminatory voting practices shook Congress into action and, by the early 1970s, barriers to voting such as restrictions requiring that voters have fathers and grandfathers who had voted, literacy tests, and whites-only primaries had finally been outlawed. In 1971, the 26th Amendment lowered the voting age to 18 for both state and federal elections, and the voting ranks swelled again with the enfranchisement of about 11 million new voters. This period also saw the dawn of the electronic age, which offered quick election returns via computer-read ballot systems. In the late 1960s IBM began selling its Votomatic, whose punch-card ballots are either processed by computer or counted by hand. By the early 1980s about half the American electorate was voting by punch card. (These machines were still in wide use when the 2002 Help America Vote Act (HAVA) decreed that they be phased out.)

Then came the Florida fiasco. In most previous national elections, the margins of victory were large enough to mask the mistakes made by both voters and vote-counting systems. But the contest between George W. Bush and Al Gore was close—it came down to 537 out of six million votes cast in Florida. Incompletely punched ballots that could not be counted by machine, misaligned ballot cards with off-center punches, and a confusing "butterfly" ballot design—a single page of presidential candidates enlarged to two pages in one Florida county—revealed failures that sparked a wholesale pessimism about our voting system. Indeed, the VTP concluded that between four and six million votes were lost in the 2000 election, through a combination of faulty equipment, confusing ballots, problems with voter registration, and polling-place difficulties.

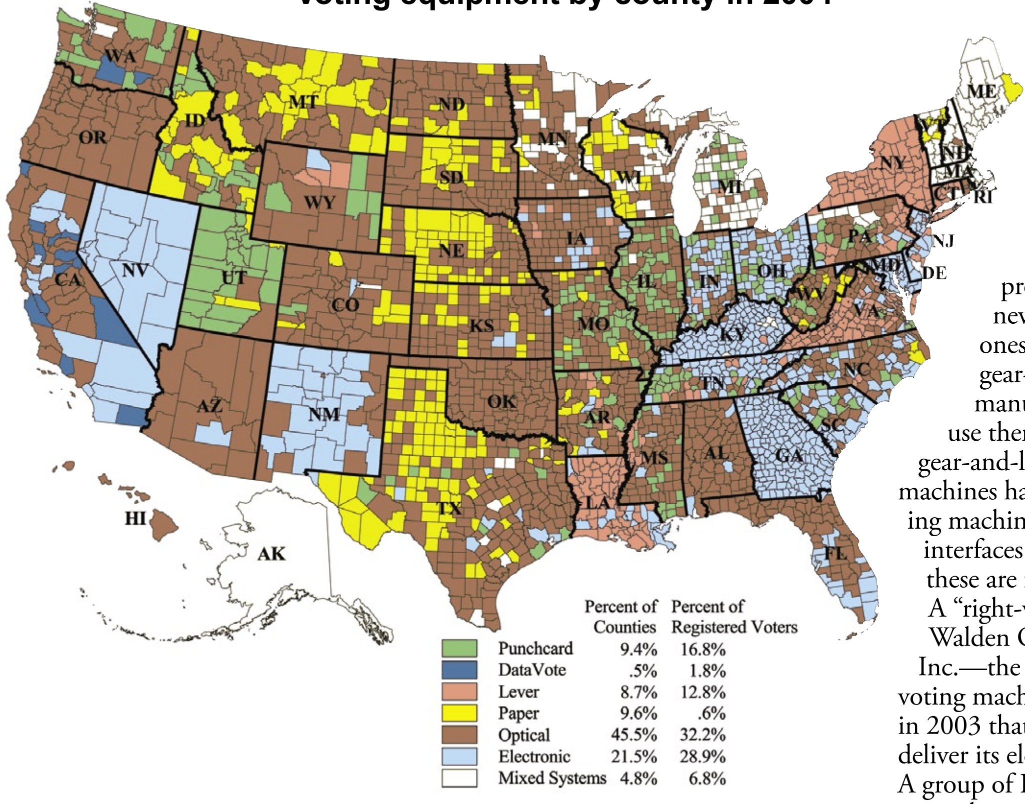
"Unfortunately, the field of election administration has not been known for developing and testing products in an orderly, systematic manner," says Alvarez. "Many of the problems that occurred in Florida during the 2000 presidential election can be traced to lack of testing or failure to use the scientific method of investigation. Imagine, for instance, that the Palm Beach County election administrator had tested the butterfly ballot in a random sample of voters before using it on Election Day, and compared that group to a control group that used a more traditional ballot format. It is likely that the problems with the butterfly ballot design would have been revealed, and it would not have been used," he explains. "Even today, after the 2000 elections illustrated the problems that voters have with almost every type of voting technology, from punch cards to optical-scan ballots, localities across the country are buying new voting technologies without conducting field tests to determine how well they will work. Florida passed election reform legislation in 2000 that allowed communities across the state to purchase optical-scan equipment, even though it has been asserted that optical-scan voting was the source of a tremendous number of voting errors in the 2000 presidential election in Georgia."



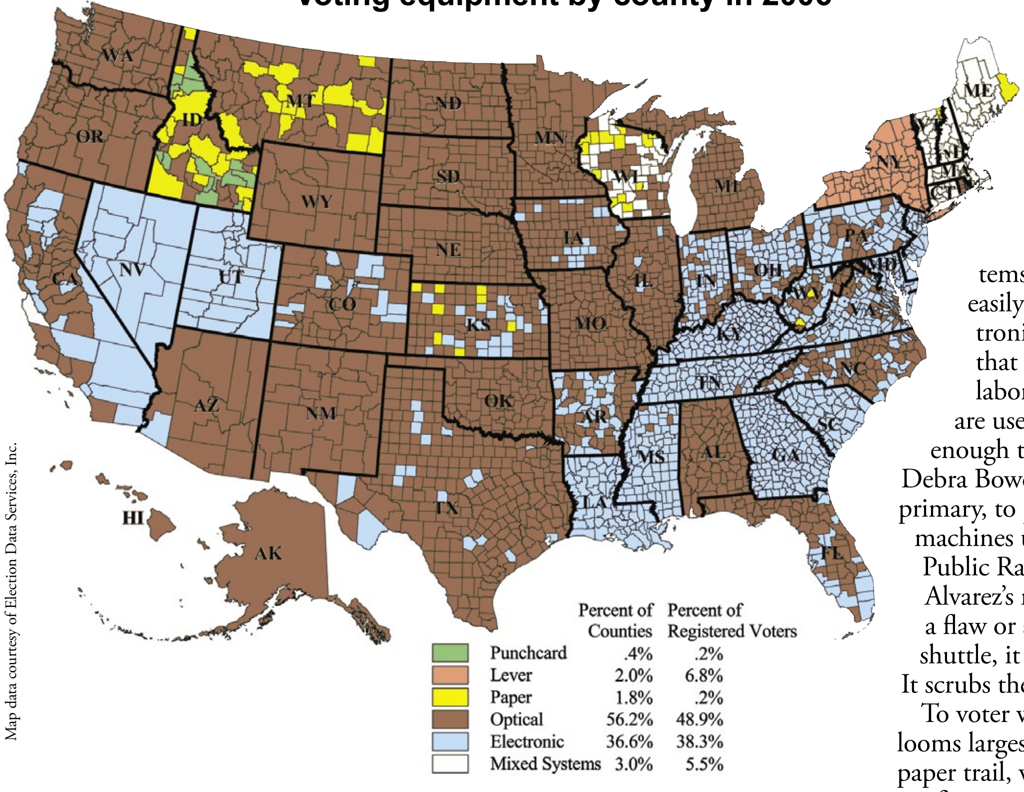
Misaligned ballot cards with off-center punches were among the culprits blamed for the 2000 presidential election debacle. The Caltech/MIT Voting Technology Project estimates that up to six million votes were lost in this election due to a variety of registration and polling-place difficulties.



Voting equipment by county in 2004



Voting equipment by county in 2006



Map data courtesy of Election Data Services, Inc.

A comparison of voting equipment in the 2004 (top) and 2006 (bottom) elections shows that states are seeking uniformity in their vote-counting systems. Most have chosen exclusively electronic machines (blue) or optical scanners of paper ballots (brown), but some states use mixed systems, and New York still relies on lever machines last manufactured 20 years ago.

Where we are now

Since 2000, the VTP and other organizations have uncovered major flaws in how we vote in this country. It's not that we don't try. But elections are poorly funded by states, leaving us with a patchwork of hundreds of voting methods. HAVA provided federal funds to states to get new voting systems and phase out old ones—it's been more than 20 years since gear-and-lever voting machines were last manufactured, and people actually still use them in New York. In most states, the gear-and-lever and Votomatic punch-card ballot machines have been replaced by electronic voting machines that directly record votes through interfaces like touch-screen or push-button, but these are fraught with their own set of problems. A "right-wing conspiracy" was invoked when Walden O'Dell, chief executive of Diebold Inc.—the primary manufacturer of electronic voting machines in the United States—declared in 2003 that he was "committed to helping Ohio deliver its electoral votes to the president next year." A group of Princeton University computer scientists subsequently demonstrated how malicious code could be installed in Diebold machines in less than a minute to steal votes undetectably and pass viruses from machine to machine. Diebold responded that the scientists had used a two-generation-old machine whose security standards had been vastly improved. The *Los Angeles Times* reported in July that three of California's electronic voting systems—Diebold, Hart, and Sequoia—were easily hacked into by both physical and electronic means. The manufacturers replied that these hacks were made in unrealistic laboratory settings, while their machines are used in secure rooms. Still, the report was enough to prompt California Secretary of State Debra Bowen, just months before the February 5 primary, to prohibit the use of electronic voting machines until the flaws are fixed. In a National Public Radio report in August, she echoed Alvarez's main concern: "When NASA discovers a flaw or a potential safety concern in the space shuttle, it doesn't continue launching missions. It scrubs the mission and fixes the problem."

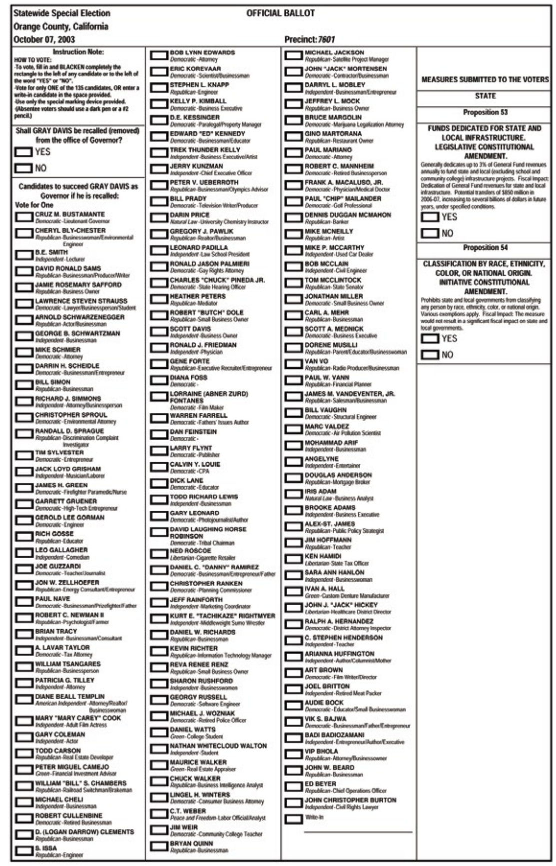
To voter watchdog groups, the bugaboo that looms largest in electronic voting is the lack of a paper trail, which leaves no possibility for vote verification and recount. "An electronic ballot is a secret from the voter who cast it!" is the mantra of Ellen Theisen, codirector of the voter advocacy group VotersUnite.Org. The organization keeps track of when and where and to what extent

Touch-screen voting machines like this one by Diebold have been at the center of the electronic voting controversy. Many think the machines are easily hacked into; they also suffer electronic glitches, and they leave no paper trail.

different electronic voting machines fail, and the list is dumbfounding: touch screens reverse voters' selections, Washington State, 2004; electronic voting machine presents invalid options, Hawaii, 2004; programming error fails to count votes—initial tallies show four times as many votes as voters—South Carolina, 2005; flawed ballot programming fails to count 432 votes, Arkansas, 2006, to name just a few of the numerous standouts. "Recording ballots electronically is a mistake," says Theisen. "Your official ballot is just the electrical charges in the computer. Voters cannot verify the vote that's counted because you can't verify the electrical charges." She argues that if these machines must prevail they should be used only if the cast vote is printed on paper, and that only those paper ballots should be counted. Unfortunately, in some machines retrofitted with printers, the ballot doesn't always match the vote that was cast, and more often than not the voter doesn't check the printout.

For Theisen, electronic voting poses too high a risk to election security. "Fraud is one of our traditions, and it's not going to stop. We have to do things in such a way that we can catch it or minimize it. That everything is counted correctly," she says. But the VTP is more concerned about the potential for mistakes. While electronics were only recently introduced for casting ballots, they've dominated vote counting for decades, typically as optical scanners of paper ballots. Each scanner is programmed anew for every election, raising valid concerns about errors. As Caltech political science professor, newly appointed chair of the Division of the Humanities and Social Sciences, and VTP codirector Jonathan Katz points out, things get complicated in a place like Los Angeles County, where a typical general election can have 3,000 different ballot forms—one for each combination of local races—written in seven different languages. While logistically complicated because the polling place needs to supply

Don't trip! This photo of a polling place from the 2006 election shows just how susceptible electronic votes are in an insecure environment. One accident could wipe out a day's worth of votes.



Statewide Special Election
Orange County, California
October 07, 2003

OFFICIAL BALLOT

Precinct: *7601*

Instruction Note:
HOW TO VOTE:
-To vote, fill in and BLACKEN completely the rectangle to the left of any candidate or to the left of the word "YES" or "NO".
-Vote for only ONE of the 135 candidates, OR enter a write-in candidate in the space provided.
-Use only the special marking device provided.
-(Absentee voters should use a dark pen or a #2 pencil.)

Shall GRAY DAVIS be recalled (removed) from the office of Governor?
YES
NO

Candidates to succeed GRAY DAVIS as Governor if he is recalled:
Vote for One

CRUZ M. BUSTAMANTE *Democratic - Lieutenant Governor*
CHERYL BLY-CHESTER *Republican - Businesswoman/Environmental Engineer*
B.E. SMITH *Independent - Lecturer*
DAVID RONALD SAMS *Republican - Businessman/Producer/Writer*
JAMIE ROSEMARY SAFFORD *Republican - Business Owner*
LAWRENCE STEVEN STRAUSS *Democratic - Lawyer/Businessperson/Student*
ARNOLD SCHWARZENEGGER *Republican - Actor/Businessman*
GEORGE B. SCHWARTZMAN *Independent - Businessman*
MIKE SCHMIER *Democratic - Attorney*
DARRIN H. SCHEIDLE *Democratic - Businessman/Entrepreneur*
BILL SIMON *Republican - Businessman*
RICHARD J. SIMMONS *Independent - Attorney/Businessperson*
CHRISTOPHER SPROUL *Democratic - Environmental Attorney*
RANDALL D. SPRAGUE *Republican - Discrimination Complaint Investigator*
TIM SYLVESTER *Democratic - Entrepreneur*
JACK LOYD GRISHAM *Independent - Musician/Laborer*
JAMES H. GREEN *Democratic - Firefighter Paramedic/Nurse*
GARRETT GRUENER *Democratic - High-Tech Entrepreneur*
GEROLD LEE GORMAN *Democratic - Engineer*
RICH GOSSE *Republican - Educator*
LEO GALLAGHER *Independent - Comedian*
JOE GUZZARDI *Democratic - Teacher/Journalist*
JON W. ZELLHOEFER *Republican - Energy Consultant/Entrepreneur*
PAUL NAVE *Democratic - Businessman/Prizefighter/Father*
ROBERT C. NEWMAN II *Republican - Psychologist/Farmer*
BRIAN TRACY *Independent - Businessman/Consultant*
A. LAVAR TAYLOR *Democratic - Tax Attorney*
WILLIAM TSANGARES *Republican - Businessperson*
PATRICIA G. TILLEY *Independent - Attorney*
DIANE BEALL TEMPLIN *American Independent - Attorney/Realtor/Businesswoman*
MARY "MARY CAREY" COOK *Independent - Adult Film Actress*
GARY COLEMAN *Independent - Actor*
TODD CARSON *Republican - Real Estate Developer*
PETER MIGUEL CAMEJO *Green - Financial Investment Advisor*
WILLIAM "BILL" S. CHAMBERS *Republican - Railroad Switchman/Brakeman*
MICHAEL CHELI *Independent - Businessman*
ROBERT CULLENBINE *Democratic - Retired Businessman*
D. (LOGAN DARROW) CLEMENTS *Republican - Businessman*
S. ISSA *Republican - Engineer*
BOB LYNN EDWARDS *Democratic - Attorney*
ERIC KOREVAAR *Democratic - Scientist/Businessman*
STEPHEN L. KNAPP *Republican - Engineer*
KELLY P. KIMBALL *Democratic - Business Executive*
D.E. KESSINGER *Democratic - Paralegal/Property Manager*
EDWARD "ED" KENNEDY *Democratic - Businessman/Educator*
TREK THUNDER KELLY *Independent - Business Executive/Artist*
JERRY KUNZMAN *Independent - Chief Executive Officer*
PETER V. UEBERROTH *Republican - Businessman/Olympics Advisor*
BILL PRADY *Democratic - Television Writer/Producer*
DARIN PRICE *Natural Law - University Chemistry Instructor*
GREGORY J. PAWLIK *Republican - Realtor/Businessman*
LEONARD PADILLA *Independent - Law School President*
RONALD JASON PALMIERI *Democratic - Gay Rights Attorney*
CHARLES "CHUCK" PINEDA JR. *Democratic - State Hearing Officer*
HEATHER PETERS *Republican - Mediator*
ROBERT "BUTCH" DOLE *Republican - Small Business Owner*
SCOTT DAVIS *Independent - Business Owner*
RONALD J. FRIEDMAN *Independent - Physician*
GENE FORTE *Republican - Executive Recruiter/Entrepreneur*
DIANA FOSS *Democratic -*
LORRAINE (ABNER ZURD) FONTANES *Democratic - Film Maker*
WARREN FARRELL *Democratic - Fathers' Issues Author*
DAN FEINSTEIN *Democratic -*
LARRY FLYNT *Democratic - Publisher*
CALVIN Y. LOUIE *Democratic - CPA*
DICK LANE *Democratic - Educator*
TODD RICHARD LEWIS *Independent - Businessman*
GARY LEONARD *Democratic - Photojournalist/Author*
DAVID LAUGHING HORSE ROBINSON *Democratic - Tribal Chairman*
NED ROSCOE *Libertarian - Cigarette Retailer*
DANIEL C. "DANNY" RAMIREZ *Democratic - Businessman/Entrepreneur/Father*
CHRISTOPHER RANKEN *Democratic - Planning Commissioner*
JEFF RAINFORTH *Independent - Marketing Coordinator*
KURT E. "TACHIKAZE" RIGHTMYER *Independent - Middleweight Sumo Wrestler*
DANIEL W. RICHARDS *Republican - Businessman*
KEVIN RICHTER *Republican - Information Technology Manager*
REVA RENEE RENZ *Republican - Small Business Owner*
SHARON RUSHFORD *Independent - Businesswomen*
GEORGY RUSSELL *Democratic - Software Engineer*
MICHAEL J. WOZNIAK *Democratic - Retired Police Officer*
DANIEL WATTS *Green - College Student*
NATHAN WHITECLOUD WALTON *Independent - Student*
MAURICE WALKER *Green - Real Estate Appraiser*
CHUCK WALKER *Republican - Business Intelligence Analyst*
LINGEL H. WINTERS *Democratic - Consumer Business Attorney*
C.T. WEBER *Peace and Freedom - Labor Official/Analyst*
JIM WEIR *Democratic - Community College Teacher*
BRYAN QUINN *Republican - Businessman*
MICHAEL JACKSON *Republican - Satellite Project Manager*
JOHN "JACK" MORTENSEN *Democratic - Contractor/Businessman*
DARRYL L. MOBLEY *Independent - Businessman/Entrepreneur*
JEFFREY L. MOCK *Republican - Business Owner*
BRUCE MARGOLIN *Democratic - Marijuana Legalization Attorney*
GINO MARTORANA *Republican - Restaurant Owner*
PAUL MARIANO *Democratic - Attorney*
ROBERT C. MANNHEIM *Democratic - Retired Businessperson*
FRANK A. MACALUSO, JR. *Democratic - Physician/Medical Doctor*
PAUL "CHIP" MAILANDER *Democratic - Golf Professional*
DENNIS DUGGAN MCMAHON *Republican - Banker*
MIKE MCNEILLY *Republican - Artist*
MIKE P. MCCARTHY *Independent - Used Car Dealer*
BOB MCCLAIN *Independent - Civil Engineer*
TOM MCCLINTOCK *Republican - State Senator*
JONATHAN MILLER *Democratic - Small Business Owner*
CARL A. MEHR *Republican - Businessman*
SCOTT A. MEDNICK *Democratic - Business Executive*
DORENE MUSILLI *Republican - Parent/Educator/Businesswoman*
VAN VO *Republican - Radio Producer/Businessman*
PAUL W. VANN *Republican - Financial Planner*
JAMES M. VANDEVENTER, JR. *Republican - Salesman/Businessman*
BILL VAUGHN *Democratic - Structural Engineer*
MARC VALDEZ *Democratic - Air Pollution Scientist*
MOHAMMAD ARIF *Independent - Businessman*
ANGELYNE *Independent - Entertainer*
DOUGLAS ANDERSON *Republican - Mortgage Broker*
IRIS ADAM *Natural Law - Business Analyst*
BROOKE ADAMS *Independent - Business Executive*
ALEX-ST. JAMES *Republican - Public Policy Strategist*
JIM HOFFMANN *Republican - Teacher*
KEN HAMIDI *Libertarian - State Tax Officer*
SARA ANN HANLON *Independent - Businesswoman*
IVAN A. HALL *Green - Custom Denture Manufacturer*
JOHN J. "JACK" HICKEY *Libertarian - Healthcare District Director*
RALPH A. HERNANDEZ *Democratic - District Attorney Inspector*
C. STEPHEN HENDERSON *Independent - Teacher*
ARIANNA HUFFINGTON *Independent - Author/Columnist/Mother*
ART BROWN *Democratic - Film Writer/Director*
JOEL BRITTON *Independent - Retired Meat Packer*
AUDIE BOCK *Democratic - Educator/Small Businesswoman*
VIK S. BAJWA *Democratic - Businessman/Father/Entrepreneur*
BADI BADIOZAMANI *Independent - Entrepreneur/Author/Executive*
VIP BHOLA *Republican - Attorney/Businessowner*
JOHN W. BEARD *Republican - Businessman*
ED BEYER *Republican - Chief Operations Officer*
JOHN CHRISTOPHER BURTON *Independent - Civil Rights Lawyer*
Write-In

MEASURES SUBMITTED TO THE VOTERS

STATE

Proposition 53

FUNDS DEDICATED FOR STATE AND LOCAL INFRASTRUCTURE. LEGISLATIVE CONSTITUTIONAL AMENDMENT.
Generally dedicates up to 3% of General Fund revenues annually to fund state and local (excluding school and community college) infrastructure projects. Fiscal Impact: Dedication of General Fund revenues for state and local infrastructure. Potential transfers of $850 million in 2006-07, increasing to several billions of dollars in future years, under specified conditions.
YES
NO

Proposition 54

CLASSIFICATION BY RACE, ETHNICITY, COLOR, OR NATIONAL ORIGIN. INITIATIVE CONSTITUTIONAL AMENDMENT.
Prohibits state and local governments from classifying any person by race, ethnicity, color, or national origin. Various exemptions apply. Fiscal Impact: The measure would not result in a significant fiscal impact on state and local governments.
YES
NO

California's 2003 governor recall election ballot listed *a lot* of candidates. The longer the ballot, the more likely a programming error in the electronic reader.

enough ballots in each language, the real problem lurks in vote tabulation. "To correctly assign the votes," Katz explains, "the tabulator software has to know which form is being used. For example, spot 50 on one ballot type may be a vote for Bush, but in another precinct it corresponds to a vote for Kerry. All those ballots then have to be read by a central card reader, which someone had to program," he says. "No one asked, prior to 2000, who wrote the code to read them. I'm not even worried about malicious intent; I'm worried about accidental readings."

As a forensic analyst for the VTP, Katz specializes in figuring out how elections directly record voters' intents, which is difficult to do because voting is anonymous in the United States. "How do you reconstruct an election?" is one question he tackles, and another is "How do you evaluate problems?" One way is to match expectation to outcome, but you might correctly imagine this is not the most reliable of checks. It's especially difficult to do

"When we make these wholesale changes, how do we know that things went wrong? How do we verify what happened? How do we verify what voters wanted? It's not an easy thing to do, given anonymous systems."

when the pace of voting reform is more like tottering than striding. Georgia, for example, unified its voting system after the 2000 election by installing Diebold electronic voting machines in every county. "Now the question is, how do we evaluate whether or not there were any problems with the Diebold system?" asks Katz. The standard way is to assume that only a small fraction of machines or precincts are problematic; to look for outliers. But, says Katz, "When we make these wholesale changes, how do we know that things went wrong? How do we verify what happened? How do we verify what voters wanted? It's not an easy thing to do, given anonymous systems."

Theisen favors a wholesale return to manual vote counting. "There would be huge resistance to going back to hand counting, but I'm convinced that hand counting paper ballots is the most efficient," she says. "People say there's so much [election] fraud, but at least with paper ballots the fraud is detectable." Barring this seeming impossibility, random manual recounts of some subset of votes seems like a fair alternative. For human errors like badly marked ballots, this practice regularly reveals vote differences ranging from one hundredth of a percent to one percent, according to Katz (though ballot programming errors are likely much higher). "They're almost always finding more votes," he says. "Because humans can look at a ballot and say, 'Oh yeah, you marked it.' You didn't completely fill in the dot, for example. The machine might have missed it."

A less-than-one-percent discrepancy seems tiny, but even 100 votes out of a million can be significant in a tight election. Alvarez points to Orange County's February 2007 county supervisor race between Trung Nguyen and Janet Nguyen. Janet Nguyen requested a recount when the election came down to a seven-vote margin of victory for her opponent. In a *Los Angeles Times* report of the recount, advisors for both sides said the outcome turned on less than three dozen ballots that were either invalidated or improperly counted the first time. Many ballots were thrown out because of comments and drawings in the margins—most of those were Vietnamese-language ballots. Tossing a vote for some doodles sounds silly, but there's a historical context for this decision: "In the 1800s, we regularly had vote buying in the U.S.," says Katz. "You would publicly cast your ballot, and I would pay you afterward. Now our ballots are void if there are stray marks, because they could possibly identify a voter." Internet voting would handily dispense with this snafu, but opponents to Internet voting wonder what would stop a politician from paying a citizen to cast an easy vote online from the privacy of their own home. Indeed, according to an ongoing study of vote fraud by the Justice Department, vote buying continues to be a tradition in rural areas, where local politicians offer $5 to $100 for an individual vote. In response to these concerns, Katz points to the same study, which, since its 2002 inception, has uncovered no evidence of *organized* fraud efforts. In fact, only 120 people have been charged so far, the majority of whom mistakenly filled out registration forms because they misunderstood—and thus violated—voting eligibility rules. These incidents speak to perhaps the biggest flaw in our voting system: the registration and voter verification process.

A CYBERSPACE SOLUTION?

Alvarez thinks the Internet holds the likeliest promise of easing voting problems in this country, including those surrounding registration. "In most states in the U.S. it's very difficult to determine whether you're even registered to vote or not," says Alvarez. "Yet you can file your taxes online." His research reinforces a long-standing view that the registration process is one of the key factors in keeping people from voting. HAVA required that states follow steps to verify the voters on their registration lists, including cross-checking voters' names with their states' motor vehicle records. According to *Point, Click, and Vote* coauthor Hall, in 2006 California's voter-registration database couldn't recognize surnames with hyphens or with spaces. "So think about Benicio del Toro—he would get kicked off immediately because he has a two-word last name," jokes Hall. "They were kicking off thousands of people a week." California eventually changed its voter verification rules, but this example reveals how unhitched voting is from other government functions. Somehow when you move, your driver's license will eventually track you, as will your car registration and your tax forms, but your voter registration never will. People become progressively alienated from voting when they have no easy way of checking where or even if they're registered to vote, and no idea where their precinct is.

Some countries have successfully implemented Internet voting, and their systems also track registered voters. In March, Alvarez and some of his VTP colleagues flew to Estonia to survey the world's first Internet votes cast in a parliamentary election. The demand for Internet voting in that country is marked by the number of people who use it, which tripled from 9,500 to more than 30,000 in the two years since the option was introduced. Alvarez and Hall credit technology penetration within a recent democracy as well as

Although vote buying is a tradition in rural areas—and some voting watchdog groups think that Internet voting would make this easier—a 2002 Department of Justice study uncovered no *organized* voting fraud efforts.

Images courtesy Estonian Citizenship and Migration Board.

An Estonian ID card stores the carrier's information on a chip and sports various security features, including a microprint poem by Estonia's poet and politician Paul-Eerik Rummo.

both public and governmental support. "People use technology in a way that you just shake your head," says Alvarez, citing old ladies texting on new Nokia pop-up phones, the ubiquity of wireless Internet throughout the country's capital Tallinn, and 80-somethings who opted for Internet voting.

To establish Internet voting, Estonia first passed a series of laws that provided a legal basis for it, including a legislative act allowing people to authenticate themselves to the government using a digital signature. (People in the United States can create a digital signature, too, but outside the military it can't be used to sign any documentation necessary to the voting process.) The rules for how Internet voting was to work, and the technology for using it, were set up independent of online voting. Now, an Estonian's ID card has her photo on it and a chip with her digital signature in it. She inserts her ID face up into any computer carrying a card reader that costs $7 to install. She types in her password to enter the government portal. From there, she can pay taxes, register her car, renew her passport, or vote.

Internet voting is available between six and three days before the election. The vote can be changed anytime during this window but not afterward, except in person by paper ballot on Election Day, a vote that replaces any previous vote. A testimony to how well the system works is that only 32 people revoted on paper, Alvarez says. It's not a completely rosy picture, though—rural parties oppose Internet voting, because their constituents typically lack computer resources. The day after the election, Alvarez and Hall visited one of the parties that strongly championed the cause and asked what their supporters were like. "They had lots of wealthy urban voters who use the Internet all the time," says Hall. "They had clearly thought through the calculus of how this was going to benefit them."

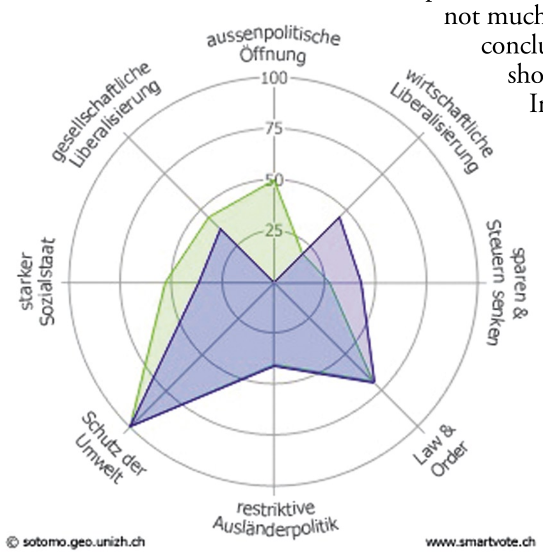
As a small and new democracy lacking the scads of ballot measures we have in the United States, Estonia might not be our best model. Switzerland, an old democracy with heaps of initiatives and referenda, is a better bet. To learn a bit more about how the Swiss successfully implemented Internet voting on a limited scale, Alvarez invited a Swiss delegation to a voting symposium at Caltech in April. The Swiss initiated the experiment in three of their 26 cantons after a 1999 parliamentary request to study Internet voting feasibility, according to Max Klaus, a scientific officer in the Federal Chancellery. Each of the three cantons—Neuchâtel, Geneva, and Zurich—takes a different approach, but all are based on a government portal similar to the one in Estonia. Citizens can log on to check their insurance, taxes, and car registrations, and print out a receipt verifying that they voted.

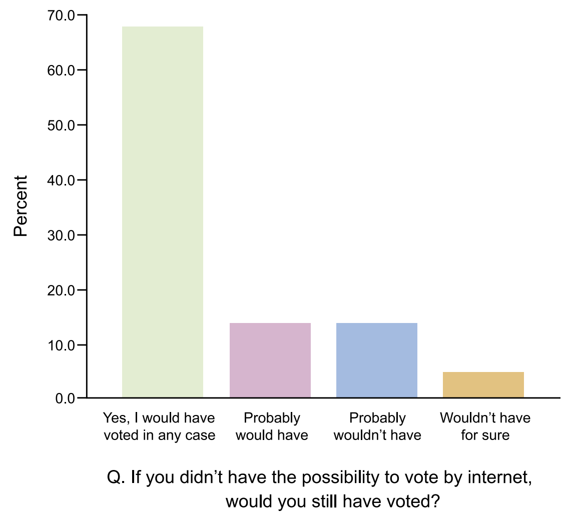
Based on its success so far, the Swiss continue to spread Internet voting in their methodical fashion. Some fundamental groundwork helps: in contrast to the United States, Switzerland automatically registers her citizens to vote when they turn 18, and when they move, their registration tracks with them. The Swiss consider themselves tech savvy—65 percent have private Internet connections, and even more use it at their jobs. Furthermore, they appear to innately trust their government. There is no real voting secrecy—people can still vote by raising their hand in the town square. Government portals allow citizens to look up anyone's license plate number. They can be as politically active as they want, challenging or proposing laws through initiatives. But because the Swiss are asked to vote often and for a lot of things, voter turnout is historically low. Internet voting proponents hope the ease of Internet accessibility will change this. Postal voting was extremely successful after its introduction 10 years ago, increasing voter turnout by 20 percent in Geneva, for example, where 80 percent of voters quickly turned to voting by mail. So after federal law was amended to allow for Internet voting, a subset of postal voters was easily transposed

Ever the tech-savvy nation, the Swiss embrace Internet voting and have devised programs to encourage it. On the website www.smartvote.ch, voters and politicians alike input their political views. The program generates a graphic showing the voter where his views (green field) overlap or diverge from those of his most closely matching candidate (purple field). It's then a quick link to cast the vote.

into cyberspace without reengineering the whole voting process.

In Geneva, 20 percent of voters now cast their ballots online, a large number that begs the question, "Does Internet voting change the political process?" Specifically, does it give one party an advantage over the other? According to Alex Trechsel, a Swiss professor of political science at the European University Institute in Florence, Italy, the answer is no. "There's a neutral effect of e-voting (Internet voting) that has been confirmed by multivariate analyses looking at all of the data," he says. He cites specifically the September 2004 Geneva referenda and the Estonia parliamentary election. "E-voting would not have changed the political result," he says. It's also shown little impact on turnout so far. "We found a small effect, but let's be honest—this effect is not huge," he says. "We asked occasional voters, who said they vote from time to time, and those who are declared abstentionists, whether the introduction of Internet voting made them reconsider. And the simple answer to that is a little bit, but not much." He adds an important conclusion, at least for now: "This should serve to remind us that Internet voting will certainly not be any panacea for increasing turnout." The recent French presidential election punctuates that statement—with no option of Internet voting, a record 85 percent of the voting population turned out.





This survey of Internet voters in the 2007 Estonian parliamentary election suggests that the Internet will play a minimal role in increasing voter turnout. The majority would have voted anyway, by other means.

Potentials and problems

What can Internet voting offer that we don't already have? Alvarez lists several possibilities, including flexibility, long-term savings, and service options. Every computer with an online connection becomes a potential voting booth, erasing inconveniences like bad weather, long lines, and polling place mix-ups. This is handy for the voter who can't take time off from work to vote, or for the overseas voter who has to work out the logistics of getting and mailing a ballot. It's also cheaper for the entire electorate in the long run, because running an election from the polling place is a logistical nightmare. "Electronic voting tabulation and counting has no standard procedure," says Alvarez. "The process in L.A. County has been compared to a military mobilization. People have to pull out ripped and written-upon ballots, which are invalid. Volunteers are often high school students, because it's a problem getting people to help. And it doesn't help that voting is on a Tuesday!"

Internet voting should be especially attractive to disabled voters, Alvarez says. A 2000 study by the General Accounting Office showed that more than 80 percent of polling places are wheelchair inaccessible, and Alvarez has seen this himself in his

A hodgepodge of signs indicating polling stations in Pasadena, California: Some are clearly not handicapped friendly, and others just seem bush-league.

countrywide surveys of voting operations. "In the U.S., we have a very serious problem with accessibility," he says. "The Americans With Disabilities Act and the Help America Vote Act require that polling places and voting devices be accessible to people with different types of disabilities, both visual and physical. I can show you hundreds of photographs of polling places within just a mile or two of Caltech that violate these provisions. We went to a polling place that's about 400 yards from here that was not accessible to someone in a wheelchair, which may be a violation of federal law." Furthermore, the overseas soldier, the frequent traveler, and the working single parent are effectively disenfranchised by our current system, Alvarez argues. Then there are the 18- to 25-year-old voters, who historically turn out to vote at the lowest rates, but who are practically hardwired to the Internet.

"Voting at polls on Election Day is an act of community, balanced with individual freedom . . ." (Norm Ornstein)

"Are people really missing joining hands with their neighbors and singing 'Kumbaya' as they go to vote?" (Thad Hall)

Increasing vote quality is another argument that Alvarez advances. Imagine the potential: one browser displays the ballot, while others show a voter guide and information about candidates and ballot measures. Voters would be allowed to cast or change ballots until 8 p.m. on Election Day, allowing decisions to be made based on last-minute information. As many as 20 percent of voters nationwide now mail their ballots weeks in advance, losing the option to change their minds if new information on a candidate surfaces.

Finally, there is the "why not?" argument. Online voting opponents raise security issues, including the possibility of hacking. But it's clear that Americans trust Internet security with some pretty major stuff: we regularly shop and conduct many forms of personal exchange online. It's how nearly 34 percent of taxpayers filed for fiscal year 2005—in raw numbers, that's more than 76 million e-filers! Perhaps it's an unfair comparison, but the voting systems in Switzerland show no successful hacks so far. Geneva's Internet voting information website claims "Internet voting is more secure than postal voting for at least four reasons: human mistakes are no longer possible; you receive an acknowledgment that we received your ballot; you cannot mistakenly invalidate your ballot; and you are told by the system if you try to vote after the system's closure, allowing you the possibility to vote in the polling station." Their point is that all other voting systems have thus far proven to be significantly flawed. Certainly, the 2000 election showed that people believe in the potential for an election to be stolen the old-fashioned way. "We never have, nor never will, make light of security and integrity," says Alvarez. "But in our work, we stress that all voting systems should be evaluated in the same manner—that is, that paper-based and electronic-based systems should be held to the same security, accuracy, auditability, verifiability, usability, accessibility, and transparency standards. We also stress that dimensions other than security are extremely important, and should not be overlooked when evaluating any type of voting system or election administration practice."

But the opposition to online voting is strong, and presents several cogent arguments beyond security from hacking, viruses, vote buying, and loss of anonymity. One is that Internet voting may erect a "digital divide" that appears to exacerbate current inequities by favoring white, wealthy, well-educated, male, Republican voters who are more abundantly and more quickly connected to the

Internet. Although the VTP study so far indicates that Internet votes will likely be more accurately counted (for example, application features would make overvoting impossible and help avoid undervoting), it doesn't necessarily see the Internet as a means to end the legacy of discrimination that limits voting access. Still, Alvarez argues that the Internet can do better in this regard when it comes to other aspects of the electoral process, like registration and administration.

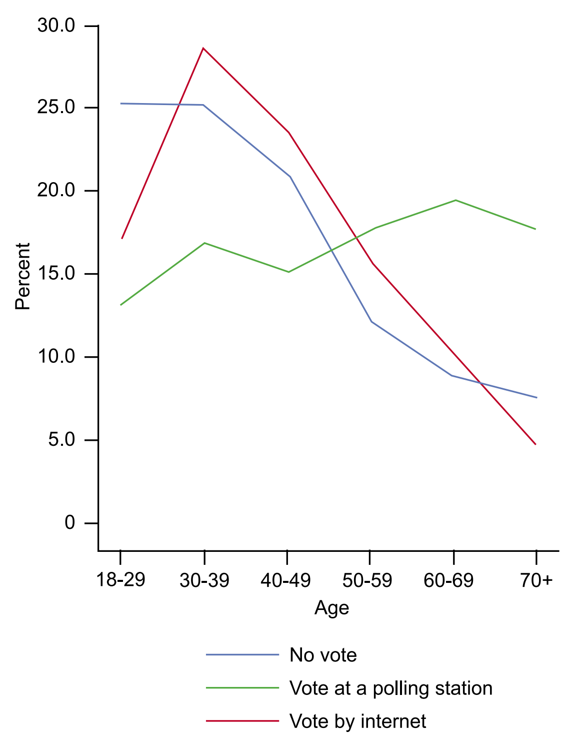
Another argument against Internet voting focuses on the communal fervor of Election Day. Opponents believe that Internet voting is the antithesis of the community-based electoral process and see it as a potential disintegrator of civic life. As Norm Ornstein, a political scientist with the American Enterprise Institute, argued recently, "Voting at polls on Election Day is an act of community, balanced with individual freedom . . . It is an exquisitely balanced act where you go to congregate with your fellow citizens, showing that you are a community, but then you move into a private booth, draw a curtain, and perform a supremely private act, an enormous act expressing the freedom of choice that exists in a democracy." Hall raised this issue at the Swiss-American voting symposium, cheekily asking, "In Switzerland, are people really missing joining hands with their neighbors and singing 'Kumbaya' as they go to vote?" In some ways this is already a nonissue. For one, the VTP proposes Internet voting only as a viable option, not a replacement. Secondly, some states appear to have already either lost faith in polling-place voting or opted for the relative convenience of the post office. Oregon abandoned the civic moment in 2000 in favor of exclusively mail-in ballots. In California, 50 percent of voters mail their ballots, and that number is likely to grow. In Washington, the rate is up to 75 percent.

The complexity of our system alone raises a fairly well-fortified barrier to Internet voting. Trying to develop an Internet voting application that covers all voting issues gets complicated quickly. The Voting Rights Act requires that ballots be provided in many different languages depending on the number of language minorities that live in a particular area. Alvarez adds, "We ask our voters to vote a lot and to vote for a lot of stuff. This will keep us from moving forward as quickly as other countries can." Contrast the United States with a country like Estonia, where there is only one vote in one race, and only one language option.

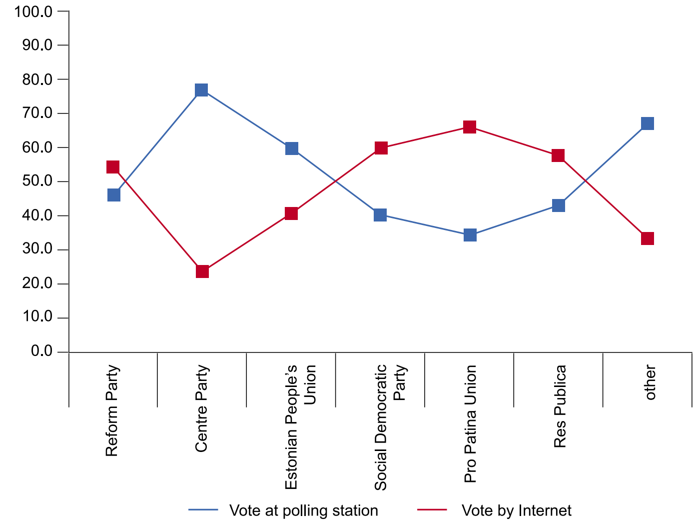
Not only are election regulations complex overall, they basically have to be reinvented with each election. "Every ballot requires new programming. That's where we see a lot of the problems," says Theisen, of VotersUnite. "We get so used to using computers, and most of the time they work great, but in almost every other application besides voting, you see what you put in and you see what comes out. With Internet voting, you put something on the screen, and then you click some button that shifts the data off somewhere, and how do you know that data has been correctly recorded? The person who voted is not ever going to see the ballot the way it gets shipped into cyberspace, and they don't know that it's going to be counted right. Internet voting is as unobservable as electronic voting."

But the ultimate resistance could come from voters who innately distrust any electronically sophisticated system that could potentially cloak subterfuge. "Conceptually, I find it difficult to accept something that is so complicated that only experts can understand it," says Theisen. "I think that it's foolishness to trust the system when it comes to something like this. I see it as a distinct advantage and a chance for us to hold on to our democracy longer because we're *not* trusting the system. One recurring theme throughout history is that those in power attempt to stay in power however they can. Theoretically, the people are in power in a democracy, and they should be the ones who observe the election."

The Internet holds the potential to lure younger voters. In this survey of Estonian voters, the majority of those who cast their votes online were under the age of 40.



Are Internet voters skewed more heavily toward one party or another? According to Estonian voters, the answer seems to be a little, but not much.



To Alvarez, the bottom line on Internet voting is obvious. "There is no way to know whether any argument regarding Internet voting is accurate unless real Internet voting systems are tested, and they should be tested in small-scale, scientific trials so that their successes and failures can be evaluated," he says. In Switzerland, comments Hall, "you actually experiment; you decide you want to see if Internet voting works, and you create some objectives for what you're going to look for; you research, you collect data, you survey people." In contrast, "in America we experiment with everybody! What I mean by that is, we get some great idea, like 'What would happen if we liberalized our laws regarding early voting or absentee voting?' and then pass a law and let everybody do it and then we don't evaluate it, or we evaluate it poorly."

Just before the 2004 election, the Department of Defense designed an experiment in ballot encryption and transfer that would also provide receipts and would be a voting option for up to 100,000 citizens in the primary and general elections. But because the Secure Electronic Registration and Voting Experiment (SERVE) was to be distributed across 50 counties in seven states with seven entirely different methods of voting, as well as to overseas soldiers, it was quickly mired in complexity and was abandoned two weeks prior to its proposed launch for the 2004 election. The four-person panel of computer scientists who posted an unofficial evaluation of SERVE on the Internet claimed, "It is impossible to estimate the probability of a successful cyber-attack (or multiple successful attacks) on any one election. But we show that the attacks we are most concerned about are quite easy to perpetrate." The sponsoring agency, the Federal Voting Assistance Program, never released an official evaluation.

There are no formal plans for Internet voting in the 2008 election, although some states are discussing pilot tests of electronic or Internet voting for their military and overseas voters, says Alvarez. He foresees lots of debate in the wake of the upcoming election: "Given what is likely to be a hotly contested presidential election, many competitive House and Senate races, unprecedented scrutiny of election procedures and technologies, and all of the problems we know of in polling-place practices, early and absentee voting procedures, voter registration, and voting technologies, we may not know until well after Election Day who the next president is, and which party will control Congress."

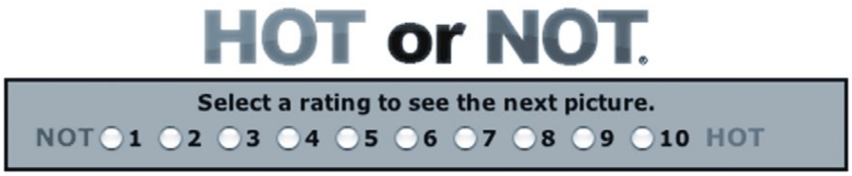
At the close of the voting symposium at Caltech, one Swiss delegate wondered, "If a Democrat was elected to the presidency, would Internet voting come quicker?" To this Hall replied that, after all, there is little incentive for change. "You have to acknowledge that the system you won by is effective," he laughed. □

Caltech VTP members Michael Alvarez (top) and Jonathan Katz (bottom) have their voter ID cards ready, just in case.

PICTURE CREDITS: 14, 15 — National Museum of Natural History, Smithsonian Institution; Bob Paz; 17, 18, 22, 24 — Melissa Slemin; 19 — Doug Cummings

Knowing What You Like

By Marcus Woo

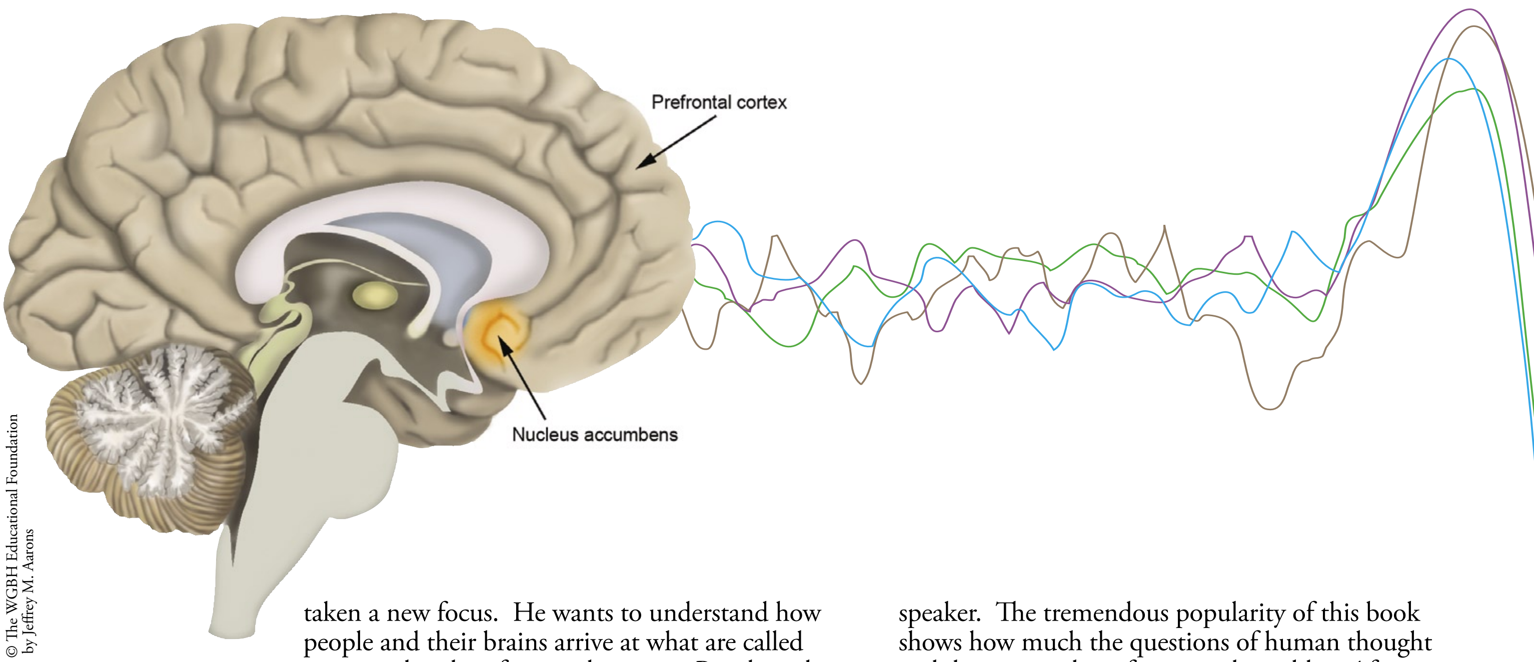


The site is simple, but it can be addictive. Picture after picture of people and faces offer themselves for your honest judgment. With a click of the mouse, you can rate the attractiveness of strangers on a scale from one to ten. Immensely popular when it first hit the Web in 2000, hotornot.com lets anyone upload photos of themselves to find out, based on ratings from thousands of Web surfers, how good-looking they are. Motivated by curiosity or an ill-conceived bet, you may even have put up your own picture. If not, you may have at least perused the site, clicking away. He's a nine, you may have said. She's a six. This other one was more of a seven, you think. You know the site is nothing more than silly fun, pandering to vanity and superficial beauty. But underneath this playful clicking between you and the pictures, something subtler is going on.

How did you decide to rate the second face higher than the first? You pause and think. You liked the gentle slope of her nose, you say. Or maybe it was her wispy eyebrows. Either way, you are confident in your rationale. You made a conscious choice supported on reasonable grounds. But did you really?

It turns out the latest developments in psychology, cognitive science, and neuroscience suggest otherwise. In fact, Professor of Biology Shinsuke Shimojo's lab is showing that your body and brain may already be making decisions before you are even aware of them. Through a series of diverse experiments, including one similar to the exercise offered by hotornot.com, Shimojo and his colleagues are finding that the unconscious behavior of the mind and body may significantly determine how people end up choosing what they like. "Your body persuades your mind," Shimojo says. "It's almost as though your body decides before your mind does."

Shimojo's lab does a variety of research in psychology, cognitive science, and neuroscience. In the last few years, however, his interests have



The squiggly lines emanating from this cross section of the brain represent electrical activity, which is measured with electroencephalography (EEG).

taken a new focus. He wants to understand how people and their brains arrive at what are called emotional and preference decisions. People make these choices daily: whether to have soup or salad, or whether to watch *The Simpsons* or the evening news. These decisions rarely have a right or wrong answer, and are often innocuous. But at the same time, they help define people as individuals—and as human beings.

The lab is attacking the problem from many directions, including an experiment in which subjects are asked to choose the better looking of two faces. By tracking their eye movements, the researchers are discovering that the quick, instinctive movements of the eyes substantially influence the subject's eventual decision. Additionally, the advent of noninvasive technologies to monitor the brain allows scientists to zoom inside the cranium to dissect the neural mechanism behind preference decision making. Shimojo's lab, in collaboration with Associate Professor of Psychology John O'Doherty's lab, is also developing techniques to train people to activate or suppress specific areas of their brain. It may sound like brainwashing, but it is not. Researchers call it neural conditioning, and it requires the subject's willing cooperation for it to work. As such, it is far from any sort of mind control—but the process is provocative, a kind of high-risk and high-reward research with potentially powerful clinical and scientific applications.

I don't think, therefore I decide

In 2005, Malcolm Gladwell published *Blink: The Power of Thinking Without Thinking*, a book about the power of first impressions in making decisions. Occupying best-seller lists for months, the book has been translated into 25 languages and propelled Gladwell to prominence. He was named one of *Time* magazine's 100 Most Influential People and has enjoyed a lucrative second career as a public speaker. The tremendous popularity of this book shows how much the questions of human thought and decision making fascinate the public. After all, Shimojo says, understanding how people make decisions—and especially preference decisions—is relevant to everyone.

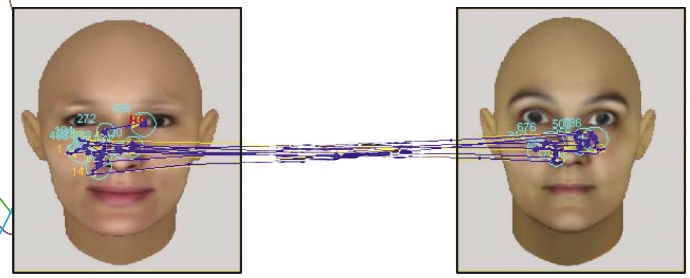
Although these decisions are common, it is still a mystery how the body and brain work together to make them, he says. "Everybody's doing this every day without effort, like when you go to the shop and buy something, or when you go to the cafeteria and choose what you want to eat," he says. But the reasons people give for buying that pair of shoes, ordering that turkey sandwich—or choosing an attractive face—are not necessarily the whole truth, and might even have been invented after the fact, Shimojo says.

Many other factors—many of which happen unconsciously—influence the decision-making process. A classic example is the "mere exposure effect": repeated exposures influence people to choose the more familiar object. Advertising agencies take advantage of this psychological effect. For example, when choosing between a well-advertised product—say, a bar of Dove soap—and a largely unknown, generic brand, people will tend to opt for the known brand. But when asked why they chose that particular bar of soap, people might say they preferred the packaging or that it was cheaper. They are not aware that exposure may have played the biggest part in their choice.

Shimojo describes a psychology experiment in which male college students were asked to rate sexy photos of women. They were then allowed to take one of the pictures home. Although the subjects were not aware, the gift was part of the experiment, and it turned out they often did not choose the photos they claimed they preferred. "There are lots of studies similar to this kind of experiment," Shimojo says. "It turns out people's behavior often betrays their conscious cognition."

Understanding the entire process, Shimojo

Eye-tracking data overlayed on the faces the subject is choosing between. Lines trace the eye movements and numbers indicate how many milliseconds the eyes lingers over a certain spot.



says—from initial sensory cues, to the unconscious, implicit cognitive decisions, to the final, conscious choice—encompasses the three biggest mysteries in neuroscience: emotion, decision making, and consciousness. All three come into play, whether you are choosing a sandwich for lunch or choosing a mate to marry, and all three drive the lab's work.

Even when he was young, Shimojo was captivated by perception and how it relates to the mind. He would sometimes squint at the patterns on the ceiling in search of a stereogram, one of those optical tricks in which an embedded three-dimensional image pops out. He wanted to study how people perceive reality. "I became interested in my own mind," he says.

Fascinated with the mind, he studied experimental psychology and neuroscience. For much of his career, he focused on visual perception, and his lab has traditionally focused on psychophysics, the branch of psychology that deals with how people interpret what they see, hear, feel, smell, and taste. Lab researchers are still involved with sensory perception—including the development of perception and cognition in infants. Meanwhile, Shimojo is applying many of the techniques he developed in his earlier work toward understanding preference decision making. One such method tracks eye movements. The eyes, after all, are like windows into the mind, Shimojo says. In this experiment, the test subject wears a head brace fitted with small cameras that monitor every eye twitch. Tracking their eyes' movements while people pick pretty faces, Shimojo and his colleagues discovered beauty might literally be in the eye of the beholder.

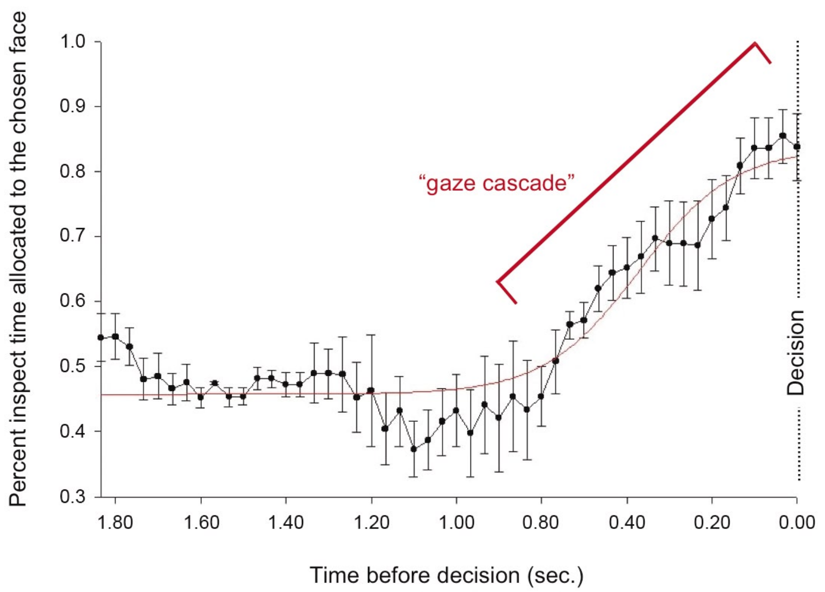
Yasuki Noguchi, visitor in biology, wears the eye-tracking device while comparing two faces.

Going face to face

Two faces, floating side by side on the computer screen, stare back at the subject. The eye-tracking headgear records the subject's eye positions 30 times per second. Meanwhile, the subject takes as much time as needed to pick out the more attractive face. Then he or she pushes a button to mark the decision. Shimojo, Claudiu Simion (BS '99, PhD '05), and their colleagues found that before people pushed the button, their eyes fell on the chosen faces more frequently than the rejected faces. Furthermore, the likelihood that their eyes would be directed at the preferred face increased as the subject neared the time of decision.

What's going on, the researchers say, may be partly a version of the mere exposure effect, in which greater exposure—such as seeing more commercials for a brand of soap—increases preference. In what they call the gaze cascade effect, the more someone looks at a face, the more he or she wants to look at it. As a result, the subject will look at that face even more, causing a rapidly rising probability that he or she will be looking at the selected face before the conscious, final decision (see the figure on the following page). But while the mere exposure effect is the result of passive behavior, the gaze cascade effect involves active and spontaneous eye movements.

Of course, there could be alternative explanations. Having already made up their mind, perhaps people lock in on the chosen face to confirm their decision. But when the researchers performed



This plot, called a likelihood curve, illustrates the gaze cascade effect. The probability of the subjects' eyes falling on the eventually chosen face rises as the subject nears the time of decision. Researchers recorded whether the subject was looking at the chosen face or not, assigning a value of one or zero. They then averaged these values over all five subjects and trials to arrive at the likelihood.

a control test, in which they asked subjects to choose which face they thought was rounder, they found different behavior. The likelihood that the subject's eyes fell on the chosen face started off at random chance, at around 50 percent, and started to rise. For the roundness test, the likelihood leveled off at 60 percent. But in the attractiveness case, the likelihood continued to increase until the moment of decision, eventually reaching more than 80 percent. If the gaze cascade effect was just the result of people focusing in on their choices, then the effect should be similar regardless of whether they were asked to choose the rounder or more attractive face.

The case was strengthened when the researchers found they could influence the subjects' choices by manipulating the gaze—by limiting how long subjects could look at the faces. In this experiment, only one face appeared, alternating between the left and right sides of the screen. Each repetition lasted either 900 or 300 milliseconds, and afterward, the subjects had to choose the most attractive face. In trials with six or more repetitions, the subjects chose the faces that appeared longer 60 percent of the time; a longer gaze seemed to cause a preferred choice.

The key factor, however, is not just the length of time, but also the active eye movements of the gaze itself. When the subjects were told to keep their eyes on the center of the screen, there was no preference bias toward the face shown for a longer time. This happened both when the faces appeared at the sides and in the middle of the screen. The researchers were unable to influence the subjects' choices, implying that the eye movements affect decision making. The researchers were also unable to manipulate the gaze cascade effect in the roundness test. These various lines of evidence lead to a conclusion that the gaze cascade effect is likely unique to preference decisions.

Furthermore, the effect probably happens for all preference decisions. For example, the same gaze cascade appeared when subjects had to choose their favorite geometric shapes. Another factor researchers tested for was novelty, since the gaze effect might only happen when people see faces for the first time. To test this, the team inserted a single-day delay, showing subjects the same face pairings as they did two days earlier. In nearly a quarter of the trials, the subjects changed their minds about which face they thought was more attractive, which itself was not too surprising, since people change their minds all the time. What was surprising was that all cases showed the same gaze cascade behavior, offering persuasive evidence that the gaze cascade effect is an intrinsic part of the decision-making process.

Without your consciously telling them to, your eyes scan your surroundings in rapid leaps called saccades, quickly gathering information as they move several times per second. Called orienting, this behavior also happens in response to something that grabs your attention, such as a flash of light. The evolutionary advantage of orienting is obvious, as it is crucial for basic survival tasks like finding food and avoiding predators. But researchers say orienting has also been shown to be the basis of higher-level brain functions such as decision making, and it certainly seems to be the case with this experiment.

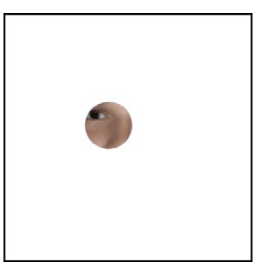
According to Shimojo and his team, the spontaneous movements of the eyes work in concert with more deliberate, cognitive tasks to make the final choice. Consistent with this idea, the researchers found a stronger gaze cascade effect when subjects had to choose between similarly attractive faces. When figuring out whether Angelina Jolie looks better than a troll, the cognitive part of your brain can handle most of the decision making without relying too much on the gaze cascade effect. But when forced to make a harder decision, say comparing Brad Pitt and George Clooney, the instinctual movements of the eyes contribute more to the decision process.

The researchers now seemed to have established a reasonable, albeit counterintuitive, model of preference decision making. But of course, as in all scientific pursuits, many questions remained.

More evidence

When you look at a face, you usually see the face as a whole. Unless the person has some odd feature, like a giant nose or cross-eyes, you do not

Choosing between Angelina Jolie and a troll; Brad Pitt and George Clooney.



In the peephole experiment, a subject only sees a small part of a face when evaluating its attractiveness.

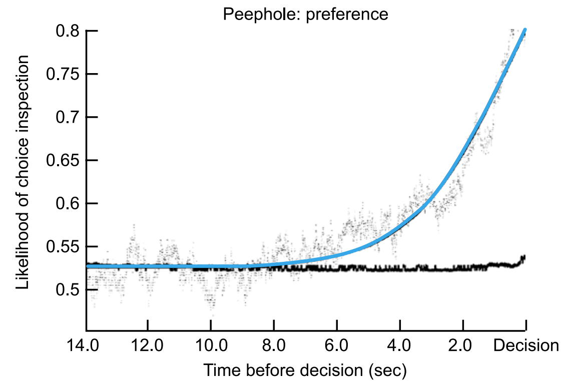
focus on specific parts of the face. This kind of overall perception is called holistic, and analyzing a face is known to be among the most holistic exercises in human perception, Shimojo says. The implication, then, is that the holistic nature of face preference might be connected to the gaze cascade effect. According to Shimojo, if the researchers could somehow remove the holistic aspect—that is, if they could force the subject to focus in on specific parts of the face—then maybe the gaze cascade effect would disappear.

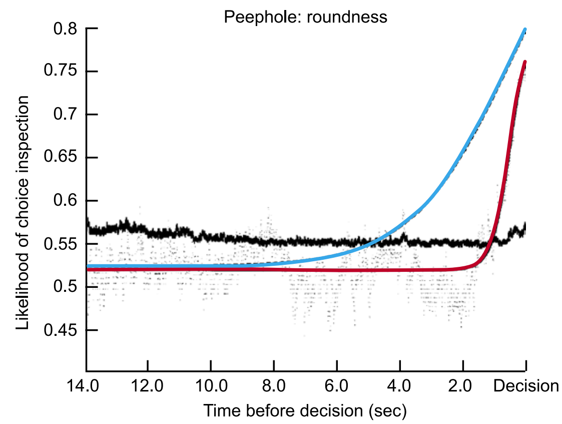
In their next experiment, the researchers only allowed a small circular patch of each face to be visible. The patch followed the direction of the eye, so that the subject could only see a single facial feature, such as an eye or a nose, at a given time. The subjects were forced to evaluate the face through what amounted to a peephole on the computer screen. What the researchers discovered was unexpected.

"We got a big bonus—a big finding," Shimojo says. Not only was the gaze cascade effect present, which meant a holistic evaluation of the face was not needed for the cascade behavior to happen, but it started early. The likelihood of looking at the chosen face was already beginning to rise eight seconds before the button was pushed. By limiting the amount of information available to the subjects, the peephole forced them to take more time in creating a mental image of the faces before making their decisions. The gaze cascade effect was stretched in time. The presence of the effect was not too surprising, but the fact that the effect was present so early invalidates a common model of decision making, Shimojo says.

Many in the field have traditionally thought of decision making as a series of steps, in what is called the sequential box model. In this model, for example, the brain might undergo the following steps: (1) identify individual facial features, (2) integrate the features together to paint a picture of the entire face, (3) incorporate memory and experience to help evaluate how good it looks, (4) respond emotionally, (5) tell the finger to press the button. In this model, Shimojo says, each step has to be completed before the next. The early appearance of the gaze cascade effect shows the decision-making process already started even while the eyes and brain were still collecting sensory information on particular facial features. "This really requires people to change their philosophy on how they look at the brain," Shimojo says.

Furthermore, the differences between the attractiveness and roundness tests further convinced Shimojo and his colleauges that the gaze effect is not just a result of subjects locking in on their chosen faces. For the attractiveness test, the gaze cascade effect began eight seconds before decision. For the roundness test, the likelihood did not start rising until less than one second before decision (see figure on the right). The researchers argue this difference rebuts the alternative explanation of a selection bias,



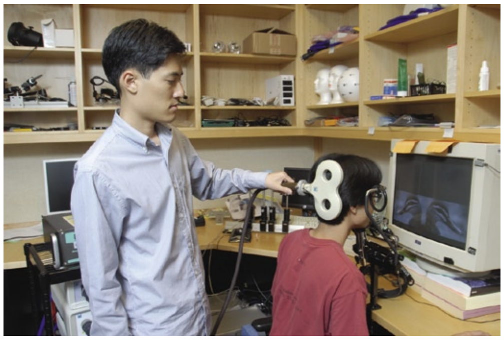


From Simion and Shimojo, *Vision Research*, vol. 46, no. 20, pp. 3331-5, 2006.

The likelihood curves (colored lines) from the peephole experiment show that the gaze cascade effect begins a lot earlier for the attractiveness test (top) than for the roundness test (bottom). The gaze cascade starts when the likelihood curve crosses the black line, which is called the significance threshold. The curve for the attractiveness test (blue) is superimposed on the roundness-test plot for comparison.

in which subjects dwell on the chosen face—regardless of whether they were asked to choose the rounder or more attractive one. Otherwise, both experiments should have shown the same effect.

The researchers next wanted to know what would happen if they interrupted the gaze cascade effect. Namely, what would happen if the pictures of faces suddenly disappeared while the subjects were still evaluating them? In this experiment, the images disappeared at random times. Even if the faces vanished before the button was pressed, the subject still had to make a decision—only now with a blank screen. The data was split into two categories: trials when subjects decided before the faces disappeared, and trials when subjects decided after the faces disappeared. In the late-decision trials, when decisions were made after the faces vanished, the data still showed a gaze cascade effect. In other words, people were still looking at the location where their preferred face had been, even though it was now empty. Since there was no



Above: Postdoc Daw-An Wu demonstrates how to induce electrical activity in graduate student Neil Halelamien's brain with transcranial magnetic stimulation. Right: A subject being prepared to undergo an MRI brain scan.

reason for people to gaze at the chosen faces, the researchers concluded the gaze cascade effect had to happen in order for people to make their decisions. It is an unavoidable and inevitable part of preference decision making, Shimojo says.

This experiment also refuted another alternative explanation: people like to look at pretty faces, and will keep on looking at their favorite face. But in the early-decision trials, people stopped looking at their preferred face after they made their decision, even though it was still there. The allure of an attractive face was not strong enough to induce this phenomenon.

The results were also consistent with an idea in perception psychology that the location of an object in your field of view is tied in with what you perceive to be more attractive. In the experiment, when they had to decide after the face disappeared, people still looked at the empty area on the screen formerly occupied by the more attractive face. The possible implication is that preferences and judgments of attractiveness depend on where the face is in your field of view.

A nagging question, however, is whether the gaze caused the decision or vice versa. In other words, which came first, the decision or the gaze? The answer is likely neither, Shimojo says. The brain might have made an internal decision long before it told the finger to press the button, and even before the gaze cascade effect started. But Shimojo does not see a way in which anyone can define and measure the precise moment a choice is made. For practical and scientific purposes, the act of pressing a button is the best marker of a decision, and he says he doubts there is a singular, decision-making moment. He likens it to a snowball rolling down the hill. The snowball of decision making keeps on growing as the gaze bias increases. Then, after passing a certain threshold, you become aware of your decision and you press the button. "It offers you a different view of decision making," Shimojo says. "In daily life, you naively expect decision making to be one moment. We're saying it's spreading over time, and that it involves the body."

An array of experiments

This work in preference decision making is still relatively new, and researchers are in the middle of an array of experiments. Scientists are probing whether an analogy of the gaze cascade effect happens with senses other than vision. Postdoc Junghyun Park is beginning a set of experiments in which blindfolded subjects touch two surfaces and decide which one they like better. He is now analyzing the data.

Park, in collaboration with biology researcher Eiko Shimojo and other lab members, is also exploring the role of familiarity versus novelty in preference decision making. People often like new things: new cell phones, new movies, new books. But people sometimes prefer the familiar: old friends, childhood photographs, and TV reruns. The researchers' preliminary studies involve images of natural landscapes and geometric shapes, in addition to faces. By incorporating videos into similar kinds of experiments, the scientists also want to uncover the mysteries of channel surfing—how do people decide what they like to watch? Additionally, the researchers are beginning experiments with animals, which would allow for a more detailed and deeper analysis of how the brain regulates the mind and body.

High-tech tools

Recent technological advances have led to a surge of research on the human brain over the last 10 to 15 years, according to Shimojo. "One of the biggest triumphs in the field is that now we're capable of playing with the human brain," he says. Armed with noninvasive techniques, scientists can probe the human brain without having to stick it with electrodes or crack the skull open. Functional magnetic resonance imaging, or fMRI, pinpoints particular parts of the brain that are activated during different tasks and processes. Electroencephalography, or EEG, can measure quick changes in electrical brain activity, and transcranial magnetic stimulation, or TMS, uses rapidly changing magnetic fields to induce electrical activity in the brain, allowing researchers to activate, inhibit, and study specific parts of the brain.

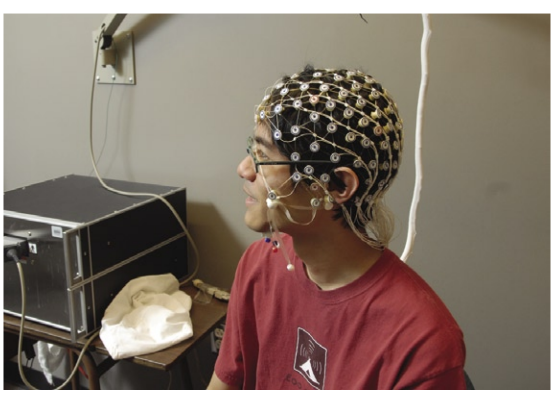
Founded in 2003, Caltech's Brain Imaging Center resides inside the stainless steel and travertine outer walls of the Broad Center for the Biological Sciences. The fMRI machine lives in the basement, where bright yellow signs greet you with ominous warnings of strong magnetic fields. And they are strong magnetic fields indeed—the scanner creates a field strength of three teslas, nearly 50,000 times stronger than Earth's. The scanner, which occupies its own room, consists of a tube just big enough for a person to lie in. The subject lies down and a motor slides the person into the tube, where the magnetic field forces atomic nuclei in the body to align in one direction. Nuclei, which are positively charged, naturally spin on their axes, giving them magnetic poles. As a result, they act like tiny compass needles. The device then shoots radio-frequency waves to knock the nuclei off their alignment. When a nucleus returns to its resting state and realigns with the magnetic field, it emits another radio signal that betrays its location. Oxygen nuclei are susceptible to this phenomenon, and active brain regions use lots of oxygen. However, the technique is only a secondary way of measuring brain activity, and the several-second delay between neural activity and signal detection does not help.

While technology has enabled scientists to observe the brain in action, Shimojo's lab is now trying to manipulate brain activity not with fancy machines, but with thinking.

A postdoc in O'Doherty's lab, Hackjin Kim also collaborates with Shimojo. Along with Bren Professor of Psychology and Neuroscience and professor of biology Ralph Adolphs, Kim, O'Doherty, and Shimojo have used fMRI to analyze the parts of the brain that light up when a person gets a reward. Kim, Shimojo, and O'Doherty recently found that avoiding a bad outcome activates the same brain area as receiving a reward. For example, saving an ice cream cone from falling on the ground and getting one for free may both lead to the same neurological response ("Woohoo!" says the brain). Knowing how the brain responds to rewards is crucial for understanding how people make decisions, since reward—or avoiding something bad—drives many choices.

Most recently, Kim, Adolphs, O'Doherty, and Shimojo applied fMRI to the problem of face preference. Instead of tracking eye movements, they tracked brain activity. By only flashing glimpses of each face, the researchers were able to limit the exposure time for the subjects, isolating the brain responses involved in decision making. For the first time, researchers were able to identify brain activity—in the nucleus accumbens and the orbital frontal cortex—at different stages of the preference decision-making process. They found that the nucleus accumbens, a region at the base of the brain known to be involved with rewards and addiction, was activated earlier. The orbital frontal cortex, which is responsible for emotions and decision making, was activated later in the decision-making process. This suggests that in preference decisions, at least, people use the nucleus accumbens for quick, intuitive decisions or making first impressions, while they use the orbital frontal cortex for more analytical or complex decisions, according to Kim. People also use the orbital frontal cortex to learn and store information relevant for future decisions, he says.

Additionally, the lab is conducting experiments with TMS and EEG. In one TMS experiment, researchers are stimulating the visual cortex to learn how the brain interprets what people see. With its ability to measure rapid changes in brain activity, EEG gives the scientists another tool to study the unconscious processes behind preference decision making. While technology has enabled scientists to observe the brain in action, Shimojo's lab is now trying to manipulate brain activity not with fancy machines, but with thinking.



Taking an EEG. Graduate student Neil Halelamien wears a cap of electrodes that measure electrical brain activity.

Make a quick buck without lifting a finger

The researchers are training people to focus their thoughts and manipulate their own brains. They are using the same techniques that animal trainers use to teach dolphins to jump through hoops. But you don't have to worry about mad scientists brainwashing subjects into becoming slaves. Called neural conditioning, the method is about activating or suppressing specific parts of the brain—not controlling them against the person's will. In fact, the process would not be possible without the subject's cooperation. The ultimate goal, Shimojo says, is to provide scientists with a powerful, noninvasive neurological tool. TMS, for instance, can activate some neurons, but cannot reach into deep places like the orbital frontal cortex, which resides behind the eyes. Right now, scientists do not have a way to noninvasively manipulate different parts of the human brain on demand, Shimojo says. "This neural conditioning technique may be the wild card in this regard," he says.

Graduate student Signe Bray, Shimojo, and O'Doherty have succeeded in conditioning some regions of the brain responsible for movement, such as wiggling fingers and toes. The researchers used fMRI to monitor brain activity and trained subjects with a reward. But instead of a tasty piece of fish, they gave them money. Subjects who successfully activated the relevant brain areas—without actually moving fingers or toes—were awarded a dollar. Scientists had tried other biological conditioning methods before, but those required that subjects have visual feedback; by watching a pulse monitor, for example, a person could slow or speed up heart rate. But in this experiment, subjects shaped their neural activity with only monetary motivation.

"What's exciting is the potential," Bray says. "What we've done is an initial demonstration. But we're really excited about the future applications." Now the researchers want to explore more sophisticated brain functions. For the next step, the researchers are applying the same conditioning techniques to the orbital frontal cortex, which Shimojo calls the core of emotional decision making. In the future, he hopes to conduct the following experiment: the subject would activate or suppress a part of the orbital frontal cortex while choosing the more attractive of two faces. From analyzing what happens, scientists could, in principle, figure out the neural mechanisms involved in the choice. "Of course, it may not be that easy," Shimojo says. "Not all areas of the brain can be conditioned—that's our suspicion now. But it might be possible."

In addition to providing insight into how the brain learns and a powerful research technique for neuroscience, neural conditioning could have numerous clinical applications. Direct manipulation of specific brain areas could help treat depression, people with nerve and spinal injuries, stroke patients, addiction, and pain. But at present, Shimojo still calls it a dream scenario, as he, Bray, and O'Doherty have only just begun this line of research. "No one has done this kind of conditioning experiment with fMRI before," he says.

A researcher inspects brain images taken with the MRI machine.

The brain vs. the mind

As a teenager in Japan, Shimojo would gaze into the sky, lost in thought over what he saw. He knew the sky was just empty air, thinning out as it extended deep into space. But at the same time, he could also interpret the image before his eyes as a smooth, blue surface at a finite distance, a sky he could reach up and touch. Shimojo was fascinated with how perception reflected reality, and how the mind works. "My original motivation—even as a teenager—was to solve the mystery of the mind," he says. But while he was captivated by the philosophy and psychology of the mind, he wanted as complete and rigorous an understanding as possible. "I decided that the religious approach is not satisfactory, and the classical psychology approach, which treats the brain as a black box, and you try not to open it, is also not satisfactory."

His lab brings together two traditionally separate ways of doing neuroscience: treating the brain purely as a biological organ, and studying it in the context of human consciousness and experience. Shimojo distinguishes the brain from the mind; the brain is where complex biochemical reactions take place, while the mind incorporates thought, consciousness, and emotion. The lab tries to investigate the brain without neglecting the mind, and vice versa, he says. "If you think about human minds, it's indeed the interaction between this hidden implicit part of the mind and the conscious part of the mind," he says. "If you understand the relationship between them, then that's the full understanding."

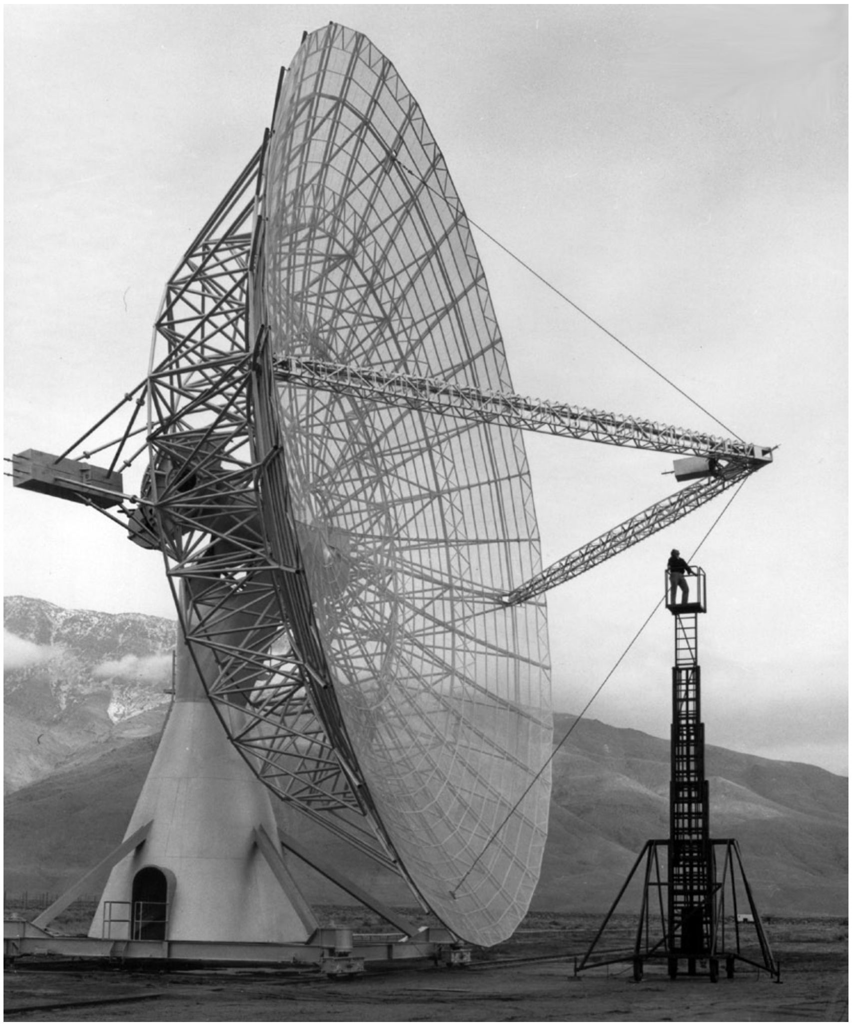
Many neuroscientists were originally interested in questions of the mind, Shimojo says. But to avoid the uncertainties and fuzziness of human thought, they sought more objective research by staying within the confines of the brain's biological mechanics. Studying brain chemistry or the rat's neural system was more cut-and-dried, possibly with more definitive results—even though these studies did not always address questions of the mind. Now, Shimojo says, the field has developed and is finally mature enough for scientists to rigorously answer the challenging questions of the mind. With the lab's diverse work as Exhibit A, research into preference decision making—and the mind in general—has taken off in many directions. "I really feel fortunate because it's such a rich and vivid field," he says.

You might even say the field is hot. □

PICTURE CREDITS: 27, 30, 31 — Bob Paz; 25, 29 — Doug Cummings; 30, 32 — Caltech Brain Imaging Center; 32 — NASA/JSC; 26, 27, 28, 29 — Shimojo lab

A History of OVRO: Part II

By Marshall H. Cohen



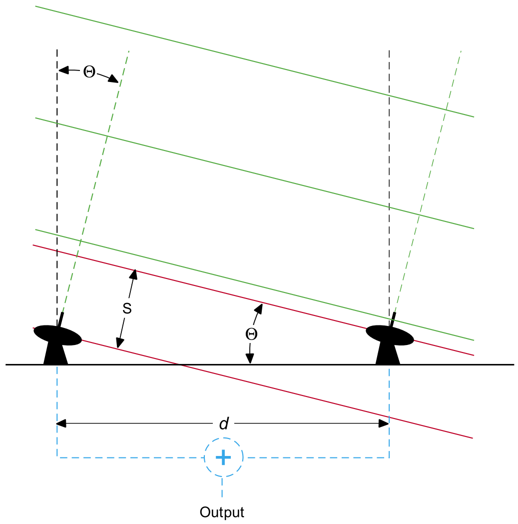
Banner: The 27.4-meter interferometer. The left dish is at the central station, and the other one is at the far end of the east-extending track. The Owens River is in the foreground. Above: Adjusting receivers was not for the vertiginous. This photo was shot before 1964, when the steel mesh of the dishes was upgraded to solid aluminum, and the bipods supporting the focus boxes were replaced with much stiffer quadrupods.

The Caltech radio astronomy program began in the late 1950s with the founding of the Owens Valley Radio Observatory (OVRO). Two prominent Australian radio astronomers, Gordon Stanley and expatriate Englishman John Bolton, found a radio-quiet site near Big Pine, in the Owens Valley 250 miles north of Pasadena, and built an interferometer—two 27.4-meter dish antennas movable to various stations on railroad tracks stretching nearly 500 meters east and north from a central station. At the time, it was one of the largest such systems in the world, unsurpassed for many purposes. OVRO's birth was described in detail in the spring 1994 issue of *E&S*; here I carry the story into the 1970s.

The OVRO Interferometer

By 1960 the pioneer days of radio astronomy were over, and the revolution they had wrought had changed our view of the universe. However, visible-light spectra of the newly discovered radio sources were needed in order to measure their redshifts (a proxy for distance) and determine their compositions; and for this their optical counterparts had to be identified. To do so, their positions in the sky had to be known to within a few seconds of arc, and this requirement was a major driver of OVRO's design—an interferometer's resolution increases with the number of waves separating the two antennas, and OVRO's long baseline and short operating wavelength (30 centimeters) provided the needed precision. The optical spectroscopy was mainly done by Caltech and Carnegie astronomers, using the five-meter Hale Telescope on Palomar Mountain.

OVRO's movable antennas allowed for more than simply fixing the sources' locations. In order to study the physics of the sources, their radio-frequency spectra needed to be analyzed, and their brightness distributions at radio wavelengths



In radio-telescope interferometry the two dishes, separated by a distance *d*, are illuminated at a wavelength λ by a distant source. The signals from the two dishes are added together. As the earth rotates, the angle θ changes, and the combined signal from the two dishes goes through a series of maxima and minima. A rotation of θ by approximately λ/*d* changes the differential path length *s* by one full wavelength, producing one full cycle, or fringe, in the output voltage. Hence λ/*d* is the angular scale, or resolution at which the source can be mapped.

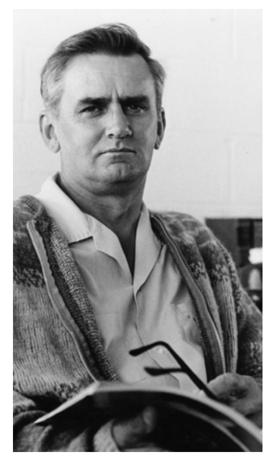
needed to be mapped. In other words, intensity contours, analogous to the elevation contours on topographic maps, had to be plotted. This required a range of angular scales, each of which needed its own spacing between the antennas. Measuring the interferometer's output—the "fringe amplitude"—at that spacing gave information for that scale. By measuring at many spacings a complete picture was built up, in a process called "aperture synthesis." (Technically speaking, the fringes are sine waves that modulate the source's brightness distribution. Each measurement is an integration over this modulation, yielding one component of the Fourier transform of the source. After measurements are made at all spacings, the desired image is found by calculating the inverse transform.)

By 1960 ingenious interferometers had been built in many countries. The one that most closely resembled OVRO's was at Nançay, France. It consisted of two modest, 7.5-meter dishes on tracks 1,480 meters long east-west and 380 north-south, and operated at a wavelength of 21 centimeters. These "Wurzburg" dishes had seen service in German radar during World War II, and were used at almost every European radio observatory for at least two decades afterward. Both interferometers took measurements at many spacings, and the observations were either fit to a model, or the image was estimated using the inverse Fourier transform. Both instruments operated at similar wavelengths, but OVRO's baseline was only a third as long and so it had less angular resolution. But OVRO's dishes had 13 times the collecting area, and its electronics were superior, giving it a much higher sensitivity that often was decisive.

Gordon Stanley was very good at electronics, and he was building the world's best centimeter-wavelength receivers for OVRO.

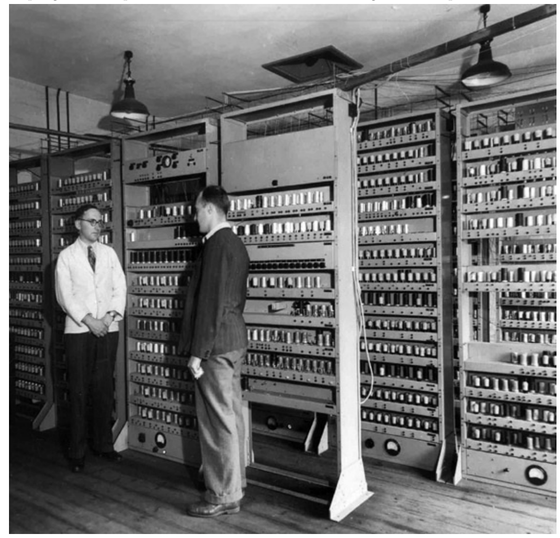
Gordon Stanley was very good at electronics, and he was building the world's best centimeter-wavelength receivers for OVRO. In addition to greater stability, the OVRO "front ends" had an equivalent noise temperature of 300 K versus 700 K at Nançay, giving OVRO an advantage of 7/3 on top of the factor of 13 from the antenna size. The result was that OVRO could study the entire Third Cambridge (England) Catalogue of Radio Sources, whereas Nançay was effectively restricted to the three dozen brightest sources. OVRO was also more flexible, as its receivers were modular and could be changed quickly. By 1963, measurements could be made at five wavelengths ranging from 63 to 10.6 centimeters.

However, the one-centimeter steel mesh that formed the radio dish was inefficient at 10.6 centimeters—generally speaking, $s/\lambda > 20$ for full efficiency, where λ is the wavelength and *s* is the size of the holes. In 1964 the mesh was replaced with solid aluminum, perforated near the rim to reduce the weight and wind resistance. This allowed shorter wavelengths to be used, and observations at three centimeters started in 1967, with an antenna efficiency of 30 percent. (A more typical figure for a paraboloid is 55 percent, but 30 percent is good for a dish operating at 10 times its original design frequency!) Such short wavelengths gave OVRO an advantage over other interferometers because of the higher resolution (the resolution attainable at three centimeters is 10 times that available at 30 centimeters), and because many compact radio sources have an "inverted" spectrum in which their emissions increase with frequency, making them easier to see at shorter wavelengths.



Gordon Stanley became OVRO's acting director when John Bolton returned to Australia in 1961. He became director in 1965 and retired in 1975.

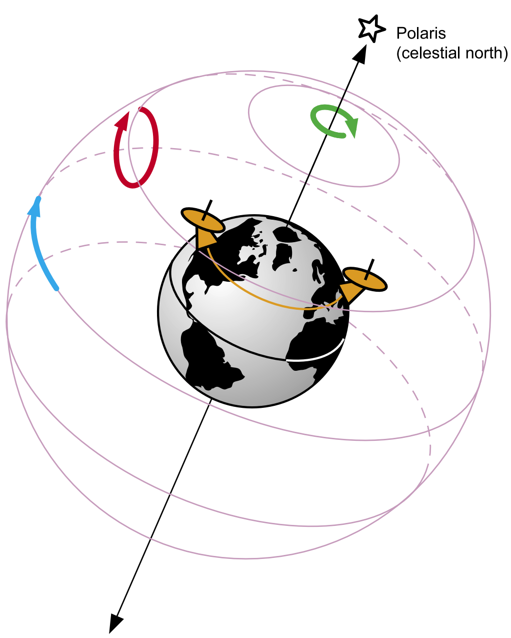
As described above, measurements made at many baselines can be converted into an image of the source. If the source is at the north pole, then east-west baselines alone suffice. As the declination—the astronomical equivalent of latitude—decreases, more north-south baselines must be used. Equatorial sources require diagonal baselines for a complete image restoration. Resolution along the east-west and diagonal baselines was improved by a 192-meter western extension of the baseline over the 1960s and '70s. However,



The Cambridge Mathematical Laboratory built EDSAC (for Electronic Delay and Storage Automatic Calculator), which ran on 3,000 vacuum tubes and debuted by computing the squares of the integers from 1 to 99 on May 6, 1949. It served Cambridge meteorologists, geneticists, and X-ray crystallographers, as well as radio astronomers from 1953 through 1958. Maurice Wilkes, its designer, is at left.

most observations were taken with only one or two baselines, which usually was sufficient to measure positions or flux densities.

Aperture synthesis is nearly impossible to do by hand, although the earliest work at OVRO, with a modest number of baselines, was done that way. In the 1950s radio astronomers at the University of Cambridge had access to EDSAC, the world's first practical stored-program digital computer, and with it they pioneered the techniques needed for aperture synthesis. But by 1960 university computing centers were common, and mechanical calculators and tables of trigonometric (and other) functions were disappearing. Caltech was late in developing a center for digital computing, but in 1962, when the first Fourier analyses from OVRO were published, we used a Burroughs 220 located in the Computing Center in the Spalding Laboratory of Engineering.



When a radio source is at the celestial pole, the east-west baseline (orange) of the interferometer effectively wheels in a circle (green) as the earth turns, giving full two-dimensional information about the source. But as the source moves toward the equator, the baseline's apparent rotation becomes an increasingly flatter ellipse (red), and north-south baselines must be added. When the source is on the celestial equator, the baseline does not rotate at all (blue), and diagonal baselines are required as well.

Science with the Interferometer

The compact extragalactic sources that were so exciting in the '50s were originally thought to be exotic stars, and the key to understanding their peculiar spectra had to wait for a source called 3C 273—the 273rd object in the original Third Cambridge Catalog. In 1962 the 64-meter radio telescope in Parkes, Australia, measured the diffraction pattern produced as the moon passed in front of 3C 273, to get an accurate position. Then in 1963 Caltech associate professor of astronomy Maarten Schmidt realized that its puzzling spectrum, obtained at Palomar, could be explained as ordinary emission lines, mostly of hydrogen, whose wavelengths had been shifted toward the red end of the spectrum by the source's great distance, about two billion light-years. However, 3C 273 had been measured at OVRO earlier, probably in 1961. Grad student Richard Read's (BS '55) 1962 PhD thesis speaks of an identification of 3C 273 with a faint object—in retrospect it seems possible that the correct bright object was simply ignored as a nearby star, and the error box was searched deeper until a suspicious galaxy was found. Alternatively, the measurement may have been in error; but in any event an opportunity was lost. OVRO could have preceded Parkes by a year in providing the position that allowed quasars to be identified.

Besides making accurate position measurements, OVRO also devoted substantial effort to measuring spectra and brightness distributions. As described in the 1994 article, graduate student Alan Moffet (PhD '61), together with postdocs Per Maltby and Tom Mathews, discovered that many extragalactic radio sources consisted of two lobes surrounding a central galaxy. Understanding this so-called "duplicity" has been a major concern of astronomers ever since. The equivalent brightness temperature—that is, the temperature of a black body that would produce the same intensity as the source, at radio wavelengths—of these sources was generally high, a million degrees or more. Synchrotron theory, in which electrons spiral in a magnetic field, was used to explain this radiation. The estimated field strengths usually turned out to be a few microgauss, which is tiny (the surface field on Earth is about half a gauss), but the enormous volumes occupied by these fields implied a huge amount of energy. The origin and evolution of this magnetism is still an important topic.

Synchrotron radiation is polarized, and a powerful new method for measuring polarized brightness distributions was worked out by postdocs Dave Morris, V. "Rad" Radhakrishnan, and George Seielstad (PhD '63, later OVRO assistant director), who used it to estimate the energetics and evolution of many sources through analyses of their magnetic fields. In addition, the variation of polarization with wavelength provided a way to study the electron density and magnetic field of our own galaxy, along the line of sight. Seielstad and Glenn Berge (MS '62, PhD '65) attempted to correlate the galactic magnetic field with the spiral arms of the Milky Way, but their mapping effort was hampered by limited data. Berge's PhD work revealed that clouds of energetic particles exist around Jupiter, analogous to the Van Allen belts around Earth. Confirmed by JPL's Voyager 1 and 2 spacecraft, these belts were an important consideration in designing the Galileo Jupiter orbiter.

Hydrogen is the most abundant element in the universe, and studying the 21-centimeter emission line of neutral atomic hydrogen (HI) was one of OVRO's largest programs. The first studies used a single-channel receiver that had to be sequentially stepped in frequency. Around 1964, a 12-channel receiver was built; this sped up the measurements by a large factor. In a series of papers published in the '60s and early '70s, the distribution, kinematics, and physical state of hydrogen in the Milky Way and in external galaxies was explored. Many people participated in this work: postdocs, students, and visitors. The most significant results were published in 1971–73 by then-postdoc David Rogstad (BS '62, MS '64, PhD '67) and Seth Shostak (PhD '72), whose HI maps of a number of spiral galaxies showed three things. First, the hydrogen motions were roughly consistent with the predictions of spiral density-wave theory. Second, the hydrogen was often in a warped disc, with a twisted hat-brim shape.

But most importantly, the extended disk of hydrogen, beyond the stars, did not rotate according to Kepler's law: $v \sim r^{-1/2}$, where v is the rotational velocity and r is the distance from the galactic nucleus. Instead, the rotation rate decreased more slowly with distance, or even stayed at a constant velocity. This showed that spiral galaxies did not have most of their mass at their centers, in the way that the sun dominates the solar system, even though the vast majority of the stars are near the galaxies' cores. Instead, the galaxies seemed to have unseen mass distributed far beyond the visible stars. The kinematics of spiral galaxies was a hot topic in 1970, with players at all the new large instruments

Below, left: The radio source Cygnus A lies in a galaxy some 600 million light-years away. The radio waves come from electrons propelled at nearly the speed of light in a long, thin jet emanating from the vicinity of the black hole at the core of the galaxy. The electrons end up in the giant radio lobes rendered here in swirls of orange and red. The lobes span 500,000 light-years.
Below, right: Jupiter's radiation belts as mapped by the Cassini spacecraft at three different points in the planet's 10-hour rotation.

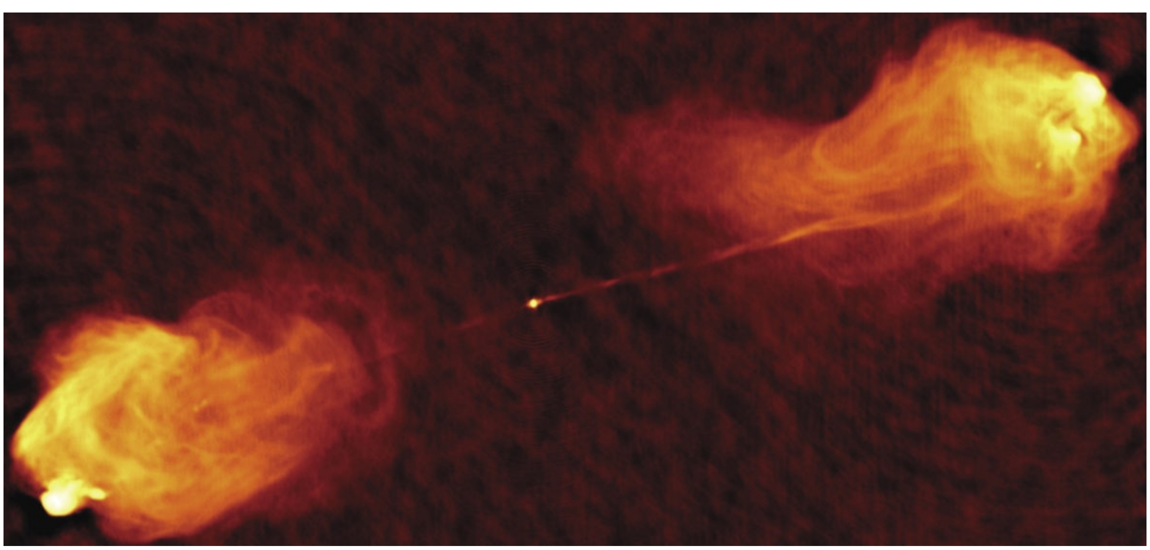


Image courtesy of the National Radio Astronomy Observatory/Associated Universites, Inc./National Science Foundation. Investigators: R. Perley, C. Carilli, and J. Dreher.

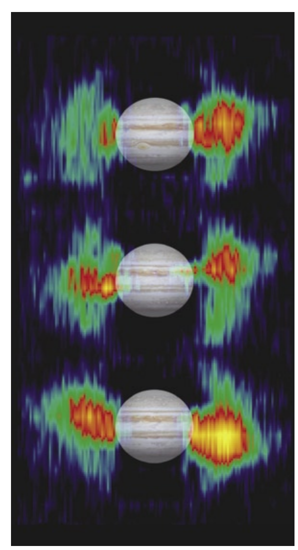


Image courtesy NASA/JPL.

Shostak hard at work at the 24.7-meter interferometer's controls.

around the world. Shostak's PhD thesis contained the first unambiguously flat rotation curve. His and Rogstad's results furthered the idea that dark matter was a basic constituent of the universe, and in a few years it became the received wisdom. The nature of dark matter is still unknown nearly 40 years later.

During the 1970s OVRO's two-dish interferometer was overtaken by larger and faster multi-element interferometers in Holland and England, and larger, more sensitive dishes, especially those in Germany and Puerto Rico. In 1979 the decision was made to devote the interferometer to solar physics, where it continues to serve, mapping the sun daily over the range 1 to 18 GHz with frequency-agile receivers.

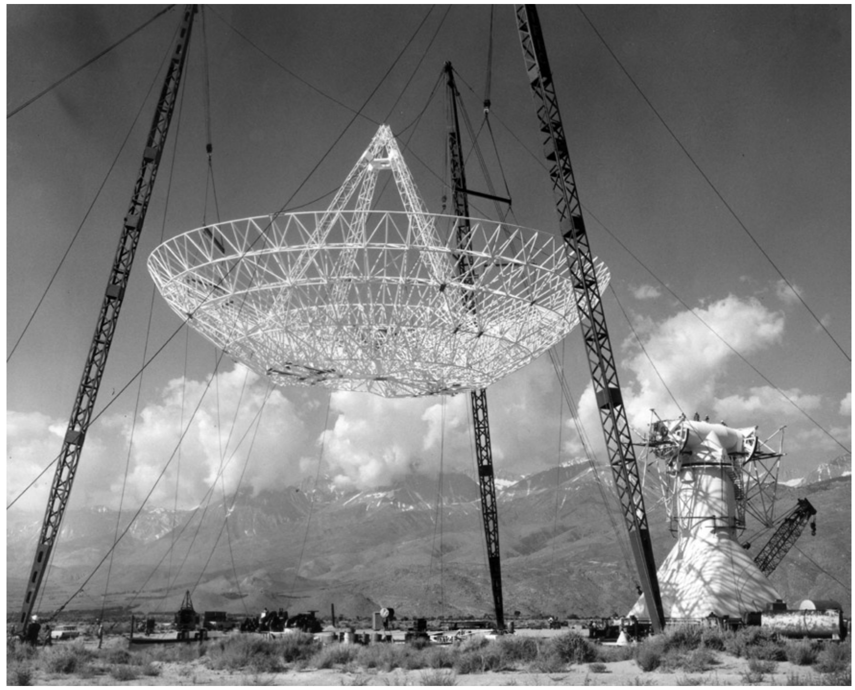
The Owens Valley Array

Stanley and Bolton were already planning to enlarge the interferometer in the late '50s, well before it was finished. This got a boost in 1961, when the National Science Foundation (NSF) issued a report pointing out the need for new large radio telescopes in the United States. In 1962 Caltech, with Stanley as the principal investigator, submitted a proposal to the NSF for a six-element interferometer, incorporating four new 38-meter dishes and extending the track 366 meters to the south. Turning the existing L into a T would add a second, perpendicular set of diagonal baselines, increasing the array's ability to build up detailed images. The NSF funded engineering studies in 1963, and in 1964 funded the construction of a prototype dish.

The first of the National Research Council's Astronomy and Astrophysics Decadal Survey reports, issued in 1964, recommended enlarging OVRO. In response, in 1966 OVRO proposed the Owens Valley Array (OVA), consisting of eight new 40-meter telescopes on tracks three kilometers long east-west, and five kilometers north-south. Westinghouse Electric Corporation was already building a 40-meter dish, using the NSF's 38-meter prototype money, and the budget for the seven remaining antennas, tracks, and electronics was close to 15 million dollars. Bruce Rule (BS '32), Caltech's chief engineer, was responsible for the design of the dish, as he had been for the 27.4-meter telescopes. But by now the National Radio Astronomy Observatory (NRAO) wanted to build a very large array consisting of 35 25-meter dishes, and MIT wanted to build a single huge dish 134 meters in diameter. In response, the NSF established a committee, chaired by Princeton's Robert Dicke. The committee chose OVA, and recommended it be managed as a national facility. (Meanwhile, Caltech and the University of California had submitted a separate proposal for a 100-meter telescope at OVRO; the committee turned this one down.)

In 1969 the NSF asked the Dicke committee to meet again. OVRO's presentations were repeated, with a revised budget of $19 million and an increased emphasis on radio spectroscopy, a subject that had gained importance in the preceding years. The committee's report this time was less explicit, recommending building all three: NRAO's Very Large Array (VLA), as it was now formally known; OVA; and MIT's big dish. That, of course, did not happen. NRAO and OVRO staff discussed the possibility of joining forces and building one array, perhaps in Owens Valley; this also came to naught.

The buck was passed to yet another committee —the National Research Council's second decadal survey committee, established in 1969 with Caltech professor of astrophysics Jesse Greenstein as chair. I was on the radio panel, which was charged with prioritizing the three proposals. It was a difficult job. Most members preferred an array because of its versatility, but which array? In the end we recommended the VLA. It was larger, and would be on a higher site, an important consideration because atmospheric water vapor partially absorbs radio-frequency waves, and water vapor decreases with altitude. Also, some panelists felt that a large national array should be built and managed by a national organization, not one university. The VLA was subsequently built near Socorro, New Mexico, although with only 27 antennas, and the MIT and Caltech projects were dropped . . . but by that time the prototype 40-meter telescope was already operating at OVRO.



The 40-meter radio telescope dish being lifted onto its pedestal in July 1967. Once the dish is high enough, the base, which has already been mounted onto its railroad tracks, will be driven into place underneath it.

The 40-meter Telescope

The 40-meter dish was dedicated on October 18, 1968. It was located on short tracks one kilometer east of the center of the interferometer, and was soon connected to that instrument, giving a three-element interferometer with a maximum east-west spacing of one kilometer, later increased to 1.25 kilometers by adding track to the west. However, adding the full electronics to go from one to three baselines was a substantial undertaking, and the antennas were used pairwise for several years.

OVRO's improved resolution benefited a number of studies, especially of the planets, where obtaining more pixels is always important. But the 40-meter made its mark in single-dish spectroscopy and in very long baseline interferometry, or VLBI, paired with antennas thousands of kilometers away.

Spectroscopy requires measuring the signal strength at closely spaced points along a continuum of frequencies. This is accurately and easily done digitally, and the world's first digital spectrometer, with 100 channels, was built in 1962 by Sander ("Sandy") Weinreb, now at JPL and a faculty associate in electrical engineering at Caltech, as part of his PhD thesis at MIT. Weinreb then built a better one at NRAO, which we later inherited and installed at OVRO in 1970. It rapidly became out-classed as Moore's Law came into play, and in a few years 1,000-channel spectrometers were the norm. These allowed astronomers to analyze increasingly

From left: John Bolton, Alan Moffet, and Bruce Rule at the dedication of the 40-meter dish; photo by Curtis Phillips. Moffet became OVRO's director in 1975 upon Stanley's retirement.

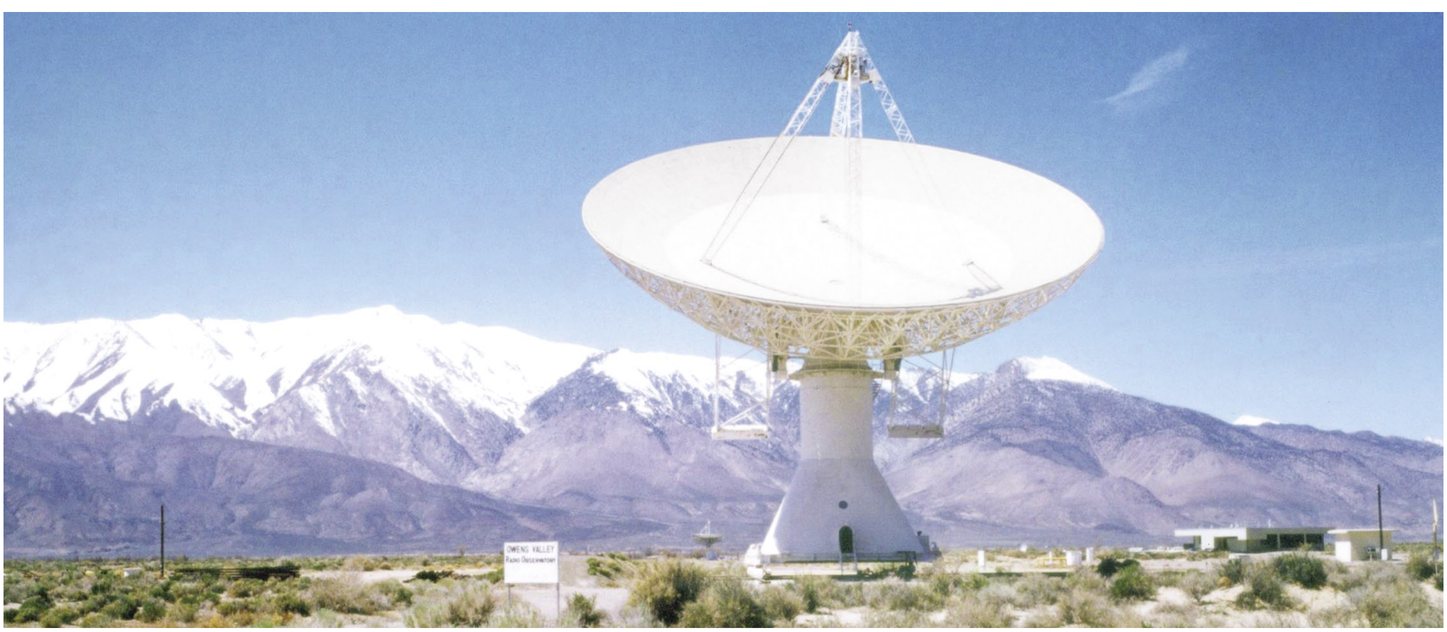
larger chunks of spectrum, or to split the channels among the many baselines of a multi-element interferometer. A modern spectrometer might have millions of channels. But OVRO's first 1,000-channel receiver was not built until around 1975, and then for the millimeter-wavelength array.

In spite of its out-of-date spectrometer, the 40-meter had a major advantage: it was lightly scheduled. Some studies require large blocks of observing time, and two-week programs were common at OVRO. Non-Caltech astronomers who needed time on a large dish were welcomed, and often found it easier to get sufficient time at OVRO than to compete for a shorter window on better-instrumented but much more heavily subscribed telescopes.

Most of the 40-meter's spectroscopy involved interstellar clouds. In the 1960s and '70s these clouds had been found to contain a dozen or so different species of molecules. Each one emitted a characteristic set of lines in the centimeter portion of the spectrum—a fingerprint whose details also reflected the molecule's concentration and the ambient temperature. Furthermore, different molecules are appropriately excited at different densities and pressures, so by looking at, say ammonia versus hydrogen cyanide, you would be seeing different depths within the cloud. This work ranged from "classical" astronomical studies of the composition, mass, and dynamics of clouds and their relation to star-forming regions, to "astrochemistry"—isotope studies and investigations of the gas-phase equilibrium. One long-running series of observations had to do with the maser lines from OH^-, the hydroxyl molecule. These lines are seen in the atmospheres of stars as well as in interstellar clouds, and in the latter case can be extremely strong, allowing clouds to be investigated that would otherwise be too distant.

Very Long Baseline Interferometry (VLBI)

Interferometry requires exacting measurements of small differences in the phase of a signal at two or more widely spaced receivers. When the dishes are directly connected to one another, via wire or radio, the signals are combined in real time and the measurement is fairly straightforward. However, this arrangement limits the separation that can be achieved between the receivers, which in turn limits the system's angular resolution—the longer the baseline, the finer the discrimination. In the mid-1960s, it became possible to tape-record data at widely separated dishes and do the correlation later. Angular resolution improved a hundredfold as the baselines quickly spread across the globe. When I arrived at Caltech in 1968, the 40-meter telescope was being commissioned, and as part of that process we added receivers and terminal equipment for VLBI. In April 1969 we mounted a three-station, six-centimeter experiment using OVRO, the NRAO 43-meter telescope at Green Bank, West Virginia, and the 64-meter dish at Parkes, Australia. The baseline from West Virginia to Australia proved marginally too long to be useful, as there was excessive phase noise caused by the antennas pointing so close to the horizon. OVRO-Parkes, however, worked well. A number of quasars showed strong fringes, indicating that their size was less than about 0.4 milli-arcseconds. Theoretical work had suggested that these sources should be extremely small, and our experimental confirmation was a major early success for VLBI. We also confirmed that the quasars' brightness temperature had to be at least 10^{11} K. This meant that they were very energetic objects, containing clouds of electrons spiraling in a magnetic field at very nearly the speed of light, and giving off synchrotron radiation as explained previously. The



The 40-meter dish gleams against the Sierra Nevada. One of the 24.7-meter dishes is barely visible in the background just to the left of the pedestal. The low building to the right of the pedestal is the Oscar Mayer Control Center.

From left: Cohen, Barry Clark (BS '59, PhD '64) of NRAO, and I.G. Moiseev, director of the Crimean Astrophysical Observatory, stand in front of the 22-meter dish at Simeis near Yalta, on the Black Sea, during the 1971 US-USSR VLBI run. This experiment also used the 64-meter Deep Space Network antenna at JPL's Goldstone station in the Mojave Desert (radio astronomers are allowed to use the dish when it isn't tracking spacecraft), as well as NRAO's 43-meter dish in Green Bank. The photo was taken by Leonid Matveenko of the Space Research Institute, Moscow, a long-time collaborator.

OVRO-Parkes baseline was 1.7×10^8 wavelengths (10,200 kilometers) long, a record that lasted only six months. The current record is 4.2×10^9 wavelengths, between telescopes in Arizona and Spain using a wavelength of two millimeters.

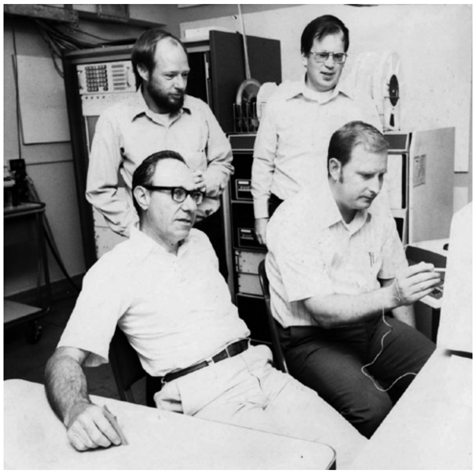
Each VLBI station had to have its own clock, and they had to be synchronized to within a few microseconds. At some stations the Navy's LORAN (LOng RAnge Navigation) signals could be used, but OVRO was too far inland. We generally "transported time" from the Point Mugu Naval Air Station, near Oxnard, or from JPL's Goldstone tracking station, near Barstow. Grad students George Purcell (MS '68, PhD '73) and Dave Shaffer (PhD '74) were usually pressed into service to drive the clock to OVRO, as they had to go to the telescope anyway to keep changing the data tapes. The transfer clock itself was either a very stable quartz-crystal oscillator or a rubidium standard oscillator, which was based on a narrow emission line produced by gaseous rubidium-87 atoms. These gave a stability of about one part in 10^{11}, and were ultimately replaced with a hydrogen maser, which was good to one part in 10^{14}. The maser was expensive and bulky, while the others were relatively cheap and small. The crystal oscillator clock was outfitted like a small suitcase, and in 1971 I took it from Pasadena to the 22-meter telescope in Simeiz, on the Crimean peninsula near Yalta, to synchronize clocks for our second US-USSR VLBI run.

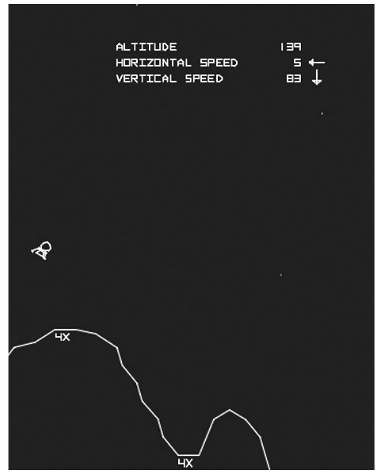
VLBI differs from most astronomy in that you only know if you have data after the tapes are correlated, which in the old days could be weeks or even months after the observations. There is no chance to fix setup problems, because they don't reveal themselves until after the fact.

The clock and I passed through airport security in Los Angeles, London, Moscow, and Simferopol without a hitch, something that might not happen today. As a precaution, I had armed myself with a letter (signed by me) explaining that Professor Marshall Cohen was on an important scientific mission and that it was vital for this particular clock to get to Crimea as rapidly as possible. I don't remember if anyone even looked at it.

The Mark I VLBI system, installed at OVRO in 1969, used half-inch reel-to-reel tapes with seven tracks recording one bit each at 720 kilobits per second, and had a net bandwidth of 330 kHz. A tape lasted about three minutes, and we typically ran tapes 10 minutes apart. They were correlated back at Caltech on an IBM 360-75 mainframe computer; correlation of a pair of three-minute tapes took about 10 minutes. This system was replaced by the Mark II, which obtained a better signal-to-noise ratio by recording a two-megahertz (MHz) band on two-inch tapes that held two hours' worth of data. These tapes had been designed for TV studio use, and were actually the first videotapes. The Mark II required a special hardware correlator, built at NRAO in 1970 or so, that was hard to use—the Ampex tape drives were extraordinarily touchy on playback, a situation compounded by the fact that we could not afford new tapes. We got used ones for free, and they had many dropouts. (We would eventually go to new one-inch RCA videotapes, which we actually purchased, and then to much better and cheaper video cassettes. Recently developed experimental systems simply store the data on removable hard drives.)

VLBI differs from most astronomy in that you only know if you have data after the tapes are correlated, which in the old days could be weeks or even months after the observations. In such a case, there is no chance to fix setup problems, because they don't reveal themselves until after the fact. And, unlike some wayward instruments on spacecraft, problems cannot be rectified with new



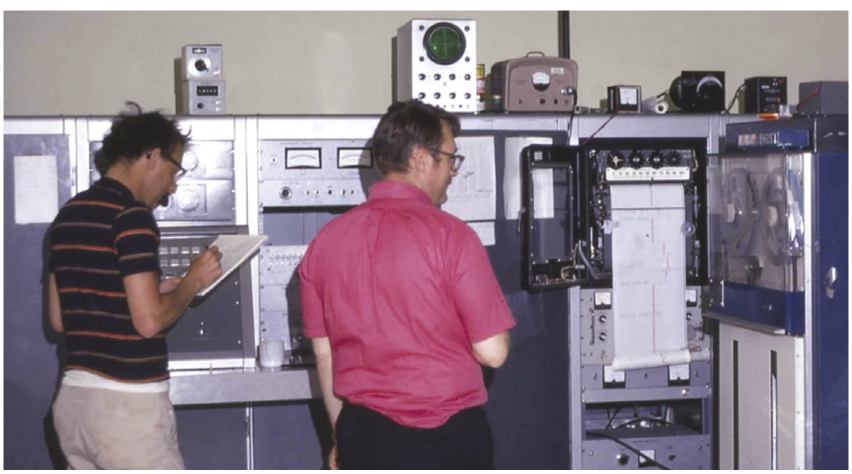


Dave Rogstad (right, seated at console) might be doing interferometry, but the odds are he's playing Lunar Lander—note the probe in his hand in lieu of a joystick. Cohen sits beside him, while Art Neill (with beard) and Marty Ewing look on. Lunar Lander (far right) was a very early computer game, with no hope of success without a good grasp of Newton's Laws. If you landed successfully a McDonald's appeared, and the pilot walked over and got a hamburger.

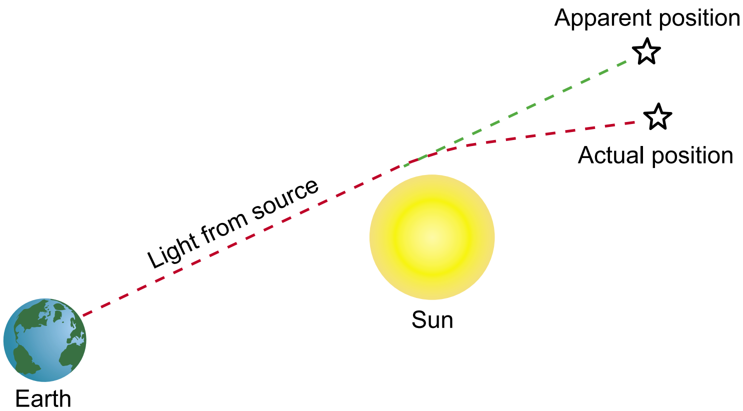
software ex post facto. This problem may become a thing of the past, however, as experimentation using fiber optics to transport the data in real time is now under way.

In the early days of VLBI, the delay between observation and correlation kept growing as more users and telescopes entered the field. (An N-station experiment requires $N \times (N - 1) / 2$ passes through the correlator.) By 1972 the Mark II system at NRAO was clogged, and Art Neill from JPL and I decided to build a new VLBI correlator here in Pasadena. The resulting collaboration lasted for 20 years. We first built a two-station Mark II system, compatible with the one at NRAO, but with the possibility of expansion to five stations. It reached this capability, with the simultaneous correlation of 10 baselines, in 1978. Dave Rogstad, by then at JPL, was the software chief for this project, and former postdoc Martin Ewing, by then on staff at OVRO, was the main hardware designer. (Ewing later moved to Yale; he and Rogstad both retired a few years ago.) Around 1980 JPL started a new effort to build a broadband correlator, and this soon became part of the collaboration. In 1986 this "Block II" system reached its full capacity, with the ability to process four 28-MHz channels, or up to 16 two-MHz channels. The five-station Mark II processor was retired when it became overshadowed by the big Block II system, and was given to the Bologna Istituto di Radioastronomia. It was used there for a number of years.

For about 15 years the correlator lab in the basement of Robinson was a world center for VLBI. At the beginning it was run like the OVRO telescope: a user came in with a stack of tapes and a student and they did nearly everything themselves. (For VLBI observations, of course, you also had to have a friend at the other end of the interferometer.) This became impractical as larger experiments became common, and "friends" were provided at both the telescopes and at the correlator. The organization that grew up to manage VLBI would require a separate story, but we had NSF support for students and postdocs to man the 40-meter, and we had both NSF and JPL support for the correlator. Stephen Unwin, who had been a postdoc in the VLBI group, became the manager of the processor laboratory, and he moved to JPL when the Block II system went there in 1992. The facility was open to all comers—in fact, OVRO or Goldstone did not have to be one of the observing stations. Most of the users were from outside Caltech, with many from Europe and Australia. Depending on the load, we would run two or three shifts a day, sometimes including weekends, with undergraduates providing much of the routine labor. This ended in 1992, when the NSF funding was transferred to NRAO's Very Long Baseline



At left is Ken Kellermann (PhD '63), now a senior scientist at NRAO, where he's been since 1965. At right is Tom Clark of the Goddard Space Flight Center. This photo, shot in May 1969, shows a VLBI experiment being run from within the "tepee"—the pyramidal base—of the 40-meter telescope. Kellermann stands in front of the telescope's manual controls; the computer-control system is out of frame to the right. The half-inch tape recorder is on the right. The strip-chart recorder monitors the system noise and the source's flux density.



When a radio source passes behind the sun, its gravitational field bends the path of the waves. To an observer tracing the waves' path back in a straight line, the source's position will appear to have shifted.

One 24.7-meter dish as shot from the catwalk of the other, circa 1966. The view is from the central station to the west, and the first leg of the western baseline extension is just getting under way.

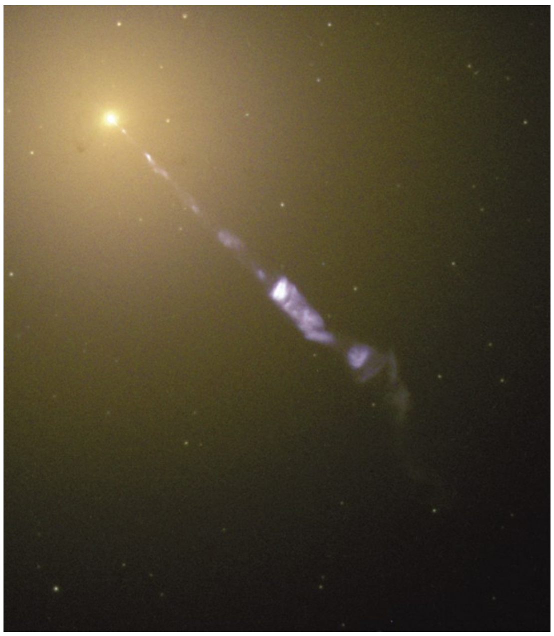
Array (VLBA), a system of 10 dedicated telescopes stretching from Hawaii to the Virgin Islands. This operation works very differently. Everything—telescopes, tapes, and correlator—is run by NRAO. The users have nothing to do with the telescopes or the equipment; they simply apply for observing time, and the results are shipped to them if their proposals are successful.

In 1969, several groups of radio astronomers proposed to use the power of interferometry to measure the gravitational bending of radio waves, when the sun, on its annual path, passed in front of the quasar 3C 279. Predicted by the theory of general relativity, this effect would cause the quasar's apparent position to change—a phenomenon first documented in the solar eclipse of 1919, when teams in Brazil and on the west African island of Principe measured shifts in the Hyades star cluster in a spectacular vindication of Einstein's theory. George Seielstad, with graduate students Dick Sramek (PhD '70) and Kurt Weiler (PhD '70), proposed to use the 40-meter with one of OVRO's 27.4-meter dishes connected in the normal way, so that the position shift would be seen as a small time shift in the interferometer fringes.

Two other groups, one led by Irwin Shapiro of MIT and the other by Tom Clark of the NASA Goddard Space Flight Center (GSFC), independently proposed to use the OVRO 40-meter in VLBI mode with the 37-meter dish at MIT's Haystack Observatory near Westford, Massachusetts. Since both groups proposed to do the same experiment with the same dish at the same time, Gordon Stanley arranged for them to work together. While this particular VLBI run ultimately proved unsuccessful, the collaboration it forged lasted for some 30 years and was very productive.

Seielstad's experiment found a solar limb bending of 1.77 ± 0.2 seconds of arc. The predicted value from general relativity was 1.75 arc seconds. (Meanwhile, Caltech associate professor of planetary science and OVRO staff member Duane Muhleman and postdocs Ron Ekers and Ed Fomalont (PhD '67), using two radio telescopes at Goldstone, measured 1.82 ± 0.2 arc seconds.) These measurements were substantially more accurate than previous optical measurements; currently, VLBI has shown the bending to agree with general relativity to about 0.02 percent.

But most of Caltech's VLBI research involved active galactic nuclei, or AGNs—the quasars or other energetic objects that lie in the hearts of some galaxies. Some of these objects seemed to be moving faster than light, which was explained by the emitting clouds moving at nearly the speed of light toward the observer. If the object's path is close to the line of sight, the apparent time scale shrinks and the transverse motion appears "superluminal." This follows from normal physics, but it made quite a stir when it was first seen



Perhaps the most photogenic AGN belongs to the giant elliptical galaxy M 87, some 50 million light-years from Earth in the constellation Virgo. It is one of the brightest objects in the sky at radio wavelengths, and is known to radio astronomers as Virgo A. This Hubble Space Telescope image combines ultraviolet, visible, and infrared light to show M 87's black-hole-powered jet of electrons. Synchrotron radiation at ultraviolet wavelengths gives the jet its bluish color. The jet shows superluminal motion—a Hubble team led by John Biretta (PhD '86) found apparent velocities of four to six times the speed of light near the black hole, which contains two billion times the mass of our sun.

in 1971, by a Caltech-NRAO-Cornell group and an MIT-Haystack-GSFC group. Actually, superluminal motion had been detected by Al Moffet and collaborators in a series of VLBI experiments in 1969 and 1970, using JPL's Deep Space Network antennas at Goldstone and Canberra, Australia; but an early component of that work did not stand up, and the results did not receive the recognition they deserved. These superluminal motions are still studied at Caltech.

For many years the VLBI program, including the correlator, was a large part of radio astronomy at Caltech. From its inception, many of its investigations were collaborations between Caltech people and astronomers from around the world. In a sense, we were ahead of the times—now, especially with space missions, multi-institution collaborations are the norm. VLBI changed completely in the late 1980s and early '90s, as the VLBA, a national facility, came into operation. The university systems were closed, and the researchers became users, much as particle physicists had in the '60s with the advent of big national (or even international) facilities such as Fermilab and CERN. In 1988, Anthony Readhead, the Rawn Professor of Astronomy, took over running OVRO's VLBI program, and I turned to optical astronomy using the Palomar and then the Keck telescopes. A half dozen years later the Caltech effort wound down as the money dried up, although I still maintain membership in a VLBI collaboration of a dozen members from California to Germany that still concentrates on AGNs.

Interferometry is more complex than using a single dish. It fits the Caltech style of doing difficult things well, and has always been OVRO's strength: first with the twin 27.4-meter dishes; then with the unfunded OVA that yielded the 40-meter dish, which made a three-element interferometer; and then with VLBI. The '80s would bring a millimeter array that, recently relocated to Cedar Flat, has morphed into the 15-element CARMA (Combined Array for Research in Millimeter-wave Astronomy) telescope; and the '90s, the CBI (Cosmic Background Imager), a 13-antenna microwave array in Chile built by Tony Readhead and his group. Caltech students have had a central role in the construction and operation of these instruments, and our graduates and postdocs have provided NRAO much of the expertise needed to build the succession of interferometers that have pushed back our horizons of knowledge over the last four decades. □

Professor of Astronomy, Emeritus, Marshall Cohen is one of the founders of modern radio astronomy. He earned his BEE from Ohio State in 1948, his MS in '49, and his PhD in '52, both in physics. He was a research associate in the Ohio State Antenna Laboratory from 1951 to 1954 and was a professor of electical engineering, then of astronomy at Cornell from 1954 to 1966. He came to Caltech briefly as a visiting associate professor while at Cornell, but wound up at U.C. San Diego as a professor of applied electrophysics (!) for two years. He returned for good as a professor of radio astronomy in 1968. He also served as executive officer for radio astronomy from 1981–85.

This article was edited by Douglas L. Smith.

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Obituaries

John Todd
1911 – 2007

John Todd, an early innovator in the field of numerical analysis, died June 21 at his home in Pasadena, California. He was 96.

Todd was born in Ireland in 1911 and raised near Belfast. He earned his bachelor's degree from Queen's University of Belfast in 1931, and then went to Cambridge University for graduate studies with renowned mathematicians J. E. Littlewood and G. H. Hardy. Littlewood did not approve of doctoral degrees—he didn't have one himself—so Todd never got one and when he eventually came to Caltech, he was one of few professors without a higher degree.

In 1937, when Todd was teaching at King's College in London, he met his intellectual and romantic match, Olga Taussky, a matrix and number theorist. They wed a year later.

When Britain declared war on Germany in 1939, Todd enlisted as a scientific officer with the British Admiralty. He was first assigned to help develop methods for neutralizing the magnetic fields around warships to prevent them from triggering German mines. Then the Germans built mines that were triggered acoustically, and Todd was sent to Portsmouth—a significant naval port and home to the world's oldest dry dock—to help find a way to quiet ships' engines. But he and his boss soon agreed that this was no place for a theoretical mathematician.

Todd convinced the Admiralty to put him in charge of centralizing their science assignments. Back in London, he organized the Admiralty Computing Service, through which he assigned computations to the mathematicians, leaving the physicists free to handle applying them.

Perhaps Todd's most notable wartime contribution was saving a mathematical research institute in Oberwolfach, Germany, at the end of World War II. Todd and his colleagues went to investigate rumors that mathematicians were being held as prisoners of war in Germany's Black Forest. What they found was an old hunting lodge where the University of Freiburg was sheltering its books and records, along with various rescued mathematicians. Todd pulled on his elaborate uniform and claimed the building for the Royal Navy, thus blocking Moroccan troops from seizing the institute and possibly destroying its work. In his Caltech oral history, Todd recalls the incident as "probably the best thing I ever did for mathematics." For his efforts, Todd was dubbed the "Savior of Oberwolfach."

With peace restored in 1945, Todd returned to teaching at King's College, where he developed a specialty in numerical analysis. He was involved in trying to create a national mathematics laboratory but was frustrated by politics, and he and Olga were invited to the United States to help establish the National Applied Mathematical Laboratories at UCLA, part of the National Bureau of Standards. Todd became chief of the computation laboratory when the lab moved to Washington, D.C., while Olga served as a consultant.

Although Caltech had turned down an offer in 1947 by the Bureau of Standards to house a computational lab, by 1956 President DuBridge was ready, and lured Todd and his

Portrait of John Todd and Olga Taussky Todd by Sylvia Posner

wife away from Washington. As a professor in the physics, math and astronomy division at Caltech, Todd developed and taught basic computation courses, including numerical analysis and numerical algebra. Olga Taussky Todd also broke new ground—she was the first woman to receive a formal Caltech teaching appointment, and, in 1971, the first to reach full professorship. She was active in research until her death in 1995.

Todd established and organized a curriculum for instruction, not only in numerical methods, but also as applied to computers. He introduced practical work in Caltech's computing classes. He recalled how the students would wait to do their homework until the last day of the term: "They had to line up in sleeping bags to use the machines." His classes were often dominated by seismologists, some of whom remained at Caltech, including Don Anderson (MS '58, PhD '62), McMillan Professor of Geophysics, Emeritus. Todd was a proponent of standardizing large machines so they wouldn't have to be changed every two years, which he felt created a barrier between the user and the machine.

Todd's theoretical work played a role in the development of early computers, and his courses laid the foundation for many of the basic principles of modern-day mathematics and computer science. He also collaborated with his wife, and together they published many papers in her specialty, linear algebra.

In addition to their scholarly endeavors, Todd and his wife were active donors within the Caltech community. They contributed to the Friends of Caltech Libraries for many years, they endowed the Taussky-Todd Fund to support a Taussky-Todd-Lonergan Professorship in Pure Mathematics, and they funded a distinguished visitors program for mathematics.

A memorial service is planned at Caltech for November; for further information, visit the math department web page at www.math.caltech.edu. □—*EN*

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