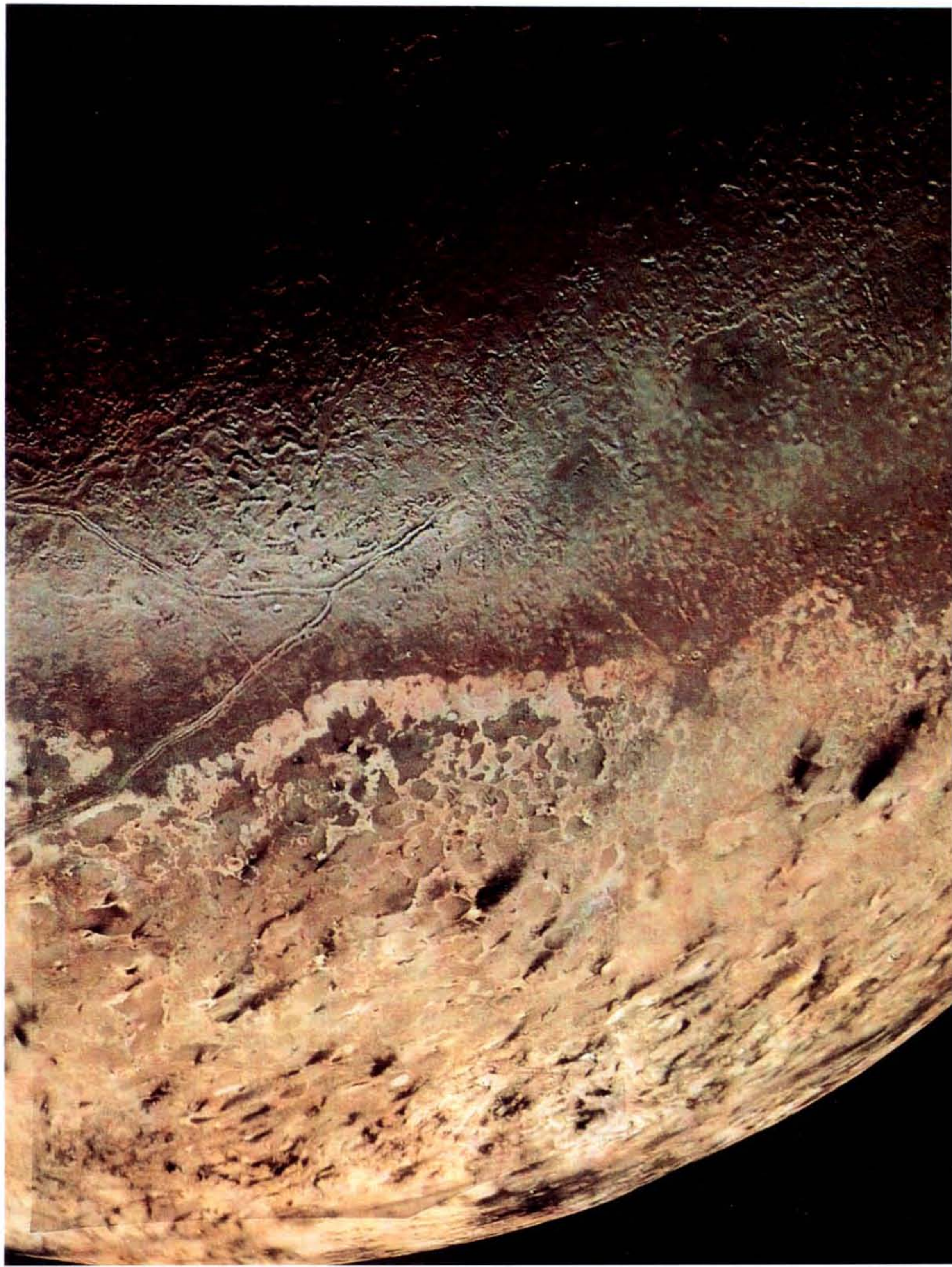
California Institute of Technology

Engineering & Science

Fall 1989



In this issue

Neptune, Triton: close encounters

SEM and VLSI

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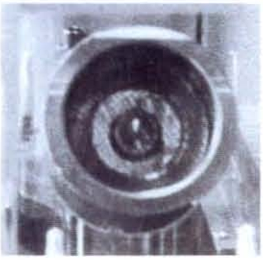

On the cover: A combination of high-resolution images provides this view of Triton's mixed assortment of terrains. The pinkish polar cap may be a layer of nitrogen ice from the previous winter, punctuated by the dark plumes of ice volcanoes. More pictures from Voyager 2's rendezvous with Neptune and its largest satellite appear in this issue beginning on page 2.

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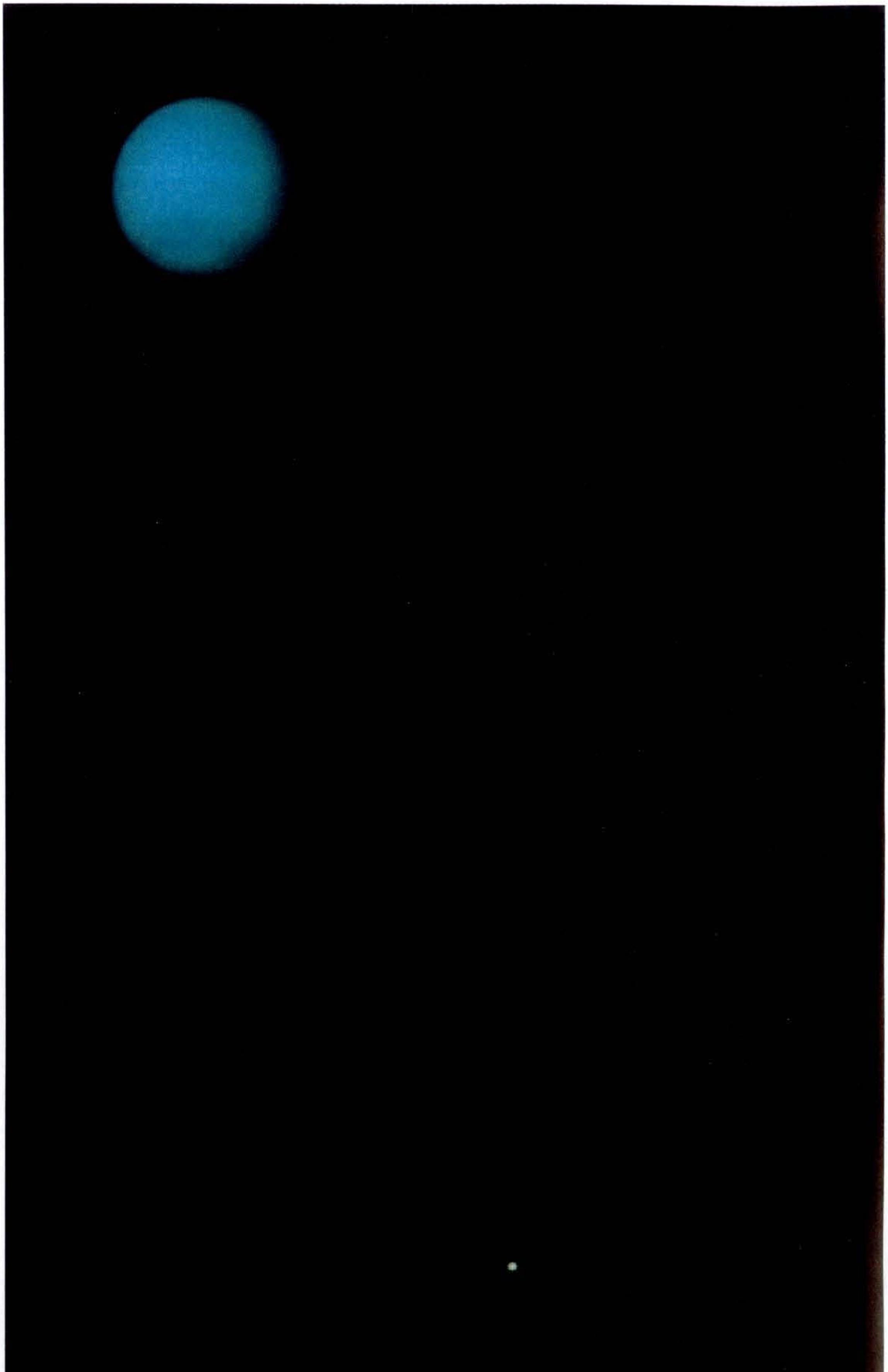


Voyager 2: Close Encounters of the Last Kind

A postcard from Neptune—nearly 3 billion miles away.

Still 76 million miles away on July 3, Voyager 2 captured Neptune and its largest satellite, Triton, in its narrow-angle camera through violet, clear, and orange filters.

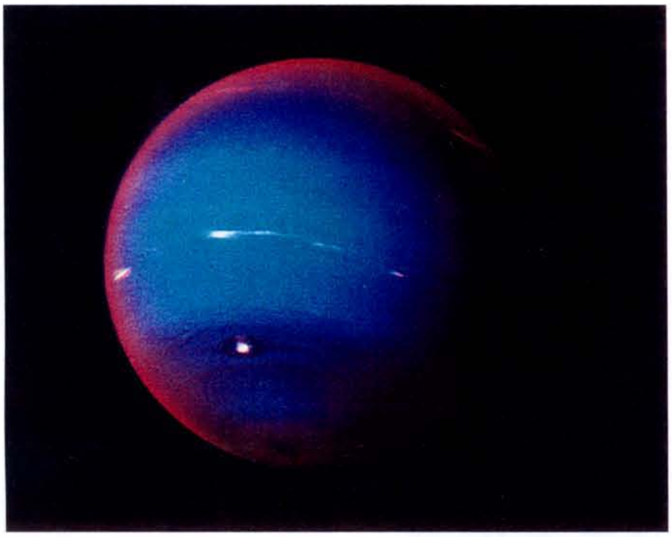
After 12 years on the road to the outer reaches of the solar system, Voyager 2 has sent us a postcard from Neptune—nearly 3 billion miles away as the crow flies, and over 4 billion miles distant along Voyager's route. But it was the addressees who were having a wonderful time and wished they were there. Scientists (and reporters), many of whom had also watched eagerly a decade ago when Voyager 1 returned the first spectacular images of Jupiter and its moons, again waited anxiously through the night of August 24 and 25 for new surprises from the final flyby. They were't disappointed. At about 9:00 PDT that evening, Voyager buzzed a mere 3,000 miles over Neptune's north pole and lit out for Triton, Neptune's largest moon and arguably one of the oddest objects in the solar system. When the close-up images of Triton began to arrive at 3:40 a.m., four hours after leaving the distant spacecraft, levity ("I think I see Elvis's footprints." "Isn't that where the 405 freeway meets the 5?") gave way to awe. Incredibly detailed, perfectly focused pictures revealed an extraordinary variety of terrains, the likes of some of which had never been seen anywhere else in the solar system.

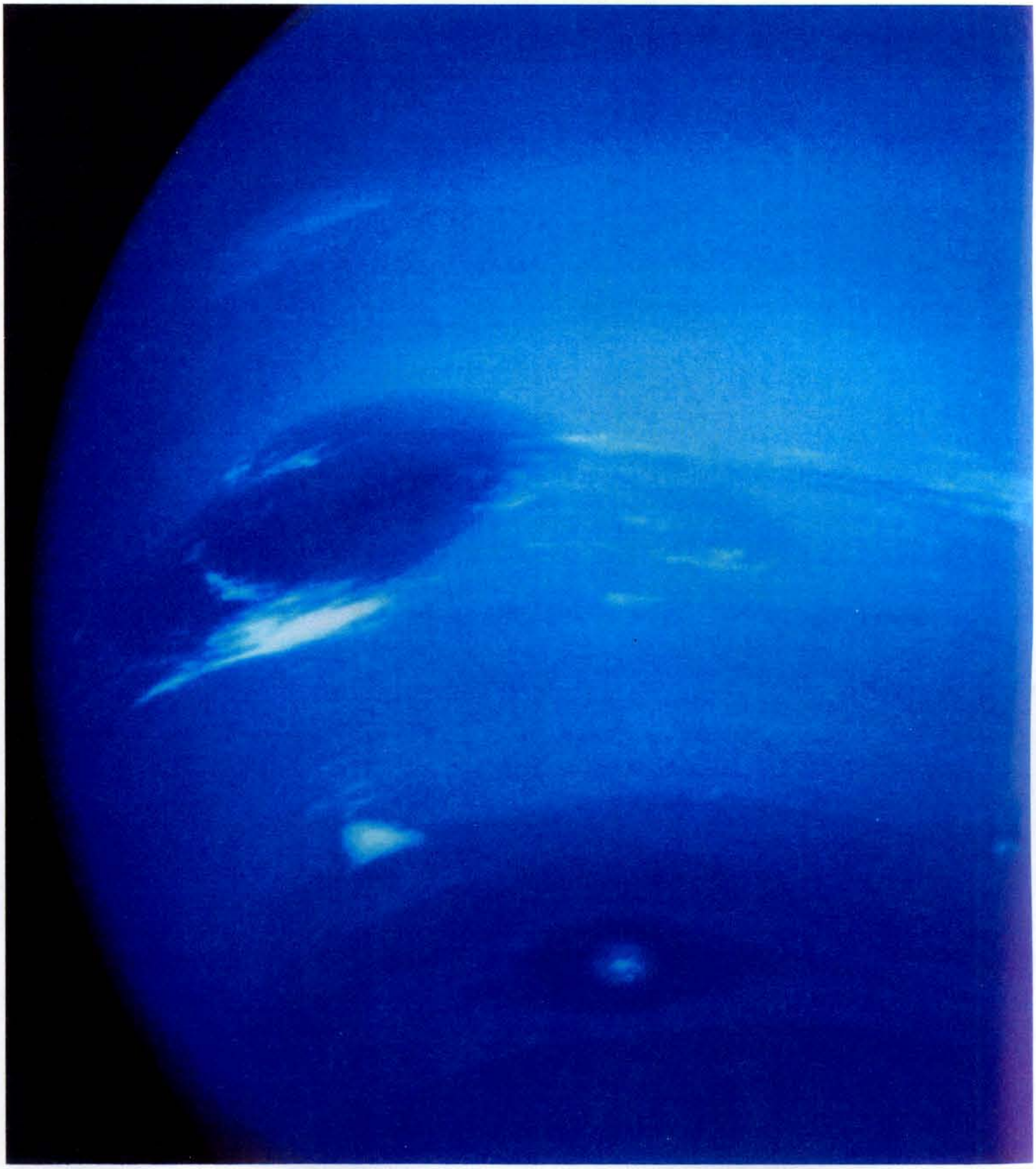
All over JPL, project scientists, engineers, and anybody else who could think of an excuse to be there stood glued to the closed-circuit monitors that served up each new frame as fast as the image-processing system could reconstruct it. Even the photogeologists, whose job it was to interpret the images, were transfixed, unwilling to begin looking closely at a print of one image for fear of missing the first glimpse of the next. In the press room, 50 reporters jockeyed for position in front of the monitors. A howl of disappointment went up part way into the hour and three-quarter's worth of images when the stream of close-ups from the narrow-angle camera was interrupted by some wide-angle camera shots of the entire surface. "Incredible," one reporter mused. "A few hours ago, when our best view of Triton was a fuzzy blob with a topknot, we'd have been thrilled by these pictures. Now we're booing them off the screen."

At the next morning's press conference, bleary-eyed but jubilant scientists traded theories with the self-styled "pressroom imaging team," while acknowledging that real, scientific interpretation of the images would take more time and sleep than anyone had yet had.

From Monday, August 21, through Tuesday, August 29, it was standing room only in von Kármán Auditorium every morning at 10:00 for the daily press briefing by a panel of Voyager scientists. The lineup changed from day to day, as various experiments got their share of the limelight, but the panel always included Project Scientist Ed Stone. At the close of the final conference, Stone, who had also presided over the Voyager encounters with Jupiter, Saturn, and Uranus, was moved to quote T. S. Eliot: "Not farewell, / But fare forward, voyagers."

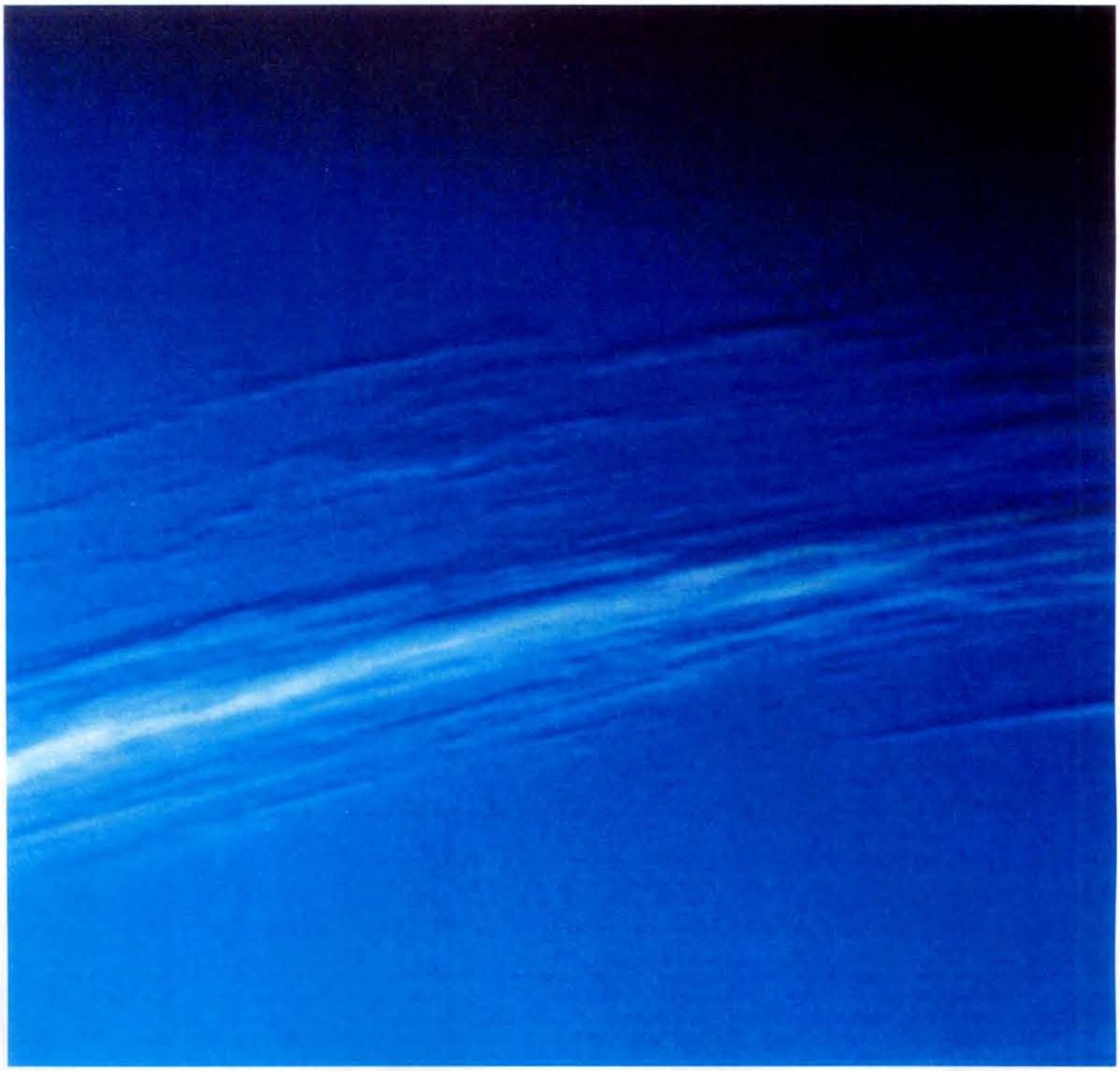
Stay tuned. An upcoming issue of *Engineering & Science* will bring you the full story of the latest discoveries from Neptune as written by Stone, who is Caltech's vice president for astronomical facilities, and a professor of physics, as well as project scientist for Voyager.

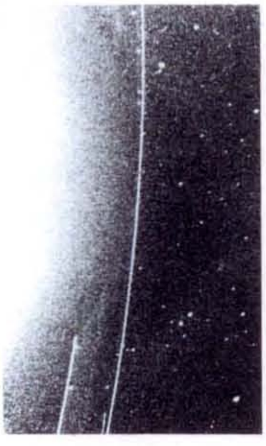


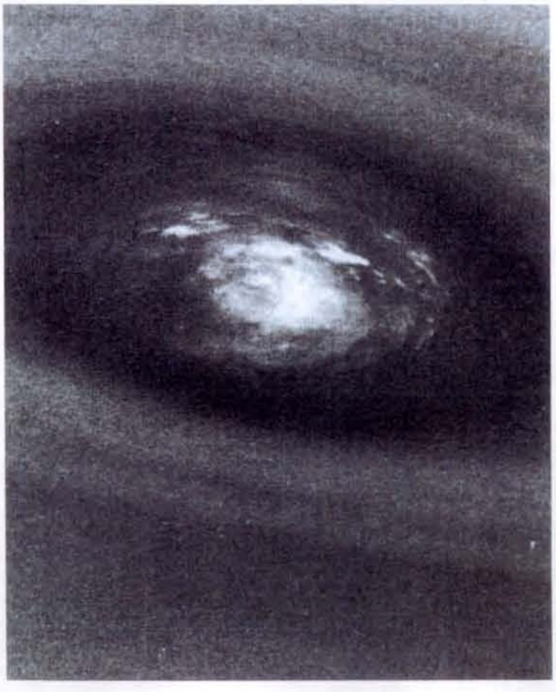


Above: Neptune's methane haze shows up in this false-color image using a filter that passes light at a wavelength absorbed by methane gas. The edge of the planet appears red because the haze is scattering sunlight before it passes through most of the methane layer where some wavelengths are absorbed. Right: Reconstructed from two images, this photograph shows Neptune's Great Dark Spot, accompanied by bright, wispy clouds. To the south lies another atmospheric feature, nicknamed "Scooter" because it travels eastward faster than other features. Still farther south is "Dark Spot 2." Because the features move at different velocities, it was rare to capture them all at once.

Right: At 97,000 miles from Neptune, just two hours from its closest approach, Voyager photographed these fluffy clouds and their shadows on the underlying cloud deck. This is the first time cloud shadows have been seen on a planet other than our own. The widths of the cloud streaks range from 30 to 125 miles, and they are about 30 miles high.

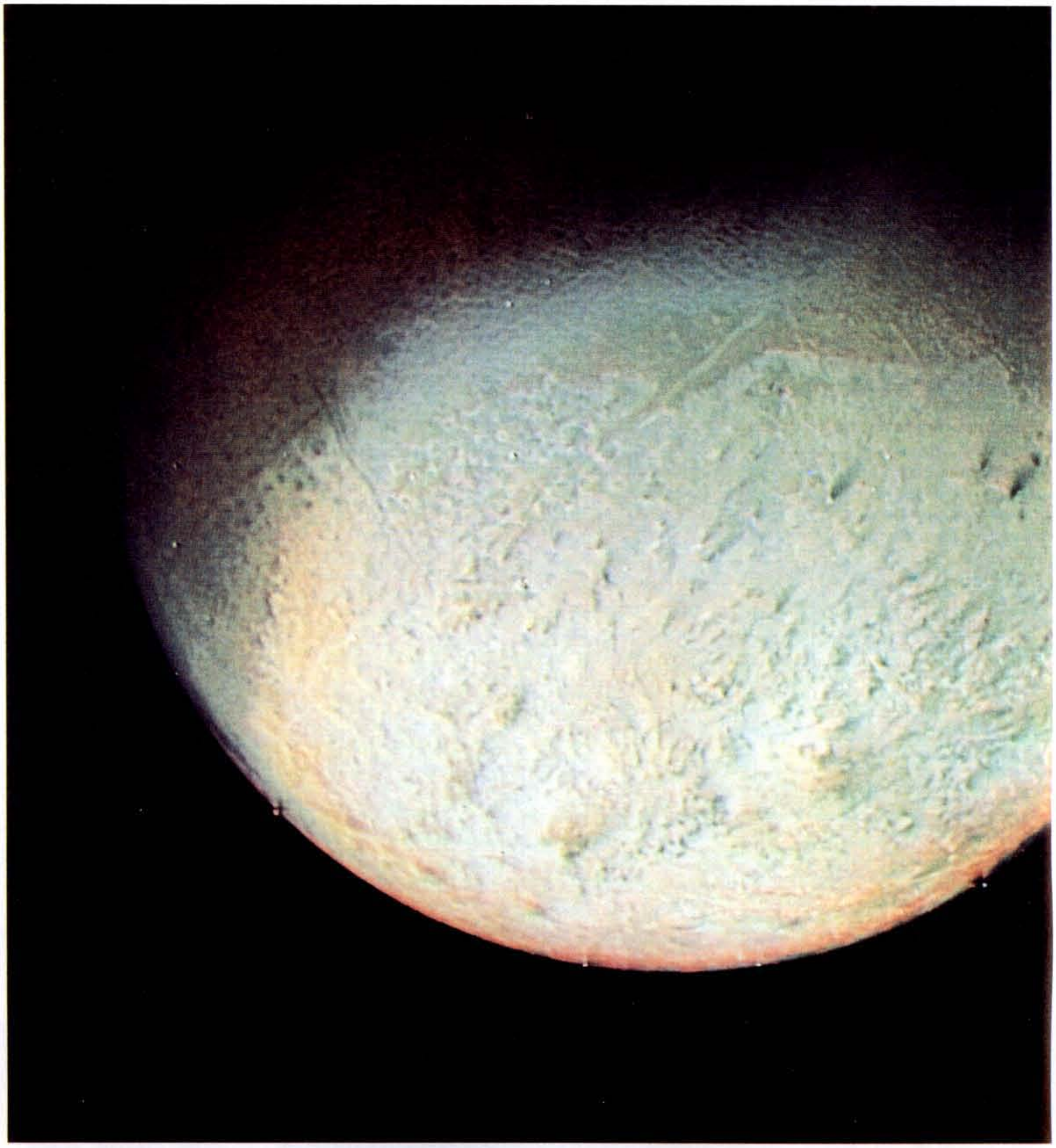


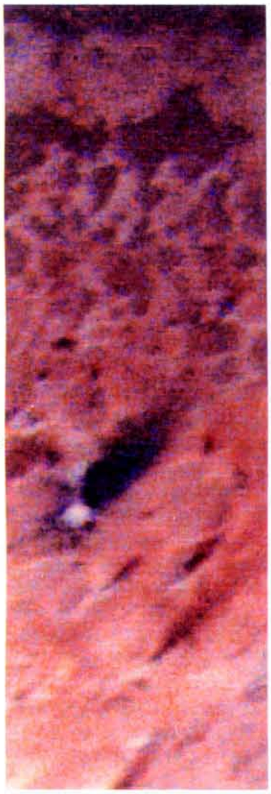




Far left (top): Dark and pitted, 1989N1, one of the Neptunian satellites discovered by Voyager, has an average radius of about 120 miles.
Far left (bottom): Neptune's shadow falls across the innermost of the two bright rings. Voyager discovered the faint, broad band of ring material just barely visible here close to the inner ring.
Left: Neptune's small dark spot was photographed at high resolution from 680,000 miles away, showing cloud structures as small as 12 miles across.

Right: Triton, Neptune's largest satellite, was photographed here at a range of 330,000 miles through the green, violet, and ultraviolet filters. Although this technique makes regions that are highly reflective in the ultraviolet appear blue in color, Triton is generally pinkish.

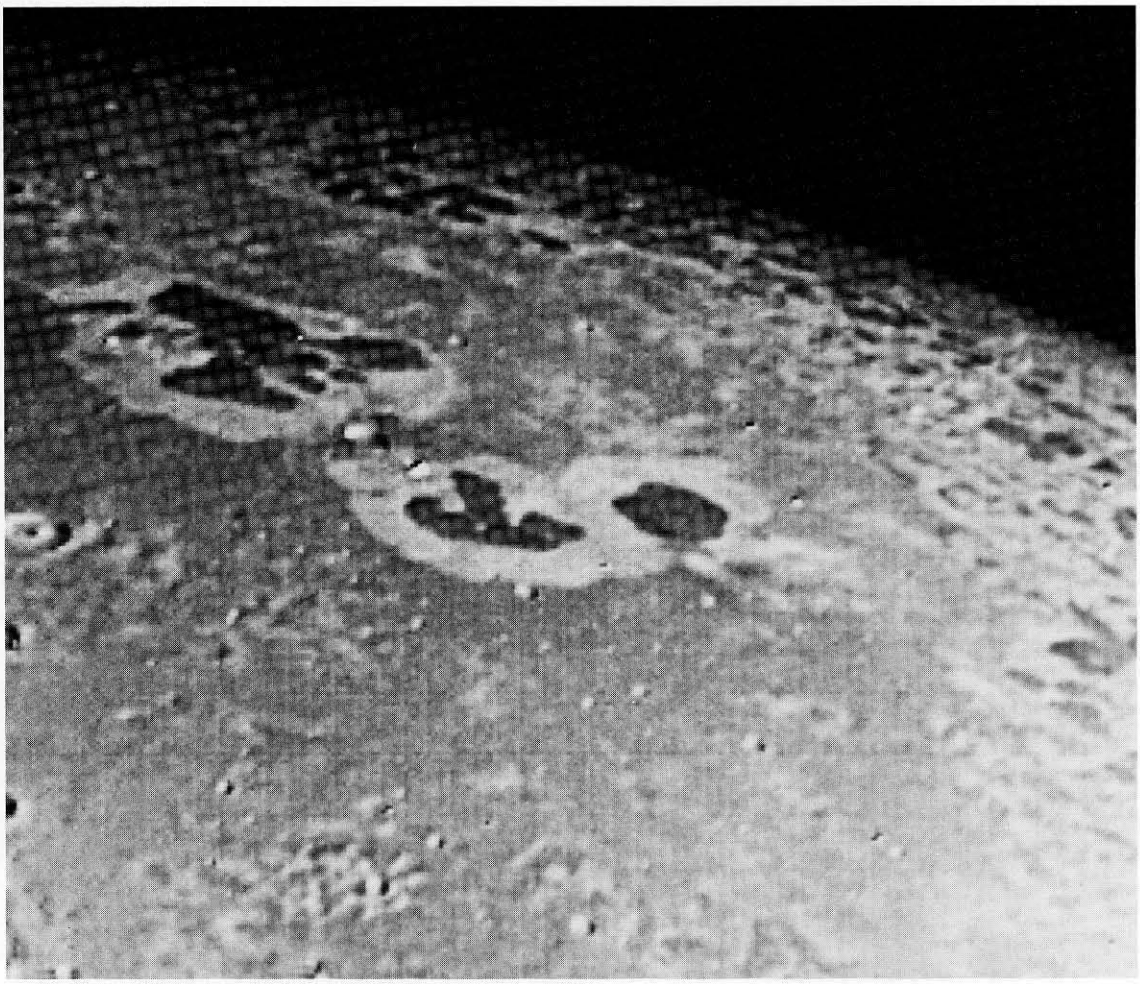




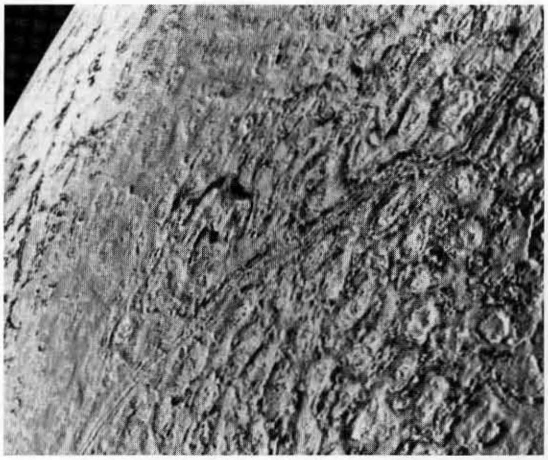
Left: Triton's south polar terrain reveals about 50 dark plumes, which are thought to be ice volcanoes spewing dark material from beneath the surface that is then carried by a southwesterly wind to form streaks as long as 100 miles. One of these volcanoes is shown in detail at far left. Subsequent studies, in which one was caught in the act of erupting, prove that the volcanoes are still active.

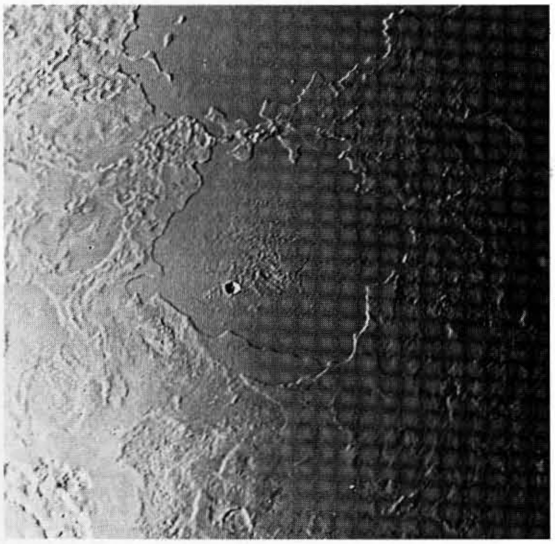
Top: Not freeways, but faults are visible on this relatively young icy surface on Triton. The vertical linear feature is a down-dropped fault block about 20 miles across. The smallest details visible here are about 1.5 miles in size.

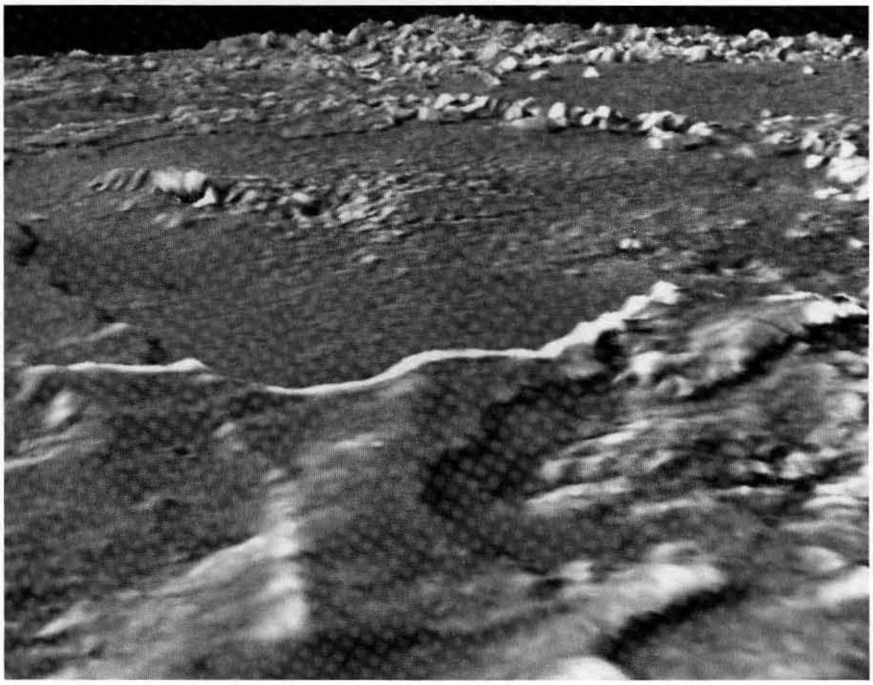
Bottom: Great dark patches surrounded by brighter material are another intriguing feature of Triton's surface. The frame here is about 600 miles wide.

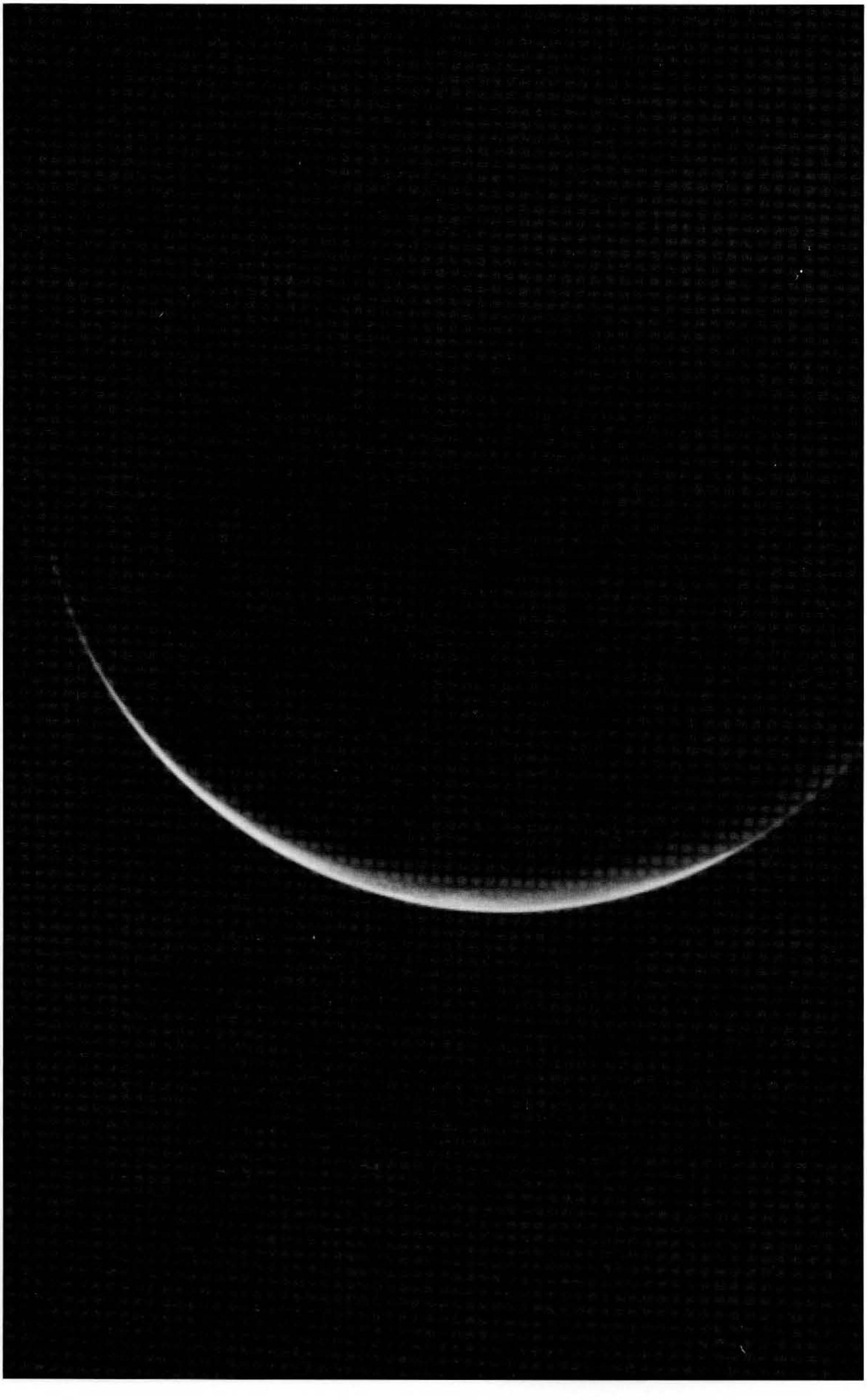


Right: One of the most detailed views of Triton, photographed by Voyager early on the morning of August 25, was made from a distance of only 25,000 miles and shows details as small as half a mile. This type of terrain, which covers much of Triton's northern hemisphere, is unlike anything seen elsewhere in the solar system. The depressions are not thought to be impact craters.
Far right: This large depression and its neighbor probably are old impact basins, heavily modified by several episodes of flooding, melting, faulting, and collapse.
Below: The same depression, about 120 miles in diameter, is rendered in computer-generated perspective, as it would appear if viewed from the northeast. The topography is vertically exaggerated 20 times. The small impact crater in the center of the image is about 8 miles across and 3,000 feet deep.









Leaving Triton, Voyager catches a look back at the thin crescent of its illuminated south polar region at a distance of 56,000 miles.

From Microscopy to Microfabrication

One example of the synergism between science and engineering is the scanning electron microscope.

by Thomas E. Everhart

Caltech President Tom Everhart holds an Everhart-Thornley secondary-electron detector from 1967, when the first commercial scanning electron microscope was produced. The encased detector was presented to him by his colleague Oliver Wells.

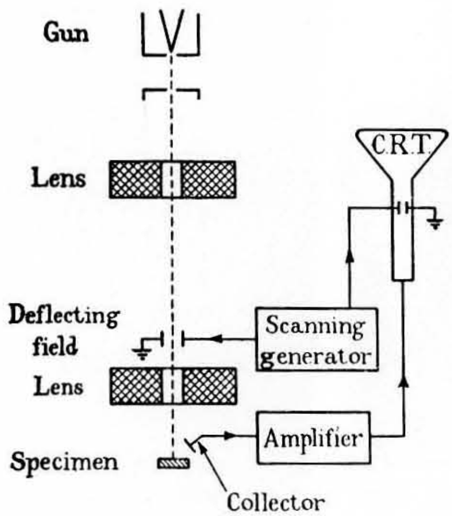
We sometimes forget how much technology has advanced during our lifetimes. These advances have been generated both by scientists, who are improving our understanding of the natural world, and by engineers, who create new devices, processes, and instruments in the man-made world. One example of this synergism between science and engineering is the scanning electron microscope, an instrument with which I have had some experience. It was used first for scientific investigations—to visualize objects to improve our understanding of nature. More recently, in a derivative form as an electron beam writer for mask making and direct exposure of integrated circuits, it has been used to fabricate microstructures that help to develop new technology.

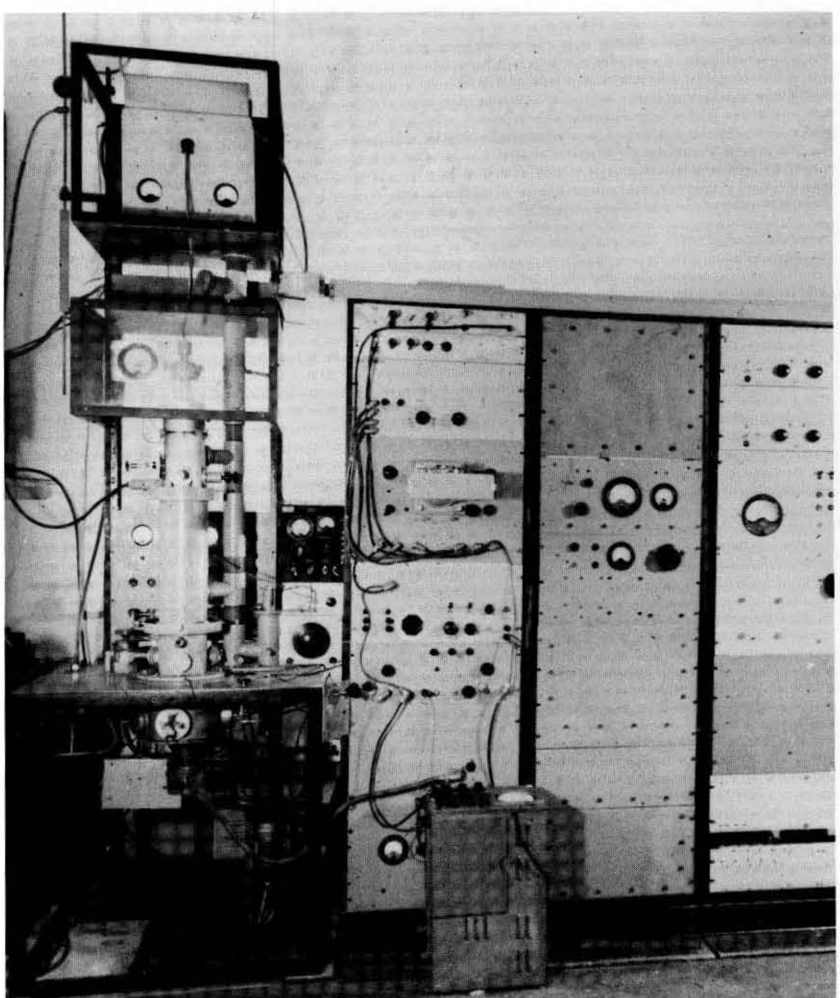
First let's look at the advances in science that led to electron optics and to the electron microscope itself. De Broglie's hypothesis that particles could have a wavelike nature provided the stimulus for thinking that suitable lenses might be used to focus particles. Slightly earlier, Busch had shown that electrons could be focused by axially symmetric magnetic fields, and these two ideas allowed Ruska to develop the first transmission electron microscope in Germany in the early 1930s, a feat for which he recently shared the Nobel Prize in Physics.

Even earlier (in 1929), a German named Stinzing had filed a patent for a *scanning* electron microscope, in which a finely focused electron beam scans across the sample, but the technology to build it did not exist at that time. Knoll in Germany worked on a rudimentary scanning electron microscope in the mid-1930s, and von Ardenne, another German, actually constructed a transmission scanning electron microscope in the late 1930s. This may have been the stimulus for Zworykin, Hillier, and Snyder, working at the RCA laboratories in the very late 1930s and early 1940s, to construct a rather sophisticated scanning electron microscope. However, by having the scanning electron beam incident perpendicular to the sample surface, they were unable to get good contrast, and they abandoned the idea to pursue others that they deemed more promising.

After World War II, C. W. Oatley at Cambridge University in England and his graduate student, Dennis McMullen, developed a scanning electron microscope (SEM) that had the sample inclined at an angle to the electron beam, used backscattered electrons as the signal source, and amplified these with a beryllium-copper electron multiplier in the demountable vacuum system. This instrument used electrostatic lenses, was built of war-surplus electron tubes, and was a remarkable instrument, considering that it was put together by one graduate student in less than four years. Ken Smith followed McMullen on this instrument. He made it work better and explored the fields of application for which it might be appropriate. The third student in Oatley's group at Cambridge was Oliver Wells, who was given the task of building a second scanning electron microscope, which he used to investigate fibers, among other applications. In 1955 I arrived at Cambridge University and was the third student to use the original McMullen

McMullen's dissertation contained this diagram (right) of a scanning electron microscope. Below is the instrument that McMullen built, which Everhart inherited in 1955, the third graduate student in Oatley's Cambridge lab to work on it.



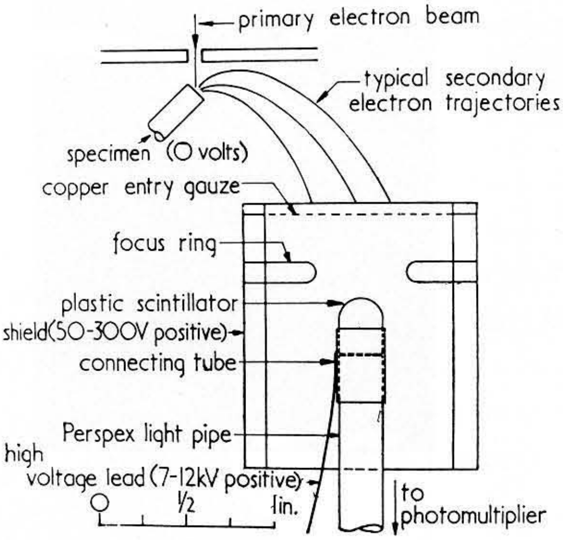


microscope, as modified by Ken Smith. My task was to investigate contrast formation in the scanning electron microscope, a topic that was very educational and that three years later resulted in an acceptable PhD thesis. I would like to explain a bit about my experiences there and how they led to subsequent developments that have been fascinating to me and, I believe, useful for many people.

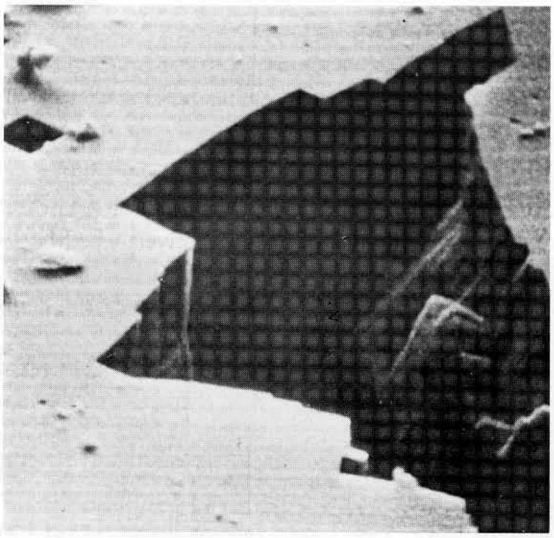
The schematic diagram of a scanning electron microscope at left is the one that Dennis McMullen actually used in his PhD thesis. The electron gun had a tungsten hairpin filament cathode, which operated well in a demountable vacuum system of 10^{-5} to 10^{-7} torr. The lenses were electrostatic; the deflecting field, which was also electrostatic, was inserted before the second lens to enable the second lens to have a very short focal length. The image was formed by signals generated by the primary electron beam, which were amplified and used to modulate the intensity of a cathode ray tube, which was scanned synchronously with the electron beam in the microscope. In this way there was a one-to-one correspondence between points on the sample surface and points on the face of the cathode ray tube. The ratio of the size of the image on the cathode ray tube divided by the size of the raster scanned on the sample provided the magnification of the microscope. In essence, the scanning electron microscope is a closed-circuit television system.

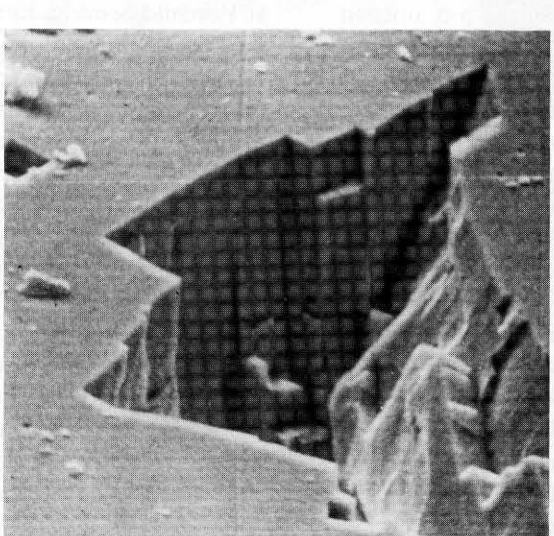
Shown at left is the instrument as I inherited it. This looks very different from one that you would buy commercially today or even from the first commercial SEM. The extra-high-tension power feed is shown at the top left. Notice the wooden dowel, which has a metal electrode and an insulated wire attached to it. This dowel was moved up to the top when you wanted the first electron lens to have the minimum focal length, and down to the bottom when you wished to ground the center electrode and remove the lens entirely from the system. You could adjust the focal length and the voltage on the center electrode of the electron lens by moving the dowel to an intermediate position. I had not learned in college-taught physics that wooden dowels were good resistors and could be used in this way to vary voltage. Dennis McMullen was ingenious, had imagination, and, because of his limited budget, used the materials that were at hand. These characteristics are important in university research even today.

McMullen believed that the signal he was detecting was produced by backscattered electrons, the primary, high-energy electrons scattered through large angles by atomic nuclei in



In the secondary electron detector known as the Everhart-Thornley detector (right), low-energy secondary electrons emitted by the sample are easily deflected and can be attracted to a gridded collector and there accelerated into a plastic scintillator by a small positive voltage. A light pipe carries the scintillation light to a photomultiplier, which amplifies it and produces a video signal.



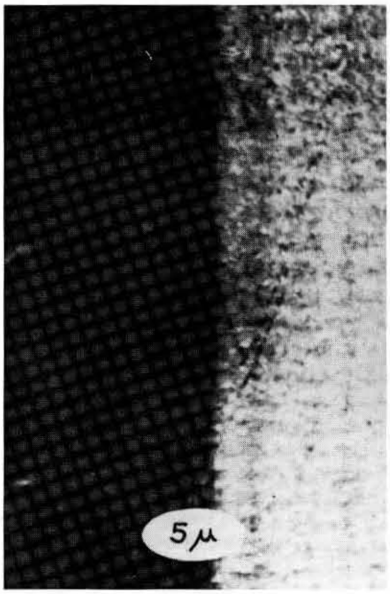


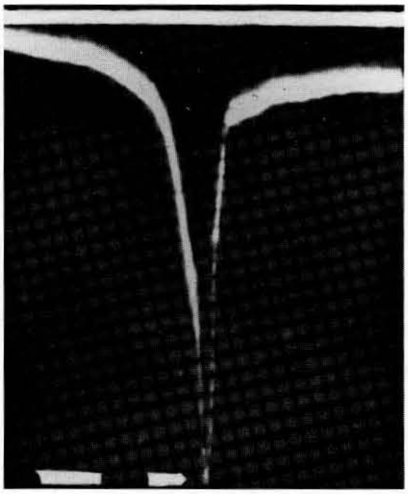
Two images of an etched piece of aluminum made with primary (backscattered) electrons (top) and secondary electrons (bottom) are shown at right. The low-energy electrons' curved paths allow the microscope to "see" into the crevice.

the sample, which, because they have high energy, travel in relatively straight trajectories. On the other hand, Smith believed it likely that secondary electrons (those emitted by the sample when hit by the primary electron beam) were producing much of the signal that he collected with the secondary electron multiplier. I set about to determine which signal was the most important and what differences, if any, could be seen by using these quite different signals from a common sample.

In the detector system that I used for backscattered electrons a large solid angle was subtended between the sample and a plastic scintillator, which would produce light when struck by electrons. This light was carried by a light pipe to a photomultiplier, which amplified the light and provided the video signal from the backscattered electrons.

The diagram above shows a collector system for secondary electrons. It also used a plastic scintillator and a light pipe, which guided the light to the same photomultiplier, but here the light was produced by secondary electrons that were attracted to the scintillator by a small positive voltage placed on the copper grid and accelerated to about 10 keV to produce light. The backscattered electron image from an etched sample of aluminum is shown in the top micrograph at left. By moving the backscattered scintillator to one side, you could image exactly the same surface with secondary electrons (bottom, left). Because the secondary electrons have low energy, they are easily deflected and follow curved trajectories. They can be extracted from





The scanning electron beam and the electronic structure of a semiconductor's p-n junction interact. In a cross-section (left) through a biased germanium-indium p-n junction, the applied voltage difference across the junction translates into a contrast difference in the image, revealing the junction's exact location. At the same time the hole-electron pairs created when the beam sweeps across the junction show up as a large spike (right) on an oscilloscope monitoring the current through the junction.

deep crevices, and you can "see" into the holes. Because backscattered electrons follow straight trajectories, a line-of-sight path did not exist from these crevices to the detector, and the holes appeared dark. Both types of signals are still used today. The secondary-electron detector, with slight modifications, has been used in most commercial SEMs and is often referred to as the Everhart-Thornley detector.

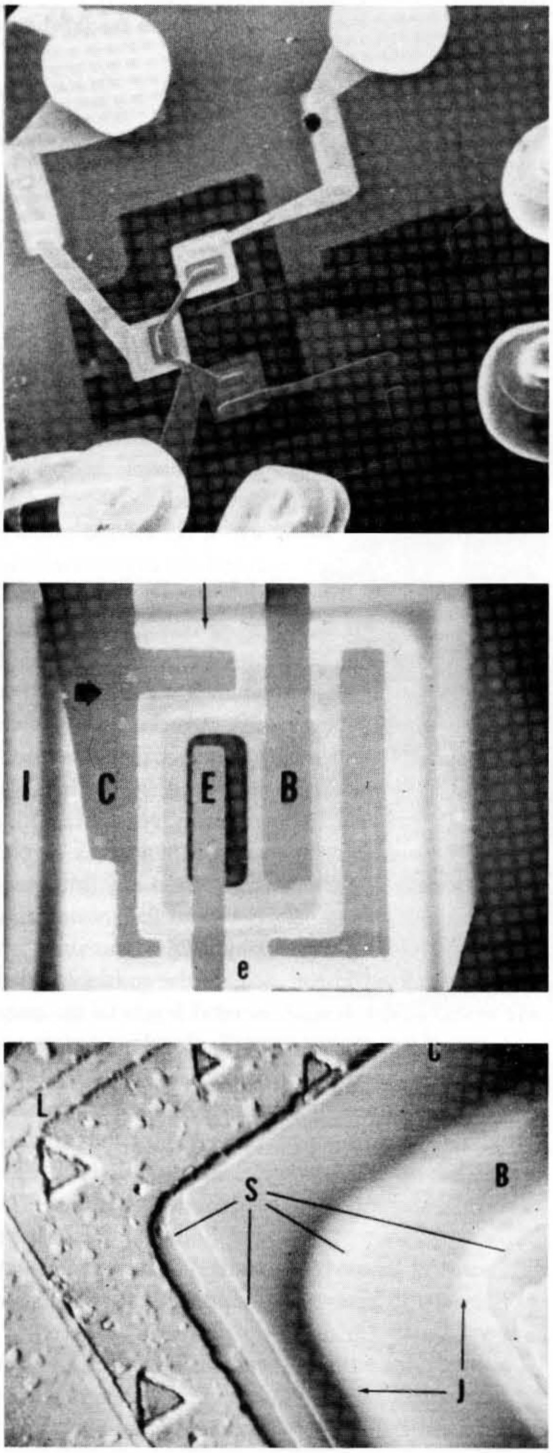
What could we do with this new technique? One of the samples we thought would be interesting to examine with the SEM was a semiconductor containing p-n junctions. Surface effects caused the locations and functioning of these junctions to be poorly understood at the time, yet they were quite important. (The transistor had been introduced in the late 1940s.) The biased germanium-indium alloyed p-n junction shown above had been polished perpendicular to the junction; by putting a voltage across the junction, we could determine exactly where the junction was, using a contrast induced by the difference in voltage between the two sides of the junction (a topic explained in my thesis). Also, when we monitored the current through the reverse-biased junction, we observed a very large current when the beam swept across the junction. This is due to electron-beam-generated hole-electron pairs, and in later work was called the electron-beam-induced current.

When I joined the faculty of the University of California at Berkeley after receiving my PhD from Cambridge in 1958, I had no desire to work on scanning electron microscopy. For one thing, I had no microscope available in the United States. A second reason was that the microscope I had used at Cambridge was not very reliable, and I didn't want to become involved with all those equipment difficulties again. And a third reason was that we had sent the micrographs of biased junctions to some semiconductor scientists at a major U.S. company and received word back that there was absolutely no interest in this technique among anyone working in semiconductors. Foolishly, I believed this.

By 1960, however, I was beginning to think that there might be some value in returning to this field because I had heard about the possibilities of integrated circuits. This idea, which, as far as I can tell, was conceived independently by Jack Kilby at Texas Instruments and Bob Noyce at Fairchild Semiconductor (who recently won the Draper Prize for this work), had the desirable feature of allowing several different electrical components to be integrated into a single circuit, so that separate electrical connections did not have to be provided between them. Our previous work with biased junctions indicated that the SEM might have very useful applications in analyzing integrated circuits. So, in 1962 I teamed up with Oliver Wells at Westinghouse Research Labs in Pittsburgh to help construct the first scanning electron microscope in an American corporate research laboratory.

Several people had assured me that passivated integrated circuits were covered with a layer of glass, which charges up under electron bombardment, and that therefore there would be no hope of observing voltage differences on the

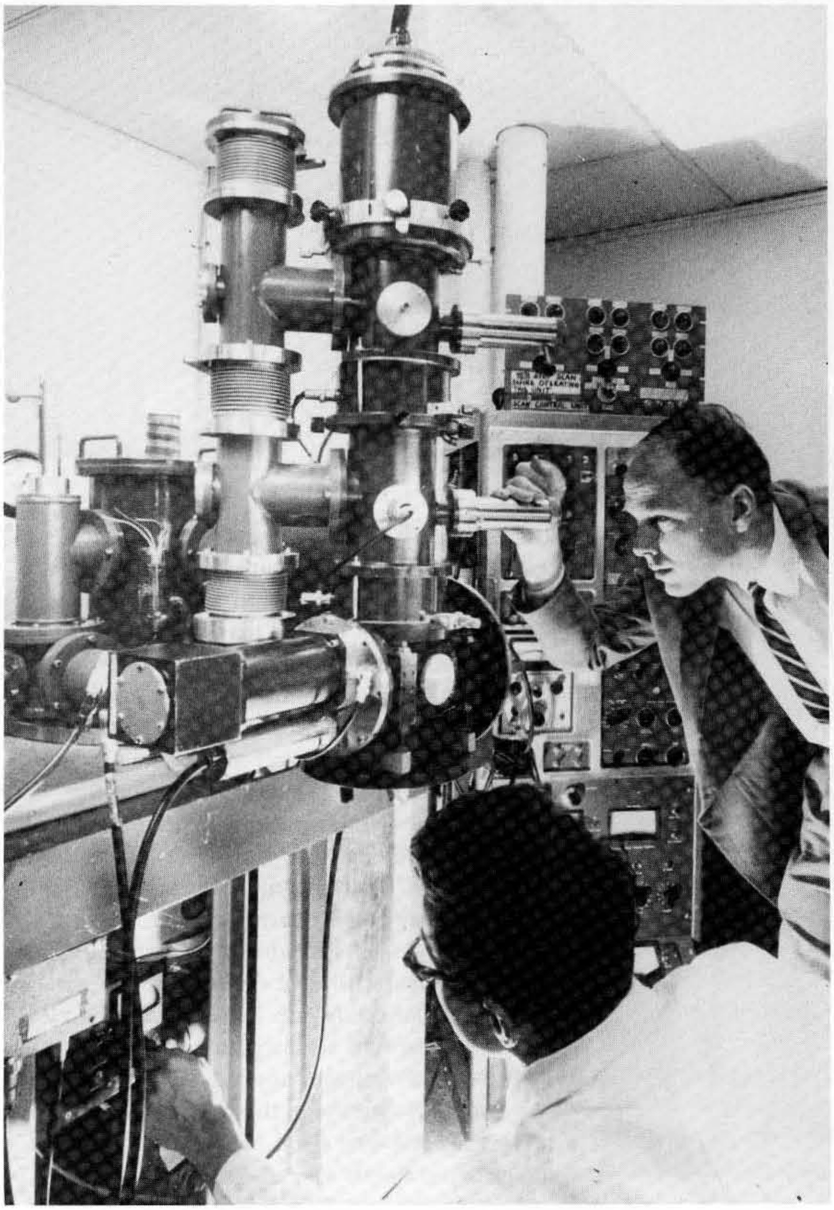
Our previous work with biased junctions indicated that the SEM might have very useful applications in analyzing integrated circuits.



This scanning electron micrograph (top) of an early-1960s integrated circuit shows three transistors as black-bordered squares. Applied voltage-induced contrast causes the transistor elements to appear as various shades of gray, and the junctions between them can be seen clearly as can the bonds to the electrical leads. A close-up of a mid-1960s transistor (middle) shows the isolation region (I) between it and its neighbors, its elements—emitter, base, and collector—and the leads (E, B, C) associated with each element. Adding the secondary signal to that current also provides information about the surface of the integrated circuit (bottom) as well as the junctions underneath.

surface of such a device by using an electron beam. But I had faith that we could do this. In Cambridge I had observed aluminum samples, and it is well known that aluminum is covered with aluminum oxide, although the oxide is only a few tens of angstroms thick. When we inspected our first integrated circuit at Westinghouse in 1962 and immediately saw voltage contrast, I had to explain this apparent paradox. The answer is electron-beam-induced conductivity through the glass layer. Later calculations proved that the primary beam had enough energy to penetrate the glass, creating conductivity in the insulator by exciting electrons from the valence band of the insulator to the conduction band. At top left is a scanning electron micrograph of an integrated circuit of the 1962 era with voltages applied, showing that one can easily determine the position of the junctions and get a very good idea of the quality of the electrical bonds as well.

After a year at Westinghouse I returned to Berkeley, where a scanning electron microscope was constructed along similar lines, using some commercial electron guns and lenses, and home-built magnetic deflection coils that were outside the vacuum. With Don Pederson and Paul Morton, we established the first integrated circuits laboratory at a U.S. university. The micrograph at left in the middle, made using electron-beam-induced currents, shows a mid-sixties transistor; you can see the isolation region (between this transistor and others in the integrated circuit), the emitter, the base, and the collector leads, as well as the junctions between



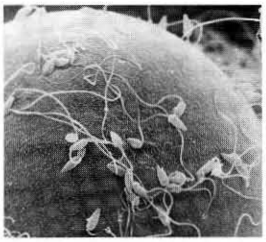
At Westinghouse Research Lab, Everhart (right) and O. C. Wells use the scanning electron microscope that was first operated in December 1962.

these regions. By mixing the secondary signal with this electron-beam-induced current, as shown in the bottom micrograph on the previous page, we could get information about the surface of the sample as well as about the junctions underneath. We had demonstrated that there was a considerable amount of information that could be determined, and thus the use of scanning electron microscopy to help in the development of integrated circuits was launched.

Berkeley later obtained one of the first commercial scanning electron microscopes in the U.S. through the efforts of Fabian Pease, and we examined many different samples in it. The original home-built SEM was connected to a computer by Noel MacDonald, and was used for early experiments on electron beam lithography. Electron beam lithography held much greater potential for miniaturization than photolithography, which was used up to the mid-1970s to create the masks for defining the patterns of the several layers of an integrated circuit. Commercially developed electron beam exposure systems for writing masks have gradually taken over much of the mask making and have led to much progress in miniaturization since then.

Indeed, Richard Feynman's prophetic speech on miniaturization ("There's Plenty of Room at the Bottom," *E&S*, February 1960) included a challenge to reduce a page of a book to an area 1/25,000 smaller in linear scale. This was finally accomplished by a Stanford grad student in the fall of 1985—using electron beam lithography to etch a text on an area 5.9 micrometers square (*E&S*, January 1986). The student, Tom

This is the way both science and engineering progress—we build on the accomplishments of one another.



Integrated circuits aren't the only application of the SEM. It's an essential tool in the study of embryonic development; the fertilization of a sea urchin egg is shown in the top micrograph. And the SEM allows geologists to "see" into meteorite inclusions. The lower picture is the first ever made of a platinum-rich nugget (called a Fremdling) cracked out of an inclusion in the Allende meteorite. These tiny balls of highly concentrated metals are thought to contain samples of the first atoms to have condensed out of the newly forming solar system. Both of these are secondary electron images.

Newman, working with the previously mentioned Fabian Pease, was involved in research to enhance electron beam lithography for writing masks for VLSI chips.

It's obvious that a great deal of technology is involved in making integrated circuits and in inspecting them. What is not generally appreciated by the public at large (or even by scientists) is to what degree technology drives science. The old reasoning that the scientist discovers new knowledge and that this new knowledge is then applied to make new technology is only partly true. Without the technology of integrated circuits and high-speed computers, many of the scientific experiments undertaken today would not be possible, and scientists would be severely limited in discovering new knowledge. Without some of the techniques of information theory that were developed because of engineers' interest in communication, the decoding of DNA would be proceeding at a much slower pace. Most of our knowledge of the biological world below the resolution of the light microscope has been achieved using the electron microscope, an instrument developed by scientists and engineers, which has provided the means to understand molecular biology and a great deal of the structure of cells and of more elementary biological units.

There have been many advances in scanning electron microscopy since the days of the early instruments I have reviewed here. We have a much better understanding of the information generated by the scanning electron beam now than we did when McMullen started his work in 1949. I am indebted to my many colleagues at Cambridge and to my graduate students at Berkeley who worked with me on some of these topics, to my colleagues at Cornell who contributed significantly to submicron fabrication, as well as to the many colleagues around the world who have worked in these fields over the last three-plus decades. This is the way both science and engineering progress—we build on the accomplishments of one another. In order for America to remain competitive, we need to invest more in building the equipment and instruments that make possible more extensive and more rapid advances in science and technology. We must also recapture the sense of urgency in this process. □

Subsequent to his significant work in the development and application of the scanning electron microscope at Cambridge and Berkeley, Tom Everhart took on some administrative posts (dean of Cornell's College of Engineering and chancellor of the University of Illinois at Urbana-Champaign) before becoming president of Caltech in 1987. The Everhart-Thornley secondary-electron detector had preceded him here, however, and it continues to be an essential part of scanning electron microscopes used on campus. This article was adapted from a talk delivered to the College of Fellows of the Institute for Advancement of Engineering in 1988.

"That's the gist of what I want to say. Now get me some statistics to base it on."

White Lies, Damned Lies, and Statistics

Year after year, decade after decade, well-meaning educational researchers and policymakers continue the search for the perfect statistic.

by Lisa C. Heinz

Education is a profligate generator of silly statistics. In particular, attempts to measure the *quality* of education produce data-rich, fervently read reports. (Warning—this article contains a good dose of said silly statistics, and three unanswerable questions.) Year after year, decade after decade, well-meaning educational researchers and policymakers continue the search for the perfect statistic. Over the past year, the U.S. Department of Education spent $78 million on educational research and statistics; the National Science Foundation doled out another $5–8 million for science-education analysis and statistics.

Caltech usually comes out immodestly high in university quality rankings, whether in magazine articles or college guides. Caltech was fourth (behind Yale, Princeton, and Harvard) in *U.S. News & World Report*'s latest ranking of major universities, released in October.

University quality = research quality?

Such rankings usually emphasize Caltech's research preeminence. For its size, Caltech comes out well—number 36—in the favorite Washington statistic for research quality, federal R&D dollars. Federal R&D receipts may be the most obvious, and easiest, metric, but is an unsatisfactory measure of a university's research performance.

The National Science Foundation is sponsoring research on more sophisticated metrics of research quality. Larry Leslie and others at the University of Arizona have compiled a multidimensional research activity index (RAI) for the top 200 research universities of 1980. The RAI combines 14 weighted variables, such as the amount of R&D funding from various sources, total research expenditures, employed scientists and engineers, numbers of full-time graduate students and postdocs, PhDs awarded, and a research library score from the Association of Research Libraries Index. However, the RAI still measures the scale, rather than quality, of research. The Top Ten on the RAI generally are the familiar big-name research universities. The University of Arizona group is currently developing RAIs which adjust for institutional size and for individual fields, and is investigating how to include measures of research outputs (for example, publications and citations) as well as research inputs (dollars and people).

But the amount of federal R&D money a university can attract is fairly far removed from the quality of its education. Unanswerable question #1: Does first-rate research foster first-rate education? Universities have multiple personalities. There is a natural tendency for the strongest persona, whether research or education, humanities or engineering, to dominate. Integrating research and education into a harmonious, yet unique, university takes deliberate effort. Nobel laureates and multimillion-dollar research grants may be all well and good for the *research* university, but the *education* part of the university must be attended to as well.

Trying to measure education

It is education, rather than research, that catches the popular headlines. Unanswerable question #2: Is it possible to measure the qual-

Unanswerable question #2: Is it possible to measure the quality of education?

Table 1
Leading Undergraduate Sources of Science and Engineering PhDs
(s/e PhD productivity)

rank, adjusted for institution size		percent*	rank, EMP **	rank, life sciences	rank, not adjusted for institution size
1	Caltech	44	1	2	32
2	Harvey Mudd	31	2	20	207
3	MIT	21	3	3	2
4	Reed	21	6	3	104
5	Swarthmore	17	11	—	78
6	Cooper Union	14	4	—	146
7	U. Chicago	14	14	10	23
8	Radcliffe	13	—	8	154
9	Rice	12	5	—	51
10	Haverford	12	—	—	179
11	Carleton	11	15	13	111
12	Pomona	10	20	13	108
13	Grinnell	10	—	17	159
14	Oberlin	10	35	32	50
15	UCSD	9	21	5	112
16	Antioch	9	—	39	131
17	Cornell	9	23	8	5
18	Princeton	9	12	—	28
19	Wesleyan	9	—	—	140
20	Wabash	9	23	13	222

* Percent of all baccalaureate graduates from that institution who went on to get s/e PhDs. The study covered graduates between 1950 and 1965, to insure that they would have earned PhDs by 1986.

** EMP is engineering. mathematical and computer sciences, and physical sciences (such as astronomy, chemistry, geology, environmental sciences, physics). Life sciences includes agricultural, biological, and health sciences.

ity of education? There is no simple quantitative measure that can be applied to so nebulous a thing as learning. People turn to proxies, such as SAT scores, class size, and student-faculty ratios to size up a university's learning environment.

The university may be considered a black box: students go in, and (for better or worse) future citizens and workers come out. When most analysts look at the black box, they see a university's dollars, books, buildings, or graduation requirements; the "quality" of its faculty and students. Less official but popular measures are the greensward-asphalt ratio, average parties per week, per-capita beer consumption, the ratio of total downhill miles plus annual snowfall to the distance to ski slopes, and the gut-course/killer-course ratio.

The more pragmatic analyst, rather than looking at the black box, might consider the *output* of a university. After all, parents and students are interested not only in the college experience, but in how an $80,000-plus college education will advance an eventual career. Today's students seek power careers and high salaries, while social activism and life enrichment have waned in value; according to a recent UCLA survey, being "very well off financially" is the top goal of incoming freshmen, a goal that has risen steadily in popularity since the mid-1970s.

Ideally we might like to measure how well a college grooms students for successful, accomplished, rewarding, and satisfying lives and careers. However, the desire to measure some-

Table 2
Leading Undergraduate Sources of s/e PhDs
(rank, not corrected for institutional size)

1 UC Berkeley
2 MIT
3 University of Illinois
4 University of Michigan
5 Cornell
6 University of Wisconsin
7 CUNY — City College
8 UCLA
9 University of Texas — Austin
10 Harvard
⋮
32 Caltech

Covers bachelor's degrees awarded between 1950 and 1975. UC Berkeley spawned nearly four times as many s/e PhDs as Caltech.

SOURCE: Betty D. Maxfield, "Institutional Productivity: The Undergraduate Origins of Science and Engineering PhDs," U.S. Office of Technology Assessment Contractor Report, July 1987, Appendix A.

However, the desire to measure something interesting, such as learning, must always be compromised by the unfortunate necessity to count what is countable.

thing interesting, such as learning, must always be compromised by the unfortunate necessity to count what is countable, such as degrees or test scores.

PhD productivity

One attractive measure for the science-minded is a college's output of students who go on to become quality researchers. Now, what we can count fairly easily is a college's baccalaureate graduates who go on to get PhDs in science or engineering. Quite a few studies over the years have attempted to calculate this sort of "PhD productivity." Although PhD productivity is a fairly coarse measure, it is one of the best proxies available for a college's "output." The rest of this article discusses a recent study of science and engineering (s/e) PhD productivity, undertaken by the U.S. Office of Technology Assessment and what it does and does not tell us. This study calculated the number of BS or BA graduates in all fields between 1950 and 1976, who received PhDs in science or engineering from any U.S. institution between the 1950s and 1986. Science/engineering includes the social sciences, and the study includes only colleges that sent more than 50 students on for PhDs during the study period. (More information on methodology and results are in the original report, available from the Office of Technology Assessment, U.S. Congress, Washington, DC 20510.)

Table 1 shows some of the results of the study of s/e PhD productivity of American colleges and universities. This study developed and evaluated universities' s/e PhD productivity ratio: the percent of all graduates from that college who went on to earn a PhD in science or engineering. The results show Caltech and Harvey Mudd as clear leaders, with MIT and Reed not far behind. Over the study period, 44 percent of Caltech baccalaureates went on to earn s/e PhDs.

This productivity ratio adjusts for the size of the institution. Certainly, it is nice to know which universities send the largest numbers of warm baccalaureate bodies on for s/e PhDs. However, as Table 2 and the last column of Table 1 show, high absolute numbers of eventual s/e PhDs do not necessarily mean that the university has a high productivity. The university that sent the greatest number on for s/e PhDs is UC Berkeley, but it ranked 26th when size is taken into account. Conversely, Caltech was first in productivity, but ranked 32nd in absolute numbers of eventual s/e PhDs. The appealing thing about PhD productivity (besides making Caltech look good) is that highly productive institutions should provide lessons about the type of college environment that fosters students' interest in s/e graduate study, and their ability to earn a PhD.

A more sophisticated measure of a university's output counts only those s/e PhDs who go on to do active research. This might be called a university's "researcher productivity." Limitations in data collection and coding make this analysis a difficult proposition. Preliminary work, done by type of institution rather than individual college, has revealed that s/e PhDs who had done their undergraduate work at technical institutions, such as Caltech, MIT, IIT, and Carnegie-Mellon, were by far the most likely to go on to careers in research. On the other hand, s/e PhDs who had come from women's or black colleges were much less likely to go into research.

One flaw in this and all similar studies so far (due to the difficulty of extracting field-specific baccalaureate data from the paper-ridden seventh circle of data hell in the Department of Education) is that the basis of all calculations—bachelor's degrees—aggregates all fields. In these studies a college's s/e PhD productivity is based on the percentage of baccalaureate graduates in all fields who went on to get s/e PhDs. In reality, schools differ strikingly in the percentage of their baccalaureates who take science or engineering degrees. Common sense would argue that colleges with a high proportion of undergraduates who major in science are much more likely to send a higher proportion of their baccalaureates on to s/e PhDs. Aggregating all

Academic reputation is the single most important consideration in students' choice among colleges.

Table 3
s/e Baccalaureate to s/e PhD Productivity of Universities

rank	productivity ratio (percent of s/e baccalaureates who earned s/e PhDs)
1 Caltech	43
2 Harvey Mudd	34
3 Reed	26
4 MIT	24
5 U. Chicago	21
6 Haverford	17
7 Swarthmore	17
8 Pomona	16
9 Oberlin	16
10 Carleton	16
11 Cooper Union	16
12 Rice	14
13 Bryn Mawr	14
14 Amherst	13
15 UCSD	13
16 Princeton	13
17 Cornell	13
18 Yale	12
19 Johns Hopkins	12
20 Brown	12

SOURCE: Betty D. Maxfield, "Persistence in Higher S/E Education: S/E Baccalaureate to S/E Doctorate Productivity of U.S. Baccalaureate-Granting Institutions," U.S. Office of Technology Assessment Contractor Report, September 1987.

fields tends to inflate the s/e PhD productivity of nerd-packed schools like Caltech. Other, more diverse schools, particularly the liberal arts colleges, are surprisingly productive of s/e PhDs, given the high percentage of their undergraduates that take degrees outside the sciences.

A follow-on study corrected this flaw, calculating an s/e PhD productivity which looked only at baccalaureates who majored in s/e. When this correction was done, however, results changed surprisingly little (see Table 3). (This constancy may in part be due to counting social sciences as part of s/e.) Some schools, such as Oberlin, Pomona, and the University of Chicago, did have much higher PhD productivities when the college's emphasis on science was taken into account.

A more significant flaw is the difficulty of controlling for differences in the quality of incoming students among various universities. Certainly, the quality of the student body is at least as important as the faculty and offerings of the university itself. Unanswerable question #3: Is the high productivity of a university like Caltech due to the superior quality of its undergraduates, or to Caltech's providing a superior education?

Another recent Office of Technology Assessment study concluded: ". . . active researchers come from graduate study at a small number of top research universities. These elite research universities, however, draw on a broader base— the successful graduates of highly productive undergraduate institutions. The career decisions made by PhD recipients are influenced as much by their college experiences as by their graduate school."

Different methodologies and different simplifications result in slightly different results, but studies tend to converge on the same set of productive colleges. Taken together, these studies argue convincingly that some institutions are more likely to send their undergraduates on for s/e PhDs. What can we learn from this?

The link between PhD productivity and educational environment

Even a partly qualitative, partly quantitative ranking allows a vaguely systematic analysis of mushy things like education.

What is it that makes a college highly productive? One answer comes from a report issued by a group of liberal arts colleges, known as the Oberlin 50. In touting the reasons why small liberal arts colleges produce more than their share of scientists, the Oberlin report claimed, "personalized instruction by senior scientists and widespread student involvement in research are the primary distinguishing features of these institutions, and account for their record in both attracting and producing young scientists."

The interesting thing is that the message of the liberal arts colleges—reknowned for their emphasis on teaching rather than research—echoes a core characteristic of Caltech: close interaction between student and mentor in an intellectual apprenticeship, in the laboratory as well as in the classroom. (Another shared characteristic is carefully selected, high-quality students.)

The PhD productivity studies and the Oberlin report share some basic lessons: small is good, research is good, interaction is good (and admitting superior students doesn't hurt either). This suggests that other institutions might encourage the intimate, interactive, research-immersed approach to education with more and better instructional labs, more chances for undergraduates to get involved in research, and more contact between senior faculty and undergraduates. To encourage faculty to dawdle with undergraduates, colleges might promote lighter teaching loads, starter grants, teaching sabbaticals for research faculty, and research sabbaticals for teaching faculty.

Are rankings worth their shortcomings?

Are rankings worth their unavoidable shortcomings? Academic reputation is the single most important consideration in students' choice among colleges, according to a 1987 UCLA study. Part of this is that many students and parents believe that a good reputation promises a good education. But these wise students and parents also realize that a good reputation also has long coattails: a degree from a prestigious school, the more ivy-covered the better, is a lifelong advantage.

Rankings are misleading, but people will insist. Even a seemingly simple, purely quantitative ranking hides biases in the choice of variables, weightings, or manipulations. At worst, statistics can be manipulated to produce almost any desired result. Yet despite their unavoidable subjectivity, university rankings are useful. Even a partly qualitative, partly quantitative ranking allows a vaguely systematic analysis of mushy things like education. And colleges should be able to tout their strong points. The above-mentioned Oberlin report carefully but appropriately crafted a credible argument for the undersung role of liberal arts colleges in educating scientists. The thoughtful statisticians selected specific fields—the basic sciences of biology, geology, physics, and chemistry—and specific colleges that played up the strengths of the liberal arts colleges. The obvious conclusion is that such carefully crafted rankings demand well-informed, skeptical consumers.

Rankings are important. They figure importantly into students' enrollment decisions. They also figure into the opinions of bureaucrats, businessmen, politicians, and other well-pocketed fund-givers, who want their names to be associated with a prestigious college. In science, federal and state patrons are always trying to rationalize their R&D and fellowship decisions. It behooves colleges being ranked to invest some effort into the art, and engineering, of rankings. □

Lisa (Cox) Heinz graduated from Caltech in 1978 with an option in biology. This article arose out of a study she recently completed at the U.S. Office of Technology Assessment, where she's employed in the communication and technologies section. Much of the data analysis she found too "entertaining" to fit in the confines of a government report, so E&S *was the beneficiary instead. She's also the Washington, D.C., chapter representative on the Alumni Association's board of directors. Although she doesn't intend to get a PhD, she thinks the quality of her Caltech education was terrific.*

The views expressed in this article are entirely those of the author and not necessarily those of OTA.

The Piper and the Physicist

by Jenijoy La Belle

When Blake wrote "sweet science reigns," he was not envisioning Caltech.

William Blake's "The Ancient of Days," 1794.

In 1969 I began teaching literature at the California Institute of Technology, a university whose primary purpose is to train scientists and engineers. When Blake wrote "sweet science reigns," he was not envisioning Caltech. There is nothing very sweet about the institution, although I did hope to bring some playful joy into scientific lives through the *Songs of Innocence* and thereby to extend the students' horizons. Since the late sixties and early seventies were, in most schools, a period of great experimentation, I initially tried to go along with the trend and create courses on Blake that would appeal to the students' interests. I went around campus putting up posters of Urizen reaching down with his dividers (Caltechers love instruments) and tried to lure pupils into the Blake circle through references to geometry.

I yearned to be able to speak in the seventies as T. R. Henn had in the forties when he gave his Cambridge "Lectures on Poetry designed (in the Main) for Science Students," published in his *The Apple and the Spectroscope*. Henn's basic approach was to convert the language of poetic metaphor into supposedly homologous structures in science. For instance, in his discussion of imagery, he cites Burns's simile "My love is like a red red rose," and then suggests: "If we look at the problem in terms of a valve, we have the girl and the rose represented by anode and cathode respectively. What in fact has happened is that certain particles of meaning, or electrons, have streamed across from the rose and attached themselves to the girl." This analogy seemed remarkably silly to me, but I was still convinced that if I could talk in scientific terminology like an updated Henn and could somehow work the "invisible worm" and "howling storm" of Blake's "The Sick Rose" into an electrical system, I could have the students (anode) eating out of my hand (cathode).

When Donald Ault's *Visionary Physics* appeared in 1974, I was delighted. I decided I would steal his subtitle and call my course Blake's Response to Newton. Ault's book would be required reading. The students would see the volume in the bookstore and immediately be attracted by the dust jacket of Blake's face (in psychedelic blue) with his left eye removed from its socket and replaced by the tiny head of Sir Isaac (in psychedelic orange). Perhaps I would team-teach the course with someone from the department of physics. All the students would flock to my class, thousands of little boys and girls raising their innocent hands.

Of course, at this point, I hadn't even opened the book. But I purchased two copies, started to read one, and took the other to my colleague Richard P. Feynman, one of the world's greatest theoretical physicists and an admirer of Blake (his favorite poem being "Fair Elenor"). Soon after, "away the vapour flew." Feynman valiantly struggled with the book for several days; then, somewhat baffled, he returned it to me and said, "I don't know what this is, but it isn't physics." Several students, whom I had also engaged as samplers of Ault, had similar responses. A few more experiences of this kind, both in and out of the classroom, disabused me of any naive notion about getting

"I don't know what this is, but it isn't physics."

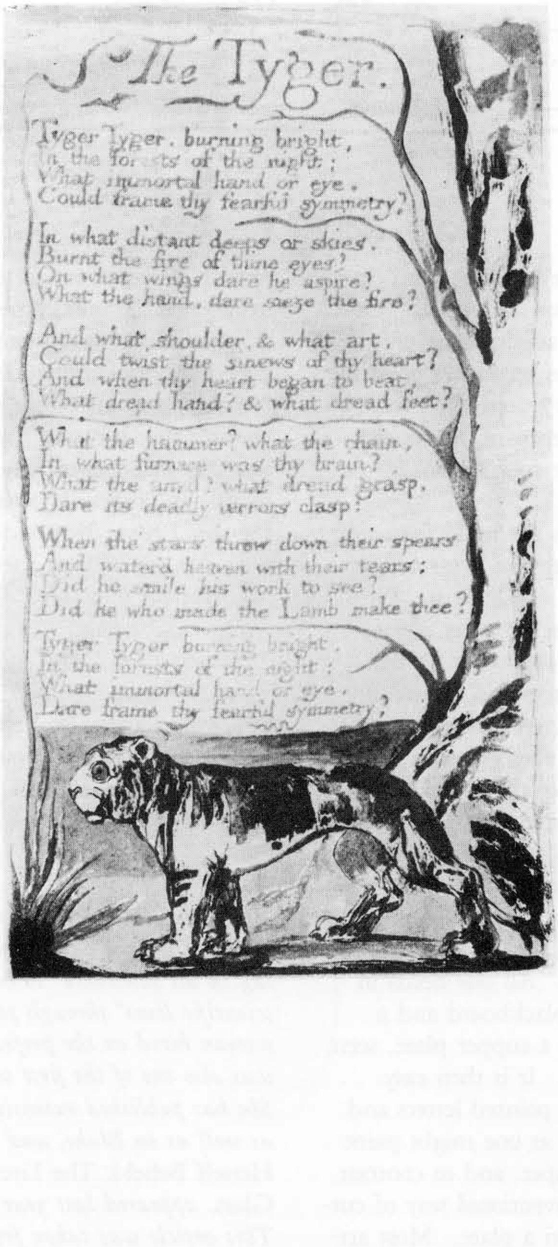
scientists interested in Blake directly through science. Ault's book is as much literary criticism as history of science, and neither field is much closer to the interests of scientists than poetry itself. Indeed, I found that Techers were willing to approach poetry recreationally, as a pleasant diversion from the real business of life. What they found most peculiar was taking poetry seriously (particularly examples such as *Songs of Innocence*) and as central rather than peripheral to anyone's academic career.

With these hard-won lessons, I decided to build on a foundation of differences rather than (supposed) similarities. This approach was more strategic than honest, for I still clung to the notion of underlying similarities, but I would admit to them only after warning (and, I hope, intriguing) the class with the idea that what was to follow was strange, totally unlike what they would encounter in their other classes, and perhaps even a little dangerous.

At a fairly early stage in their university work, Caltech's apprentice scientists encounter the notion of alternative models for the explanation of physical phenomena. I have frequently seen my faculty colleagues in the sciences solve a problem in mathematics or present an explanation of a subatomic event and then say, "Another way of solving this problem is . . ." or something to that effect. Even civil engineers have more than one way to bridge a river. In some cases, particularly in the more theoretically oriented fields, the instructor could not come to a conclusion about the one right or best way of finding a solution. And this sense of undecidability increases as one approaches the frontiers of science.

Here, then, was the portal through which I could introduce students to Blake. Not only do Blake's *Songs* provide an alternative range of thoughts and sensibilities to those promoted by science courses, they also prompt us to seek alternative perspectives as an intrinsic part of their structure. My opening gambit ("and now for something completely different") thus led into a detailed consideration of the poems themselves, stressing point of view and context as organizing principles for class discussion. This approach is hardly revolutionary, and there is nothing particularly "scientific" about it, but one can introduce it to science students quickly and efficiently and engage their attention in traditional literary activities in such a way that they no longer see them as trivial. To put the matter in Hennish terms, the "two contrary states of the human soul" and the study of the poems arranged according to those contraries exercise the same need for double perspective as does the scientific study of light—sometimes a wave, sometimes a particle. For instance, one might compare and contrast "The Divine Image" in *Innocence* with "A Divine Image" in *Experience*. In the first poem, Blake presents the human body as an image of four virtues and an embodiment of God. In the second poem, the anatomy lesson takes a different point of view and offers us a

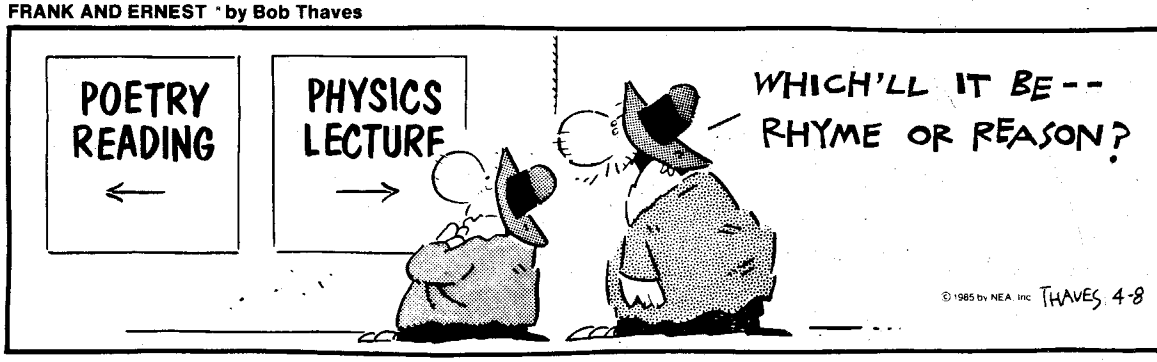
A discussion of the two poems in these terms can lead a class of budding scientists to a consideration of the way they see the forces of nature.



body of cruel sins. One can also explore the contrast in tone as a way of complementing and underscoring the contrast in perspective. Blake has observed and made poetic use of the same object in two different ways, but neither poem is "truer" than the other in any scientific sense.

After pursuing conventional literary approaches to several poems in *Songs of Innocence* and their opposites in *Experience*, I often find it helpful to return to my initial leitmotiv—the differences between Blake and science, at least classical science. The latter has for several centuries stressed an absolute distinction between subject and object as a necessary prerequisite to the discovery of objective truth. This precept is tantamount to a kind of "purity" theory. The chemical sample or the organism must be untainted by other substances, much as the objective investigation must be untainted by the personality and prejudices of its investigator. The much heralded Heisenberg principle (it has almost become a cliché, even in certain kinds of literary studies) tends to break down the doctrine of noninterference, but in the vast majority of their studies my students are not encumbered by any philosophical doubts prompted by Heisenberg. Thus Blake provides a strong contrast to the theory of knowledge implicit in classical science. In *Songs of Innocence*, to know something is to be a part of it, and this participatory mode breaks down the subject-object dichotomy. The continual impulse toward a unity of being in *Innocence* questions—and thereby reveals—the epistemology that my students bring to class but of which they are generally unaware. The next pleasant shock that Blake's *Songs* can offer the interested scientist is the way in which the fall into Experience is both cause and consequence of a perspective instituting the split between subject and object. Even a brief comparison of the child's relation with the lamb and its creator in *Innocence* and the speaker's relation with the beast and its creator in "The Tyger" can bring this point home. In "The Lamb," the child, the animal, and Jesus all tend toward a single mode of being. The child identifies with the lamb and, through it, with the Christ child, thus gaining spiritual knowledge through identification with the object of observation. Although one may say that the speaker in "The Tyger" projects his or her psychological condition onto the beast, the terror with which the speaker beholds the tiger creates a pattern of dissociation between the human world and the material cosmos and its origins. A discussion of the two poems in these terms can lead a class of budding scientists to a consideration of the way they see the forces of

FRANK AND ERNEST ® by Bob Thaves



nature. Do the students see humanity as one with nature, a part of all that we behold? Or does the objective world of science exist only through a suppression of the subjective or of the spiritual? After these heady questions, I have generally found it wise to return to the poems themselves, regrounding our speculations in the particulars of Blake's text.

I have come to expect less of myself as a pseudoscientist but have found that I can expect more of my students as readers of Blake.

The preceding represents the main features of my method of introducing the *Songs* to the young scientists at Caltech. Students frequently respond, however, to another property of Blake's poems. Many of them are engineering majors and thus have a primary interest in technology rather than in the outer reaches of theoretical science. They can respond to the notion of Blake as a craftsman—like many of them, a worker with metals and acids. A brief digression from purely literary concerns into the relief etching techniques Blake used to publish the *Songs* often attracts student interest. This topic also provides a method for introducing Blake's illustrations to the technologically oriented. All one needs in the way of materials are a blackboard and a piece of chalk for sketching a copper plate, seen face on and in cross section. It is then easy enough to show how Blake painted letters and designs onto his plates, just as one might paint watercolors on a piece of paper, and to contrast these processes with the conventional way of cutting lines through varnish on a plate. Most art-supply shops have etching tools and small zinc or copper plates, which can be used to flesh out an introduction to the technical aspects of the *Songs*.

I have now been teaching at Caltech for almost 20 years; innocence has given way to experience. I have come to expect less of myself as a pseudoscientist but have found that I can expect more of my students as readers of Blake. I endeavor to introduce scientists to Blake's *Songs* in ways that preserve the intellectual seriousness that the students usually reserve for their chosen fields. By indicating a few points of contact of the sort I have discussed here between thought processes essential to science and those engaged in a reading of Blake's *Songs*, one can lead even students who think poetry trivial to take a different view. After that, science students at Caltech—and, I suspect, elsewhere—are capable of learning about and enjoying *Songs of Innocence and of Experience* without continued references to physics or chemistry. □

Jenijoy La Belle is professor of literature at Caltech. When she joined the faculty in 1969, hoping in all innocence "to bring some playful joy into scientific lives" through poetry, she was the first woman hired on the professorial faculty here; she was also one of the first women granted tenure. She has published extensively on Theodore Roethke as well as on Blake, and her most recent book, Herself Beheld: The Literature of the Looking Glass, *appeared last year* (E&S, *Summer 1989). This article was taken from* Approaches to Teaching Blake's Songs of Innocence and of Experience, *edited by R. F. Gleckner and M. L. Greenberg and published in 1989 by the Modern Language Association.*

Channeling

Drosophila melanogaster, the geneticist's friend.

You have to go through channels to get things done in any well-organized bureaucracy, and the nervous system is no exception. Nerve cells "fire"—conduct an electrical impulse through themselves—by creating a traveling ripple in their internal ion balance. To do so, each cell moves ions in and out of itself through channels—protein molecules spanning the cell membrane. Each molecule is designed to admit a particular ion: sodium, say, or potassium. The channels are such an infinitesimal proportion of the cell's protein—perhaps one molecule in a million—that the first one, a relatively abundant sodium channel, wasn't isolated and purified until the late 1970s. It took almost another decade to discover the gene responsible for producing it.

Last year a group led by Assistant Professor of Biology Mark Tanouye located the gene responsible for potassium-ion channels in *Drosophila melanogaster*, the fruit fly. Cellular conductivity studies had indicated that there were many different types of potassium channel per cell, implying that each individual protein would be correspondingly rarer. So instead of taking the conventional approach—isolating the protein, determining its amino acid sequence, and using this sequence to find the corresponding DNA sequence in the chromosome—the group took a novel tack. They zapped fruit flies with enough x-rays to jumble their genes just a bit. Some mutant offspring had aberrant potassium conductivity, and these flies were examined for visible chromosome damage to find the gene's general neighborhood. Then the researchers "walked" an overlapping series of DNA-binding probes along the chromosome to reach the gene's exact address. The gene resides within the "Shaker locus," a region named by earlier gene mappers because mutations therein produce twitching flies.

The group has since used the *Drosophila* gene to find corresponding genes

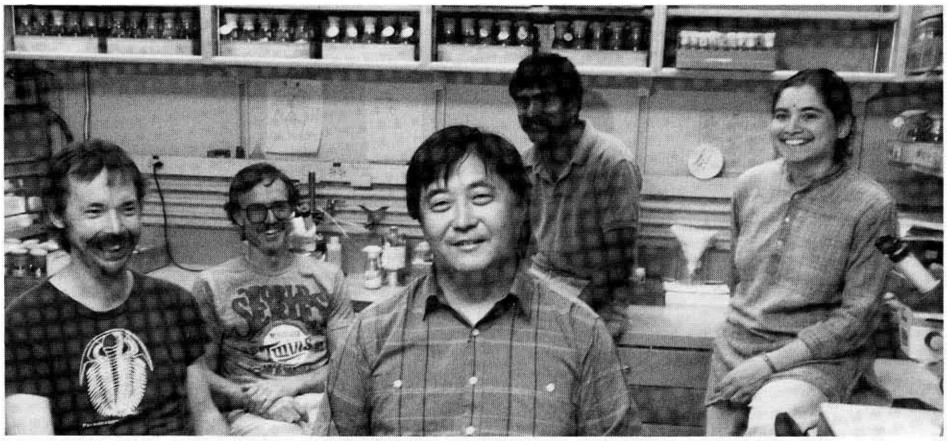
Right: A set of Drosophila chromosomes. An x-ray dose has broken the x-chomosome at the "Shaker locus," and reattached part of the x-chromosome to chromosome 3. Far right: In this close-up, the two sets of black blotches mark where a radioactively labeled probe has bound to both fragments of the Shaker locus. The lower blotches show where the x-chromosome (extending off to the left) has fused with chromosome 3, which curls away to the right and down.

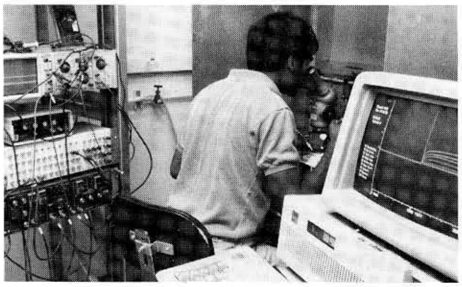
in rats, and recently in humans, by assuming that vital parts of each gene would be sufficiently similar that a probe able to recognize and bind to one would also recognize and bind to the other. So far they've found six different channels in human brain tissue. The search also turned up a channel peculiar to rat heart tissue, and is closing in on the human equivalent. Potassium-channel-blocking drugs are given to cardiac patients to control heart arrhythmias. Unfortunately, these drugs block potassium channels throughout the body, causing all sorts of unpleasant side effects. A drug that blocked only heart-tissue potassium channels would create far fewer problems.

Surprisingly, while the channels in flies, rats, and people are quite similar, and are produced by similar bits of genetic code, the code comes in different formats. *Drosophila* uses one long gene that resembles a Chinese menu. Column A contains six initial segments, any one of which may be chosen when creating a channel type. Column B contains a single midsection, and Column C has four terminal segments. The fly creates some 20-odd channel types by mixing and matching segments. Mammals, however, have a separate gene for each channel type. Tanouye estimates that there may be as many as 100 different types of human potassium channel.

One hundred flavors might seem to be too much of a good thing, but it really isn't. There are four basic types of nerve impulse, or "action potential." The nerves running to the central nervous system (the brain and spinal cord) typically fire isolated impulses lasting about one thousandth of a second each, while central nervous system cells fire complex bursts lasting for hundredths of a second. Heart tissue "plateaus," maintaining an elevated action potential for half a second at a time to drive the pump stroke. "Pacemaker" tissue provides regularly repeated pulses, over and over. "There are different waveforms within each impulse category," says Tanouye. "But the rising phase, which is generated almost totally by a fast influx of sodium ions into the cell, is always the same. So to make each category and the small variations within it, the cell sculpts the falling phase by modulating the outward current of potassium ions. And a slow inward current of calcium ions keeps the potential high to make plateaus. That's why there are so many kinds of potassium channels, but only a few types of sodium and calcium channels. Each different cell has its own distribution of potassium channels to get the right waveform, which can be fairly complex."

Channels go through a three-step cycle: activation, which enables them to





Above: Measuring an individual cell's conductivity is exacting work. A microelectrode is inserted into the cell, using the microscope to guide the hand. Conductivity profiles appear on the computer monitor at right.

Right: The Tanouye group. From left: William Trevarrow, Ross McMahon, Tanouye, Mani Ramaswami, and Mehda Gautam. (Missing: Mathew K. Mathew and Ken McCormack.) The flasks on the shelves in the background are home to various Drosophila strains.

pass ions; inactivation, which stops ion passage; and recovery, during which an inactivated channel resets itself to be activated again. Activation and inactivation are controlled, or "gated," by the voltage differential on either side of the cell membrane. Potassium channels vary in their gating voltage, and some channels need to have calcium or magnesium ions, or messenger molecules such as serotonin, present as well. Activation, inactivation, and recovery rates also vary. Tanouye's group has found that in *Drosophila*, choices from Column A (the so-called 5′ end of the gene) build in the channel's inactivation rate, while Column C (the 3′ end) sets the recovery rate.

The constant region (Column B) presumably encodes features that don't change much, such as ion selectivity. "We really didn't want to make a catalog of potassium channels per se, but we had to look at a collection of them to find the natural variations of structure and function in the constant region, as well as going after human channels of clinical significance."

Some things have already been learned. Other researchers have found a repeating amino acid sequence lying squarely in the middle of every ion channel found to date, in a region christened S4. S4 is believed to be the channel's voltage sensor.

Tanouye's group has found another region, overlapping S4 a little bit and continuing into the channel's interior, called a "leucine zipper." A leucine zipper contains the amino acid leucine followed by six others in a sequence repeated four to six times. When the protein coils into its natural shape, all the leucines line up along the coil like teeth in a zipper. Leucine zippers are believed to play a role in DNA-binding proteins, another hot area of molecular biology. What the zipper does in the ion channel remains a mystery, but Tanouye speculates that it may be part of the actual gateway. "We've found leucine zippers in every single potassium channel so far, and sodium and calcium channels also have zippers. So we thought, naively, if the S4 region moved a little bit in response to a voltage change, the channel might unzip so ions could go through. It's probably more complex than that."

To find out, Tanouye's group is now making channels with the zipper leucines replaced by the closely related amino acids valine and alanine. "These are really very subtle changes, to another hydrophobic amino acid that's somewhat smaller. But we've found that gating is strongly affected, in voltage sensitivity and other things. Now we're looking for the logical framework, the story of what this all means."□—*DS*

Bid Me Up, Scotty

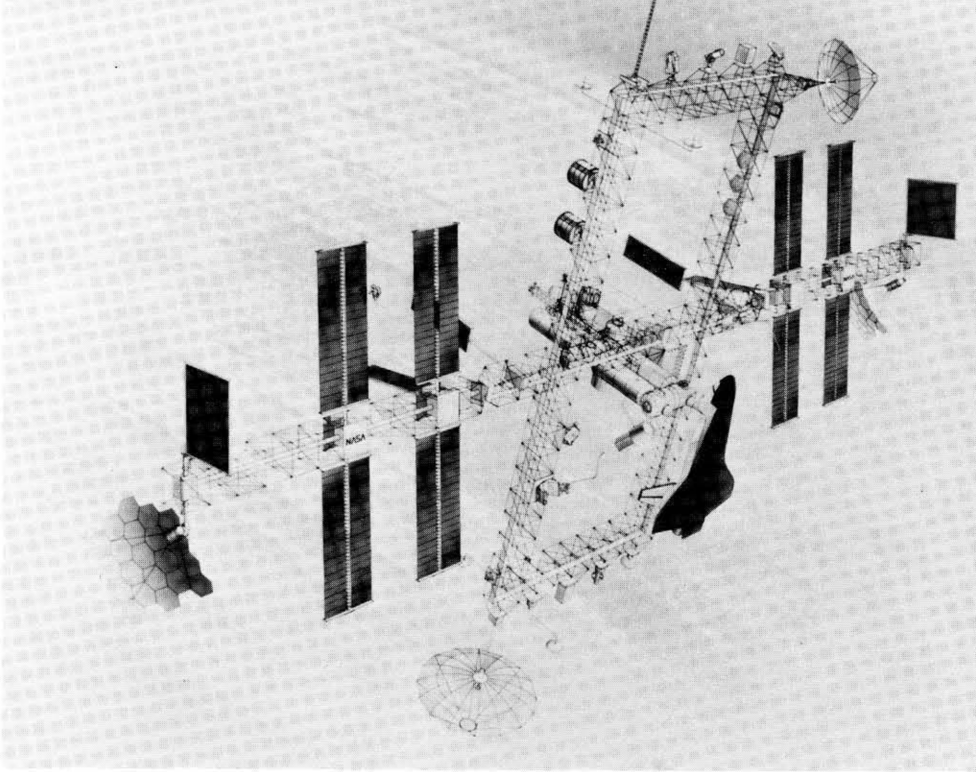
> *"NASA's problem is to get the information needed to make the best use of scarce resources, and normal bureaucratic processes simply can't do it."*

When the space station opens for business, it will have some room for commercial payloads. And if it's treated like the shuttle, that room will be allocated haphazardly to all comers. NASA tries to ensure that the best payloads fly, but their selection system can have unintended consequences. Relatively worthless payloads may go up while better cargoes languish in warehouses. And there's no built-in incentive to conserve the spacecraft's resources; thus the payloads that fly may squander what could be better used by others.

NASA doesn't always know which payloads are the best, nor if their design could be improved. It's not that easy to find out, says John O. Ledyard, professor of economics and social sciences. "A commercial payload's value includes both its immediate benefits—projected cash returns—and its long-term benefits—perhaps research results leading to marketable products in 20 years. Some long-term benefits are unforeseeable, but most firms have a pretty good idea of their payload's worth. They don't want to share this information because it's proprietary. And everyone wants a bargain, so if you just ask, 'How much are you willing to pay to fly this?' they'll say, 'Well, I can't afford much, but my payload is really important.' NASA's problem is to get the information needed to make the best use of scarce resources, and normal bureaucratic processes simply can't do it. A properly designed pricing strategy will."

Instead, NASA's payload-selection procedure has been divorced from its pricing policy. Engineers allocated shuttle space as best they could, evaluating payloads based on their own experience. Then the accountants sent a bill to cover launch costs. This cost-based pricing has its roots in "marginal-cost" pricing, developed in the 19th century to help set bridge tolls. The marginal cost for a bridge built to carry 100 cars a day is the extra cost of carrying the 101st car. The marginal cost of a shuttle payload is the cost NASA incurs beyond the cost of launching the shuttle anyway, sans payload. Bridges have been around for centuries and the rules for finding their marginal costs are well known, but the shuttle is so new that its marginal cost is still being debated. So NASA guessed at a price, and, to ensure a clientele, probably guessed too low. Low prices may be fine for abundant resources, but not for an infrequent-flier shuttle, or for a space station, where you can't just build another room over the garage. Resource allocation becomes first-come, first-served. Nothing prevents the first arrival from claiming *all* the resources, preempting the competition.

Ledyard, who in 1983 joined a group studying pricing policies at the



Low prices may be fine for an abundant resource, but not for an infrequent-flier shuttle, or for a space station, where you can't just build another room over the garage.

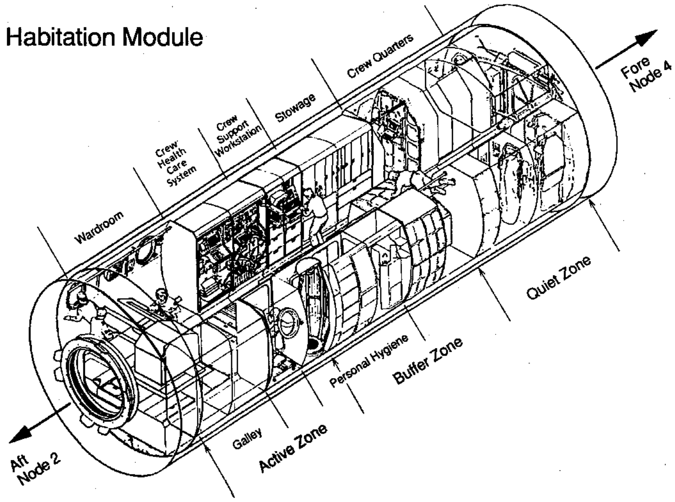
Jet Propulsion Laboratory (JPL), thinks there's a better way. "Any economist knows that pricing policy and resource allocation are intimately linked." Those gaining the most from a scarce resource will pay the most to secure its use, so auction it off. Assuming the bidders have *some* idea of their potential benefits, the bids become proxies for the payloads' real worth. The winning bids reflect the "opportunity cost" of the payloads that don't fly—the benefits lost to the unsuccessful bidders. Such a system is called "demand-based" pricing.

"The fact that the winners paid that price isn't as important, from the public-policy point of view, as the fact that they got on," says Ledyard. "The bidding has indirectly sorted out the good proposals from the bad ones."

In its simplest form, this isn't a particularly new idea. Cattle are sold at auction, as are soybean futures and van Goghs. When a single commodity is being sold, it's fairly easy to figure out how to bid. But a shuttle berth involves several "resources": weight, volume, electrical power, manpower, and other factors come into play. Each payload has specific requirements—a communications satellite might be large and heavy, but need no electricity and take only one man-hour to launch, while a compact crystal-growing project might draw lots of power and require constant human attention—and it's pointless to fly a payload if all its needs aren't met. It's impractical to auction each resource, as bids for any one item depend on the prices of the others. Even with a computer tracking all the various auctions, most people would suffer brain failure trying to plan their next bid.

Ledyard proposes an adaptive user selection mechanism, or AUSM (pronounced "awesome"). Each bidder submits a package, containing one bid for a list of resources, to a computer. Like a camper with more gear than will fit into a knapsack deciding what to pack, AUSM sorts through the bids to find the highest bid (or bids) whose combined resource demands can be accommodated. The highest bid always wins in a simple auction, but with the knapsack problem this isn't necessarily true; if 1,000 cubic feet of space are available, say, 10 bidders offering \$100 each for 100 cubic feet will beat one bidder offering \$700 for all the space. Thus many small bidders flying modest projects can collectively outbid a mammoth communications satellite. In practice, AUSM accepts every bid until all available resources are committed. Then prospective users must displace one or more payloads already on board by outbidding them.

The system could run for months, allowing users who've been bumped



"You can get a huge bang for your buck when people start redesigning their payloads to fit better."

to refine and resubmit their bids based on the current roster of successful bids. Says Ledyard, "You can get a huge bang for your buck when people start redesigning their payloads to fit better. [A fixed bid and a scaled-down resource demand is tantamount to a higher bid, encouraging efficient resource use.] We can measure that bang experimentally."

Ledyard and Charles R. Plott, Harkness Professor of Economics and Political Science, use Caltech's Laboratory for Experiments in Economics and Political Science to test AUSM against other pricing systems, including cost-based ones like NASA's. The lab allows researchers to study economic and political behavior under rigorously controlled conditions. An experiment can include up to 20 people linked by a network of PCs.

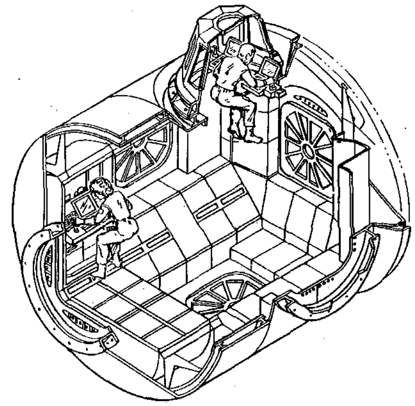
In the first experiments, seven "payload managers" could choose to sponsor one of several possible payloads. Each payload needed a different mix of resources and promised various rates of short- and long-term return with an associated probability of failure. Managers could bid, rebid, alter their payloads, or even choose new ones as the computer noted their every move. After a set interval, the computer closed the auction and "launched" the shuttle with the winners' payloads aboard. The computer calculated how well these payloads performed in orbit, paid their managers accordingly, and began the cycle again. The managers were paid real cash, giving an incentive to succeed.

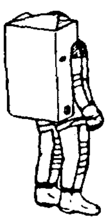
Unlike NASA, the experimenters knew every payload's true value (rate of return times probability of success). They measured a pricing system's ability to find the best payloads by the ratio of the value of the payloads that flew to the highest possible value attainable from any flyable combination of payloads. The cost-based mechanism a la NASA was about 65 percent efficient. AUSM was about 90 percent efficient.

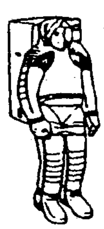
Ledyard had spent two and a half years trying to sell the AUSM theory to NASA brass, engineers with a healthy skepticism of economics in general. It was an uphill struggle—a complicated issue challenging many vested interests. He'd penetrated several layers of bureaucracy with no end in sight when he, Plott, and the JPLers made one more trip to Washington. "Plott put up a viewgraph with the two data points on it and said, 'See, this is how it works.' And all the NASA people said, 'Wow! That's great!'" Ledyard recalls. "Suddenly they were willing to listen. The power of experimental analysis to convince people who otherwise don't understand economics is just amazing."

More proof came in a few months, when Ledyard and Plott ran a pricing experiment on NASA managers. The

"We simulated NASA's cost-based policy, and we warned them that the highest-priority bidder would try to grab everything. They said, 'Scientists don't act that way. That's crazy.'"





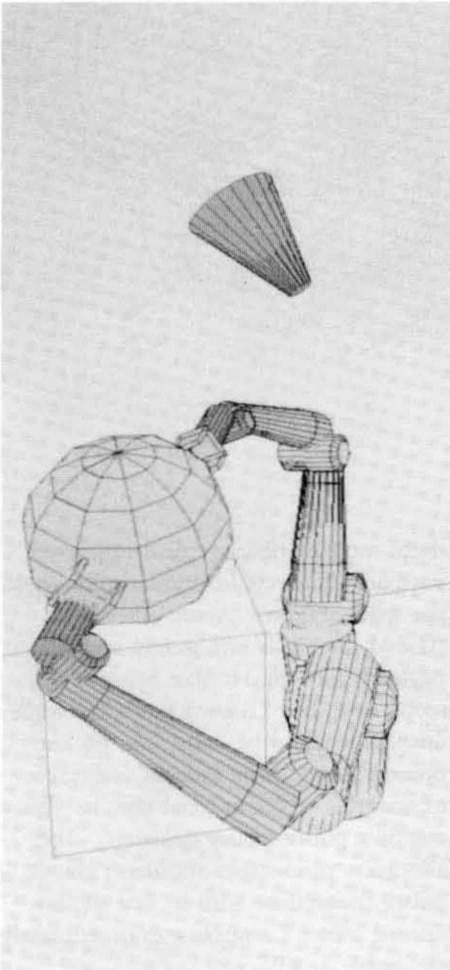


relative efficiencies held true, and NASA folks acted just like everyone else. "We simulated NASA's cost-based policy, drawing numbers from a hat for the first-come, first-served aspect, and we warned them that the highest-priority bidder would try to grab everything. They said, 'Scientists don't act that way. That's crazy.' And 15 minutes into the run, one guy was doing it. We asked him afterward, 'Didn't you know what you were doing?' and he said, 'I knew from the space station's perspective I shouldn't do it, but from my point of view, dammit, I *had* to!' Later, at a high-level NASA briefing, we were arguing that AUSM prevented this excessive demand of resources by guys who don't really need them. The person we were briefing said, 'We don't do that at NASA.' And this other guy stood up and said, '*I* did it.' There was no other way we could have proven it."

The next step will be to try AUSM on a real shuttle flight. There are still a couple of political hurdles to clear, but Ledyard is optimistic that it will fly one day. Meanwhile, AUSM's back in the lab for stress testing—seeing how well it holds up under various conditions.

The space station's clientele will probably be 90 percent scientific and technical, but AUSM would still be a boon to mission planners. Competition for resources favors payloads that use them most efficiently. And improved payload design could dramatically boost the space station's overall efficiency. AUSM can't evaluate purely scientific payloads like the Hubble Space Telescope now, but Ledyard has some ideas on how it could be done. As for the broader issue of the ratio of military to scientific to commercial use, he says that is a public-policy question. The allocation mechanism shouldn't decide policy or interfere with it, but should instead reflect Congress's, and ultimately the public's, will.

"AUSM would require a change in organizational culture," says Ledyard. "NASA sees allocation as its job, and pricing as a necessary nuisance imposed by Congress. NASA feels it would be nice if they somehow collected money, maybe, but it really has nothing to do with them. We feel we can significantly improve the allocation process while still raising some money for the government. What we're really looking at here is how you run government, good and bad ways to manage programs. Using economic data, generated under controlled conditions, in a policy debate is new for economists, but the opportunities are unlimited. And Caltech is remarkably well-equipped to worry about this kind of issue, because of our strength in integrating political science, economics, and experimental work."□—*DS*



This graphic simulation shows JPL's robot arm in action. Many tasks take two arms working together. While Gutierrez was working on the problem of one moving arm, seniors Alvin Law and Ming Lee were simulating two stationary arms holding an object between them. Kenneth Kreutz, who, with Abhinda Jain, directed the two-arm work, notes that this project is harder than it appears because the arms must exert enough force on the object to keep it in their grasp, but not enough to crush it. Animation created by Mark Long.

A robot arm will need flexible programming as well as flexible joints.

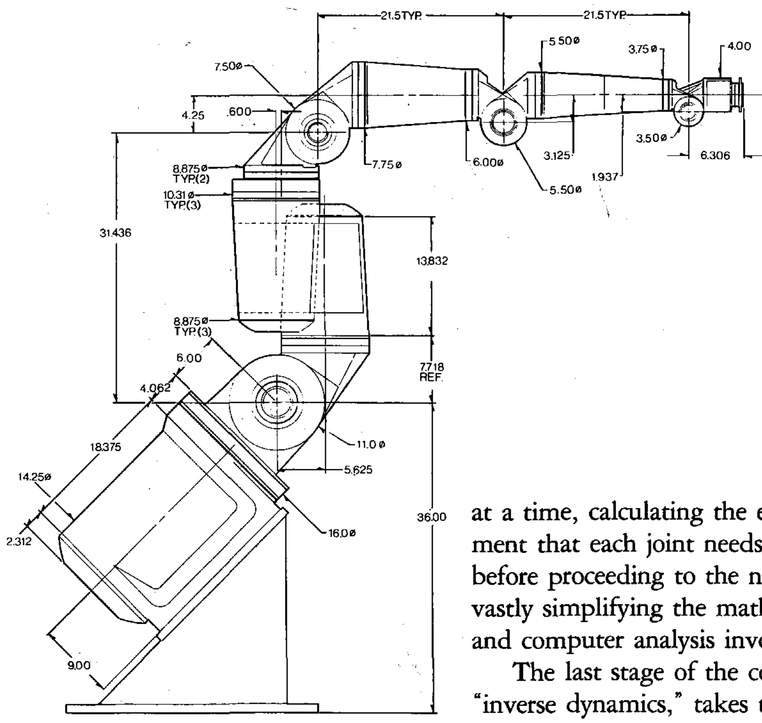
Arms and the Robot

Imagine a job washing windows, wiping each pane clean with a smooth, circular motion. Pretty simple stuff, right? Not for a robot. This past summer Roman Gutierrez, now a junior in applied physics, used a Summer Undergraduate Research Fellowship (SURF) grant to work with Guillermo Rodriguez, a senior member of the technical staff at JPL, on a software package to control a robot arm's motion in two dimensions. Eventually, the program will be a part of the operating software for a robot arm that JPL is installing in one of their laboratories, a prototype for the ones that will be needed to service and repair satellites and assemble structures in earth orbit.

These arms will need much more sophisticated control programs than the ones used in earthbound factories. An arm welding fenders for Ford has a real no-brainer job. The arm and its assembly line are set in concrete, figuratively as well as literally. The assembly line brings each fender, in exactly the same orientation as the previous one, to within a millimeter or so of a given spot, and holds it there. Then the robot follows an explicit list of instructions to make a set of predetermined motions that touch the fender at designated spots. But there are no concrete floors in orbit, so a robot arm will need flexible programming as well as flexible joints, matching its motions to where things really are. The tasks to be performed in space are also more complex.

Telling a robot arm how to reach out and touch a desired spot isn't easy. First of all, the arm's mechanical elements must be defined for the computer—how many joints it has, each joint's range of motion, and the dimensions of the links connecting the joints—and the arm's initial position must be specified. Then the computer decides what position the arm would have to be in to reach the desired spot. Using a process called "inverse kinematics," the computer compares the arm's current position to the position it needs to assume and decides how to move it to that position. This analysis has generally been handled after the fashion of a series of still photos strung together to make a movie of the whole arm in motion, with each joint moving incrementally between frames. With everything moving at once, the mathematics becomes quite formidable.

Gutierrez used a new method, recently developed by Rodriguez, for designing robot movements based on state estimation theory. (State estimation theory allows the overall state of a complex system to be reconstructed from a limited sample of data.) The method essentially starts at the point to be touched and moves inward one joint



The robot arm. Dimensions are in inches.

at a time, calculating the entire movement that each joint needs to make before proceeding to the next joint, vastly simplifying the mathematics and computer analysis involved.

The last stage of the computation, "inverse dynamics," takes the motion information just calculated, factors in the forces at work—the load on the arm, friction, the arm's springiness, and so forth—and, working out from the shoulder, decides what force is needed at each joint to move the arm.

When the arm's operating software is complete, the inverse dynamic data will drive another set of programs controlling the electrical mechanisms that actually move the arm. For the immediate future, the data will be input to another computer simulation, which will calculate the arm's motion and display it on screen as it moves. (This second simulation package wasn't part of the summer's work, but is being created as part of JPL's Space Automation and Robotics Program.)

Most robot arms have six degrees of freedom, or ways in which they can move. The arm bends at the shoulder joint, rotates around it, and bends at the elbow. The other three degrees are in the wrist, which bends, rotates, and yaws—moving from side to side like a metronome or those mechanical waving hands sometimes seen in the rear windows of pickup trucks. JPL's arm will have one additional degree of freedom, a second elbow-like hinge in the forearm. "This will enable the arm to use the sort of bending motion a snake uses to lift the front of its body," says Rodriguez. "It will allow the arm to reach around obstacles that would otherwise block it." The arm is mechanically complete now, and is undergoing preliminary tests. It will become fully operational within a year.

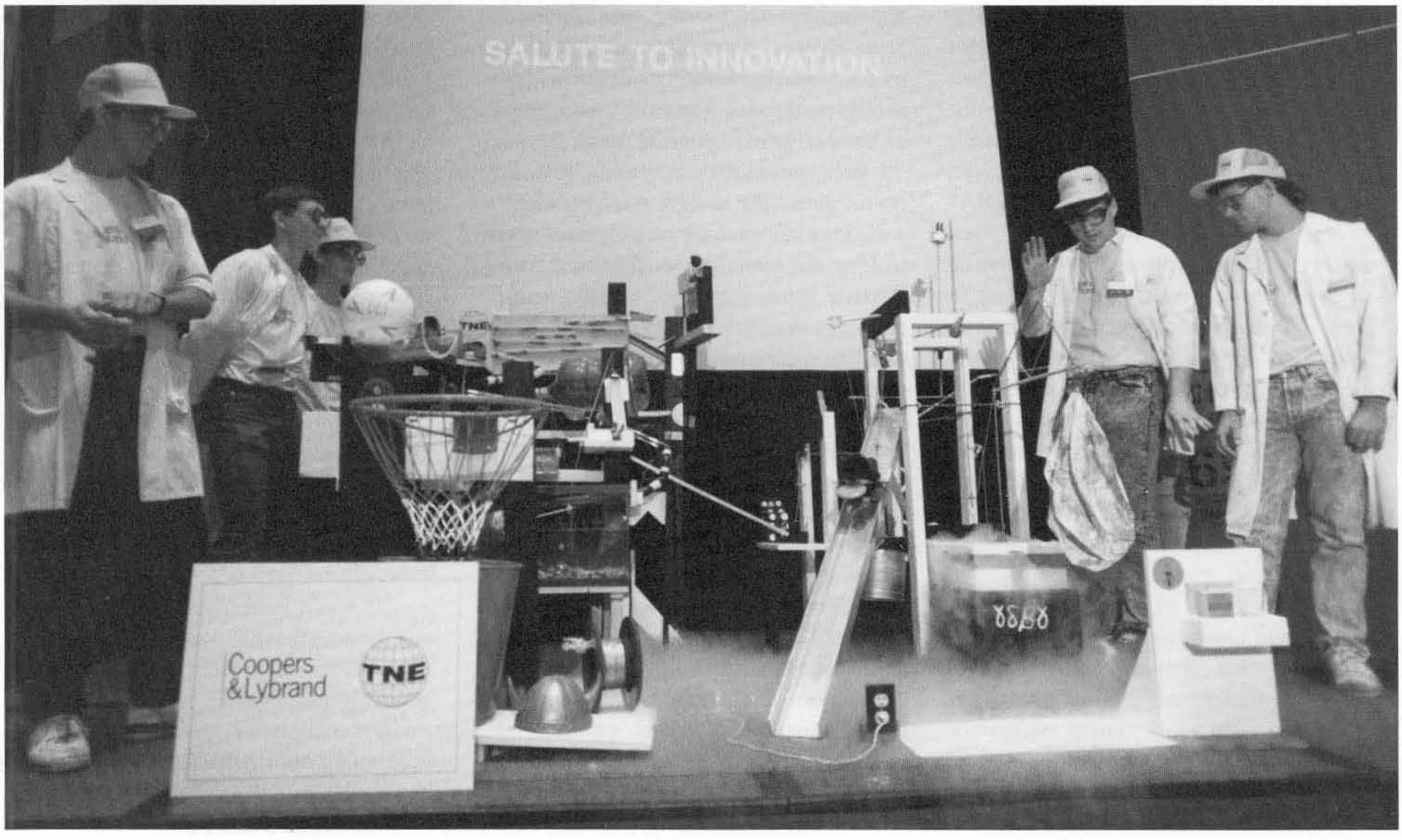
The mathematical analysis needed to generate the arm's motion—even using state estimation theory—is no pushover, involving Newton-Euler recursive equations and the like. It's very difficult to interpret the data from complex arm motions, so at the moment Gutierrez's arm moves only in two dimensions instead of three, and doesn't have the mechanical arm's second elbow. "I was going to do an arm with three links," says Gutierrez, "but I ended up doing it with two. The computer doesn't mind how complicated it gets, but it got very complicated very quickly."

"It was a simplified arm, but it will still be very useful as a pilot project," says Rodriguez. "Roman developed a good motion analysis, and the programming is extendable." And if all else fails, its two-dimensional motions would be ideally suited for doing the space station's windows.□—*DS*

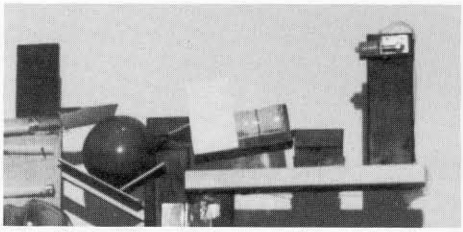
Random Walk

Not Exactly a Better Mousetrap

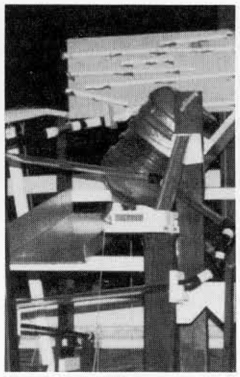
The Nobel prizes for physics and chemistry were announced on October 12. Caltech didn't win any, but that same day a team of five undergrads beat teams from UC Irvine, UCLA, and USC in the Coopers & Lybrand Collegiate Technology Challenge, netting a $10,000 scholarship. The challenge, held as part of a conference for high-tech business leaders, was to design and construct a Rube Goldberg contraption to inflate a 16" globe. The judging was based on whether the device worked; the design's complexity and its creative use of unrelated parts; and overall presentation. Top: (from left) Albert Thiess, managing partner of C & L's L.A. office, with Chris Hurwitz (senior, AE), Randy Pollock (senior, APh), team captain Eric Hassenzahl (senior, ME), Mike Ricci (junior, EAS), and Drazen Fabris (senior, EE). Behind them are faculty advisors Joel Burdick, assistant professor of mechanical engineering, and Chris Brennen, professor of mechanical engineering and dean of students. Middle: The contraption was built in the garage of an off-campus house. Bottom: The device stands poised for action, its liquid-nitrogen reservoir adding fog to the drama.



How does it work? Funny you should ask. A little liquid nitrogen cools the thermostat to below 50°F. . .

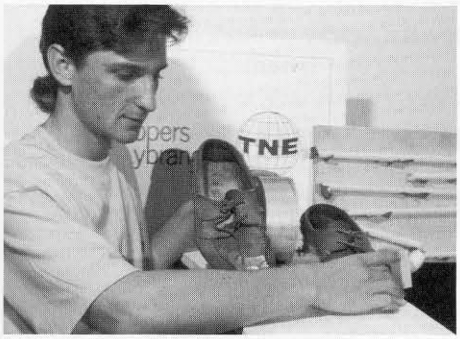


. . . closing a circuit that makes a pinball plunger knock over a soda bottle. Vinegar in the bottle mixes with baking soda in the balloon taped to the bottle neck. The inflated balloon tips a steel ball bearing out of the manila envelope. . .

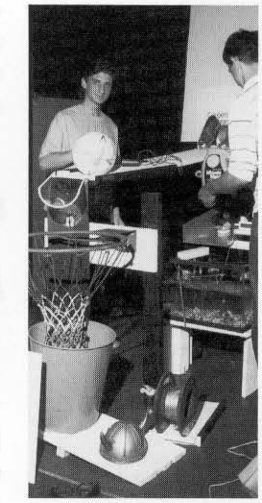


. . . and down into the troughs, through the pipes, and into a funnel. . .

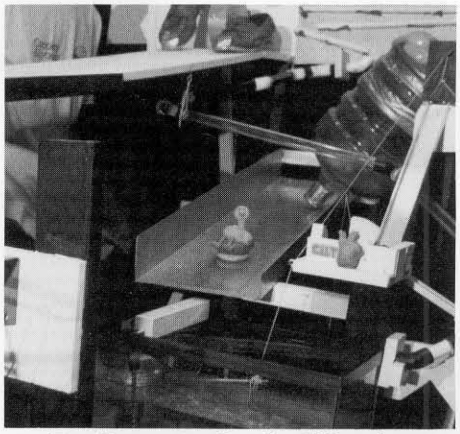
. . . springing the rat trap. . .



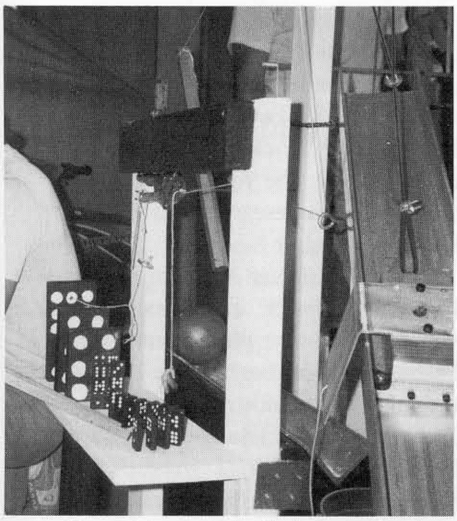
. . . knocking the walking shoes down the ramp. . .



. . . to kick the soccer ball into the gutter, through the basketball net, and into the wastebasket, tripping a lever rolling the disc-brake rotors across the floor, winding up string to pull over the. . .



. . . 5-gallon water bottle, filling the aquarium until the toilet-tank float pulls a string to lift a hinge sending a toy off-road vehicle plunging down the hill into a golf ball, which rolls down a ramp to tip over the first of. . .

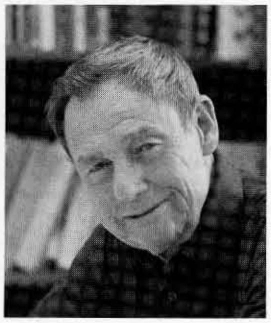


. . . a line of increasingly larger dominoes, the last of which opens the jaws of the vice-grips, releasing the string which lowers the boom on the shotput, sending it along the channel. . .

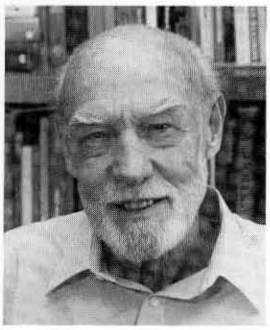
. . . into a bucket of sand with a beaver aboard, which slides down an incline, pulling the rope which raises the copper tube full of liquified air out of the styrofoam chest filled with liquid nitrogen. . .

. . . and the liquid air evaporates, inflating the globe.

Rudolph Marcus



Robert Sharp



Roger Sperry

Arnold Beckman

National Medal of Science

Three members of the Caltech faculty are recipients of the National Medal of Science. This was the largest number presented to any one institution out of the 19 medals given this year. It's also the most awarded to Caltech in any one year.

Rudolph A. Marcus, the Arthur Amos Noyes Professor of Chemistry, won the award "for his fundamental, far-reaching, and eminently useful developments of theories of unimolecular reactions and of electron transfers in chemistry and biochemistry."

Robert P. Sharp, the Robert P. Sharp Professor of Geology, Emeritus, was honored "for his research that has illuminated the nature and origin of the forms and formation processes of planetary surfaces and for teaching two generations of scientists and laymen to appreciate them; for his recruitment and leadership of a successful multidisciplinary department of earth and planetary scientists who have gained world recognition."

Roger W. Sperry, Nobel laureate and Board of Trustees Professor of Psychobiology, Emeritus, received the medal "for his work on neurospecificity which showed how the intricate brain networks for behavior are effected through a system of chemical coding of individual cells, which has made fundamental contributions to the understanding of human nature."

Also a recipient of the National Medal of Science was Arnold O. Beckman, a member of Caltech's board of trustees and a generous benefactor of the Institute, "for his leadership in the development of analytical instrumentation, and for his deep and abiding concern for the vitality of the nation's scientific enterprise." Beckman also received the National Medal of Technology last year.

Honors and Awards

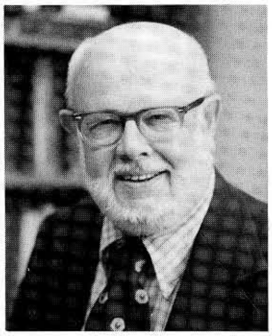
The $70,000 International Prize "Antonio Feltrinelli" for Medicine has been awarded to Giuseppe Attardi, the Grace C. Steele Professor of Molecular Biology, by the Accademia Nazionale dei Lincei.

Pamela Bjorkman, assistant professor of biology, is one of 20 outstanding young researchers nationwide to be named a 1989 Pew Scholar in the Biomedical Sciences by the Pew Charitable Trusts. She will receive $200,000 to support her research over the next four years.

Nobel Laureate William Fowler, Institute Professor of Physics, Emeritus, was inducted into the *Legion d'Honneur*, France's highest honor. He received the insignia of the rank of *Officier* from French President Francois Mitterand in Paris October 19.

Edward Lewis, the Thomas Hunt Morgan Professor of Biology, Emeritus, has been elected a Foreign Member of the Royal Society of London.

Vito Vanoni, professor of hydraulics,



Willy Fowler

emeritus, is the first recipient of the American Society of Engineers Hans Albert Einstein Award, named for the son of Albert Einstein.

Two young faculty members are among the 20 recipients nationwide of David and Lucile Packard Fellowships in Science and Engineering. Frances Arnold, assistant professor of chemical engineering, and Andrew Myers, assistant professor of chemistry, will each receive $100,000 per year for five years.

Four members of the faculty received awards for excellence in teaching from the Associated Students of the California Institute of Technology: Yaser Abu-Mostafa, associate professor of electrical engineering and computer science; Clinton Dodd, swimming coach; Morgan Kousser, professor of history and social science; and Robert McEliece, professor of electrical engineering.

IRC Hosts Speakers

Caltech's Industrial Relations Center is sponsoring a Distinguished Speaker Series to celebrate its 50th anniversary and to lead into Caltech's 100th. Under the theme "Technological Leadership: A New Global Game Plan," the series will include John Young, CEO of Hewlett Packard; David Kearns, CEO of Xerox; Harvard economist Martin Feldstein, who was Reagan's chief economic adviser; and Lester Thurow, dean of MIT's Sloan School of Management.

Random Walk
continued

Celina Mikolajczak (foreground) and Eleanor Helin work in the dome office of the 18-inch Schmidt telescope at Palomar Observatory, where Mikolajczak discovered a supernova on photographic films last summer.

Supernova Sighted

A SURF (Summer Undergraduate Research Fellowship) project this summer yielded the discovery of a supernova for Celina Mikolajczak. Working with Eleanor Helin, a planetary scientist at the Jet Propulsion Laboratory, the 19-year-old junior discovered the supernova on photographic films taken on the 18-inch Schmidt telescope at Palomar Observatory on the night of June 29–30. The supernova has been named SN 1989N and is located in NGC 3646, a large spiral galaxy 137 million light years away.

Although she enjoys astronomy, her discovery and the media attention it evoked has not persuaded her to become an astronomer. Mikolajczak's main interest is aeronautics, and her major is engineering. "I believe astronomy is closely related to the goals of aeronautics. They both involve space, either studying it or getting there," she said.

Professorships Announced

James Bailey has been named the Chevron Professor of Chemical Engineering. Bailey, who came to Caltech in 1980 as professor of chemical engineering, works in biochemical reaction engineering and is a pioneer in the new field of metabolic engineering. The professorship was established in 1980 by a gift from the Chevron Corporation.

Succeeding the late John Benton, who held the first Dreyfuss chair, Alan Donagan will be the Doris and Henry Dreyfuss Professor of Philosophy. Donagan, whose research focuses on 17th-century philosophy and on the theory of ethics, has been at Caltech as professor of philosophy since 1984. The endowed professorship is named after the late industrial designer and his wife, who were deeply involved with the Caltech community.

John Schwarz, one of the founders of superstring theory, considered the best candidate for the long-sought unified field theory, has been named the Harold Brown Professor of Theoretical Physics. The Institute-wide chair (any division) was recently established in honor of Caltech's former president through the support of several members of Caltech's board of trustees and through corporate gifts. Schwarz joined the Caltech faculty in 1972; two years ago he received a MacArthur Foundation award.

Fellowships

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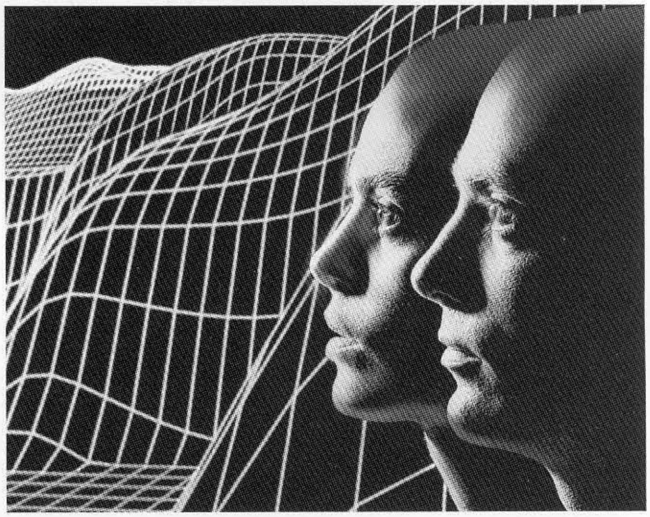

All of the technological advancements that have been created at Hughes are merely an indication of greater things to come.

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Minimum GPA-3.0/4.0. Proof of U.S. Citizenship May Be Required. Equal Opportunity Employer.

HUGHES

Random Walk
continued

On the evening of September 21, as Hurricane Hugo threatened the coast of the Carolinas, Hans Hornung, the Clarence L. Johnson Professor of Aeronautics and director of GALCIT, obligingly subjected his body to 115-mph winds for Ted Koppel's "Nightline." Simulation of the force of the hurricane, live, in Caltech's 10-foot wind tunnel kept Hornung's mouth shut, so Professor of Aeronautics Brad Sturtevant also made his TV debut as narrator. This photo was taken by grad student Ichiro Sugioka before the wind was turned on.

New Division Heads

John Abelson, professor of biology since 1982, has been named chairman of the Division of Biology. Abelson, who earned his PhD in biophysics from Johns Hopkins University in 1965, has done significant research on the mechanisms of gene expression in yeast.

The new chairman of the Division of Geological and Planetary Sciences is David Stevenson. A professor of planetary science who is known for his work on the formation, evolution, and internal structure of the solar system and the planets, he joined the Caltech faculty in 1980. His PhD in theoretical physics is from Cornell (1976).

Centennial Float

To help celebrate its centennial Caltech will enter a float in the 1991 Rose Parade, whose general theme is humor. The committee in charge of the float is soliciting humorous ideas. A rough sketch of the concept and theme title (a word or phrase) may be submitted to Hall Daily, Caltech 1-71, Pasadena, CA 91125. The deadline is December 1.

The last Caltech Rose Parade entry was in 1950—a flower-bedecked model of Palomar Observatory. It was built by nine students in two months. But things have changed in 40 years, and beginning a year ahead is none too soon.

Watson Lectures

Coming up in the Earnest C. Watson Lecture Series are: November 8 — Daniel Kevles, "Patenting Life: Animals, Ethics, and Politics"; November 29 — Moustafa Chahine, "Global Warming: Fact or Fiction?"; January 10 — Barclay Kamb, "Is the Antarctic Ice Sheet Disintegrating?"; January 24 — Kip Thorne, "Wormholes Through Hyperspace and Travel Through Time."