California Institute of Technology

# Engineering and Science

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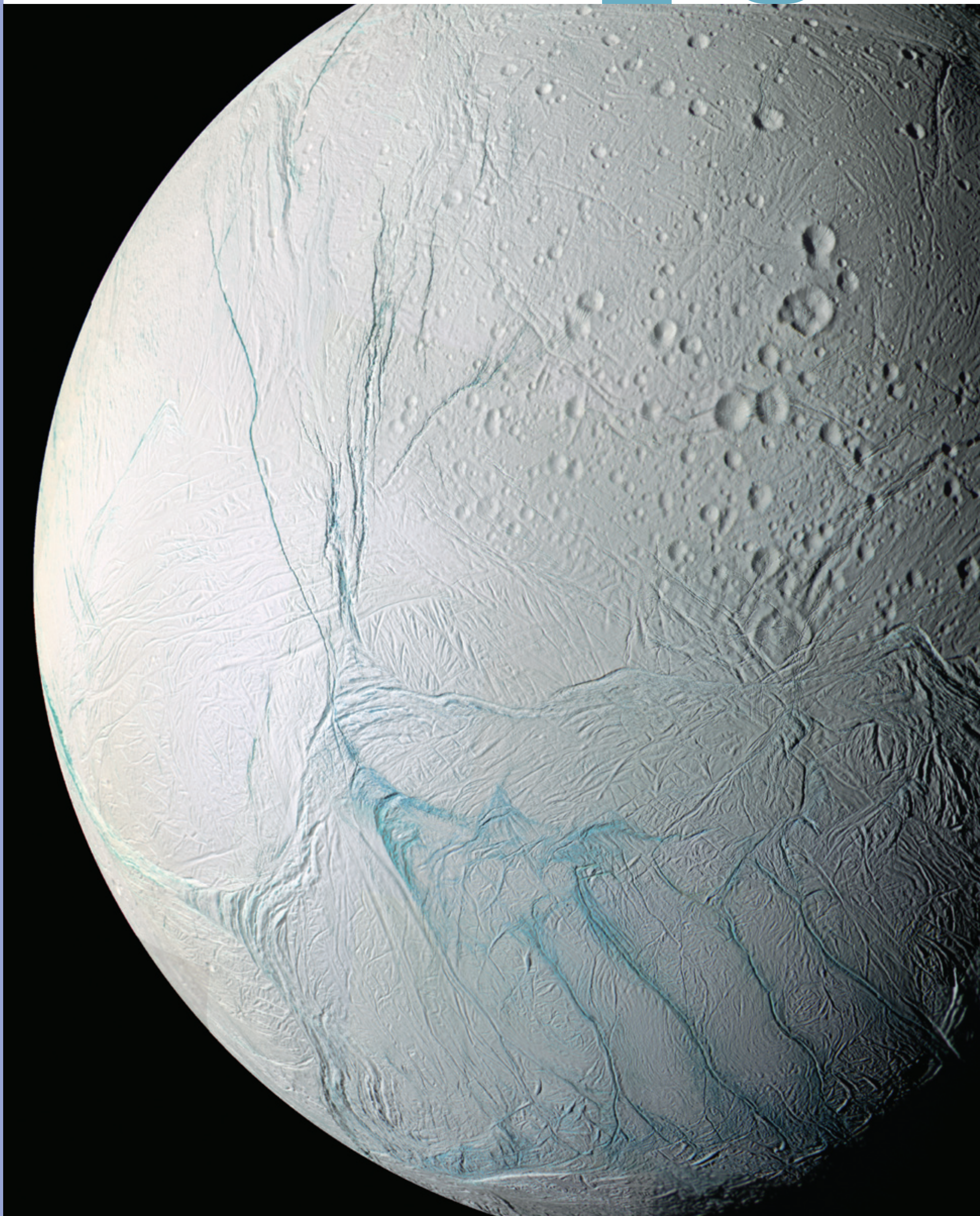

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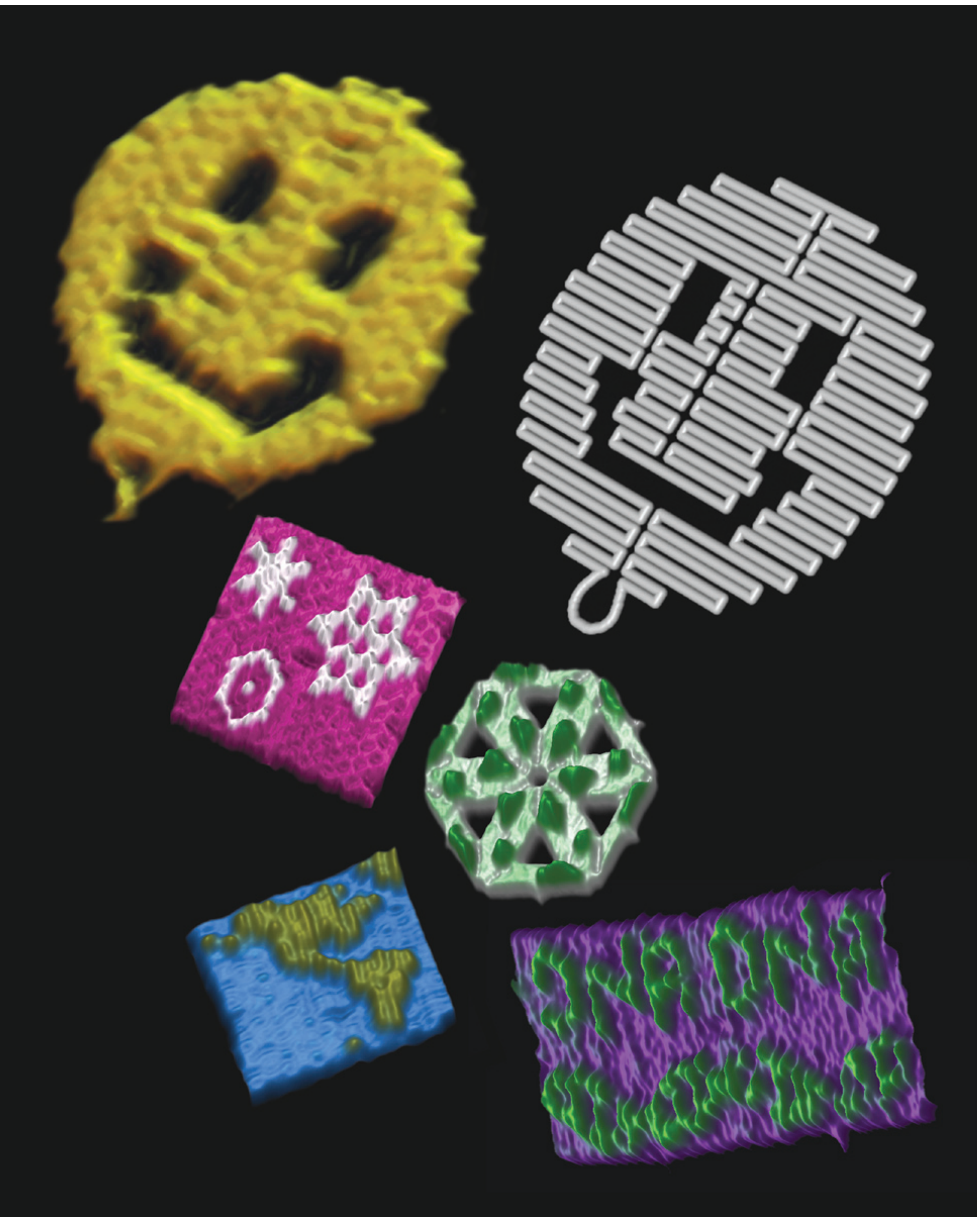
In This Issue



New gummi treats? No, tiny DNA shapes about 100 nanometers across (one nanometer is a millionth of a millimeter) made by Paul Rothemund, senior research fellow in computation and neural systems and computer science, using a technique he's dubbed "DNA origami" whereby a long strand of DNA is looped into the desired shape and "stapled" together with shorter DNA strands. Other small DNAs make the surface patterns and letters. The gray smiley shows the path of the strand of the yellow smiley, which, like the other gummis, is a false-colored atomic force microscope image. The DNAs self-assemble when mixed, and billions of the little shapes precipitate out. As well as giving us maps on a scale of 1:200 trillion, DNA origami could be used to make "nanobreadboards" for attaching molecular components such as proteins, carbon nanotubes, or quantum dots.

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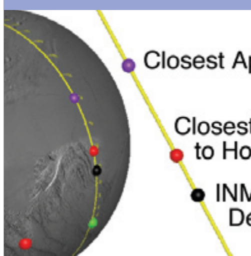

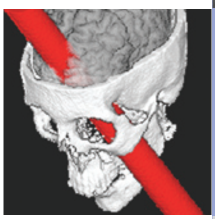



**On the cover: Enceladus, discovered by William Herschel in 1789, is hard to see from Earth because it is obscured by the glare from Saturn's rings. (Its orbit is only four Saturn radii wide, and the bright A ring goes out to beyond two Saturn radii.) And with an orbital period of only 1.37 days, it's hard to keep track of. But it's well worth a close look, as JPL's Cassini spacecraft has discovered—it appears to have liquid water just below the surface of the south pole. For the full story, see page 20.**

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## San Francisco's "Big One" Turns 100


**Two images from the exhibit: San Francisco's city hall was demolished, and a statue of Harvard paleontologist and glaciologist Louis Agassiz got no respect, being tossed from its niche above the arches around the Stanford Quad. Both photographs are from the earthquake commission's report.**

April 18 is the centennial of the great San Francisco earthquake, and the Caltech Archives is marking the occasion with *Documenting Earthquakes: A Virtual Exhibit in Six Parts* (http://archives.caltech.edu/exhibits/earthquake/index.html). Compiled from the Archives' own collections, the six parts will be presented serially over the next six months.

Part One, "Documenting the 1906 Quake," offers an in-depth look at the earthquake's social, political, scientific, and economic repercussions. Included are excerpts from the State Earthquake Investigation Commission's report, comprising two volumes and an atlas, which introduced a significant feature of the local landscape that, up to that time, had largely escaped notice: the "San Andreas Rift." Next, photographs graphically depict the devastation, followed by a sampling of what senior archivist Shelley Erwin calls the "sensationalist literature" chronicling the "San Francisco horror" in which, among other outrages, soldiers compelled even the "fashionably attired to assist in cleaning streets." The section ends with a recap of the post-quake "spin" that transformed "The Great San Francisco Earthquake" into "The Great San Francisco Fire," allaying the fears of residents and tourists alike by turning a calamity of unknown origin that might possibly recur into an everyday disaster.

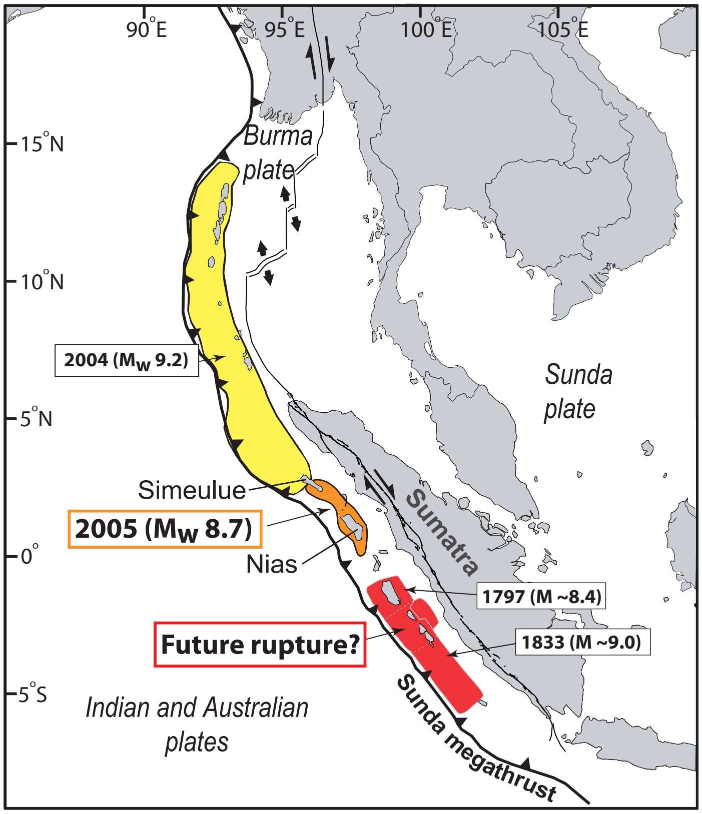
The next two segments will go live later this spring. “The Beginnings of Seismology at Caltech” and “Charles Richter and the Earthquake Magnitude Scale” feature Caltech’s contributions to a budding science.

Components four and five showcase rare earthquake-related books and artwork donated by George Housner (PhD ’41), the Braun Professor of Engineering, Emeritus, and the father of modern earthquake engineering. The Housner collection includes one of the earliest printed books on earthquakes, published in Germany in 1531, and woodblock prints of the 1855 Tokyo earthquake that recount the Japanese folk belief that the wriggling of a giant catfish was responsible.

The final section includes images from Sir William Hamilton’s *Campi Phlegraei*, prepared in the 1770s as a report to the Royal Society in London on earthquakes, volcanoes, and other geologic hazards.

*Documenting Earthquakes* is curated by Erwin, in collaboration with archivists Judith Goodstein, Kevin Knox, and Elisa Piccio, and was designed and produced by Wayne Waller and Leslie Maxfield of Caltech’s Digital Media Services. □—*DW-H*

**The rupture zone of the December 2004 megaquake is shown in yellow and that of the March 2005 quake in orange. The region shown in red appears poised to go next.**




## More Earthquakes to Worry About

Follow-up work on the great Sumatran quake of December 26, 2004, and its March 28, 2005, aftershock (itself the seventh largest quake ever recorded; the main shock comes in at number three) shows that there may be one more big one coming in the near future. Postdoc Richard Briggs and a host of coworkers at Caltech’s Tectonics Observatory, the Indonesian Institute of Sciences, and the Scripps Institution of Oceanography have found that another fault segment farther south is showing the same signs of decades-long subsidence that the region around Nias Island did before it let go last March. Parts of this segment, which runs for some 600 kilometers, last broke in 1797 (estimated magnitude 8.4) and 1833 (estimated magnitude 9.0). Either or both of those zones could slip this time, so it’s going to be a punisher, and could quite possibly set off a tsunami. Says Kerry Sieh, the Sharp Professor of Geology and a coauthor of the paper, “It could happen tomorrow, or it could happen 30 years from now, but I’d be very surprised if it were delayed much beyond that.”

The paper appers in the March 31 issue of *Science*. □—*RT*

## Darkness and Light

Every few days, a telescope peering into the night sky over Mauna Kea, Hawaii, detects an enormous firecracker going off—somewhere deep in space, a star detonates. This cosmic catastrophe is a supernova. “Supernovas are so intense,” says Richard Ellis, Caltech’s Steele Family Professor of Astronomy, “that for many weeks, they outshine the entire galaxy in which they lie.”

There are two types of supernovas: in the first, a single star runs out of fuel, collapses due to gravity, becomes unstable, and explodes; in the second, a parasitic star sucks in material from another star, becomes unstable, and similarly explodes. The latter is the focus of Ellis and the international research team called the Supernova Legacy Survey (SNLS), because this parasitic star—called a white dwarf—can slurp up only so much matter before getting sick. When the dwarf hits the Chandrasekhar limit, 1.4 times the mass of our sun, it bursts to create a supernova that emits the same amount of light every time. Astronomers call such supernovas “standard candles.”

Most galaxies have a supernova eruption every few decades, and when this happens even those in very distant galaxies become visible. In the same way that the loudness and change in pitch of a passing police siren reveal how far away the car is and how fast it is going, a supernova's brightness and the shift in the frequency peaks of its spectrum reveal its distance and velocity. Light from a supernova can take billions of years to reach us, so that our telescopes literally allow us to see history unfold.

In January 2003, when SNLS's camera was ready for use, it was the world's largest digital imager. Appropriately named MegaCam, this 340,000,000-pixel camera can fit four full moons in an image, spanning a full square degree of the sky. The camera is attached to the 3.6-meter Canada-France-Hawaii telescope, and every month it detects about 40 supernovas. Once a supernova of the correct type (about one in four) is detected, larger telescopes like the 10-meter Keck and the 8-meter Gemini are used to verify its type and record its spectrum. Because of this unprecedented combination of a large camera that looks at just one spot in the sky and the extensive time available on many telescopes, postdoc Mark Sullivan of the University of Toronto says that "the data we collect is a huge improvement over previous studies."

To understand why this data is crucial to resolving cosmological mysteries, we need to delve into the history of the field. A century ago, everyone assumed the universe was static. However, in 1916, Albert Einstein was working on his theory of relativity and found that when he applied it to the universe, it predicted that the universe could not exist! A static universe was impossible; it would collapse inward. So a baffled Einstein was forced to add a new number, which he called the "cosmological constant," into his equations to balance gravity.

Einstein decided that the cosmological constant was an embarrassing mistake when, in 1921, Edwin Hubble found that the farther away a galaxy is, the faster it is moving away from us. This finding is now called Hubble's law. The inescapable conclusion was that the universe is not static, but expanding. To return to the police car analogy, this does not just mean that the cars are moving away from us, but that the road is being stretched, dragging the cars along with it.

In 1998, two groups using supernovas to verify Hubble's law found an anomaly: the most distant celestial objects are not just moving away, they are *accelerating* away from us. In other words, the farther away the galaxy is, the faster the rate of expansion of the universe increases—meaning that the universe was expanding more slowly in the distant past. No known force can explain this.

Since then, there has been feverish activity: astronomers trying to obtain precise data, and theorists trying to explain the findings. Many of these theories resurrect the cosmological constant—this time using it to *cause* the acceleration. The most popular postulate is that some kind of mysterious energy is pushing the universe apart. Perhaps reflecting a Hollywood influence, it's been given the peculiar name of "dark energy."

Data from the SNLS survey can sort out this tangle of possibilities by putting constraints on the possible theories. For instance, some theories predict that the dark energy's strength should change with time. However, Ellis says, "SNLS data show, to within 10 percent error, that the acceleration has been constant for half the age of the universe." This puts theories involving a cosmological constant on firmer experimental ground. Ellis expects the error will be reduced by more than half when all the data are in. □—*SV*

## The Brain Trust

The workings of the human brain are being probed by several Caltech research groups through collaborations with various hospitals and medical schools. Some of these studies use Caltech's fMRI facility, in which volunteers literally have their heads examined, allowing the experimenters to see what parts of the brain "light up" when different things are being done. (Functional Magnetic Resonance Imaging, or fMRI, is closely related to the MRI scans you may have had if you've ever torn a ligament.)

If all numbers look alike to you, you may have "dyscalculia," which is the digital equivalent of dyslexia. Caltech postdoc Fulvia Castelli and Daniel Glaser and Brian Butterworth at the Institute of Cognitive Neuroscience at University College London have found that an area of the brain known as the intraparietal sulcus, located toward the top and back of the brain and across both lobes and known to be the seat of numerical knowledge, determines *how many* things are perceived, as opposed to *how much*.

To appreciate the difference, consider the checkout lines at your local Trader Joe's. "How do you really pick the shortest checkout line?" says Castelli. "You could count the number of shoppers in each line, in which case you'd be thinking discretely in terms of numerosity. But if you're a hurried shopper, you probably take a quick glance at each line and pick the one that seems the shortest. In this case you're thinking in terms of continuous quantity."

The two modes of thinking are so similar that it's very hard to isolate the specific networks within the intraparietal sulcus that are responsible for each. So Castelli and her colleagues devised a test in which subjects were shown either a series of flashing blue or green lights or a chessboard with blue and green rectangles and were asked to estimate whether they saw more green or more blue.

The results show that when subjects see separate colors, sequentially or in an in-focus chessboard, the brain automatically counts the objects. But when presented with either a continuous blue and green light or a blurry chessboard, the brain instead estimates *how much* blue and green is visible.

The article was published in the March 13 issue of the *Proceedings of the National Academy of Sciences*.

Another fMRI study by researchers at Caltech and the University of Iowa College of Medicine explains why you might have second thoughts when ordering a strange-sounding dish at an exotic restaurant. This fear of getting fricasseed eye of newt—or something even worse—comes from certain neurons saying that the reward potential for this risk is unknown.

Colin Camerer, the Axline Professor of Business Economics, Ralph Adolphs, the Bren Professor of Psychology and Neuroscience, grad students Ming Hsu and Meghana Bhatt, and Daniel

Tranel of the University of Iowa College of Medicine ran a series of betting experiments on Caltech student volunteers and patients with specific types of brain damage at the University of Iowa.

The results show that the brain behaves differently when there is a degree of ambiguity to the risk. In simple wagers, where the chances of getting a payoff are clearly known, the dorsal striatum tends to light up. But in a nearly identical game in which the chances of winning are unknown, the more emotional parts of the brain known as the amygdala and orbitofrontal cortex (OFC) are involved.

According to Camerer, "The amygdala has been hypothesized as a generalized vigilance module in the brain. We know, for example, that anyone with damage to the amygdala cannot pick up certain facial cues that normally allow humans to know whether they should trust someone else." Problems with the amygdala are also known to be associated with autism, a brain disorder that causes sufferers to have trouble recognizing emotions in other people's faces. (See page 13.) And the OFC is associated with the integration of emotional and cognitive input. So the two regions presumably work together in facing the unknown—the amygdala sends a "caution" message that the OFC processes.

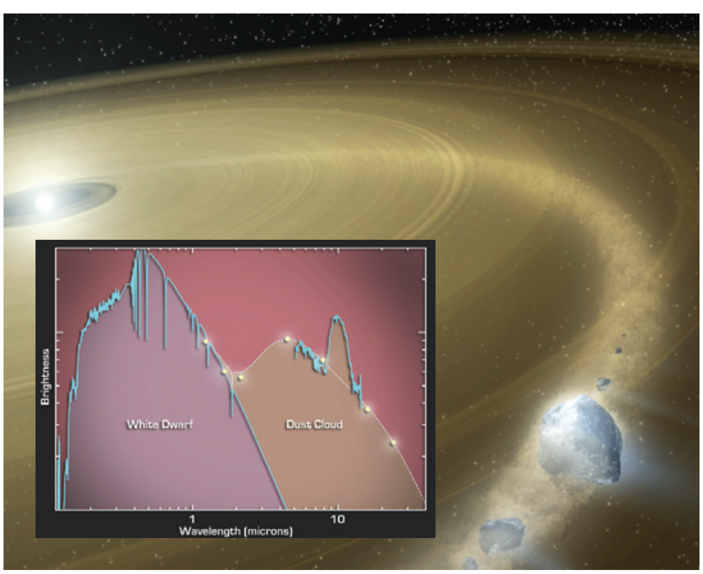
In the "risk" games, subjects chose a card that could be either red or blue. Red cards paid cash, blue cards paid nothing, and the subjects knew that the chance of drawing a red card from the 20-card deck was 50 percent. In the "ambiguity" games, subjects were told that the deck contained 20 cards, but not how many were red or blue. In either case, subjects made a series of 24 choices, with different sums of money at risk and the option of drawing different numbers of cards.

Caltech students drew more cards in the risk game than in the ambiguity game, because people dislike betting when they do not know the odds. But the medical school patients, who had lesions to the OFC, played entirely differently. On average, they were much more tolerant of risk and ambiguity. Caltech students also showed more intense activity in the amygdala and OFC when the chance of winning was ambiguous. (The Iowa patients were not scanned.)

On a societal level, Camerer says that fear of the economic unknown creates a strong preference for the familiar. Thus investors often hold too many stocks they are familiar with, for example, and do not diversify sufficiently. A sort of opposite response may be driving entrepreneurs, who often thrive under uncertainty. "It could be that aversion to ambiguity is like a primitive freezing response that we've had for millions of years," he says. "In this case, it would be an economic freezing response."

The study appeared in the December 9 issue of *Science*.

And studies of epileptic patients awaiting brain surgery have located single neurons that help recognize whether a stimulus is brand-new or has been seen just once before. The patients, who suffer from drug-resistant epileptic seizures, have had electrodes implanted in their medial temporal lobes. Inserting small additional wires inside these electrodes allows researchers to observe the




**Billions of years from now, our dying sun will become a red giant. In its final throes, it will engulf Earth before shrinking to a white dwarf. Life on Mars won't be much fun either, but if it's any consolation, the outer gas giants and the comets should survive. Now the Spitzer Space Telescope has found the first traces of such a comet in a ring of dust around a white dwarf named G29-38. It's hypothesized that the comet strayed too close to G29-38 and was ripped apart, as shown in the rendering—the actual data (inset) shows the excess infrared emissions that betray the dust cloud; the 10-micron peak is the signature of silicate grains like those seen in comet Hale-Bopp. The telescope was built by Lockheed Martin and is managed by JPL; the Spitzer Science Center, which programs the observations and processes the data, is located on the Caltech campus.**

firing of individual brain cells. These cells are located in the amygdala and the hippocampus, both of which are known to be important for learning and memory.

Says grad student Ueli Rutishauser, this "shows that single-trial learning is observable at the single-cell level. We've suspected it for a long time, but it has proven difficult to conduct these experiments with laboratory animals because you can't ask the animal whether it has seen something only once—500 times, yes, but not once." Rutishauser is in Caltech's computation and neural systems program, working with Erin Schuman, professor of biology and an investigator with the Howard Hughes Medical Institute.

The six patients were shown 12 different visual images. Then, 30 minutes or 24 hours later, each subject was shown some of the same images plus new ones and asked whether each image was new or old. The subjects correctly recognized nearly 90 percent of the images they had already seen. Meanwhile, certain neurons increased their firing rate only if the image was being seen for the first time and certain others only if it was the second time, but neither fired for both.

The second type, the "familiarity detectors," went off even when the subject mistakenly reported that the stimulus was new. This could account for subconscious recollections—"even if the patients think they haven't seen the stimulus, their neurons still indicate that they have," Rutishauser says. "These neurons seem to have better memories than we do."

The third author of the paper, which ran in the March 16 issue of the journal *Neuron*, is Adam Mamelak, a neurosurgeon at the Huntington Memorial Hospital and the Maxine Dunitz Neurosurgical Institute at Cedars-Sinai Medical Center. ☐—*RT*

## WE'VE BEEN PUNKED!

**Left: The Fleming cannon, adorned with an MIT class ring, sits in front of Building 54, which last spring was "painted" with a laser that spelled out CALTECH.**
**Above: The "brass rat."**

The Fleming cannon, displaced from its usual spot on Caltech's Olive Walk by the rehabbing of the South Houses, vanished altogether on the morning of March 28. On April 6, pranksters from That Other Institute of Technology revealed that it had been relocated from sunny, palmy Pasadena to the gritty urban confines of Cambridge.

The stunt, a year in the planning, was in retaliation for a series of pranks at MIT's pre-frosh weekend last spring that culminated in the distribution of hundreds of shrink-wrapped t-shirts that read "MIT" on the front, and when unfolded, "Because not everyone can go to Caltech" on the back.

The well-prepared perps struck around 5:00 in the morning, loading the cannon on a flatbed trailer pulled by a pickup truck bearing a construction company's logo. When intercepted by campus security near the 210 freeway, they produced bogus work orders supporting their cover story that they were moving the cannon to a parking lot across campus so that a proper concrete slab could be poured at its temporary home. They even had a map, with the route to the parking lot marked with a highlighter, and explained that they had gotten lost. Security obligingly led them to their putative destination, but once the coast was clear the cannon was on the road again.

But the pranksters' crowning touch was the class ring, known in MIT parlance as a "brass rat," machined for the cannon's barrel at the cost of some 1,000 man-hours.

Suspicion was originally directed at Harvey Mudd College. Besides being a more plausible 25 miles east of Caltech, Mudders stole the cannon 20 years ago in a very similar manner—right down to the fake work orders.

The cannon is on its way back home at this writing, although the denizens of Fleming House who retrieved it left behind a miniature version under glass. Says Caltech security chief Gregg Henderson, who takes these things in stride, "Ditch Day is tomorrow, and we're going to need it." ☐—*DS*

# The Dawn of the Computer Age

by Irving S. Reed

Northrop's Snark, armed with a four-megaton thermonuclear warhead, was in production from 1959 to 1961, when the Atlas intercontinental ballistic missile made it obsolete.

More than a half century ago, I was lucky enough to witness perhaps the fastest mathematical mind of the 20th century going head to head with one of the earliest digital computers—a machine that I had helped develop. Like the epic contest between John Henry and the steam drill, the event symbolized the changes of the coming era.

My part in the story began when I was discharged from the Navy after World War II and returned to Caltech—where I had received a BS in mathematics in 1944—to attend graduate school. My wife and I lived in Caltech's grad-student housing in Temple City, and money was tight, forcing us to economize wherever possible. To that end, I usually biked the four and a half miles to the Caltech campus, where as a teaching assistant I taught freshman math. I also graded graduate students' papers on advanced mathematical analysis.

In the spring of 1947, I began to look in earnest for a better-paying summer job. Eric Ackerlind, an amiable, heavyset electrical engineer in charge of what was later to become the Northrop computer group, hired me to work on the company's Project MX-775, the Snark. This was what would now be called a cruise missile—a pilotless subsonic jet airplane designed to fly itself 5,000 miles and deliver a warhead inside a circle 200 yards in diameter. I was hired to help design the navigation system.

The woes of high-tech workers toiling in tiny cubicles have now been the subject of books, movies, and comic strips. At the risk of sounding like the person who claims he walked 10 miles uphill to school—both ways!—I say, at least the present-day personnel have cubicles. On my first day at Northrop, I beheld a large rectangular room, approximately 100 feet by 50 feet, filled with a sea of aircraft draftsmen, row upon row upon row, all working away at their drafting tables. Dr. Ackerlind sat in one corner of the room like a schoolteacher.

Management later moved the Snark navigation group to another room, not quite as enormous as the first, but still without partitions. Among my new colleagues was Floyd Steele [MS ’41], with whom I would work intimately in coming years. Others included George Fenn [BS ’45, MS ’46], Chester Stone [BS ’45], and Herman Kahn [MS ’47], who later made a name for himself as a physicist at the RAND Corporation before emerging as a world-famous expert on thermonuclear warfare. (He was rumored to have been one of the models for the title character in the film *Dr. Strangelove*.)

The guidance problem was difficult. The Snark had to fly for hours at an elevation of 30,000 to 50,000 feet. It was not just a matter of installing a simple autopilot and entering a compass heading; this is what the Germans had done with their notoriously inaccurate V-1.

The initial thought was that the Snark would find its way by celestial navigation: star trackers would lock onto two or three stars, and by constantly calculating the azimuth and elevation of those stars, a more sophisticated autopilot (the Greek word for “helmsman” is *kybernetes*, the source of the word “cybernetics”) would determine the missile’s position and orientation and make the steering adjustments needed to stay on course. But upon analyzing the problem, we decided that instead of stargazing, inertial guidance—which required continuously solving a set of differential equations—should to be used to control the servos that guided the missile.

We were vaguely aware that on the East Coast, John Mauchly and J. A. Presper “Pres” Eckert Jr. were building an electronic computing device named ENIAC—but it weighed 30 tons, took up 1,800 square feet of floor space, and could not possibly go airborne.

It would not be easy to create a machine that could solve those equations in real time. We were vaguely aware that on the East Coast, John Mauchly and J. A. Presper “Pres” Eckert Jr. were building an electronic computing device named ENIAC—but it weighed 30 tons, took up 1,800 square feet of floor space, and could not possibly go airborne.

Steele, who worked full-time on the project, instead took his cues from the mechanical differential analyzers that had been developed in the 1930s by Vannevar Bush at MIT, based on 19th-century work by William Thomson, the first Baron Kelvin. These machines used wheels, gears, and cams to create a mechanical analogue of the equations. (A drafting compass can be thought of as a simple analog computer, programmed to solve the equation that describes a circle of a given radius.) The famous Norden bombsight used in World War II was a small, mechanical, very clever Kelvin-inspired differential analyzer.

Steele had a brilliantly simple idea. He would model the actions of the gears and cogs in the mechanism with what he called a DIgital Differential Analyzer, or DIDA. The linkages between the moving parts would be encoded in the arrangement of the wires between digital integrators—assemblies of vacuum tubes that added ones and zeroes.

But it was not clear that DIDA’s mathematical representation was in fact a full and accurate statement of the problem—that is, whether its digital shorthand faithfully modeled the differential equations it was designed to solve. I was given the assignment of proving that it did. This was more than a summer project, so when classes resumed, I left Northrop but remained on the payroll as a consultant.

My approach to the problem was heavily influenced by another, quite different, line of “research.” At that time, Chester Stone and I and another classmate, Leonard Abrams [BS ’44], were attempting to turn our mathematical skills into tangible financial rewards. Leonard was fascinated with probability theory—specifically, he wanted to find the probability that a given horse in a race would finish first. We used a year’s worth of the *Racing Form* and a model we developed based on assigning a Gaussian probability distribution to the speeds of each horse in different races.

We performed the intensive calculations by hand, using mechanical calculators, tables, and slide rules. The best solution required running all the horses in the race simultaneously, which was totally out of reach of our computational abilities. But Leonard and I found a simplified method, where we imagined running each horse against what we called a “standard superhorse” that we constructed from the *Racing Form* records.

Then Leonard, sometimes with Chester and me, took his slide rule and notes to the local tracks—Santa Anita or Hollywood Park—and watched the tote board. He’d multiply our calculated probability of winning (say, 0.1) by the payoff shown on the board for a one-dollar bet (which might be $5.00), and when the product was more than a dollar, he’d bet. And he won—not spectacularly, but consistently. Alas, none of us had enough capital to take advantage of the small margin the system gave us, and Leonard failed to convince well-to-do friends to invest in a racetrack system—even though this one was sound and genuinely worked.

But my immersion in probability study paid off: instead of a hard proof that DIDA produced a completely accurate representation of a differential analyzer, I found a soft one that showed that DIDA could be trusted to find the correct answer to within a specified margin of error.

My rising enthusiasm for the possibilities of this electronic digital computer dovetailed neatly with a mathematical logic course I had just completed, taught by my hero and mentor, Eric Temple Bell. I had read Bell’s *Men of Mathematics* as a 15-year-old in Fairbanks, Alaska. He had kindly replied to my fan letter, recommending the books he thought I needed to continue my studies, and was in large part responsible for my coming to Caltech.

Bell was tweedy, Scottish, very professorial, and seldom without a large unlit cigar. He lived, with a housekeeper, across the street from Caltech in a modest home that was overgrown with bamboo and weeds, much to the dismay of his house-proud neighbors. He seemed to find time for everything but gardening, including writing science fiction—under the pen name of John Taine—in his gazebo.

As I worked on the DIDA problem, Bell's course and my shipboard experience with radar led me to think about how configurations of switches and relays could represent mathematical logic. Conversations with grad student John Harris [BS '48, MS '49 and '50], who, like me, had spent the war working with electronics (Harris had been in the Signal Corps), led me to the idea of hooking two switches together in series to represent an AND statement, and two switches in parallel to represent an OR statement. I also had the idea of utilizing "gang switches"—switches and relays with several contacts—to simulate *N*-valued logic.

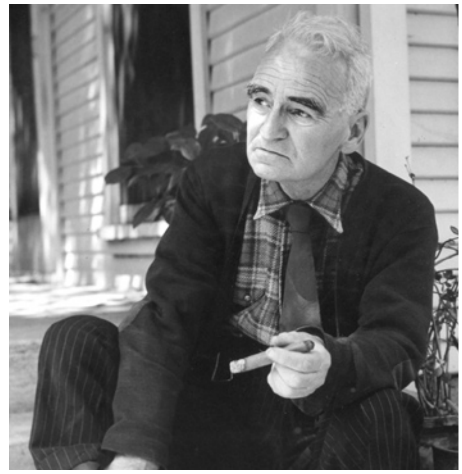
It was a eureka moment for me—a sudden rush of insight: a whole world to open up. Like Archimedes rushing from his bathtub, I raced to Bell's office, confident that I had found a truly original application of mathematical logic.

"I could do a dissertation on logic," I told him, "by making electro-mechanical devices or possibly even electronic computing devices, which would be, in effect, logic machines." I anxiously awaited his affirmation.

"That's a great idea," he said. "But you've been preceded by almost a decade."

He then went on to tell me about an obscure paper, "A Symbolic Analysis of Relay and Switching Circuits," published in the *Transactions of the American Institute of Electrical Engineers* in 1938 by a then-unknown researcher named Claude Shannon, who had been working under Bush at MIT. (The paper was actually a version of Shannon's master's thesis, written in 1937.) Today, Shannon is recognized as one of the seminal mathematical thinkers of the 20th century and the founder of the science of information theory—its premier prize, the Shannon Award (which I much later was privileged to receive), was established in his honor. But at the time he had not yet published "A Mathematical Theory of Communication," and at Caltech he was not a household word. Bell knew of him from a presentation a student had made in his class three years before.

I raced to the library to read the paper, and digested it carefully. I at once recognized its power as a guide for digital computer design. While I was chagrined that someone else had discovered the existence of this exciting new trail, I nonetheless realized that an enormous amount of practical work had to be done for anyone to actually use it. I was in a perfect position to help make this happen.



**Professor of Mathematics Eric Temple Bell in a 1953 photograph.**

Shannon's paper had been written when the switches and relays to embody his circuits were slow and primitive. But World War II and a decade of intensive, forced-draft research had brought a revolution in electronic hardware. It was now far more possible to actually build a machine based on his ideas, and my Navy experience with practical electronics gave me the requisite technical background.

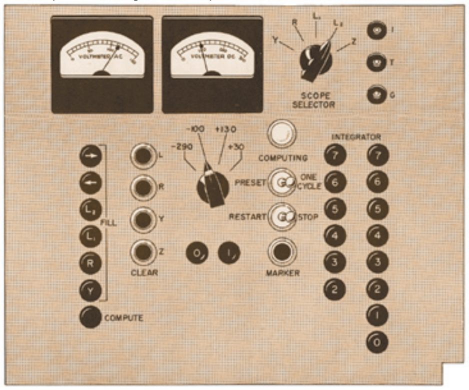
I could hardly wait to share Shannon's paper with Steele. Excitedly, I told him it offered a clear, well-developed intellectual framework that could be applied to the Snark guidance problem. Steele took the information and diligently pursued it. He quickly found that others had already set out on a similar trail, notably the researchers at the Harvard Computation Laboratory under Howard Aiken, whom he contacted to gather more information on electronic digital logic.

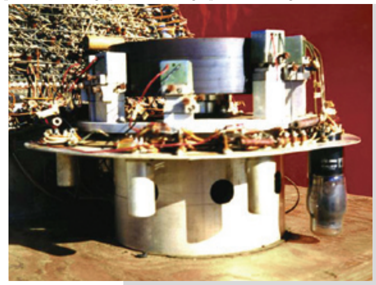
I joined Northrop as a full-time employee after finishing my PhD in the spring of 1949, and Steele and I plunged into development of the digital computer. Ackerlind's group was now working on a new and much more powerful type of DIDA: the MADDIDA (MAgnetic Drum DIgital Differential Analyzer).

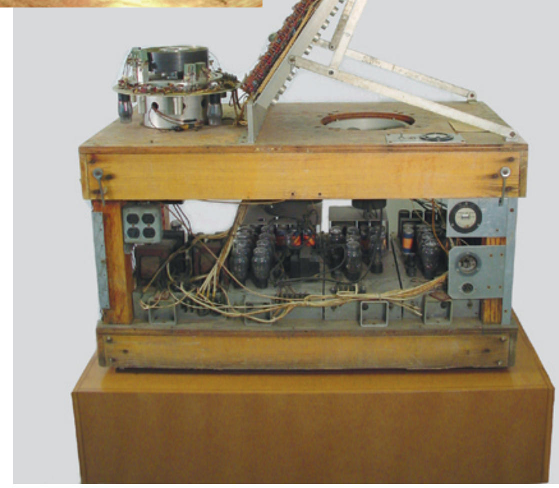
We made outstanding progress on the design, building, and testing of MADDIDA. Thus we were quite shocked that summer when Northrop management revealed to us that they had let a contract to another company to design and build a ground-based, general-purpose guidance computer for the Snark. Because of this, we were told, MADDIDA was no longer a major priority.

Our competition was a company founded by ENIAC's Eckert and Mauchly, and the agreement to build what would become known as BINAC had been forged in December 1947, when Robert Rawlins, our former project manager, had contracted with them for an *airborne* digital computer. I've since learned that Eckert and Mauchly, strapped

Courtesy of the Computer History Museum, Mountain View, CA, www.computerhistory.org; photos by Dag Spicer, drawing from a Northrop brochure.





**The original MADDIDA (far right) had 22 integrators that performed the actual mathematics. Each integrator had two registers, called Y and R, to hold the two numbers to be added or subtracted. At MADDIDA's heart was a primitive hard drive (inset). About the size of a brake drum, it had only four tracks around its circumference. One track was the clock track, which was permanently scribed on the drum. The drum rotated past the read/write heads at a constant speed, with the clock track identifying what part of the drum was being read—the addresses of the bits on the other tracks, in other words. A "circulating register" track temporarily stored the contents of the various integrators (and the device numbers of said integrators) while the computation was being performed on them. The final two tracks—one each for the Y and R registers—contained the machine's program. These tracks specified at each step which integrators should be read into the circulating register and to which integrators the circulating track's outputs should be sent. So, for example, the circulating track might be holding the contents of integrator 5 and might be instructed to send the results to the Y register of integrator 19 and the R register of integrator 6. The output would be read off an oscilloscope (note the "scope selector" switch on the control panel, above). MADDIDA was programmed—in machine language, of course!—by pushing the "0" and "1" buttons in the middle of the panel.**

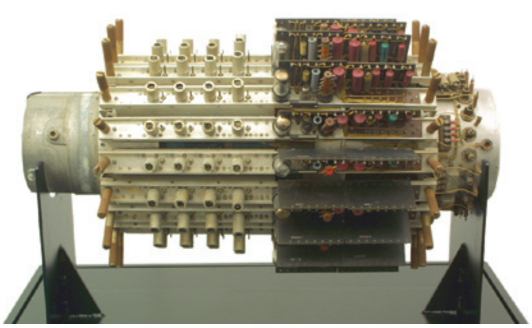
for cash, had undertaken to build BINAC for an absurdly low figure—$100,000. Furthermore, in the course of negotiations, a requirement that the resulting system actually be installable in the Snark (or any other aircraft!) was essentially dropped. (These and many other details can be found in *ENIAC: The Triumphs and Tragedies of the World's First Computer*, by Scott McCartney, published by Walker and Company in 1999.)

Given how far along we were, our group was agonized by the news. Team member Richard Sprague would later write of us "swallowing our resentment" and agreeing to serve as liaison engineers with the Eckert and Mauchly Computer Company, whose executives worked with us and tutored us in ways that some members of our team found condescending.

The pill was bitter, but it came with a sweetening of additional information: we got a chance to look at BINAC and learn what another team faced with a similar problem had done. Two separate units of Northrop employees were flown to Philadelphia to watch the E&M staff conduct acceptance demonstrations of the new machine during a very hot August.

Of the E&M staff, BINAC's logic designer Bob Shaw especially stands out in my memory. A nearly blind, severely handicapped albino, he may have needed assistance drawing the computer's intricately detailed circuit diagrams, but he was gifted with a phenomenal recall. To compensate for his poor eyesight, he had simply memorized the diagrams!

I tried consciously to keep an open mind, and perhaps because of this, I was more impressed than my colleagues. BINAC proved to be a fine, though quite complex and not very reliable, machine that had at least the potential to do the job, given considerable modifications. In modern terminology, it used 32-bit words, each word being made up of two 16-bit instruction/address sets. With its 512 words of memory, one could enter a relatively sophisticated but limited program into it. It used mercury acoustic delay lines for high-speed memory. (These ingenious devices were mercury-filled tubes some five feet long, down which data was propagated in the form of sound waves. A transducer at the tube's front end converted the incoming electrical impulses into sound, and a

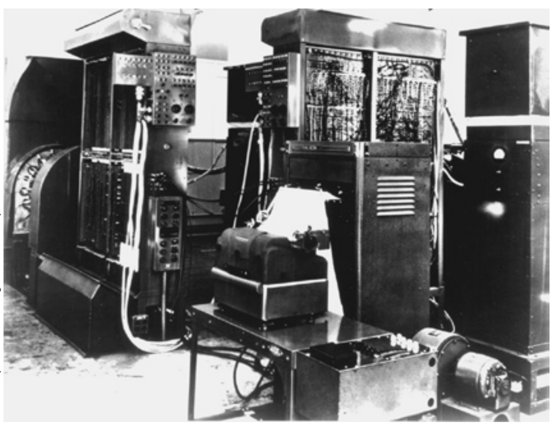


Courtesy of the Computer History Museum

**A mercury delay-line memory from UNIVAC I—high technology in 1951. The 18 long, thin, rectangular boxes running the length of the unit each contain a mercury-filled tube capable of storing 120 bits. This chunk of hardware weighs about 1,000 pounds.**

transducer at the other end converted the sound back to electricity. Since sound in mercury travels much slower than electrons in copper, this allowed the data to be stored for a fraction of a second while the computation proceeded apace.) BINAC had, by the standards of the day, an extremely high clock rate—four megabits per second—and was, in fact, a pacesetter for all general-purpose computers to come. It was essentially the prototype for the famous UNIVAC, which was built by the firm that ultimately absorbed E&M.

Even though BINAC was not designed using Shannon's insights, it could be programmed to solve any type of problem, including a very small fraction of the system of differential equations needed to guide the Snark. By contrast, MADDIDA was a special-purpose machine, designed specifically to solve those equations efficiently. And while BINAC—which consisted of two large racks of electronic equipment, all that heavy mercury plus the apparatus needed to heat it to its optimal operating temperature of 40° C, and an air conditioner to cool everything else—might possibly someday have flown in a large cargo plane, MADDIDA could actually fit into the fighter-sized Snark. Including its power supply, MADDIDA was a self-contained box about the size of a small four-cylinder gasoline engine.



Courtesy of the Computer History Museum

**BINAC was a room-filling machine. The mercury memory is just visible in the background on the far left.**

We lobbied Northrop's management to pursue our approach while still allowing for, and even encouraging, the use of BINAC as what we would now call a mainframe computer to do engineering calculations. In February 1950, Steele and I approached Jack Northrop, whose door was open to all employees, and suggested that we have mathematician John von Neumann of Princeton University's Institute for Advanced Study evaluate MADDIDA. Northrop agreed to this, but since von Neumann wasn't able to travel west at the time, MADDIDA was put on board a commercial airliner and flown east.

Lee Ohlinger, representing Northrop management, joined Steele, engineer Don Eckdahl, and me on the journey. We installed the machine in a fourth-floor room of the Princeton Inn—and immediately realized that the hotel didn't have the three-phase power MADDIDA needed. Eckdahl noticed that an electric company was located directly across the street, and that evening we implored them to string the required three cables to MADDIDA's hotel room. They somehow agreed, and we were in business.

Courtesy of the Computer History Museum

**John von Neumann**

The father of game theory, von Neumann was a legend in his own time, which is why we had proposed him as the judge of our project's worth: his voice carried unique weight. He was renowned not just for the depth and originality of his thought, but for the sheer speed with which his mind worked. He was a lightning calculator with a photographic memory. We met him the next morning in his office, where he told us that he had been carefully examining any reports he could find about the machine. He said he had felt that a differential analyzer such as ours could be extremely helpful in setting up aircraft control simulators—an important need at the time, given that the first jet airliners were being designed and that jets flew too fast to be controlled in the same manner as propeller aircraft.

He asked to see a diagram of the machine; the diagram was a large set of logic equations. This seemed to impress him in no small way. All the flip-flops of the machine were set or reset by ZERO-ONE logic statements or Boolean algebraic equations. "I always felt one should design a machine this way," he told us.

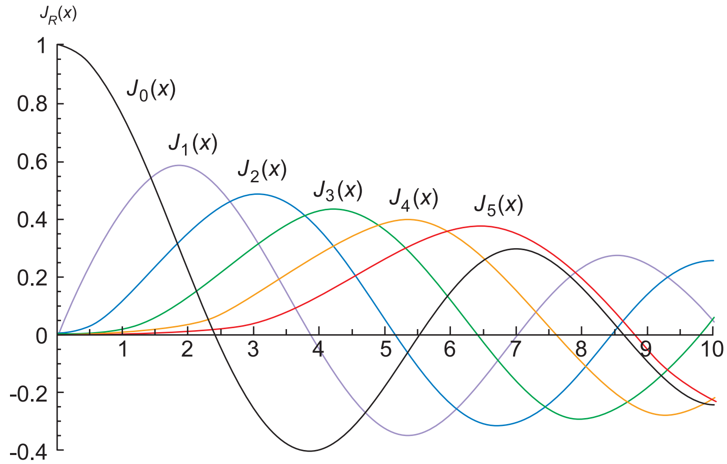
He asked us about the programming of the machine, so I moved to the blackboard to show him how we did it. This was a moment that was both exhilarating and daunting, as I now was demonstrating our programming techniques to a man I had long considered to be omniscient in mathematics.

Then Eckdahl explained how we performed logic design and computed the resistor values associated with the design process. This had to be done carefully, due to the considerable forward impedance in the germanium point-contact crystal diodes of the time. We then discussed what today would be called MADDIDA's architecture.

Our actual demonstration was set for the next day. Our tests that afternoon were complicated by a misbehaving DC power supply. Steele found the problem—a bad solder joint—and the next morning we programmed the machine with the Bessel differential equation.

This wasn't easy. Everything had to be entered using two pushbuttons for ONE and ZERO—we had no keyboard—and Eckdahl was the only person in the room, and probably one of three people in the world, who knew how to both encode the program and operate the machine.

We programmed MADDIDA to calculate $J_{1/2}(x)$, a simple program that was relatively easy to enter. Eckdahl checked the program, started the machine, and launched the program as a test. Just then von




**This set of Bessel functions, $J_0(x)$, $J_1(x)$, $J_2(x)$, $J_3(x)$, $J_4(x)$, and $J_5(x)$, are the solutions to the differential equation $x^2 \frac{d^2 y}{d x^2} + x \frac{d y}{d x} + (x^2 - n^2)\, y = 0$ ; John von Neumann kept pace with pencil and paper as MADDIDA solved the equation for $x = 1$, $x = 2$, $x = 3$, and so forth.**

Neumann arrived unexpectedly and asked us what we were computing. He immediately sat down with a pencil and paper to compute the series himself. The machine calculated to the point $x =$ 1, then stopped so the output could be read, then went to $x = 2$, stopped again, and so forth. Von Neumann kept pace.

He had no printed formulas or tables available. He had an almost instantaneous method for calculating the cosine of $t$ and square roots—perhaps he had them all in memory—and was stunningly rapid at making estimates. (I've since learned from *A Beautiful Mind*, Sylvia Nasar's biography of John Nash, that von Neumann did similar feats versus other early computers.)

After the demonstration, von Neumann was visibly excited by what we had accomplished and said it was a genuine privilege to meet us. That was my last encounter with this mathematical hero, although I have kept with me a copy of the letter he wrote on March 14 to Jack Northrop, in which he called MADDIDA "a most remarkable and promising instrument" and suggested various applications for it, including determining molecular wave functions for quantum-theoretical chemistry—an application that remained beyond the reach of general-purpose machines until the supercomputers of the last decade. He concluded, "The fact that your machine could be transported by airplane and by truck from Los Angeles to Princeton and be satisfactorily running within 24 hours after its delivery is one of the most impressive engineering feats I have ever observed in this field. One has to be familiar with the great difficulties of running equipment of this type under even the most ideal laboratory conditions in order to appreciate the extraordinary tour de force of your group."

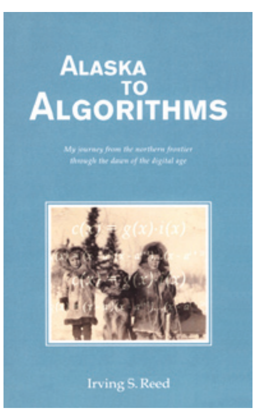
I've also kept a story from the March 28 *Newark Evening News* reporting on our demonstration (on that same trip) at the very first computer conference, cosponsored by Rutgers University's College of Engineering and the Association of Computing Machinery. We stole the show as the only full-scale, working electronic computing machine there—the others, behemoths that were very far from portable, were represented as models, photographs, or pieces of hardware. Headlined "Brainy 'MADDIDA' Makes First Appearance: Machine Can Operate Whole Factories," the article began with the sensational question: "Will people become obsolete?" and went on to say "A mechanical brain was placed on public display here last night which makes possible production of goods without help from the human hand or human brain. Its inventor called it the forerunner of the automatic factory. . . . Until last week, the awesome 'MADDIDA' was classified secret by the Air Force, for which it was built. Last night its inventor, Floyd Steele, an earnest, 31-year-old physicist and aeronautical engineer of Manhattan Beach, Cal., said of his handiwork: 'It will make a big impact on the American economy—bigger than the industrial revolution.'"

In an illustration of how the English language had not yet found words to describe the new electronic frontier, the accompanying photo had a caption that read: "That round thing in the foreground is MADDIDA's memory gadget."

The trip home was one of the happiest and most hopeful journeys of my life. I was only 26 years old, and had not only met a personal hero, but had had a hand in introducing him to a world-changing technology that I had helped bring forth. I had reason to be excited. □

*Irving S. Reed (BS '44, PhD '49, both in mathematics) left Northrop in May 1950 to found the Computer Research Corporation with Steele, Harold Sarkissian, Sprague, and Eckdahl. This small start-up company was acquired by NCR in 1952, but by then Reed had already left for MIT's Lincoln Laboratory, which was working on a semi-automatic radar system to detect, identify, and track enemy aircraft that might be carrying atomic bombs before they got within striking distance of the United States. There he developed the first register-transfer-design language, which made it possible to translate large, complex logic statements into computer hardware almost automatically. In 1960, he and Gustave Solomon, a former grad student of John Nash, developed the Reed-Solomon error-correcting codes that allowed the Voyager missions to return images of the outer planets in unprecedented detail. Revolutionary at the time, Reed-Solomon codes are now used in everything from CDs to fax machines. (For more on Reed-Solomon codes, see* E&S*, Summer 1989.) Reed returned to Southern California shortly thereafter, joining the senior staff of the Rand Corporation in Santa Monica. In 1963, he left industry for academe, joining the University of Southern California as an associate professor of electrical engineering. He is now the Powell Professor of Electrical Engineering and Computer Science, Emeritus. His awards are too numerous to mention.*

*This article is condensed from Chapter Three of his autobiography,* Alaska to Algorithms.




***Alaska to Algorithms***
**By Irving S. Reed**
**Xlibris Corporation**
**2005**
**209 pages; $31.99 hardcover, $21.99 paperback**

# The Social Brain

by Ralph Adolphs

The Adolphs lab uses an eye tracker to find out how people look at each other's faces in normal social situations. Caltech may be the only place on the planet where such headgear might actually work as a pickup line. "What's that you're wearing?" "My eye tracker." "Cool!" Tiny cameras at cheek level record the subject's eye movements and send the data to a laptop. The couple in the Rathskeller bar are grad students Jessica Edwards and Dirk Neumann, while postdoc Nao Tsuchiya serves drinks, and undergrad Sam Huang works the laptop.

I'm studying how our brains generate emotions and guide our social behavior. To give you an idea of the kinds of questions my lab is working on, consider the talk that I'm giving to you right now. As I stand at the front of the auditorium, I look at your faces and imagine what you are thinking about me. Are you interested? Are you bored? At the same time, you in the audience are looking at me and wondering how I feel as I'm standing here. Am I nervous? Am I happy? Now, what is very interesting is that none of the answers to these questions are known objectively. It's not like asking what color shirt I'm wearing. You can't see what's going on in my mind, and I can't see what's going on in yours—yet we manage to attribute thoughts and feelings in both cases, and we do so easily and automatically. How do our brains do this?

One feature of essentially any psychiatric disease is an inability to interact appropriately with other people. Some diseases—autism, for example—have this precise dysfunction as their main feature. But I'm also interested in the *normal* processing of social information. Do men and women process social information differently? Do young and old people? What comes into play when we interact in groups? What social factors drive the stock market? And what makes us elect a particular political candidate? By investigating the mechanisms by which the brain processes information about other people, we will gain some insight into questions such as these, and at the same time contribute toward understanding illnesses such as autism.

Let's begin with a brief review of the brains, social behaviors, and success as a species of different mammals in order to highlight what is so unusual about us humans. Primitive mammals, such as European hedgehogs, have a relatively simple repertoire of social behaviors, without a complex social hierarchy. Their brains are very small, weigh only three grams or so, and don't have many folds, which means that there's not much room for many

University of Wisconsin and Michigan State Comparative Mammalian Brain Collections, prepared with NSF and NIH funding, http://brainmuseum.org.

**The brains above, in order of size and complexity of folding, are those of a hedgehog, a macaque monkey, a chimpanzee, and a human.**

brain cells. Hedgehogs are only found in parts of Europe—outside of pet stores, that is.

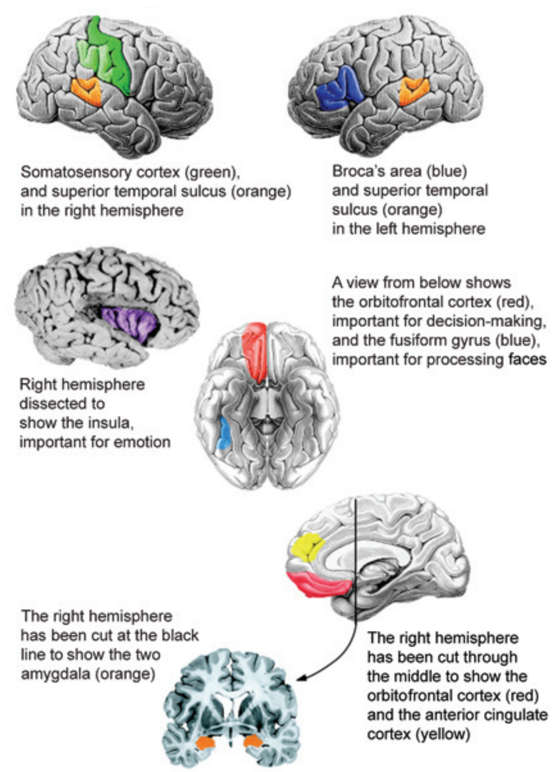
The social behavior of macaque monkeys is substantially more complicated. They live in groups with a hierarchy, and can derive socially relevant information from looking at one another's faces and gestures. Their brains weigh about 100 grams and have a larger surface-area-to-volume ratio than those of the hedgehog, so they have a lot more brain cells. But macaques still haven't done all that well in the global scheme of things, and their range in the wild is relatively restricted.

Our closest living relatives, the chimpanzees, have very complex social behaviors. Like us, they can go to war, and they can make peace. And they also have the precursors to many social emotions, such as shame and guilt. Their convoluted, complex brains weigh around 400 grams, which is about the brain weight that our hominid ancestors likely had four million years ago, and the large surface-area-to-volume ratio means there's a lot of cortex and, consequently, a lot of processing power. Nevertheless, apes haven't done all that well globally, and it's very likely that many—if not all—of them are going to become extinct in my lifetime.

Then we have *Homo sapiens*. Our habitat is the entire planet; in the last 30,000 years or so, especially in the last several hundred, we've taken it over and transformed it. Our brains weigh about 1,300 grams (slightly more, on average, in men than in women), and are even more convoluted than those of the chimpanzee, which means that we have a lot of brain cells packed into the cortex. Our social behavior, as you know from first-hand experience, is very, very complex. We live in huge groups, in institutions, and in countries—in fact, we now have a global society. And because we have culture, we can store and transmit a gigantic amount of knowledge.

What makes our minds so different from those of any other species that we can generate such complex social structures? One thing that we can do much better than other animals is to think flexibly and abstractly. In particular, we can think of things that are not the case. We can imagine unicorns and dragons, we can recollect things from far in the past, and we can plan years, even decades, into the future. Thus we can adopt points of view that are outside the current context. We can also adopt the point of view of another person and, by imagining what it would be like to be that person, we can empathize with and understand him or her. It is likely that no other animal can do this to the same extent humans can (though apes show some of the precursors of this ability.)

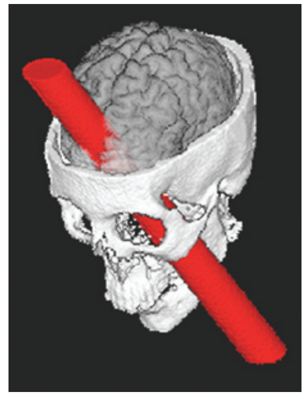
While increase in overall brain size may well be correlated with our complex social adaptations, there is also good evidence that specific regions, shown below, are specialized to process information about other people. Some are involved in language, whose basic social function is, I think, to create a shared consensual point of view between people. But the two main structures my lab is studying are the orbitofrontal cortex, which is located at the base of the frontal lobes, right behind the eyes, and the amygdala, a small structure deep within the brain. These two seem to integrate cognition and emotion, linking what we see in the outside world to an emotional response to it.




**The above views of the brain show areas involved in language processing, social perception, decision making, and emotion.**

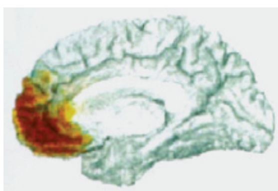
**Right: Phineas Gage's life mask and skull are preserved in a Harvard museum, along with the tamping iron that shot through his head (not shown). Far right: In 1994, a team led by Antonio and Hanna Damasio used these exhibits to compute the route the rod must have taken through Gage's brain. They found that it had destroyed his orbitofrontal region.**

Warren Anatomical Museum, Francis A. Countway Library of Medicine



Damasio *et al.*, *Science* (1994), 264, 1102—1104.

The role of the orbitofrontal cortex was a mystery until a gruesome accident to a man named Phineas Gage provided the first insight. In 1848, Gage, a railway construction gang foreman, was laying track for the Rutland & Burlington Railroad near Cavendish, Vermont. He had drilled a hole into the rock, put gunpowder in it, and was tamping down the powder with a large metal rod when he accidentally struck a spark, and the gunpowder exploded. The tamping rod shot straight through his head and landed many yards away. Amazingly, Gage survived this severe accident, and lived for many more years. But, although he still seemed to have normal intelligence, could speak, and had a good memory, he had completely changed as a person. Prior to the accident, he was a very polite and diligent young man who cared about other people, had lots of friends, and held down a good job. After the accident, all of this changed. Gage didn't care about people any more, he didn't regulate his emotional responses to them, and it didn't bother him what people thought. He became very rude and profane, and soon lost his job and all his friends.



**After frontal brain-tumor surgery, some people are left with damage to the regions highlighted on the right. The orbitofrontal cortex is the very bottom part of this area.**

One of the areas of the brain damaged in Gage's accident was the orbitofrontal cortex. As a postdoctoral fellow at the University of Iowa working with neurologist Antonio Damasio, I was able to observe patients with similar damage, usually due to the surgical removal of a brain tumor. Like Gage, these patients develop something that's been dubbed "acquired sociopathy." They perform normally on IQ tests, and have normal language, memory, and perception, but are unable to guide their behavior with respect to other people. They can't make decisions that are in their best interests, typically fail to hold a job, and are unable to maintain lasting social relationships.

To study what is going on in the brains of these patients, Dan Tranel of the University of Iowa showed them a series of images that varied in terms of their emotional content, and recorded the patients' emotional response by measuring changes in skin conductance of the palms of their hands. Some of the pictures they looked at were neutral, like landscapes or chairs, some were pleasant, like puppies or babies, and some were highly aversive images of mutilation, disease, or war.

The results were striking. In healthy control subjects, Dan had measured a large response specifically to the emotionally arousing pictures, but in the patients with orbitofrontal cortex damage, there was no emotional response at all. When asked to describe what they saw in the aversive pictures, the patients said things like "It looks like a gunshot wound" or "There's a lot of blood." But when asked how they felt when they were looking at these pictures, they said they didn't feel anything.

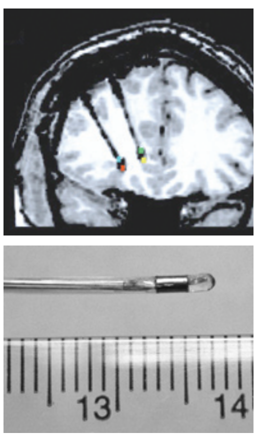
To get a more detailed look at what the orbitofrontal cortex does, I teamed up with neurosurgeon Matt Howard and postdoctoral fellow Hiroto Kawasaki. We began experiments in patients with epilepsy who had had electrodes implanted in this region. This allowed us to record the activity of *single* brain cells when the patients looked at the images. Let me stress that we hadn't implanted the electrodes for our research—a surgeon had implanted them in order to figure out where the epileptic seizures were originating, so that he could remove that part of the brain. While these patients were being monitored, often over a week or two, they had to lie in their hospital beds with all the electrodes embedded, so we asked them if they would like to participate in our research. If they agreed, we recorded the electrical responses of their neurons while they looked at our pictures on a screen.

Our results are shown in the graph below, in which the little vertical bars indicate the firing of individual neurons, while the horizontal axis represents time and the red line indicates the point when we showed the subject the picture. When we put a pleasant picture on the screen, the neurons pretty much kept firing in the same way that they had been. The same thing happened with a neutral picture. But when we flashed up an aversive image, we saw, after a short delay, a cessation of firing followed by a prolonged increase in the firing rate. So even *single* neurons in this region of the brain can encode information about the emotions signaled by the stimuli and, moreover, they can do so very rapidly—the time between seeing the picture and the start of rapid firing was about 120 milliseconds. We checked that this effect was not just due to simple visual differences—for example, we made sure the aversive pictures were not simply brighter, or larger, or had more of a certain color in them.

Apart from suffering from severe epilepsy, these patients were normal. But we were also able to do this experiment on a patient whose orbitofrontal cortex had been partially lesioned, and found that the disturbing images had no effect on the firing rate of individual neurons (not shown). Again, this patient failed to be affected emotionally by what she saw.

The amygdala is connected to the orbitofrontal cortex, and in many ways serves a similar function. "Amygdala" is Greek for almond, and there are two of these almond-shaped structures inside the brain on either side of the midline. We've been studying a 40-year-old woman who has a very rare genetic disease that results in lesions of the amygdala because of calcification. Patients with this type of lesion can show a selective deficit when they look at the faces of other people. They're unable to recognize one single, specific, emotion—fear.

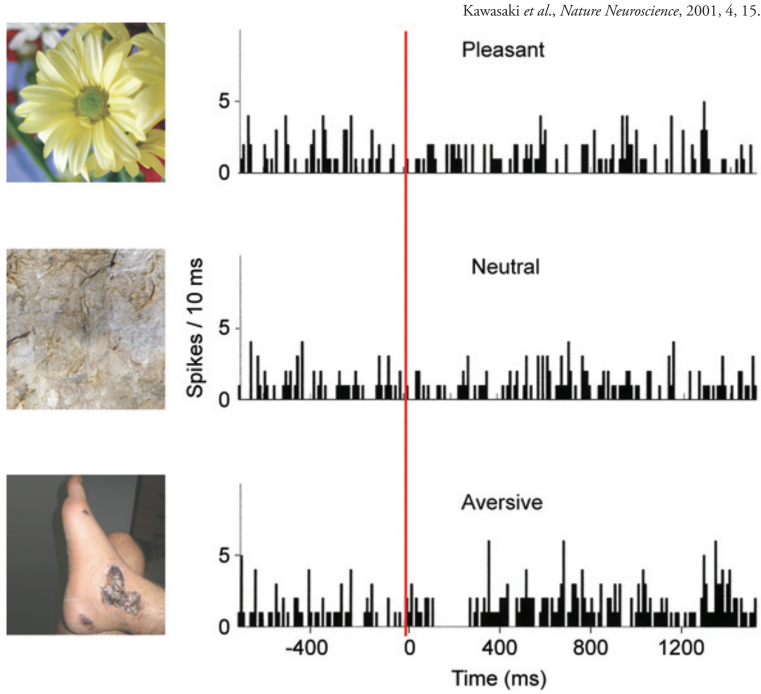
In order to work out the mechanism behind this,



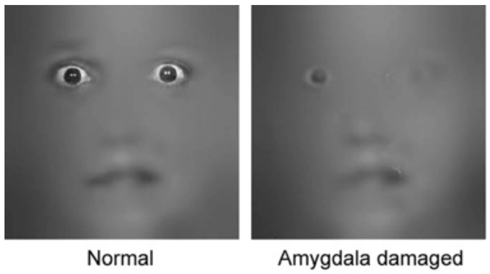

Kawasaki *et al.*, *J. Cognitive Neurosci.*, 2005, 17:20, 1509.

**Above: The top image is a brain scan that shows two electrodes embedded in a patient's orbitofrontal cortex to record the activity of single neurons. The image below that is a magnified view of one of these electrodes (the scale is in centimeters). Two tiny metal contacts on either side of the large silver contact on the electrode record the neuronal activity.**

Kawasaki *et al.*, *Nature Neuroscience*, 2001, 4, 15.




**While a patient looked at photos of varying emotional content, recordings were made from a single neuron in the orbitofrontal cortex. The red line marks the point at which the photo was shown. There was no change in neuron activity when pleasant or neutral images were shown, but an aversive image evoked a brief lull in brain cell activity, followed by a burst of firing.**




Adolphs *et al.*, *Nature* (2005) 433: 68—72.

**Normal people shown only parts of photographs of fearful faces used information from the eyes and mouth to detect the look of fear (left image), whereas a woman with nonfunctioning amygdala used much less information from the eyes (right image).**

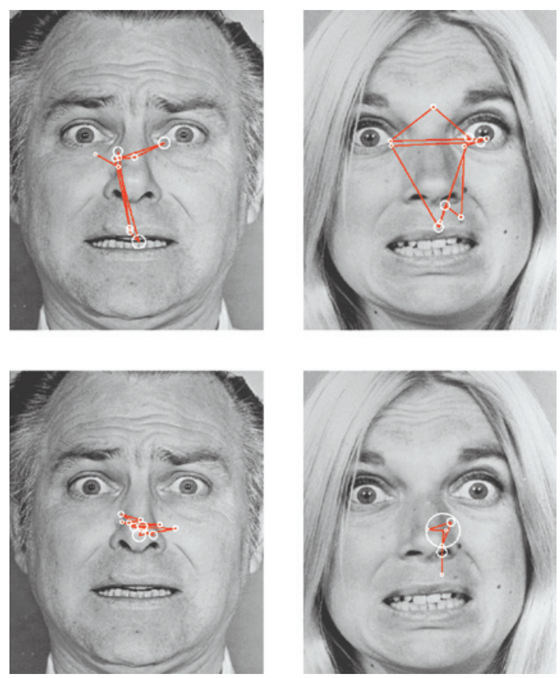
we showed faces that looked either fearful or happy to a wide range of normal people, and asked them to push a button to tell us which of these expressions each face had. But instead of showing the whole face, we made the task much more difficult by manipulating the image so that only little bits were visible at one time. Sometimes the subjects saw an eye, or a nose, or a piece of the mouth, or an ear, and they had to judge happiness or fear from that. After showing thousands of images to a large number of people, we found that some bits are, indeed, more helpful than others. Part of the ear doesn't help, because the ear looks exactly the same whether someone is fearful or happy. A little bit of the mouth is more helpful, and the nose less so. When we put together all the pieces for which people were able to say correctly that it was fear, and subtracted all the bits for which they were not able to recognize fear, it revealed that normal people discriminated fear from happiness mainly by using information about the eyes. Big, staring eyes show fear.

The patient with amygdala damage was strikingly different. Like normal people, she made use of the mouth and nose to some extent, but she failed to make normal use of the eye region. We concluded, therefore, that this patient was impaired in recognizing fear because her brain was unable to use information about the eyes in other people's faces.

Now one explanation that might have occurred to you is that perhaps people with amygdala damage never look at the eyes in the first place. We investigated that possibility by using an eye tracker, which is basically a little video camera that measures with great precision where someone is looking when viewing a picture of a face. Humans make about three or four fast eye movements, called saccades, per second, and normal people, when viewing a face, often sweep it in a triangular arrangement, looking a lot at both the eyes and making frequent excursions down to the mouth. The patient with the lesioned amygdala didn't do that; she just stared at the face and didn't explore it at all. In particular, she didn't look at the eyes. So it seems that people with damage to this part of the brain don't spontaneously look at the eyes—and without the information about the eyes, they're impaired in recognizing fear.

We wondered what would happen once this patient was told to look at the eyes, so we ran the experiment again after instructing her to do this, and found that her performance became completely normal. In this simple way, we were able to "rescue" her impaired fear recognition—in essence, we had instructed her to do something consciously that her amygdala would normally have instructed her to do unconsciously.

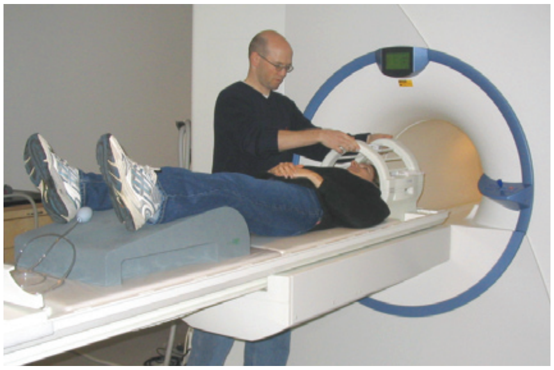
We are now pursuing many other lines of investigation with this subject, and with others who have similar damage to the amygdala. This past January, for example, we began brain-imaging studies where we again showed pictures of faces and measured the eye movements, only this time we did so while the subjects were lying inside Caltech's new magnetic resonance scanner in the basement of the Broad Center. In this way, we could see what was going on in their brains while they were looking at the faces. Such research is showing us how the *rest* of the brain changes when a small part of it—in this case, the amygdala—is damaged. Some of the changes reflect impaired functioning, since the



Adolphs *et al.*, *Nature* (2005) 433: 68—72.

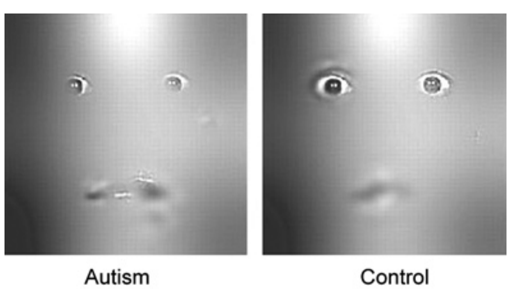
**How normal people scan faces is shown in the top row, while the bottom row shows how an amygdala-damaged woman goes about it. The white circles denote the areas at which viewers stare, or fixate; the bigger the circle, the longer they fixate. The red lines represent the eye movements between fixations.**

**Magnetic resonance technology manager Steve Flaherty prepares a subject for a brain scan in the state-of-the-art Siemens Trio 3 Tesla whole-body scanner housed in Caltech's Brain Imaging Center.**



brain is no longer getting normal input from the amygdala, but some changes are compensatory—the rest of the brain can make up, to some degree, for the damage.

In a collaboration with Joe Piven at the University of North Carolina, we're also studying people with high-functioning autism and Asperger's syndrome. These are people who have a clinical diagnosis of autism, but have normal IQs. With funding from the Cure Autism Now Foundation, postdoc Michael Spezio and graduate student Dirk Neumann have been exploring how such people look at faces. When we asked them to detect happiness or fear from bits of faces, and compared the results with those from a control group of healthy subjects with similar IQs, we found that the people with autism made less use of information about the eyes, and somewhat more use of information about the mouth, as shown below. It could be that they're compensating by making more than normal use of the mouth. We hope to extend these studies to see if we can do the kind of intervention that we did with the amygdala patient. Can we change their social cognitive abilities if we instruct them how to look at other people's faces?



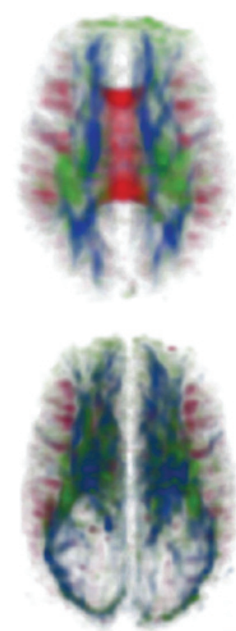

**Above: Autistic people, when asked to detect fear in faces, used some information from the eyes and some from the mouth (left), while normal viewers used a lot more information from the eyes and less from the mouth (right).**

Joe and I are extending these studies to the parents of people with autism. Given that autism is highly heritable, we believe that it has a substantial genetic component. Do the parents already have some of these abnormal genes, and do they show subtle differences in how they process faces?

We're also studying people born without a connection between the left and right halves of their brain, a line of research made possible by a grant from the Pfeiffer Foundation. The two hemispheres are usually connected by a big bundle of about 200 million or so nerve fibers, or axons, called the corpus callosum, but in these people, it is missing. Using the magnetic resonance scanner, staff member Lynn Paul is taking scans of these unusual brains to get detailed information about their structure with a technique called diffusion tensor imaging that allows us to see in which direction the axons run. Lynn has found that the millions of axons that would normally have crossed the midline to the other hemisphere have grown in a fore and aft direction within each hemisphere. As a result, the cells in each hemisphere may actually be more densely interconnected than in the brains of normal people.

If you ask these patients what their main difficulty in life is, they'll tell you it's social—they can't understand other people's emotions. One thing they have great difficulty with is getting jokes. This makes sense: The left hemisphere processes language-based information, such as reading the joke, while the right hemisphere processes emotional information. The humor in a joke often arises from the mismatch of the verbal and emotional components, so if there's no communication between the two hemispheres, the person can't "see"

**Right: In these diffusion tensor images of brains viewed from above, the front of the brain is toward the top of the page. Axons that run from left to right are colored red, and axons that run from front to back are blue. In the top, normal, brain, the corpus callosum is the mass of red axons bridging the hemispheres. The bottom brain, that of a person born without a corpus callosum, lacks this red bridge, but has more blue axons within each hemisphere.**



the joke. For the same reason, puns and metaphors are also hard for them to understand. In fact, their impairments in many respects resemble those seen in people with high-functioning autism.

Taken together, these studies will give us a better understanding of how humans behave socially, both in health and in disease. Our findings mesh nicely with single-neuron recordings in animals, where investigators have also found that the orbitofrontal cortex and amygdala play a role in emotion and social processing.

We are now extending our studies to the "real" world. Last summer, two SURF (Summer Undergraduate Research Fellowships) students, Sam Huang and Lisa Lyons, initiated a study in which a subject wore an eye tracker while interacting with another person in a social situation. In this way, we were able to measure how we look at other people in actual face-to-face conversations rather than as faces in a photograph.

We're also trying to study the differences in social judgments made by men and women. Graduate student Jessica Edwards and SURF student Jessica Stockburger have been looking at how we make moral judgments regarding how "right" or "wrong" an action is, focusing on actions that in some way involve cheating on a partner or spouse. The question they asked was: Would men think that it is more "wrong" for women to cheat on their husbands than for men to cheat on their wives? To do this, they took actual moral memories that real people had produced, where they remembered having had an affair with someone else—having cheated on their spouse. Jessica Stockburger took these real-life stories and used both the original versions and also another version that she had made, which switched the genders in the story but kept everything else the same. She then presented these to both men and women and asked them to rate how right or wrong they thought the action was.

As was predicted, for at least some of these stories, they found that men think it is much worse if a woman cheats on her husband or boyfriend than if a man cheats on his wife or girlfriend, even though the actions and details were identical in the two cases. There were also some converse effects for women readers. This study is one example, among several, that also illustrates the rich cross-talk between different disciplines. In this study, we have biologists, psychologists, and philosophers all collaborating to figure out how moral judgments are made.

I hope that the data from all these studies will give us a better picture of how we think about other people. When we interact, what goes on in our minds and in our brains? How do these processes break down in diseases such as autism? And what does it imply about the things that set us apart from other animals? Or, looking at it the other way around, what does it imply about how similar our brains and minds are to those of other animals? If we understand these issues better, we will end up understanding ourselves better. □

**A camping trip to one of the Channel islands allowed the Adolphs group to interact socially; Adolphs is sixth from the left. Check out the rest of the group on the lab's website, www.emotion.caltech.edu.**

*Ralph Adolphs holds a joint appointment as the Bren Professor of Psychology and Neuroscience and professor of biology. He was born in Germany, raised in Canada, and educated in the United States, gaining a bachelor's degree from Stanford in 1986, and a PhD from Caltech in 1992. His graduate work with Mark Konishi, the Bing Professor of Behavioral Biology, was on the auditory brainstem of the owl, but he moved on to the human brain when he joined the University of Iowa as a postdoc of cognitive neuropsychologist Antonio Damasio. Adolphs became an assistant professor at Iowa in 1997, and an associate professor in 2003. He joined Caltech in January 2004 as a half-time professor of psychology and neuroscience, but continued at Iowa for another year to complete his research on patients at the university's medical school. In January 2005, he joined Caltech full time. Adolphs gained a Klingenstein Award in the Neurosciences in 2000, a McDonnell Foundation 21st Century Science Award in 2002, and a National Alliance for Research on Schizophrenia and Depression (NARSAD) Distinguished Investigator Award in 2005.*

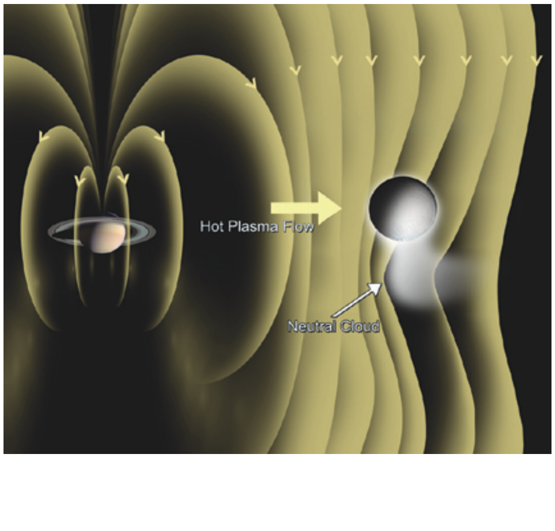
*This article is based on a Seminar Day talk given in May 2005.*

# A Nice Place to Visit?

by Douglas L. Smith

If you saw last month's headlines, you know that Enceladus is the hottest little moon around Saturn. The March 10 issue of *Science* carried a slew of papers from the Cassini mission, and the front-page news was that this tiny, bitterly cold world seems to have liquid water literally right underfoot. Some scientists even mentioned the L-word, putting Enceladus on the very short list of places that might harbor our next of kin. Here's the full story.

Saturn's sixth-largest moon has an equatorial diameter of 504 kilometers—a little farther than the drive from Pasadena to Las Vegas—and is the most reflective object in the solar system. It is entirely coated with something shiny, and Dale Cruikshank of the University of Hawaii identified water ice on its surface back in 1980. Voyager 2 got a look at Enceladus in 1981, but "didn't have the instruments to determine the surface's composition," says Torrence Johnson, a senior research scientist and the chief planetary scientist for the Solar System Exploration Directorate at the Jet Propulsion Laboratory, a member of the Voyager imaging science team, and now a member of Cassini's imaging team. (The Jet Propulsion Lab built and is operating the Voyagers and Cassini; Caltech manages JPL for NASA.) Voyager did find Enceladus's northern hemisphere to be heavily cratered, enough to be nearly as old as the solar system itself, while other regions are very smooth and therefore relatively young—perhaps just a few hundred million years old. Voyager got a pretty good look from the north pole to down past the equator, but only a glimpse farther south.

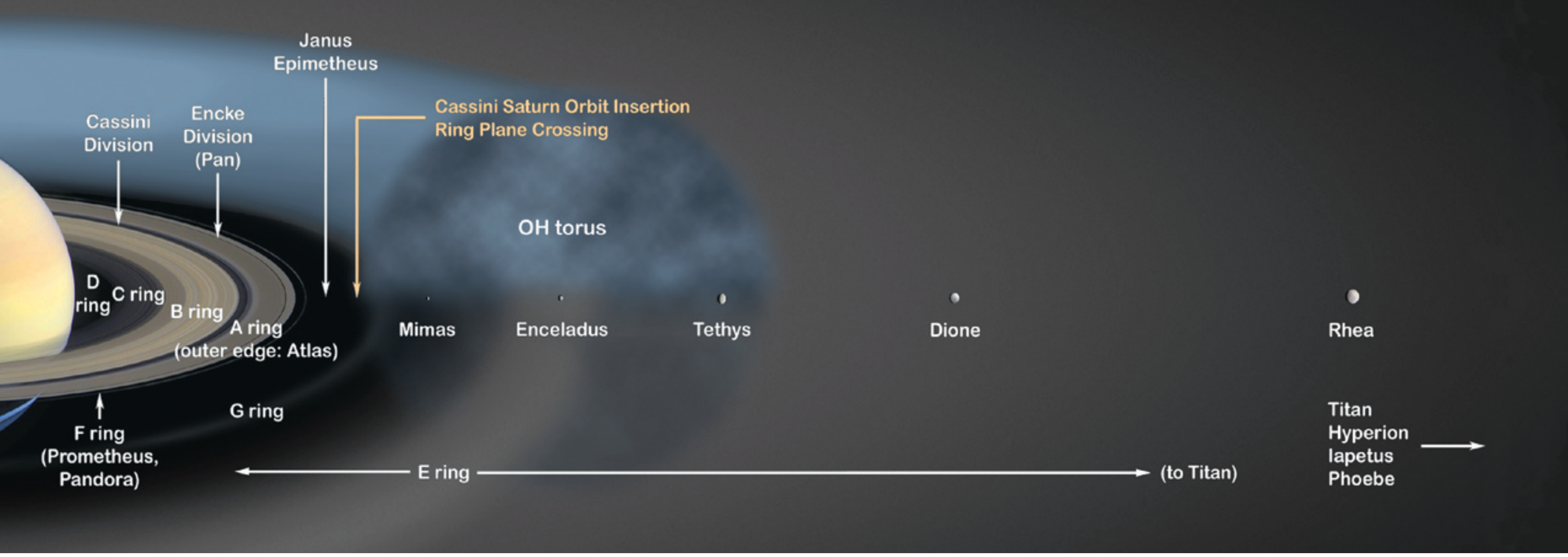



**Saturn's magnetic field is embedded in a plasma, or cloud of charged particles, that's draped around Enceladus in a way that suggests it's colliding with something coming from the moon's southern hemisphere. Cassini's magnetometer also picked up oscillations, caused by ionized molecules spiraling along the field's lines, at a frequency characteristic of water vapor. The magnetometer was built and is operated by a team based at Imperial College, London, England.**

Cassini has confirmed that the whole moon is frosted with very pure water—new-fallen snow, essentially. The moon's dazzling brightness, says Bonnie Buratti, a principal scientist at JPL and a member of Cassini's Visible and Infrared Mapping Spectrometer (VIMS) science team, "reflects freshness. Add any little impurity, a bit of space dust, and it gets dimmer and dimmer." But with an average temperature of 67 kelvins (–206° C), Enceladus is far too cold to be making snow, so a debate has been going on since the '80s—is the bright stuff coming from Saturn's E ring, which shares Enceladus's orbit, or is Enceladus the source of the E ring, which then coats the moon?

Says Andrew Ingersoll, Caltech's Anthony Professor of Planetary Science and a member of Cassini's imaging team, "The mysterious E ring, which has been glimpsed, on and off, throughout the 20th century, seems to reach its maximum density at about the orbit of Enceladus. And we knew from the way the ring particles scatter light that they're micron-sized." (A micron is one millionth of a meter.) Beacuse they are so small, they must be continually replenished. Otherwise they would disappear in as little as 50 years, because molecules would be knocked off their surface by the plasma trapped in Saturn's magnetosphere.

Furthermore, Enceladus's orbit plows right along the center of a vast, diffuse donut-shaped cloud, or torus, of neutral OH molecules, discovered with the Hubble Space Telescope in 1993. About a kilogram's worth of ice particles per second would keep the E ring going, and the OH torus needs a supply of some 100 kilograms of OH per second.



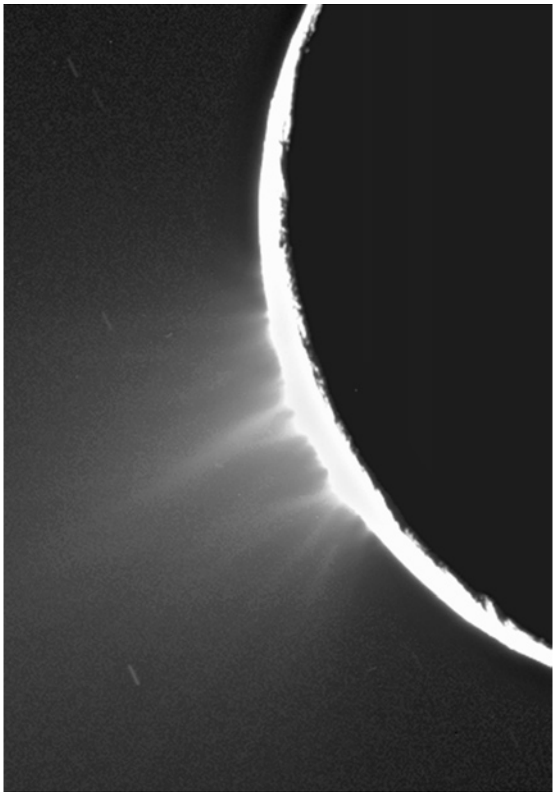

**Above: Saturn, its rings, and some of its moons. The diffuse E ring is much broader than the classical ring system, extending for more than a million kilometers between the orbit of Mimas and that of Titan, which, at this scale, lies some nine inches to the right of this page. The OH torus, like the E ring, is densest at Enceladus's orbit. Neither really has a sharp boundary, but instead each trails off into space.**

Also, Saturn's magnetosphere is filled with oxygen and hydrogen ions of unexplained origin. If you put all this together, there could be a boatload of water coming from Enceladus.

Cassini arrived at Saturn on June 30, 2004, to explore this and other mysteries. The mission includes contributions from 17 nations—some on the school-bus-sized orbiter and the rest on the European Space Agency's Huygens probe, which landed on the methane-drenched, planet-sized moon Titan on January 14, 2005. Cassini follows a wildly looping orbit, allowing its dozen instruments to get repeated, intimate views of all of Saturn's major moons and a number of the minor ones while also making a detailed examination of the planet and its rings.

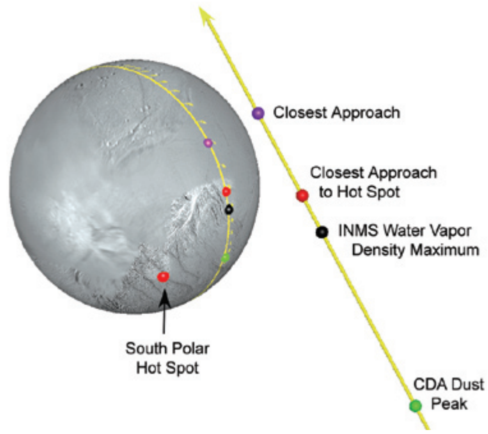
Cassini's first two Enceladus flybys, on February 17 and March 9, 2005, were equatorial passes. On the first one, the magnetometer found that Saturn's magnetic field draped around Enceladus in a way that hinted at a tenuous atmosphere. The second flyby showed that the atmosphere was confined to the southern hemisphere, and the magnetometer discovered ionized forms of water such as $H_3O^+$ streaming from the vicinity of the south pole. Then a photo shot on May 20 revealed parallel sets of dark features, dubbed "tiger stripes," in the south polar region. Each stripe is about 130 kilometers long, and they're spaced some 35 kilometers apart.

So Cassini's third flyby, on July 14, 2005, was altered to buzz the south polar region at an altitude of some 170 kilometers. And behold—it found a huge plume of water hanging over Enceladus's south polar region. The Ultraviolet Imaging Spectrograph, or UVIS, discovered the plume by looking at a star whose light would pass through the plume if one existed. And indeed, the star dimmed as some of its light was absorbed, and a comparison of spectra taken outside the plume with one from the thick of it proved it to be water vapor. Another instrument, the Ion and Neutral Mass Spectrometer, or INMS, confirmed this; VIMS follow-up



**This picture was shot on November 27, 2005, approximately broadside to the plume, which is backlit by the sun. A dozen or so jets of material can be seen shooting into space like a very wimpy comet. Cassini's cameras were designed and built at JPL, but the imaging team is based at the Space Science Institute in Boulder, Colorado. The imaging science team leader is Carolyn Porco (MS '79, PhD '83).**

**The July flyby in 3-D, and its projection onto Enceladus's surface.**



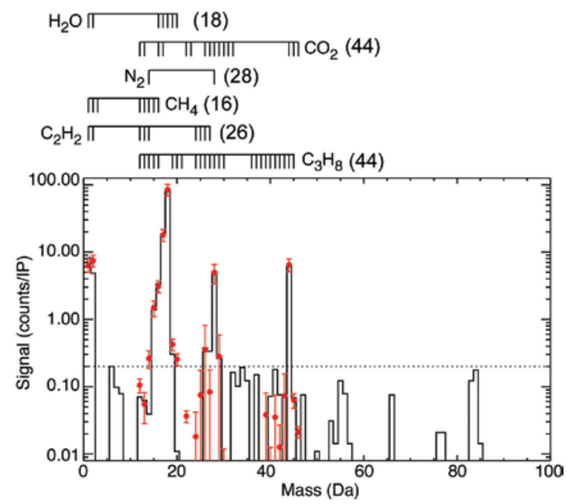



observations on November 26 found particles of water ice averaging 10 microns in the plume and determined that the E ring is made of water ice as well, the latter with an average particle size of three microns.

As Cassini sped by, UVIS also measured the plume's column density, which allows the vapor's escape rate to be estimated—$5 \times 10^{27}$ molecules, or more than 150 kilograms, of water per second, which is plenty to provide for the OH torus. Comets' tails are also mixtures of gas and dust, says Candice Hansen, a research scientist at JPL and a coinvestigator on the UVIS team, and although "comparing Enceladus to a comet is perhaps skating on thin ice, a comet that is not very dusty at all still has about 10 percent as much dust as gas. If you apply that to our 150 kilograms per second you get 15 kilograms per second, more than enough to re-supply the E ring." (UVIS was built by, and the team is based at, the University of Colorado at Boulder.)

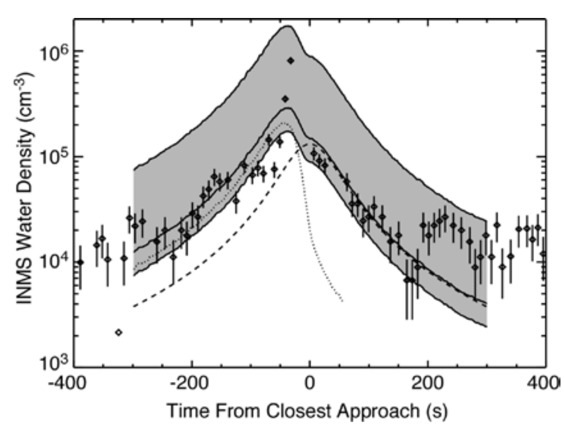
Meanwhile, the INMS and the Cosmic Dust Analyzer (CDA) were measuring the gases and particles that the spacecraft was actually flying through. (The INMS began seeing the plume at 4,000 kilometers out.) Cassini crossed over the south pole before its closest approach to the surface of Enceladus, which allowed discrimination between a global and a local source for the plume. A global source, such as ice molecules chipped from the surface by particles in Saturn's magnetosphere, or lots of tiny vents all over the place that we can't yet see, would have shown up as a broad peak centered on the point of closest approach—the lower the altitude, the denser the stuff should hang all over the moon. But a local source would have peaked when the detector was nearest the source, regardless of the altitude.

According to the INMS, the plume is 91 percent water vapor, 3.2 percent carbon dioxide, and 1.1 percent methane, with possible traces of acetylene and propane. The readings peaked when Cassini was

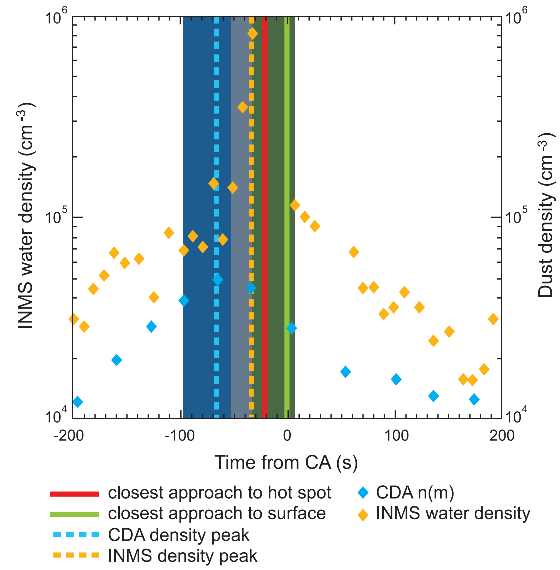



**Above: The average INMS spectrum for altitudes below 500 kilometers. The branched bars labeled $H_2O$, etc., above the data show what masses you would expect to see if the chemical named were present; the numbers in parentheses are the chemicals' molecular weights. The INMS was built by NASA's Goddard Space Flight Center in Greenbelt, Maryland, and the operations team is headquartered at the University of Michigan, Ann Arbor.**

**Below: INMS water density measurements (diamonds with error bars) compared to the predicted density from a global-source model (dashed line) and a polar model (dotted line). The solid line in the middle of the gray region is the sum of these two models, and the gray envelope itself shows the density fluctuations possible if the outbound data are the remnants of a gusher a few hours old.**



A tiny little moon that has been in the deep freeze since its creation has got no business showing any signs of life whatsoever, let alone spewing ice geysers to a height of its own diameter.




**The density peaks from the INMS and the CDA came at different times. The blue band is the uncertainty in the CDA peak, the green band is the uncertainty in the INMS peak, and the gray band is the overlap between the two uncertainties. The CDA was built by scientists at the Max Planck Institute in Heidelberg, Germany, and the University of Chicago; the head honcho hangs his hat in Heidelberg.**

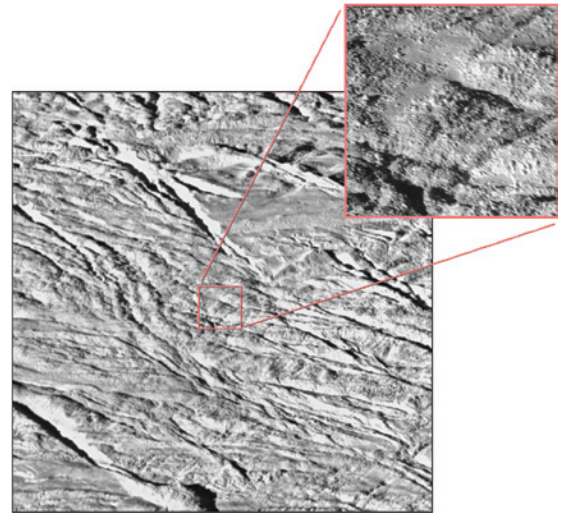
nearest to the south pole, about 35 seconds before closest approach to the surface. But the plume's source doesn't appear to be exclusively polar—the best fit to the data has a roughly 50 percent global contribution. (This, however, is far too tenuous to be detectable as an "atmosphere," even by occultation of starlight.) The INMS measured 1.5 to 4.5 $\times 10^{26}$ molecules per second, or some four to 11 kilograms per second, which is not enough to supply the OH torus. But the measurements don't fall off on the outbound leg the way the models say they should; instead, they flatten out. If the plume spurts every few hours, and this plateau is the undissipated residue from an earlier gusher, the source rate could be up to eight times higher than what was observed—about 80 kilograms per second, which is close enough to 100 for government work. (Or planetary science, for that matter—at least it gets you in the ballpark.)

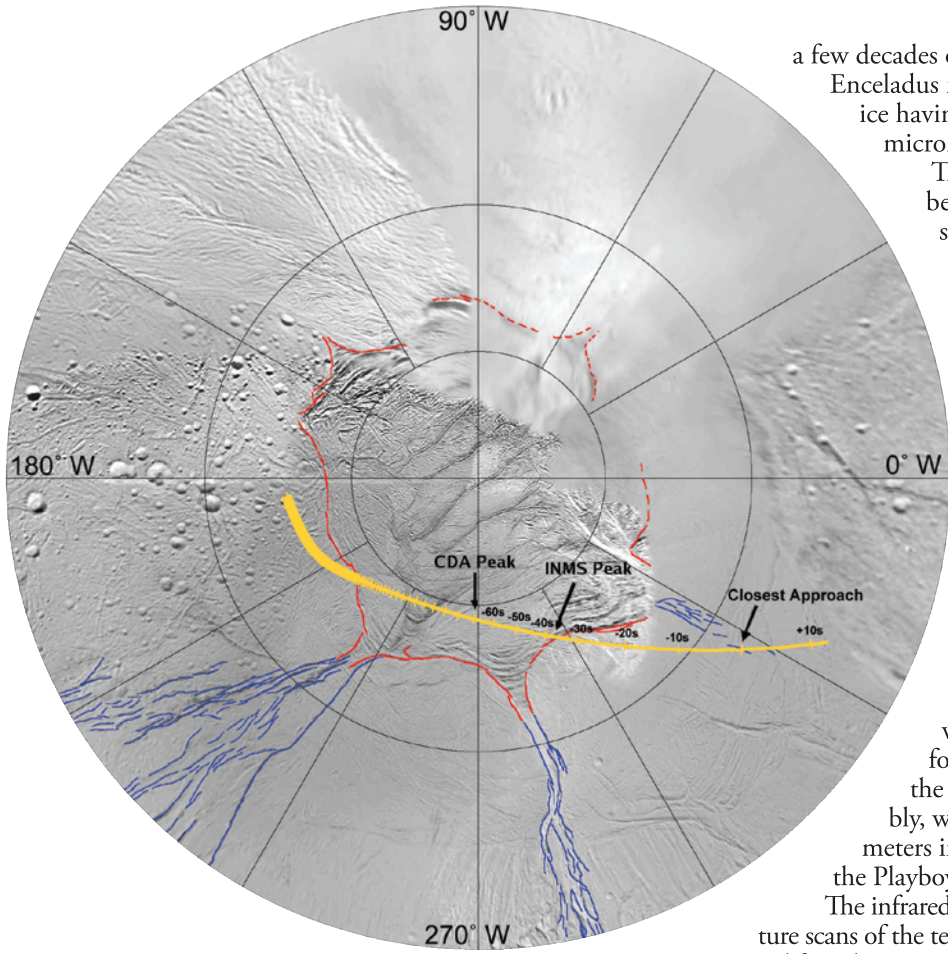
The Cosmic Dust Analyzer's High Rate Detector sees particles of two microns in radius or larger. It found particles with radii of up to 10 microns, and the peak—of four particles per second—was about one minute before closest approach, although there was a significant increase over background from 10 minutes before closest approach to 10 minutes after. But because the CDA peak came earlier than the INMS peak, the CDA folks calculate that the local source supplies about five times as many particles as the global one. The differing peak times also suggest that the gas and the particles act independently of each other after leaving the vents.

A tiny little moon that has been in the deep freeze since its creation has got no business showing any signs of life whatsoever, let alone spewing ice geysers to a height of its own diameter. The propulsive gas requires a rock-bottom minimum temperature, somewhere below that frozen landscape, of 200 K, says Ingersoll, "which is incredibly hot for a body which, if its surface is in equilibrium with the sunlight, is going to be below 70 kelvins." The sun is only 23 degrees above the horizon at the south pole, and it's about 100 times dimmer than it is on Earth. Cassini's Composite Infrared Spectrometer, or CIRS, reaffirmed Voyager's global average temperature readings, and also took a close look at an 80-kilometer-diameter region centered on the north pole, which hasn't seen the light of day since 1995. It's a brisk 33 K there, and that's an *upper* limit.

Which brings us to the tiger stripes. Close-up photos show them to be fissures some 500 meters deeper than the surrounding plains and a couple of kilometers wide, flanked by ridges about 100 meters high. Their bluish tint betrays relatively large particles of crystalline ice—100 to 300 microns, according to the Visible and Infrared Mapping Spectrometer. (The larger an ice crystal, the deeper its absorption in the near-infrared, so the bluer the light it reflects. This is why icebergs and pack ice on Earth have a distinctly bluish cast—they are made of larger ice crystals than, say, snow.) The larger, bluer ice crystals also lie on the surrounding plains, making each dark stripe about seven kilometers across. The crystal size is significant, says Ingersoll, "because if you put a crystal of 100 microns in size anywhere in the Saturnian system and come back a little while later, it will have turned into amorphous ice just due to the bombardment of radiation. So in other words, this is youthful ice." In fact, it may only be

The large picture shows a swath of hummocky terrain in what may be the transition between a tiger stripe and the surrounding plain. The resolution is about 37 meters per pixel. The inset shows the best-yet glimpse of the surface, at a resolution of four meters per pixel but somewhat blurred by Cassini's motion. Each of those little blobs is a block of ice tens of meters in size—a few are 100 meters across.






This composite of Cassini and Voyager images shows Enceladus's southern hemisphere all the way up to the equator, with latitude and longitude lines every 30 degrees. The tiger stripes are squarely in the middle of the picture, surrounding the south pole. The red lines are the chain of fractures at 55° south (marked with dashed lines where inferred on the Voyager pictures) that separate the older, cratered surface from younger terrain. The blue lines are the fractures running north from the Y-shaped features, and the folds between the arms of the Ys are visible as ripples. The yellow line marks Cassini's path over the surface, with tick marks every 10 seconds before and after the point of closest approach.

a few decades old. (VIMS says the rest of Enceladus is covered with amorphous ice having a grain size of 50 to 150 microns.)

The tiger stripes turn out to be part of a larger fracture system. The whole region south of about 55° S is bounded by a continuous chain of fractures and ridges, also bluish in parts, that meet at Y-shaped features. Between the arms of the Ys, the terrain is folded into belts standing hundreds of meters tall, and the stems of the Ys are more bluish fissures that go north into the midlatitudes.

And an extreme close-up, with a resolution of about four meters per pixel, shows the place is covered, inexplicably, with boulders of ice 20 to 50 meters in size—ice cubes as big as the Playboy Mansion, in other words.

The infrared spectrometer took temperature scans of the terrain the camera was shooting, and found a series of hot spots designated A to G. (Source C, incidentally, is very close to the south pole.) These spots are on or near the tiger stripes, and their thermal spectra are not those of blackbodies, meaning that the temperature in CIRS's field of view is not uniform. For instance, a little shoulder in the spectrum of D, the hottest spot, implies that some 4.6 percent of the radiometer's footprint—about 25 square kilometers, or the equivalent of a 250-meter-wide strip along a 100-kilometer-long fracture, is actually at 145 kelvins. (There is some

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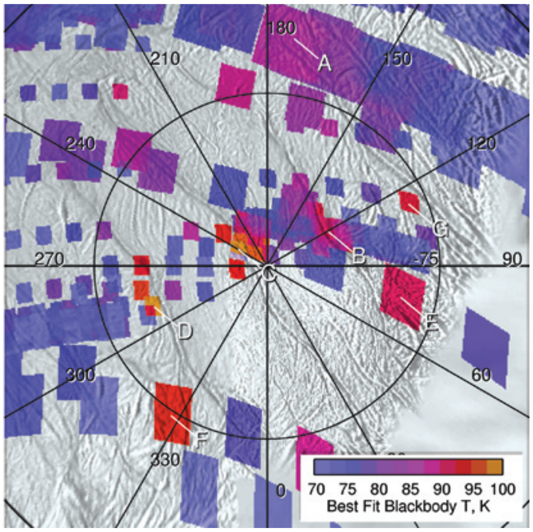
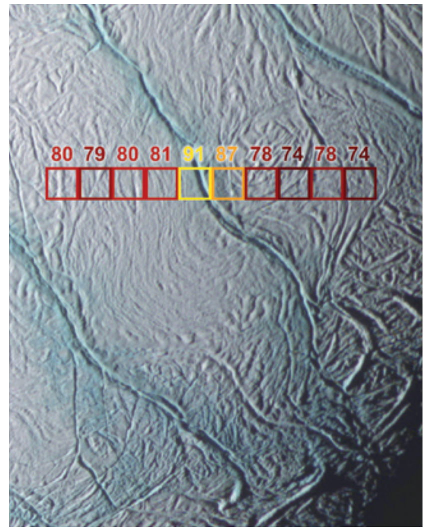
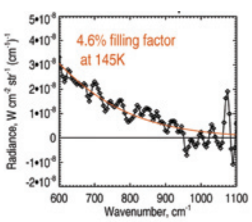



**Right: CIRS made a temperature map of a fair piece of the south polar region, including the seven hot spots marked A – G. CIRS was built and is run by the Goddard Space Flight Center.**

**Far right: In this close-up of hot spot B, each colored square is a single CIRS measurement of a patch of ground six kilometers across, at wavelengths from nine to 16.5 microns. The numbers show the average temperature for each square.**




**The tail of the infrared spectrum for hot spot D. The red line is the best-fit graybody spectrum.**

uncertainty in that estimate, as the smaller the "filling factor," that is, the 4.6 percent, the higher the temperature needs to be in that filled area. So the temperature could be as high as 180 K.)

One is almost tempted to say this is boiling hot. Which is not that far off the mark—the Cassini team's best explanation is the "Cold Yellowstone" model, in which a reservoir of liquid water is venting to space through fissures in Enceladus's crust. "A bit like the Yellowstone area, but with about a tenth the heat flow," is how Johnson puts it. The heat radiated by a 145 K hot spot implies a temperature of 273 kelvins, the melting point of water, a mere 20 meters below the surface. The imaging team takes a different route to a similar conclusion: They start with Enceladus's weak gravity, which is about one percent of Earth's, and calculate how much pressure the overlying ice would have to exert to reach water's triple point—where solid, liquid, and vapor coexist—and hence how thick the ice would need to be in order to weigh that much. Seven meters will do the trick.

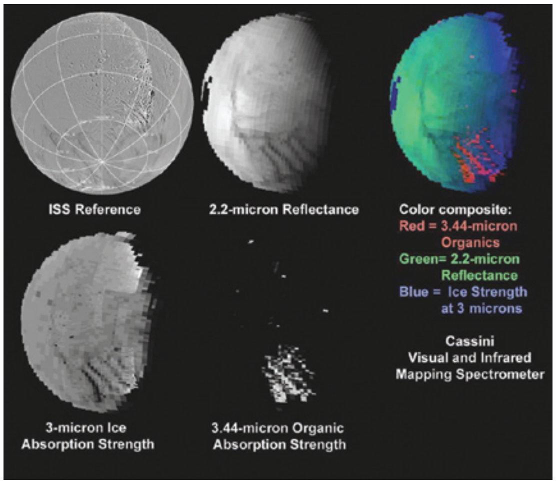
This is not as outrageous a claim as it may seem—the CIRS measurements of the entire south polar region show that it is giving off, at the very least, four more gigawatts of thermal energy than can be accounted for by reradiated sunlight.

The water is kept liquid by the pressure of the ice cap above it, but, like the aftermath of a bungled assault with a bottle opener on a non-twist-off beer, foam escapes through whatever gaps it finds. Any water caught up in the gas freezes into ice particles, and the lot comes shooting out the top. Some of it gets lofted into space at supersonic speeds, twice Enceladus's escape velocity of 235 meters per second, feeding the E ring and the OH torus; the rest falls back as snow.

How Enceladus's cockles got warmed is anybody's guess. Since the moon's northern hemisphere is, geologically speaking, dead as a doornail, the mechanism is clearly a local—or at best regional—process. Various theories conjure past orbital resonances, librations (wobbles of Enceladus's rotational axis), or orbital eccentricities—none of which are happening now—that squeezed the poor satellite like a Koosh ball to melt its interior. And the imaging team found that Enceladus *is* out of round—or, to be perfectly accurate, out of elliptical—by +400 meters at 50° south latitude and –400 meters at the south pole. The north-south fractures running from the midlatitudes, as well as the ring at 55° south latitude that those fractures join, could have occurred when Enceladus began to bulge, since the crust would have cracked to accommodate the shifting fluid below.

Another alternative, proposed by Caltech-JPL postdoc Julie Castillo and others, posits that Enceladus coalesced at just the right time in the solar system's evolution to have collected a lot of aluminum-26. Aluminum-26 has a half-life of only 720,000 years, says Castillo, and its rapid decay would have put out an awful lot of heat, which could have partially melted the rocky core. This, in turn, would have heated the underside of the ice and "melted enough of it to create hydrothermal vents like the ones along the mid-ocean ridges on Earth. And with Enceladus's low gravity, it would be easy for warm water to work its way up to the surface." The mystery of what's driving the geysers is not unlike the story of plate tectonics—Alfred Wegener proposed in 1915 that Earth's continents were drifting apart, and it then took another 47 years to establish how.

After the first few million years, other decaying radioisotopes might help keep the chill from Enceladus's south polar interior. Cassini's measurements of the moon's mass and density are both higher than Voyager's. This means the core is bigger than previously thought, which implies that it could be putting out two or three times more heat than had been plausible before. But most of the heat comes from the tidal flexing induced by Saturn's gravitational field.




**The VIMS data at wavelengths absorbed by organics (red) and small-grained crystalline ice (blue). The 2.2 micron reflectance is a sort of calibration—a band that is the same for amorphous and for crystalline ice. The VIMS was built by JPL with contributions from the Italian Space Agency, and operations are based at the University of Arizona in Tucson.**

But there's one more feature of interest, as Sherlock Holmes might say. The Visual and Infrared Mapping Spectrometer surveyed the materials on Enceladus's surface, and found simple organic molecules such as acetylene along the tiger stripes.

Which raises a possibility that has everyone all atwitter: Life. "This is the most exciting thing to come out of Cassini," says Yuk Yung, professor of planetary science. "It's very much like the biblical story of Saul, who went out to look for his donkeys and found a kingdom." Yung is a coinvestigator on Cassini for the study of organic molecules on Saturn's moon Titan—a line of work that he actually began back in the Voyager days. "Titan is what we call prebiotic. It has the precursors of life. It is a natural laboratory for all this complex organic chemistry, some of which we are still trying to figure out. And then we have Enceladus, where we think Titan's evolution has taken another step forward, and may have moved to the point of spontaneous generation of life."

As far as we know, life demands three things. The first, of course, is liquid water. The second (we'll get to the third a bit later) is an oxidation-reduction, or redox, cycle: a set of chemical reactions in which electrons are liberated from inorganic matter to carry out the business of life. Some earthly bacteria use a sulfur cycle, others use iron. (Photosynthesis is out of the question—it's a tad too dark out there.) Yung thinks that life on Enceladus could be powered by $H_2O_2$, hydrogen peroxide, which is easily made by irradiating water molecules with electrons or ultraviolet photons, and has been found at 0.13 percent abundance on the surface of Jupiter's moon Europa—another iceball suspected of having a subsurface ocean. Hydrogen peroxide has not been seen yet on Enceladus, but, says Yung, "We haven't been looking hard enough."

Peroxide-eating bacteria once existed on Earth, Yung believes. He bases this claim on work he and Joe Kirschvink (BS, MS '75), the Van Wingen Professor of Geobiology, have been doing on an era of global glaciation. In 1997, Kirschvink and grad student Dave Evans (MS '94, PhD '98) discovered that glaciers extended to within a few degrees of the equator some 2.2 billion years ago—one of two episodes that Kirschvink has dubbed "Snowball Earth." (See *E&S* No. 2, 1997.) The global average temperature would have plunged to 223 K, yet some bacteria managed to survive. Says Yung, "Snowball Earth was very much like things are now out in the outer solar system. And under those conditions, you can create lots of hydrogen peroxide, which will be trapped in the ice." On Earth, the ice melted relatively suddenly, and huge amounts of oxygen were released. Life at that time was anaerobic, and oxygen would have been a deadly poison. (See *E&S* No. 4, 2005.) Most everything died, but some bacteria evolved an enzyme called superoxide dismutase, which breaks down hydrogen peroxide, says Yung. While no peroxide-munching bugs exist today, Yung points out that a yeast named *Hansenula polymorpha* is able to snack on $H_2O_2$. "So the biosphere figured out how to deal with this oxygen-containing substance before it ever had to deal with molecular oxygen, and that was a necessary precursor to oxygen-releasing photosynthesis. Otherwise, whatever was producing oxygen would have been killed in the process." Yung and Kirschvink are collaborating on future Enceladus work.

Life's third prerequisite, which is far less obvious, is a geological cycle. Life requires rocks to have been weathered into clay, says Yung, because "in order to create life, you need to create all these complex molecules. DNA, the genetic code, gives us the blueprint now, but in the beginning, everything had to self-assemble." It's like building an arched bridge of stone—the Romans couldn't just stack rocks on top of one another so that the piles leaned out from each bank and met in midstream. A scaffolding was needed to hold the rocks in place until the keystone went in and the whole thing became self-supporting. James Ferris at Rensselaer Polytechnic Institute has shown that montmorillonite, a

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fairly common clay mineral, can serve as a template that rapidly assembles short strands of RNA out of individual nucleic acids. It's quite a leap from a string of a few dozen nucleotides to an RNA system that can copy itself and could charitably be called alive, but you've got to start somewhere. "Clay is nature's catalyst," says Yung.

At some 70 kilometers down, Enceladus's stony core is far too deeply buried to do any good, but not to worry—Yung's rocks fall from the sky. A continual rain of micrometeorites pummels the surface; Enceladus would be as dark as Saturn's other moons if it were not for the snow from the south pole. The snowfall gradually buries the micrometeorites, and Yung calculates they'd be 20 meters deep in a mere 20,000 years. And once they come into contact with the liquid water, they'd turn to clay in another million years or so—a blink of an eye, in geologic time.

Says Yung, "Other than Earth, Enceladus is the only place in our solar system that meets these three conditions. Mars has evidence that in the past there was a hydrological cycle, and there is sedimentary rock. Life could have started on Mars, but certainly not today. Europa is believed to have an ocean under the ice, but everything is sealed. It's a closed system. Joe has pointed out that Europa's oceans would be in thermodynamic equilibrium after only a couple of million years, and once that happens, there is no redox potential and no life." But "not everyone is so pessimistic," says JPL's Torrence Johnson. "Since Europa's surface is young, there must be some overturn and exchange between surface and ocean." It's not really a closed system, he says, and electron-donating molecules made on the surface—that hydrogen peroxide again—"may supply the energy for life. Likewise, ocean-floor hydrothermal vents might provide chemical nutrients." Most people think of hydrogen peroxide as an oxidant, or electron acceptor, as it is when you buy it over the counter as an antiseptic. But, depending on what it is paired with, it can also act as a reductant, that is, as an electron donor. "That's the amazing thing about hydrogen peroxide," says Yung. "It's so versatile."

But we're not out of the woods yet. Or in a position to start growing trees, if you prefer. Life needs the right mix of chemical elements in order to get started, and one of them, nitrogen, has not yet been found on Enceladus. No ammonia has been seen on the surface so far, yet one would expect to find it if amino acids were being made. Worse, there's no sign of ammonia in the plume. But even if ammonia is never found, all is not lost—the best prebiotic gas mixture for making life's necessities, says Yung, is actually methane, water, and nitrogen in the form of $N_2$. There's an unidentified peak in the mass spectrometer data at mass 28, which is just where $N_2$ would register, that accounts for four percent of the plume. It's not yet clear that this peak is nitrogen and not carbon monoxide, which has the same molecular weight and is found in about four percent abundance in cometary gases. But the plume's ultraviolet spectrum sets an upper limit for carbon monoxide at less than one percent, and Titan's atmosphere is mostly nitrogen, so that's the way the INMS team is leaning.

And the best part is that these hypothetical bugs are *right there*. Seven meters down is the equivalent of having water in the subbasement: descend two flights of stairs, and you're ready to mop it up. But getting a probe to land on Enceladus's surface (or Europa's, for that matter) will take some doing—any spacecraft in orbit around a giant planet will need a big rocket and a lot of fuel to slow itself down enough to be captured by a tiny moon's weak gravity. That's a lot of weight to be flinging into the solar system's outer reaches, and "NASA is not planning any large, 'flagship-' class missions in the next five years or so, given the current budget reductions. So don't look for anything until 2015 or beyond," Johnson sighs.

Meanwhile, Cassini's next flyby will occur on March 12, 2008. The trajectory will be lowered to part Enceladus's hair—a 25-kilometer altitude has been proposed—but the point of closest approach will be equatorial. The spacecraft will still pass within 200 kilometers of the plume source, says the University of Michigan's J. Hunter Waite Jr., the INMS team leader, which will give a tenfold better signal-to-noise ratio and may allow $N_2$ to be distinguished from carbon monoxide. And the infrared spectrometer team's John Spencer, of the Southwest Research Institute, says, "We'll get an excellent view of the south pole as we speed away, except that Enceladus goes into Saturn's shadow right after our closest approach and we'll be looking in the dark. So we won't get any good visible-light images of the south pole, but we should get superb infrared data. If there really is liquid water in those cracks we might, if we're lucky, see temperatures as high as 273 K." That's the final close pass of the four-year primary mission, but Cassini will keep an eye on the geysers from afar. A two-year extended mission has already won preliminary approval, with Enceladus sharing top billing with Titan as the moon attractions. □

Many boys dream of being a backhoe operator when they grow up, but Scott achieved the ultimate: He was the first person to dig on the moon. The instrument he designed and operated, shown here on Surveyor 3 shortly before its 1967 launch, had a telescopic arm with a box-like scoop at the end. Scott's results gave the green light for Apollo 11.

## Ronald F. Scott
## 1929 – 2005

Ronald Fraser Scott, the Dotty and Dick Hayman Professor of Engineering, Emeritus, died on August 16, 2005. He was 76. An internationally acclaimed expert in soil mechanics and foundation engineering—or geotechnical engineering as it is now known—his research interests included the basic properties of soils and how they deform, the dynamics of landslides, the behavior of soil in earthquakes, the physical chemistry and mechanics of ocean-bottom soil, the physics of the freezing and thawing processes in soils, and the properties of the moon's surface.

Scott was born in London and grew up in Perth, Scotland. After gaining a bachelor's degree in civil engineering from Glasgow University in 1951 and an ScD in civil engineering (soil mechanics) from MIT in 1955, he worked with the U.S. Army Corps of Engineers on the construction of pavements on permafrost in Greenland, and with consulting engineers Racey, McCallum and Associates in Toronto, before joining Caltech as an assistant professor of civil engineering in 1958. Rising through the ranks, he became the Hayman Professor in 1987, and retired in 1998.

On February 11, a memorial gathering in Scott's honor was hosted by Norman Brooks (PhD '54), Irvine Professor of Environmental and Civil Engineering, Emeritus. Caltech provost and professor of civil engineering and applied mechanics Paul Jennings, (MS '60, PhD '63, who took one of Scott's soil mechanics classes as a graduate student), told the gathering that Scott had taken on a challenging field. "As engineering materials, soils are simply not nice," he said. "They are complicated two-phase media, composed of a porous collection of particles and a fluid in the pores, typically water. As such, soils are kind of noneverything—nonlinear, nonelastic, nonhomogeneous, nonisotropic and therefore from the viewpoint of solid mechanics, noneasy." But, he said, Scott was a Caltech type of engineer—half engineer, half scientist—who developed engineering tools and approaches based on a rigorous understanding of the fundamental mechanics involved.

"This real-world messiness of soils translates to the classroom," Jennings added. "Around the country, soil mechanics courses are often not popular because the material resists the elegant mathematical simplifications that take one so far in other materials, like metals. Ron's courses were different; they were well-appreciated and popular because he met the challenges of soil complexity head-on in his unique and interesting way."

When he began teaching, there were no textbooks that suited Scott's rigorous scientific approach based on the mathematical principles of solid and fluid mechanics, so he wrote several of his own, including *Principles of Soil Mechanics* (1963) and *Foundation Analysis* (1981).

"His understanding of the theoretical issues was profound," said James Knowles, the Kenan, Jr., Professor and Professor of Applied Mechanics, Emeritus, "but his work was always motivated by real-world problems and needs, and he accumulated much practical experience by consulting on such problems as landslides and soil liquefaction." Living as he did in a region highly prone to landslides and earthquakes, Scott's expertise was called upon many times by consulting firms and government agencies. He was an advisor during the investigations that followed the Baldwin Hills Dam failure in Los Angeles in 1963 and the Bluebird Canyon landslide in Laguna Beach in 1978, and worked with Fred Raichlen, professor of civil and mechanical engineering, emeritus, to design the foundations of submarine wastewater outfalls to withstand earthquakes and high waves.

Scott pioneered the use of centrifuges in soil dynamics, recognizing that the mechanical properties of soils depend on the pressures to which they're subjected. The soil at the bottom of a large earthen dam, for example, is under an enormous amount of pressure from the weight of the soil above and around it. Laboratory-sized scale models, using much less soil, can't reproduce this. Scott's solution was to spin the model in a large centrifuge to achieve forces 50 to 100 times the acceleration due to gravity. His centrifuge also incorporated a computer-controlled shaking table that could model the intense motion of soil during an earthquake. "This technology has been copied and refined at other labs around the world, but Ron was the originator," said John Hall, professor of civil engineering and dean of students.

In the 1960s, Scott's expertise made him the ideal person to evaluate whether the surface of the moon would be safe to walk on. At the time, many people thought it was covered in a deep layer of fine dust, like talc, that wouldn't support the weight of a human. As a principal investigator for Surveyors 3 and 7, two unmanned craft preparing the way for the Apollo 11 manned landing, he designed an instrument to examine the structure and load-bearing strength of the lunar soil.

Scott's box-shaped, claw-mouthed scoop, or "soil mechanics surface sampler," as NASA called it, was attached to a telescopic arm and could be moved around and lifted up and down by radio signals from Earth. The scoop could dig trenches, scrape up soil, and even lift large clods and drop them to break up the lumps. And by filling the scoop with soil and compressing it, Scott and JPL engineer Floyd Roberson could estimate its bearing strength.

Surveyor 3 landed on the moon in 1967, and "for the next two weeks . . . Floyd and I happily and sleeplessly played with the lunar surface soil on the inside surface of a 650-foot-diameter crater."

Surveyor 3 landed on the moon in 1967, and "for the next two weeks," Scott later wrote in the February 1970 issue of *E&S*, "Floyd and I happily and sleeplessly played with the lunar surface soil on the inside surface of a 650-foot-diameter crater." The moon's surface, they concluded, was like damp sand, and safe to walk on.

When the time came for the manned landing, Scott waited anxiously on July 20, 1969, as Neil Armstrong climbed down the ladder of the lunar module *Eagle*. Everyone remembers Armstrong's first words, "That's one small step for man, one giant leap for mankind," but not many remember what he said next: "I sink in about an eighth of an inch. I've left a print on the surface." Those were the words Scott wanted to hear.

There's a postcript to this story. In November 1969, Apollo 12's module landed close to Surveyor 3, and Charles Conrad and Alan Bean walked over to take a look at it. Conrad cut off the scoop and brought it back to Earth in two Teflon bags. Scott was present when the bags were opened. "If I had known I would see it again," Scott told *E&S*, "I would have left the scoop completely packed with lunar soil."

The two Viking spacecraft that landed on Mars in 1976 also needed soil scoops, and again, Scott worked on those. As mentioned in *E&S*, No. 4, 2005, some of the soil collected by the scoops was used in a life-detection experiment designed by another Caltech faculty member, Norman Horowitz, who died shortly before Scott.

Former students and colleagues at the memorial gathering mentioned Scott's high standards. "He did not tolerate sloppy or inaccurate research or engineering," said Raichlen, "and he had little patience with others who fell into that category." A "fiercely independent thinker," Scott "valued academic integrity above all else," said John Ting, MS '76, professor and dean of engineering at the University of Massachusetts at Lowell. "It wasn't about the size of the research group, or the amount of funding—it was about the purity of the academic pursuit, and asking and then answering the key questions in the most elegant (and often the least expensive) way." Two of Scott's former graduate students, Hon-Yim Ko (MS '63, PhD '66), Murphy Professor of Engineering at the University of Colorado at Boulder, and Thiam-Soon Tan (MS '82, PhD '86), associate professor of civil engineering at the National University of Singapore, also paid tribute to their mentor and friend. Many of the speakers remarked on Scott's wit, his wry sense of humor, and his infectious laugh.

Scott cultivated a love of literature and was an omnivorous reader, said his son, Grant, a professor of English at Muhlenberg College in Pennsylvania. And in a fitting tribute to his soil-engineer father, he said "My father loved words—especially puns—where there was slippage in the slope of language, perhaps a kind of liquefaction where two letters supporting a dam of meaning gave way or there was a semantic friction or failure. He liked to see words collapse into other words, and watch as a seismic shift altered the landscape of a sentence."

Scott was elected to the National Academy of Engineering in 1974. His awards included the American Society of Civil Engineers' Walter L. Huber Civil Engineering Research Prize in 1969, the Norman Medal in 1972, and the Thomas A. Middlebrooks Award in 1982. He was also selected to be the ASCE's Terzaghi lecturer in 1983, and the British Geotechnical Society's Rankine lecturer in 1987. Considered to be the two highest honors in Scott's field, they are rarely awarded to a single person.

He is survived by Pamela, his wife of over 46 years, sons Grant, Craig, and Rod, and seven grandchildren. □

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