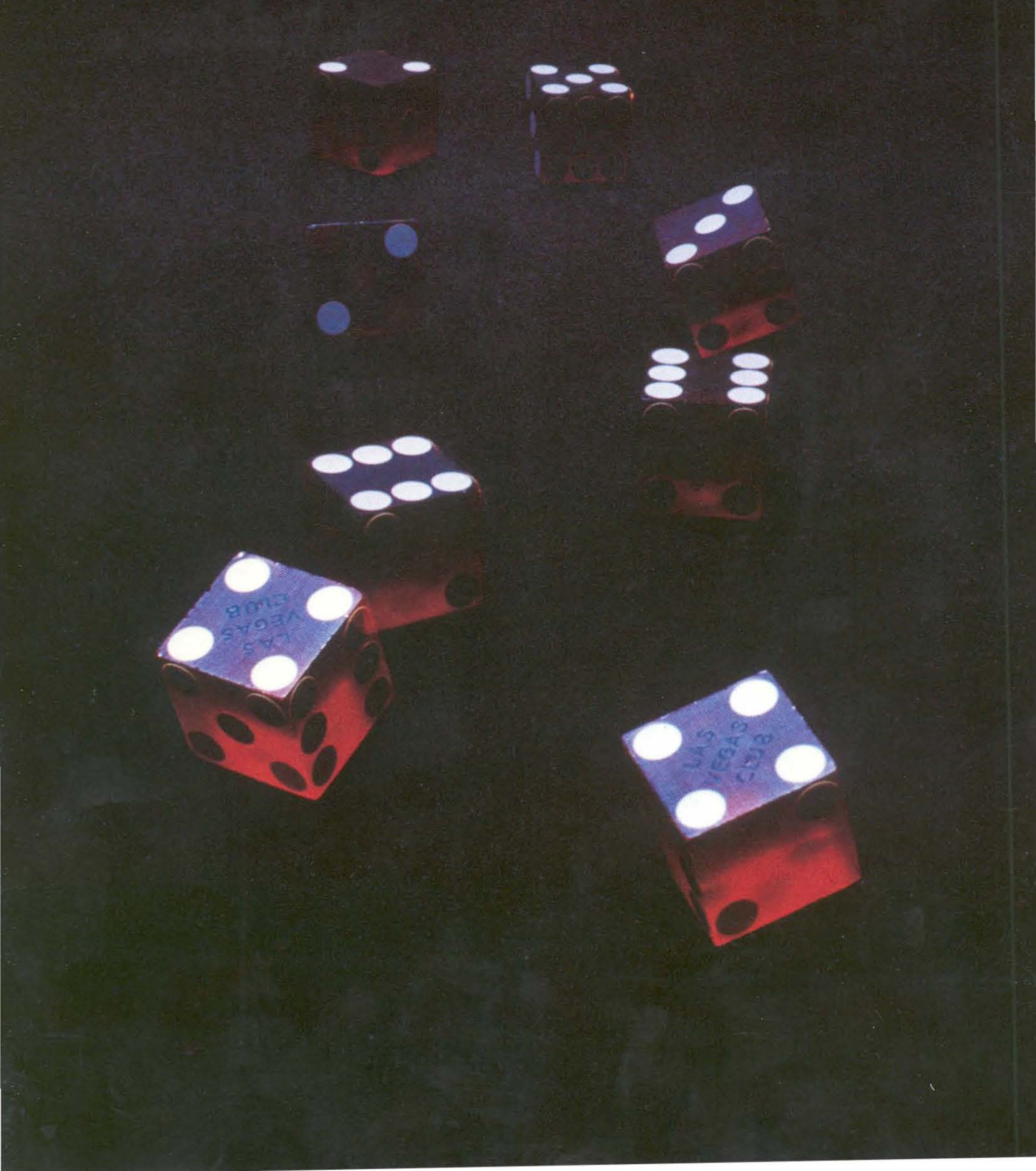
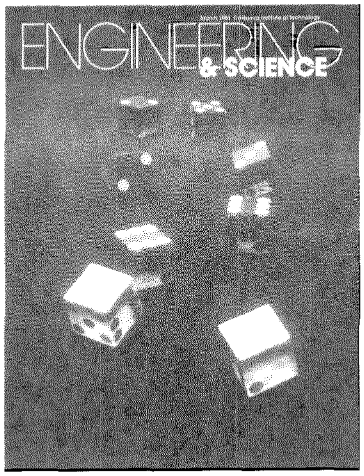
March 1986 California Institute of Technology

ENGINEERING & SCIENCE

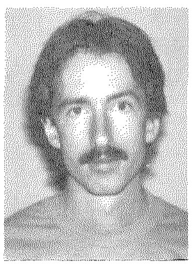


In This Issue



The Die Is Cast
On the cover — a couple of three-dimensional particles interacting with a flat plane in the presence of a gravitational field. Understanding how such particles behave is a fundamental problem in the dynamics of granular materials.

Grad student Brad Werner is interested in the physics of such systems and fortunately is fond of exploring and hiking in deserts where many granular systems reside. But rolling boulders (large particles) into canyons turned out to be harder work than rolling cubes on an office floor, so Werner turned his attention to dice. His article, "Particles in Motion: The Case of the Loaded Die," begins on page 20. Although Werner used dice from a worn-out Monopoly game for his study, the ones on our cover are "perfect dice" such as gambling establishments use — square to a tolerance of about 1/5000 of an inch (and they are *not* loaded). The dice were lent by Big Al's Game Rentals.



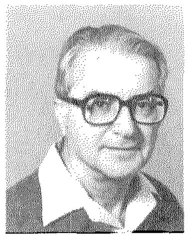
Werner received his BS from Caltech in 1981 and his MS in 1982. He works with Tom Tombrello, professor of physics, and Peter Haff, senior research associate.

Caltech Communicates
At the IEEE International Symposium on Information Theory held in Brighton, England last June, Caltech was a dominating presence — Robert McEliece was co-general chairman, Rod Goodman was chairman of the host committee, and Ed Posner, the program chairman. The three are members of the communications research group in Electrical Engineering, which is making significant contributions in both traditional and new areas of a field that has impact on just about everyone's day-to-day activities — from telephones to computers.

Posner, a visiting professor at Caltech from JPL's Telecommunications and Data Acquisition Office, earned his degrees at the University of Chicago (BA '52, MS '53, PhD '57) and has been at JPL or on campus (or both) since 1973. Goodman came to Caltech as associate professor last year with a B.Sc from Leeds University (1968), a PhD from the University of Kent (1975), and a background in British revue theater. McEliece, professor of electrical engineering, graduated from Caltech in 1964, earned his PhD in 1967, and returned to his alma mater in 1982 from the University of Illinois. Their article, " Speaking of Communication," starting on page 25, gives an overview of some of the group's varied research projects.

Martian Chronicle
Norman Horowitz, professor of biology, emeritus, has long been interested in the biochemical aspects of the origin of life and the possibility of its existence on other planets, Mars in particular. His evolving views have been chronicled in *E&S* over the years [March 1961, "Is There Life on Other Planets?" (maybe microbial life on Mars); April 1971, "Life on Mars? Possible, but Still Improbable"]. In a soon-to-be-published book, *To Utopia and Back: The Search for Life in the Solar System*, Horowitz recounts the history of that search and submits his latest conclusions. "Mars: Myth and Reality," a chapter from the book, is published here with permission of the publisher, W. H. Freeman and Company. It begins on page 4.

Horowitz himself has not been merely a bystander in the search for life on Mars. As chief of the Bioscience Section at JPL from 1965 to 1970, he was deeply involved with the scientific aspects of all the Mars missions and had biological experiments on *Mariners 6* and *7* and the *Viking* landers. (The "Utopia" in his title was the site of the *Viking 2* landing on Mars.)



Horowitz earned his BS from the University of Pittsburgh in 1936 and his PhD from Caltech in 1939. He returned to Caltech from Stanford with George Beadle in 1946 as associate professor of biology. He was named full professor in 1953, was division chairman from 1977 to 1980, and became professor, emeritus, in 1982.

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ENGINEERING & SCIENCE

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SCIENCE/SCOPE®

The feasibility of turning sea water into electricity is being studied in fusion energy experiments at Kyoto University in Japan. The studies involve a Hughes Aircraft Company gyrotron, a microwave tube that uses a spiraling stream of electrons to produce extremely high power microwave frequencies. Fusion energy holds tremendous potential because its source of fuel (hydrogen) can be extracted from sea water. It could produce large amounts of power with little or no radioactive waste and no threat of meltdown or explosion. In fusion energy research, the gyrotron's high-power radio waves heat hydrogen particles (plasma) to temperatures of tens of millions of degrees. These particles fuse under pressure, causing a thermonuclear reaction that provides energy for driving steam turbines.

A new technique may expand the use of lasers in commercial and military applications. The approach, called optical phase conjugation, is considered a major advance in optics because it offers a solution to distortion problems that have limited the use of lasers. When a laser beam passes through a turbulent atmosphere or a severely strained optical component, the beam is distorted and the information it carries is degraded. The Hughes technique, however, forces the laser to retrace its path through the distorting medium so the beam emerges free of distortion. The method eliminates the need for complex electro-optical and mechanical components to correct the distortions.

A MIDAS touch will create the factory of the future by introducing computer technology throughout one Hughes manufacturing division. The new Manufacturing Information Distribution and Acquisition System (MIDAS) is a flexible, high-speed data communication network. It will transmit and gather millions of bits of data per day by linking computer terminals, laser printers, bar-code scanners, and other equipment. MIDAS will serve graphic workstations and facilitate paperless planning. Similarly, it will relay numerical-control programs from main computers to machines in the factory, eliminating the need for paper tape. MIDAS will let all users share important peripherals, such as a laser printer, which now is impossible due to the incompatibility of equipment from different manufacturers.

NASA's Project Galileo, which will explore the planet Jupiter later this decade, must arrive at a precise angle if it is to carry out its measurements of the chemical composition and physical state of the Jovian atmosphere. The Hughes-built probe will arrive at 107,000 miles per hour, fast enough to travel between Los Angeles and Las Vegas in nine seconds. If the probe hits at too shallow an angle, it will skip off into space; too steep, it will be reduced to ashes. Even at the proper angle, the probe will encounter extremes never before faced by spacecraft. In less than two minutes, much of the forward heat shield will be eroded by temperatures of thousands of degrees. With atmospheric entry forces reaching 360 times the gravitational pull of Earth, the 742-pound probe will take on a weight equal to an empty DC-10 jetliner. Project Galileo is scheduled to be launched from the space shuttle in May 1986 and to arrive at Jupiter in August 1988.

Hughes needs graduates with degrees in EE, ME, physics, computer science, and electronics technology. To find out how to become involved in any one of the 1,500 high-technology projects, ranging from submicron microelectronics to advanced large-scale electronics systems, contact *Corporate College Relations Office, Hughes Aircraft Company, Dept. C2/B178-SS, P.O. Box 1042, El* Segundo, CA 90245. Equal opportunity employer. U.S. citizenship required.

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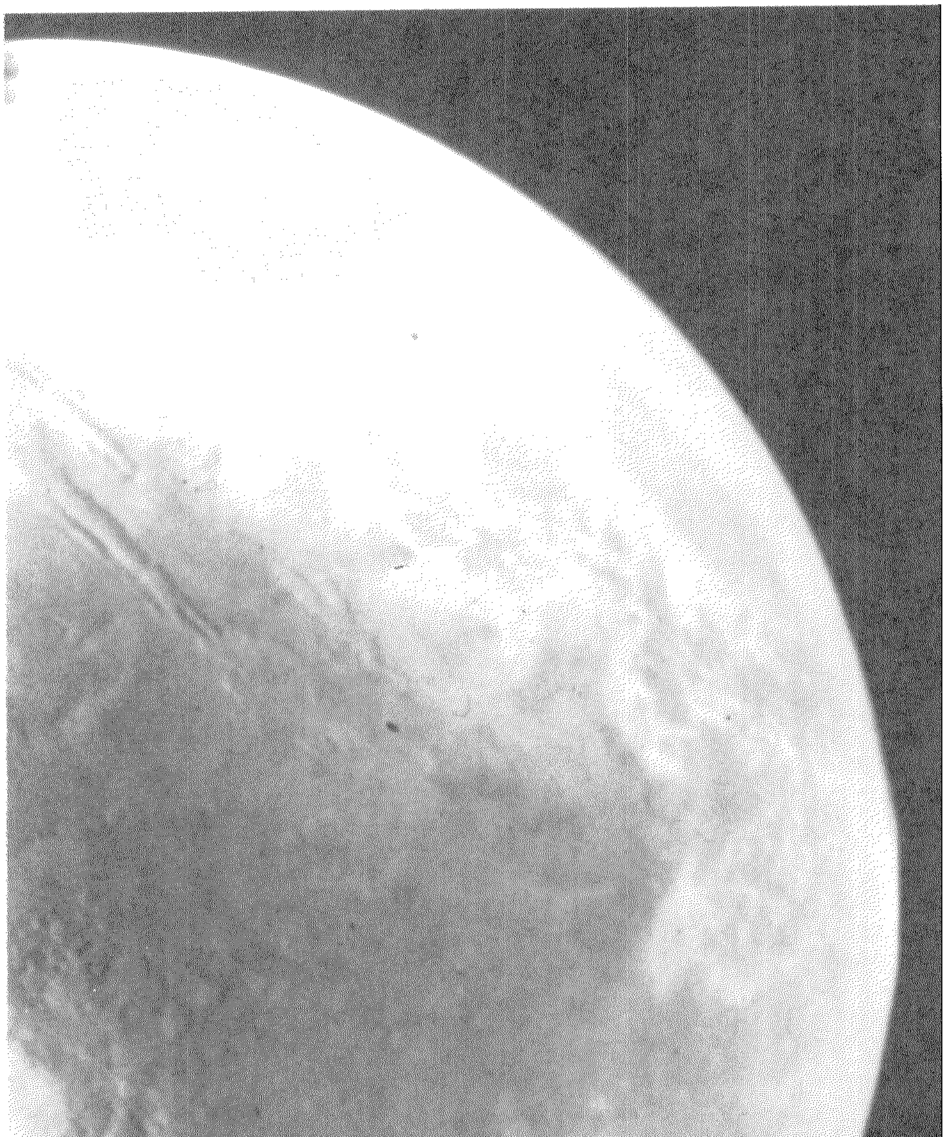
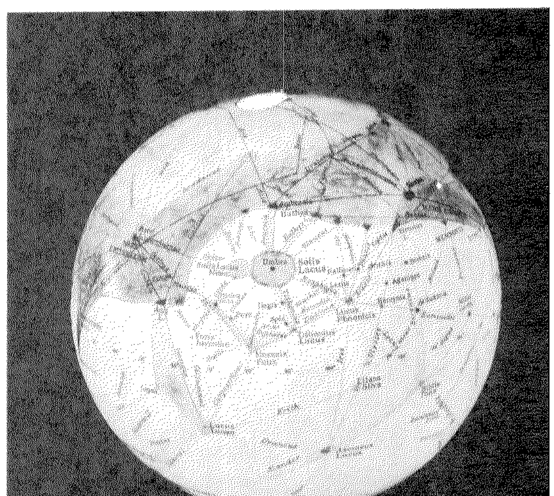


Mars: Myth and Reality

by Norman H. Horowitz



Above: Percival Lowell's 1907 globe of Mars with canals. The place names were given by Schiaparelli. (Lowell Observatory Photograph)
Left: Mars as seen by Viking 1.

Our knowledge of Mars steadily progresses. Each opposition adds something to what we knew before. Since the theory of life on the planet was first enunciated some fifty years ago, every new fact discovered has been found to be accordant with it. Not a single thing has been detected which it does not explain. Every year adds to the number of those who have seen the evidence for themselves. Thus theory and observations coincide.

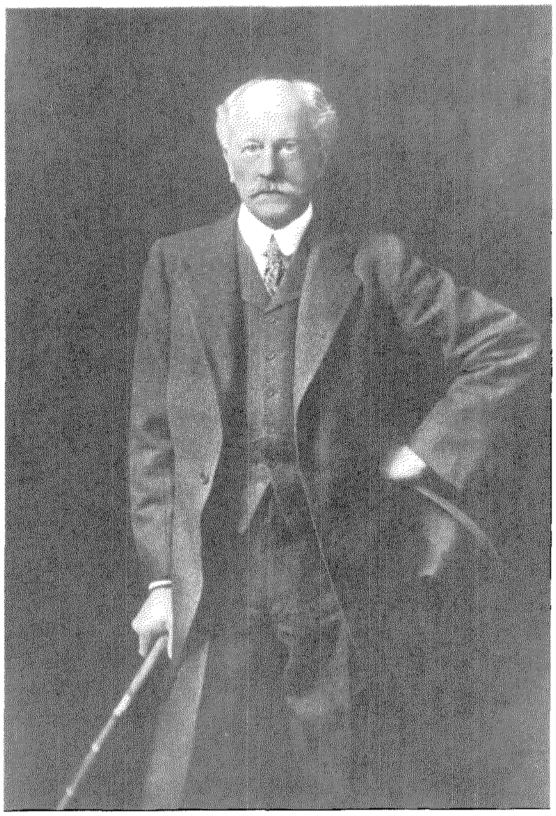
— E.C. Slipher, *The Photographic Story of Mars* (1962)

In *The Golden Bough*, anthropologist Sir James Frazer told us that Mars was originally a god of vegetation, not war. Roman farmers prayed to him for the success of their crops, and the vernal month of March was consecrated to him. In view of this ancient association of the god Mars with the awakening of plant life in the spring, it seems fitting that the planet Mars should be the least hostile of all the extraterrestrial bodies in the solar system, the planet other than the earth that comes closest to providing a suitable habitat for life.

Although only about half the diameter of the earth, Mars looks remarkably earthlike from a distance, and it does share certain similarities. In one of the earliest telescopic studies of the planet in 1659, Christian Huygens discovered a permanent marking on the Martian surface that enabled him to measure the planet's rotational period. He found that Mars, like the earth, rotates on its axis once in 24 hours. Later, more accurate measurements showed that the length of the Martian solar day is exactly 24 hours, 37 minutes, and 22 seconds — a period that became known as a "sol" during the Viking mission in order to avoid confusing it with the terrestrial day. Furthermore, in the present era the spin axis of Mars tilts at an angle of 25 degrees from the plane of its orbit, compared to the 23.5 degree tilt of the earth. This means that Mars has seasons like the earth's, as first one hemisphere and then the other leans toward the sun. The Martian year is 687 earth days in length (669 sols), or about six weeks short of two earth years, so that the Martian seasons last roughly twice as long as those on the earth. Because of the eccentricity of Mars's orbit, however, Martian seasons are not of nearly equal durations as our planet's are. On Mars, for example, northern summer (and southern winter) lasts 178 sols, while northern winter (and southern summer) lasts 154 sols. On the earth, these seasons last 94 and 89 days respectively.

The impression of an earthlike planet is reinforced by seasonal changes on the Martian surface that can be seen through the telescope. The most striking of these changes is the annual advance and retreat of the polar ice caps. Other, more subtle alterations occur at lower latitudes, where the Martian surface is broken up into bright and dark areas. The bright areas, formerly called deserts, are reddish orange in color. The dark areas, in the past called maria (seas) because they were thought to be bodies of water, have been variously described as gray, brown, blue and green. Seasonal changes in color and contrast — the maria appeared a dark bluish green in the late spring and summer, but faded to a brownish tone in fall and winter, then darkened again in the spring — were reported by astronomers in the 19th century. Such changes made it appear more likely that vegetation rather than water covered these areas, an idea that was first advanced in 1860. Some observers also described a network of pencil-thin, straight lines extending for hundreds of miles over the Martian surface. These lines, called "canali" (channels) by Giovanni Schiaparelli (1835-1910), the foremost Mars-mapper of the 19th century, changed seasonally like the maria — they were dark in the local spring and summertime, but faded in fall and winter. Schiaparelli noted that the canali looked like the work of intelligent beings, but he did not commit himself to this interpretation.

These intriguing observations, which were made possible by improvements in telescopes in the 19th century, convinced some people that direct evidence for life on another planet had at last been achieved. One of those



Percival Lowell. (Lowell Observatory Photograph)

stirred by the new findings was Percival Lowell (1855-1916), an American who would found the Lowell Observatory in Flagstaff, Arizona, for the express purpose of studying Mars. Lowell's place in the extraordinary history of Martian biological investigations is special enough to require a more detailed examination.

THE LEGACY OF PERCIVAL LOWELL

Percival Lowell belonged to an eminent New England family: Abbott Lawrence, his brother, became president of Harvard University, and his sister Amy was the Imagist poet. Lowell was not trained as an astronomer — he devoted himself to studies of Japanese and Korean culture, subjects on which he wrote a number of books — and his fascination with Mars developed relatively late in life. According to William Graves Hoyt, author of a recent biography of Lowell, astronomy had long been among Lowell's many enthusiasms, and he was inspired by Schiaparelli's discovery of canali on Mars. Schiaparelli's description, it appears, all but convinced Lowell that Mars was inhabited by intelligent beings. This belief, or near-belief, led him to commit his considerable wealth and talent to the founding of the Flagstaff observatory. Dedicated to the study of Mars, the observatory opened in May, 1894. By July of the same year, barely two months after operations began, Lowell was ready to formulate his very definite views about life on Mars — views from which, Hoyt notes, he did not deviate for the rest of his life.

Although Lowell came to Martian studies late in his career, his authority and influence in matters relating to Mars soon became quite important. His observatory was well equipped and staffed, and it occupied a superior observing site, a fact that Lowell did not neglect to mention when others failed to confirm his observations. Furthermore, the observatory spent almost its entire effort on Mars and missed no opportunity to study it. Lowell therefore accumulated a vast amount of systematic information on the planet, and these intensive studies made him probably the best-informed Mars-watcher of his day. (Criticisms directed at Lowell during his lifetime and later aimed less at his data than at his interpretations of them.) Finally, Lowell tirelessly communicated his great enthusiasm for his subject and his unwavering confidence in the correctness of his conclusions to the general public in books, articles, and public lectures. Through these and other efforts, he succeeded in making Mars a topic of general interest, not one reserved for specialists alone.

Lowell's theory was simple enough. It began with the premise that the polar caps of Mars are composed of water ice. To support this belief, he pointed to a dark blue band, or collar, that appeared around the caps as they began to shrink in the spring and that dwindled with them. Only liquid water, produced by melting of the caps, could explain the collar, he argued, and he often referred to these bands as "polar seas." Lowell knew that, aside from the polar regions, Mars is very dry. Its dark areas could not be bodies of water because, although they changed color seasonally as if drying up, the water apparently lost from them did not turn up anywhere else on the planet. And as others had pointed out, if the maria contained water, they would reflect sunlight, yet such reflections were never seen. Given the dryness of the planet, Lowell deduced that the seasonal disappearance of one polar cap, coupled with growth of the other, meant that water was transferred from one pole to the other: "Meteorological conditions carry (water) to deposit at one pole, then liberate it and convey it to imprisonment at the other, and this pendulumlike swing of water is all in the way of moisture that the planet knows." This semiannual transfer of water was accompanied by a darkening of the dark areas that spread wavelike "across the face of the planet from one pole to the other in the course of a Martian six months." Such regular darkening, he was convinced, demonstrated that plant life exists on Mars. The observations proved, he wrote, that the condition of the planet "is not only compatible with life, but that vegetal life shows itself there as patently as could possibly be expected, and that nothing but vegetation could produce the observed phenomena."

In Volume 1 of the *Annals of the Lowell Observatory*, Lowell continues:

> Now if there were any life of an order higher than the vegetal upon the planet — an order capable of something more advanced than simply vegetating, an order able to turn natural conditions to its own ends — its first and final endeavors would be to contrive means to use every particle of that necessary and yet scanty sustainer of life, water. For there is no organism which can exist without water. In short, irrigation for agricultural purposes would be the fundamental Martian concern. . . .

Lowell then summarizes his observations on the canali and concludes:

> These are just the features a gigantic system of irrigation would present. Upon the above results of the observation is based the deduction I have here put forward, — (1) of the general habitability of the planet; (2) of its actual habitation at the present moment by some form of local intelligence.

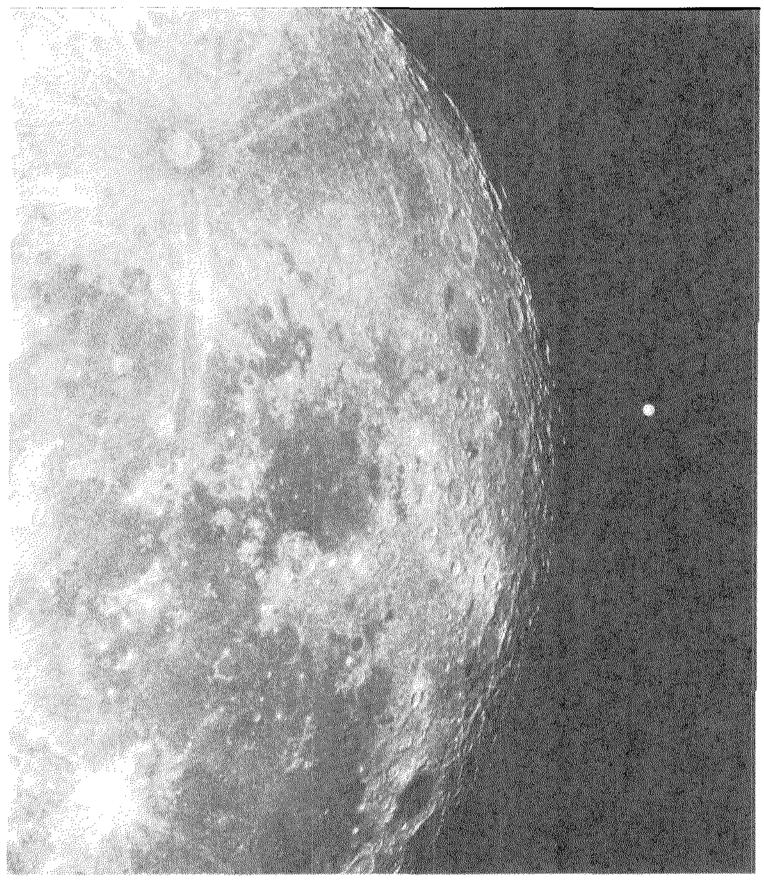
And so Lowell arrived at the belief in a civilization on Mars. Abetted by his French contemporary, the astronomer Camille Flammarion (1842-1925), he popularized the familiar drama of a courageous race of Martians, superior to ourselves, struggling for survival on a desiccated and dying planet. Lowell saw nothing speculative in these ideas. In a typical passage from his book, *Mars as the Abode of Life*, he writes:

> In our exposition of what we have gleaned about Mars, we have been careful to indulge in no speculation. The laws of physics and the present knowledge of geology and biology, affected by what astronomy has to say of the former subject, have conducted us, starting from the observations, to the recognition of other intelligent life.

The idea of a Martian civilization, although embraced enthusiastically by the public, was viewed with scepticism by scientists even in Lowell's day, and it did not survive his death. The "canals" — always controversial and now known not to exist — were probably an illusion caused by viewing difficulties. The rest of Lowell's theory, however — the polar ice, the movement of water, the vegetation — not only survived him, but took on new life. It was as if, relieved of its burden of heroic Martians, the Lowellian thesis of an earthlike Mars had acquired scientific respectability and could be accepted as a reasonable approximation to the truth. Lowell's views would eventually be disproved in every significant detail. Yet — and this is the strange part of the story — as observations of Mars continued, they seemed increasingly to show that Lowell was right. As a result, the Lowellian view was widely accepted for most of the 20th century.

The epigraph at the beginning of this chapter, quoted from a book by a longtime associate of Lowell's, summarizes the state of

This 1911 photograph of Mars (the small dot at right) emerging from occultation by the moon (the large hemisphere at left) illustrates why it was difficult to study Mars from the earth in the early part of the century. (Lowell Observatory Photograph)



affairs as they appeared to one observer in 1962. The optimism that shines through Slipher's statement could, in fact, be defended in 1962. Unfortunately for this view, new results soon to be obtained would show that this optimism was unfounded and that the Lowellian picture of Mars, with or without canal-building Martians, was pure fantasy. Within a few years, scientific ideas about the planet would take an entirely different turn. The rise and fall of Lowellian Mars in our time is our subject in the rest of this chapter.

PRE-1963, OR LOWELLIAN, MARS

Ice Caps

The waxing and waning of the Martian ice caps proved to early observers that Mars has an atmosphere of some kind, but its composition and its quantity remained a mystery for a long time. Carbon dioxide, now known to be the major component of the Martian atmosphere, was first identified on Mars by the well-known Dutch-American astronomer, Gerard P. Kuiper (1905-1973) in 1947. To make this finding, Kuiper used infrared spectroscopy. In planetary spectroscopy generally, sunlight reflected from a planet is collected by a telescope and broken up by a prism or grating into its spectrum — in this case, its infrared spectrum. This spectrum is then compared to a similarly prepared spectrum from the moon, for example, or, depending on the question being investigated, from a different area of the same planet. Different substances absorb light of different wavelengths, a fact that makes chemical identifications possible. By comparing the spectrum from a planet that has an atmosphere with one obtained from the moon, which has no atmosphere, once the absorption by the earth's atmosphere is subtracted out, what remains is the spectrum of the planet's atmosphere. Because the amount of energy absorbed depends on the amount of absorbing material, such spectra contain quantitative as well as qualitative information. Thus, the observer can say not only what the absorbing gas in the light path is but how much of it there is.

The wavelength region that lies beyond the red end of the visible spectrum, called the infrared, is very rich in specific chemical absorptions. When Kuiper compared the infrared reflections from Mars with those from the moon, he found a diminution in the energy at several wavelengths in the neighborhood of 1.6 micrometers in the Martian spectrum; these wavelengths corresponded to known carbon dioxide absorptions. Kuiper estimated that the amount of carbon dioxide over a given area of Martian surface is twice that over the same area on the earth. From this, he calculated the pressure of carbon dioxide on Mars, taking into account the lower force of gravity on Mars compared with that on the earth. He arrived at a pressure equal to that of 0.26 millimeter of mercury, or 0.35 millibar. Here Kuiper erred. His estimate was too low by a factor of about 16, an error that had important consequences because it allowed Kuiper to argue that the Martian polar caps could not be composed of frozen carbon dioxide (dry ice). If the carbon dioxide pressure were as low as his calculations indicated, an unrealistically low temperature would be required to freeze the gas out of the atmosphere. It was discovered some years later that Kuiper had incorrectly calculated the carbon dioxide pressure, but this finding had no effect on the course of events.

The only other substance that was reasonable for the caps was frozen water — ice, snow, or frost — but other astronomers had already searched without success for water vapor in the Martian atmosphere. Kuiper therefore proceeded to examine the north polar cap of Mars directly by infrared spectroscopy. The analysis was difficult, owing to the small size of the ice cap, but by modifying his spectrometer to improve its sensitivity and by repeating the observations many times, Kuiper finally convinced himself that "the Mars polar caps are not composed of CO_2 and are almost certainly composed of H_2O frost at low temperature." The note of caution discernible in the second part of this statement reflects the fact that the spectrum of the polar cap did not quite match the spectrum Kuiper had obtained for terrestrial snow.

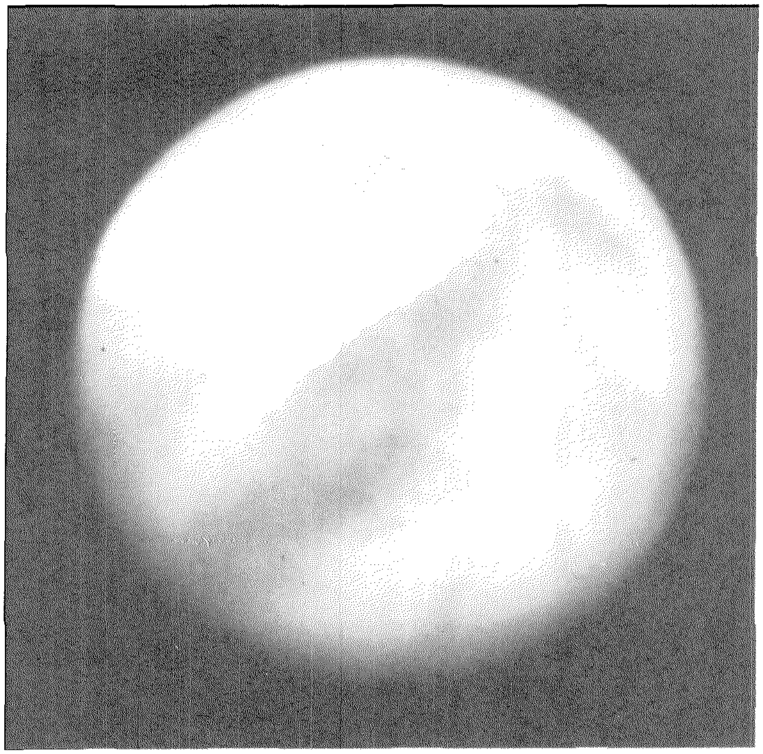
Here Kuiper erred again — the seasonally variable portions of the caps are actually frozen carbon dioxide, not water — but his error would not be discovered for nearly 20 years. Instead, the incorrect result was seemingly confirmed by another investigator, Audouin Dollfus of the Paris Observatory, using a different method, one based on the polarization of reflected light. Ordinary, unpolarized sunlight consists of electromagnetic waves that vibrate in all directions in the plane perpendicular to the direction of propagation of the light ray. In light that has been reflected or scattered, however, or that has passed through certain kinds of materials (such as polaroid), the waves vibrate in only one direction. Such light is said to be polarized. The degree of polarization of reflected light depends on the angle of vision, as well as on the structure, transparency, and other physical properties of the reflecting surface. Dollfus, who had much experience with planetary polarization measurements, decided to apply the method to the ice-cap problem.

As had Kuiper before him, Dollfus noted that the caps were small and difficult to study. He succeeded in making some measurements, however, and found that the polarization of the caps was much less than that of ice, frost, and snow on terrestrial mountains observed at the same angle. He then performed laboratory experiments showing that the polarization of frost deposits could be made to resemble that of the Martian ice caps if, first, the frost were deposited on a cold surface with a low atmospheric pressure (as would be the case on Mars) and, second, if the deposits were partly sublimed — that is, evaporated without melting — by exposing them to an arc lamp, as might happen to Martian ice caps exposed to the sun. He concluded that the ice caps were probably deposits of hoarfrost.

Dollfus did not perform comparable experiments with solid carbon dioxide, but his apparent confirmation of Kuiper's result convinced many students of Mars that the ice-cap question was solved. The following quotation, for example, reflects the views of a panel of informed scientists, many of whom later made important contributions to our knowledge of Mars, that was appointed by the Space Science Board to advise NASA in the early stages of its planetary program:

> Infrared reflection spectra of the polar caps show conclusively that they are not composed of frozen carbon dioxide, the only condensible substance which might be expected besides water; the reflection spectra are also consistent with the assumption that the polar caps are made of ice. . . . The polarization data indicate that the polar caps are composed of hoarfrost. . . .

Later in its report, this same panel drew an inference identical to the one reached by Lowell in 1898, 63 years before. In their view:



> Since the polar caps are composed of frozen water, their seasonal retreat directly suggests that there is some water vapor in the Martian atmosphere. Because of the alternating formation of polar caps in opposite hemispheres, the circulation in the lower atmosphere must be such that water vapor is transferred from one hemisphere to the other.

Robert Leighton captured the best earth-based photograph of Mars from Mt. Wilson in the early 1950s. Leighton and Bruce Murray, both of Caltech, predicted in 1966 that the polar ice caps were made of solid carbon dioxide, a fact confirmed by Mariner 7 three years later.

Atmospheric Pressure

Mutually supporting errors also produced a spurious conclusion about the atmospheric pressure, another crucial biological parameter. And once again, the effect was to make Mars appear more earthlike than it actually is. In the Lowellian period, the two principal methods used to estimate the Martian atmospheric pressure were photometry and polarimetry. Light is scattered by gas molecules. It is this scattering that accounts, for example, for the blue sky: the atmosphere scatters incoming sunlight in all directions, but because light of short wavelengths (blue and violet) is scattered very much more than long-wavelength (red) light, we see a blue sky when we look away from the sun. Since scattering by its atmosphere affects the surface brightness of a planet, measurement of that brightness at different wavelengths and under different thicknesses of atmosphere (obtained

continued on page 35

Chairman of the Board

In January 1985 Ruben Mettler became chairman of Caltech's board of trustees, succeeding Stanton Avery. Mettler has Caltech roots going back 43 years to when, by his own admission, he distinguished himself on campus by getting a zero on his initial physics test during the first week of class. Undaunted, by the time he earned his BS in 1944 he was "doing reasonably well." He's currently chairman of the board and chief executive officer of TRW Inc.

Mettler didn't choose Caltech right off the bat. Born in Shafter, California, near Bakersfield, one of ten children, he enrolled at Stanford in 1941, planning to major in the humanities with an eventual goal of law school. Then World War II intervened, and he joined the Navy. But he had been at Stanford long enough to come under the influence of history professor Rixford Snyder, "who thought," notes Mettler, "that in order to be literate in the humanities, one should know something about chemistry, physics, and mathematics. It's particularly true in this day and age, but it was true then too. Snyder's argument wasn't just that an engineer, to be literate, should know something about Shakespeare or economics, but that a *humanist*, to be literate, should know something about *science*. That science and technology and the humanities are inextricably bound together was a rare concept, especially then."

Although the Navy recruiters didn't care much about his being literate in the humanities, they looked at all the science courses he had taken and routed him in a V-12 unit. The Naval V-12 College Training Program was set up to train engineering students as junior officers for the fleet. At Caltech the sailors were considered students like everybody else, and Robert Millikan expressed the hope that "the whole student body, whether in uniform or out of uniform, will become . . . integrated into a *single, compact body of California Institute men.*"

So Mettler ended up at Caltech, soon to make his mark on the first physics test. Since Caltech didn't offer V-12 students special treatment ("they just shoved us into the courses"), many of the Navy men dropped back a year or two just to survive. Failing the courses meant getting bounced out of the program. Although Mettler was officially a junior, Registrar Winch Jones looked at his academic background and, not as impressed as the Navy, suggested that the Stanford humanities major register as a freshman or sophomore. But since it was a four-term program, registering as an underclassman meant no degree. Mettler felt he could catch up, took the risk, and registered as a junior.

"It was certainly one of the most difficult, intense learning experiences that I can imagine," says Mettler. "It was possible to get decent grades by the end of the term, but at the beginning . . ." In addition to the rigors of Caltech courses, V-12 students had to do all the military sorts of things — up at 5:30 every day for calisthenics and a run in Tournament Park, for example. And as a Navy student commander, Mettler had to lead a parade down California Boulevard every week.

Mettler earned his degree in electrical engineering in 1944. After that came officer's candidate school, radar studies at MIT's Radiation Laboratory (headed by Lee DuBridge), and then into the Pacific with the Electronic Field Service Group. Its assignment was to go from ship to ship to submarine to carrier ("miserable logistics") diagnosing radar problems. At the time Mettler wasn't giving much thought to the possibility of graduate school — "mostly I was just happy to get through the war." After the war ended, when he was involved with the Crossroads Project setting up instrumentation for atomic tests, a letter arrived out of the blue from S. S. MacKeown, then professor of electrical engineering, suggesting that Mettler come back to Caltech.

"I answered, first of all, that I hadn't even applied; and second, I didn't know whether they would take me," says Mettler. That was in July of 1946. Shortly thereafter he received a wire from MacKeown saying that if he could be on campus by a certain date in September, he could start right away. "Maybe Caltech was short of students or something," Mettler speculates. But he got out of the Navy at the end of August and arrived in Pasadena the following week.

Because of his Navy experience in radar and electronics, as well as the courses he had taken previously, Mettler signed up for electrical engineering. "It sounded like a good plan, and I knew I could always go back to Stanford or something if I didn't like it. And I loved it; I just loved it. I was turned on by it; I found it exciting. I plunged right into the very difficult courses — difficult for me after having been in the service and away from school for a few years."

Mettler also signed up for a minor in aeronautical engineering — he wrote his dissertation on a combined electronics/aerodynamics project. He was an instructor in applied mechanics, and he worked in GALCIT under Clark Millikan and Hans Liepmann, now the Theodore von Kármán Professor of Aeronautics and director of GALCIT. Liepmann remembers him as one of a remarkable group of young men to come out of Caltech right after the war, a group that also included Allen Puckett (PhD '49), now chairman of the board and chief executive officer of Hughes Aircraft Company, and T. A. Wilson (MS '48), chairman of the board of The Boeing Company. Fred Lindvall, now professor of electrical and mechanical engineering, emeritus, was Mettler's thesis adviser. Lindvall particularly remembers how well Mettler handled his job as resident associate ("We always called them housemothers then," says Lindvall) of Ricketts House. "He had a natural ability to manage people," Lindvall remembers. "He would just quietly ask students to desist from doing something wrong and they would desist. It didn't take any pressure." Then, when Col. E. C. Goldsworthy, master of student houses became ill, Mettler took over as his deputy.

The years following the war were difficult ones for an RA, because in addition to the 17- and 18-year-old students entering Caltech right out of high school, there were also returning veterans in their late 20s. "So it was next to impossible to get the veterans who had been in the service for four or five years to accept the same constraints that one would hope applied to 17- and 18-year olds," Mettler recalls. "It was an unusual time in the student houses. Some of the younger students probably picked up some bad habits from some of the older ones — and vice versa."

Mettler finished his PhD in 1949. Bill Pickering, professor of electrical engineering (now emeritus), who became director of the Jet Propulsion Laboratory in 1954, tried to recruit Mettler to JPL. Lindvall also remembers Mettler as a "very good student, careful and dependable," whom he tried to persuade to make a career in engineering education instead of industry. "But Si Ramo was a better talker than I was, so he went the business route." Simon Ramo and Dean Wooldridge (both PhD '36) were research associates at Caltech during the time that Mettler was a grad student, and when he left Caltech in 1949, they took him to Hughes Aircraft Company.

Ruben Mettler (left) enjoys a convivial moment with President Goldberger and Stanton Avery (right), chairman emeritus of the board of trustees.

At Hughes he became the leader of a group designing and developing a new integrated avionics system (navigation, communications, guidance control, weapons control) for fighter planes, eventually becoming project manager, responsible for building the system and flight testing it. The system was selected by the Air Force for quantity production for its fighter interceptors. For this work Mettler was named the nation's Most Outstanding Young Electrical Engineer by Eta Kappa Nu in 1954. In the same year he was appointed a full-time consultant to the Department of Defense and spent a year in Washington, working for the President's Scientific Advisory Council in the White House in the morning and in the Pentagon in the afternoon, an experience he found fascinating. "This gave me an opportunity to work on important projects in the Pentagon but also to get some sense of how they fit into a bigger mosaic." Among those projects were the technical intelligence programs that gathered the first evidence that the Soviets were launching long-range ICBMs.

But in 1955 he returned to California — to the newly formed Ramo-Wooldridge Corporation. Here he was initially system design leader and then program director for the Thor intermediate-range ballistic missile and then took over responsibility for technical supervision of the Atlas, Titan, and Minuteman missile programs as well. During the early years of Ramo-Wooldridge, Mettler was also involved in developing some of the earliest U.S. scientific satellites, including Pioneer 1.

When Ramo-Wooldridge merged with Thompson Products (of Cleveland, Ohio) in 1958, Mettler became executive vice president of the renamed TRW Inc., as well as president of TRW Space Technology Laboratories. When the latter became part of the TRW Systems Group in 1965, Mettler was again named president (as well as a director of the company). For the next six years Mettler's group was responsible for a number of key elements of the U.S. scientific satellite program, including the Pioneer and OGO (Orbiting Geophysical Observatories) satellites, as well as the 1968 Global Communications Network. It also designed and built the lunar module descent engine and was involved in such military applications as nuclear detection satellites and antisubmarine warfare. He became president and chief operating officer of TRW Inc. in 1969 and established a home in Cleveland, Ohio; he moved up to the positions of chairman of the board and chief executive officer in 1977.

Mettler lives with his wife, Donna, in Cleveland and in West Los Angeles. Their older son, Matthew, 28, graduated from Stanford in electrical engineering, earned an MS in computer science, and helps manage a fledgling venture capital group in Silicon Valley. Daniel, 25, lives at the Jay Nolan Center in the San Fernando Valley. As an autistic child, Daniel could not communicate through normal spoken language, but the Mettlers discovered when he was six that he could read and that he had exceptional musical talent. "It just shows that the human mind is capable of prodigious leaps," says Mettler. Daniel is now an accomplished pianist. "Music has become his life, and we went through some exhilarating experiences as this happened." Mettler himself plays the piano, which led to the initial breakthrough in communication through music, "but I can't even touch what he now plays."

Perhaps because of his son, Mettler has been deeply concerned with the problems of the disadvantaged — the physically, economically, or ethnically disadvantaged. And, as in other areas of his life, he has devoted his considerable energies to finding solutions to some of the problems. In 1977 President Carter asked him to develop a program to urge private industry to hire more Vietnam veterans. Working through the National Alliance of Business, Mettler's committee placed several hundred thousand disadvantaged workers in jobs, among them 150,000 veterans. The unemployment rate for Vietnam veterans went from over 15 to under 8 percent in about a year. For this work and for helping to raise 110 million dollars in two years as chairman of the national campaign for the United Negro College Fund, Mettler was honored in 1979 with the National Human Relations Award of the National Conference of Christians and Jews.

Caltech isn't exactly disadvantaged, but Mettler's activities have always included his alma mater also. He's been active in the Alumni Association and has chaired the Alumni Fund. In 1966 he was one of the first recipients of the Distinguished Alumni Award. He's been a life member of The Associates since 1968 and a member of the board of trustees since 1969.

Because of this long-time association with Caltech and its trustees, the chairmanship didn't hold many surprises for Mettler. But a year as chairman has strengthened some of the ideas he already held about the Institute. "The last year has very strongly reinforced my sense that Caltech has its comparative advantage relative to other institutions in the exceptional number of incredibly talented individuals in an institutional setting that is small enough for them to really communicate with each other. I think the strong and unrelenting commitment to excellence at Caltech is exactly right."

But he also thinks it extremely important to articulate a vision of the Institute's future and to project that vision outside the Caltech community. "The trustees should participate, along with the administration, the faculty, and the staff, in shaping a coherent vision of what the Institute can do and can be — a vision that maintains the excellence of the past, builds on it, and sets new goals. The trustees need particularly to focus on developing the resources that are necessary to carry out that vision." □ — *JD*

The Tax Compliance Game

Using game theory to study the interaction between the IRS and the taxpayer, Caltech economists are turning up some surprising results.

In 1968 Gary S. Becker of the University of Chicago published a seminal paper called "Crime and Punishment: An Economic Approach." In it he put forth the radical notion that criminal behavior is not necessarily aberrent and senseless. Rather, crime can be seen as a rational economic decision made by an individual who weighs the expected gains from criminal activity, the probability of being caught and convicted, and the levels of punishment.

Since then, Becker's method has been applied to many different crimes, including the crime of tax avoidance. But until a group of current and former Caltech researchers started working on the problem, these studies suffered from a serious defect: they failed to properly consider the actions of the Internal Revenue Service (IRS). The early studies assumed that the only economic actor in the system is a taxpayer who is certain about both the probability of being detected and the level of sanctions.

It turns out that the results of such studies are overly determined by things like an individual's attitude to risk, while at the same time they ignore factors that enhance or inhibit the IRS's ability to enforce tax laws. For example, these studies are forced to conclude that in a truly efficient tax system, cheats would be tortured and hanged when discovered. Under those circumstances enforcement costs would be low, since few would risk the penalty. While this scheme might well work, in the real world such theoretically desirable sanctions are, of course, inconceivable because of a variety of legal, moral, and political constraints.

A major contribution of the Caltech researchers to the analysis of the tax system is their inclusion of the IRS as an active participant. Using the mathematics of game theory, they model the interaction between the IRS and the taxpayer as a two-player game in which each player tries to maximize his self-interest. The taxpayer in such a game has the option of underreporting his income to lessen his tax liability, but he knows that there's a chance that the IRS will catch him and force him to pay additional taxes and fines. The IRS can audit a tax return to determine a taxpayer's true income, but conducting an audit is costly.

In addition, the Caltech models are more realistic in their inclusion of a variety of real-world constraints. For example, the sum of taxes and fines is prohibited from exceeding a taxpayer's total income.

In their first attempts at modeling tax compliance, Louis Wilde, professor of economics, Jennifer Reinganum, associate professor of economics, and Michael Graetz, a lawyer formerly at Caltech and now at the Yale Law School, used a "principal-agent" framework. In a principal-agent game the two players are not equivalent. The principal — in this case the IRS — moves first, pre-committing to a strategy that it must follow, even if it later turns out not to be in its interest to do so. The taxpayer is the agent in this game and responds to the principal's announced strategy with his own best strategy.

In the principal-agent framework the IRS's strategy takes the form of pre-announced audit policies. For example, the IRS could announce that it will audit all taxpayers who report incomes below a certain cutoff level and no taxpayers who report incomes above that level. Taxpayers with high incomes may underreport a little bit — down to the cutoff level — without fear of discovery. Taxpayers with incomes below the cutoff level must report their true income since they're certain to be audited. In such a scheme, the only people who get audited are those with no incentive to lie. In one sense, the IRS's audit costs are wasted, since auditing will not generate additional revenue. But the IRS must carry through on its threats in order to maintain the incentives against serious underreporting by high-income taxpayers. In their first principal-agent study, Reinganum and Wilde determined that cutoff schemes are more efficient (that is, they generate more revenue to the IRS at less cost) than schemes in which the IRS audits a random selection of tax returns.

While Reinganum and Wilde demonstrated the advantages of an audit policy that exploits the information provided to the IRS by taxpayers, they did not characterize the *best* such policy. This was done in a related principal-agent analysis by Kim Border, associate professor of economics, and Joel Sobel, a former visiting associate professor in economics, now back at the University of California, San Diego. Their work led to the conclusion that audit schemes exist that are more efficient than either of the schemes Reinganum and Wilde evaluated. Border and Sobel determined that the most efficient tax system should have the following properties:

- The higher a taxpayer's income, the more he should pay in taxes.
- Within any given class of taxpayers the probability of being audited should decrease with increasing reported income. This would deter high income taxpayers from reporting lower incomes since, if they did so, there would be a greater likelihood of being audited.
- Taxpayers who are found to have lied about their incomes after an audit should be fined, while taxpayers who are found to have told the truth should actually be given a rebate. In this way taxpayers would prefer to tell the truth and would want to be audited.

The somewhat startling idea of giving rebates to truth tellers is at first glance appealing, but Border does not expect rebates ever to become part of tax law. "It's not clear that it would be fair for the government to throw the dice and give certain people rebates for telling the truth, while other people who told the truth without being audited receive no rebates," he says. He also believes it unlikely that American lawmakers could be persuaded to reward people for doing what they ought to be doing as good citizens without reward. And, to create the proper balance of incentives, the theory predicts that only certain income classes should receive rebates for truth-telling. Which income classes would be eligible for rebates depends crucially on actual distributions of income in the population. Getting such a fine-tuned system through even a willing Congress would be difficult, if not impossible, according to Border.

The purpose of the Border/Sobel study was to analyze the properties of an idealized revenue collection system, in which the IRS can both precommit and choose all the relevant policy variables. For those reasons, many of their assumptions are, in practice, unrealistic. They assume, for example, an IRS that has the freedom to set tax rates, fine schedules, and audit probabilities, when in reality the IRS has control only over the last of these. Congress sets taxes and fines and has other objectives aside from maximizing revenue: stimulating certain industries and promoting certain social goals are two examples. Another, less crucial, unrealistic assumption of the model is that taxpayers receive only one sort of income and that an audit unambiguously reveals the truth. In reality, the tax code treats wages differently from capital gains and dividend income. And the tax code is so filled with gray areas that an unambiguous determination of true income is often impossible. A third assumption is that all taxpayers are "risk-neutral," that is, they have no preference between receiving *X* dollars right away or taking a gamble that, on average, returns *X* dollars. Psychological studies have shown, however, that most people are risk-averse — they prefer the certain return to the gamble.

While studies of idealized revenue collection systems are valuable, they are limited in their practical usefulness. Recently, Graetz, Reinganum, and Wilde have developed a model of the tax compliance problem that incorporates additional features of the real world. The most significant difference between this latest approach and the earlier one is that it no longer assumes a principal-agent framework. Instead, it assumes that the IRS must use an audit strategy that maximizes revenue net of audit costs given the tax returns it actually receives, instead of precommitting to a strategy ahead of time. An examination of how the IRS actually conducts audits reveals why this is a reasonable change.

The IRS conducts three sorts of audits. The simplist of these is an automatic comparison of tax returns with third-party reports such as W2 and 1099 forms, which are submitted by employers to the IRS and which detail payments to wage earners and to outside contractors. A computer kicks out any discrepant returns, which are then audited. It is this program that most approaches precommitment on the part of the IRS — everyone knows that if the wage income he claims is lower than that listed on the W2 form, he's certain to be audited. Strategic behavior thus becomes futile.

The second type of audit is part of the

In a recent model of the tax system, Graetz, Reinganum, and Wilde divide taxpayers into two classes: strategic players who are willing to "game the system" and habitual compliers. A taxpayer can have a high income (I_H) or a low income (I_L). A strategic player can choose to lie about his income. The IRS has no reason to audit high-income reports, but does have an incentive to audit a certain percentage of low-income reports.

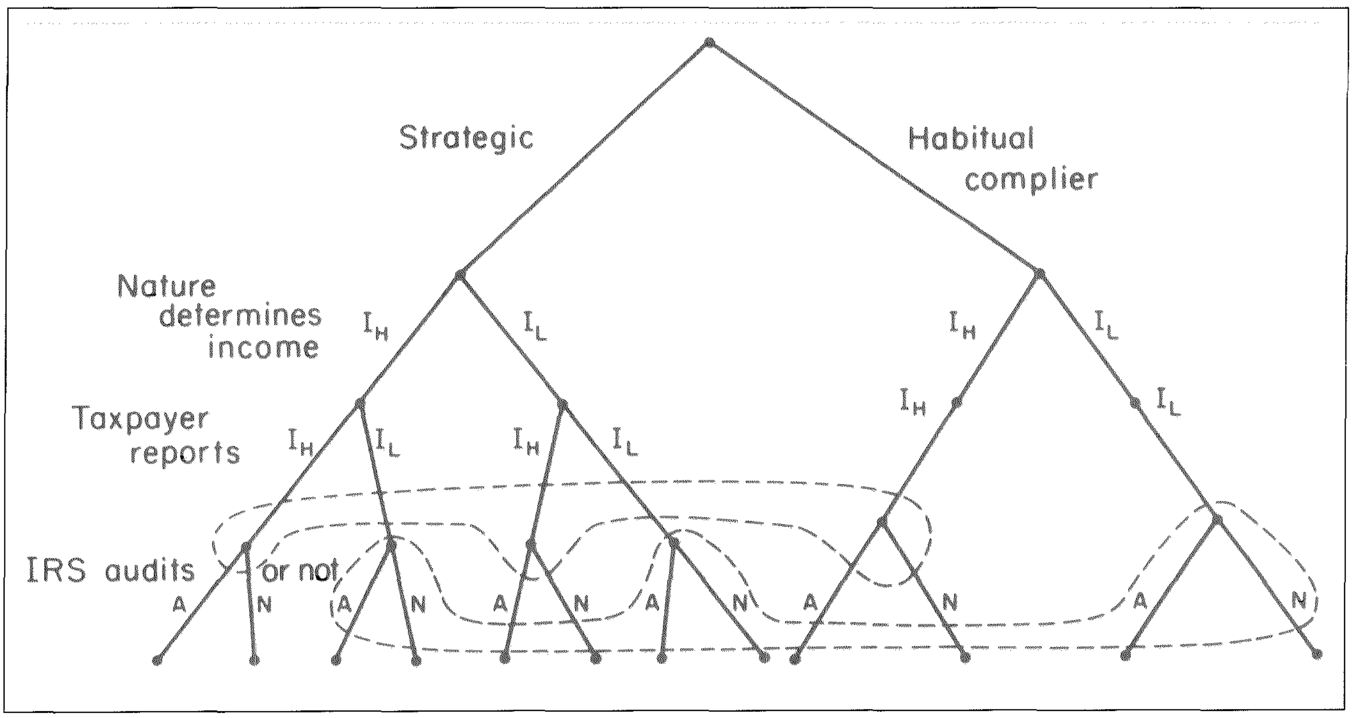


Figure 1

Taxpayer Compliance Monitoring Program (TCMP). Explains Wilde, "Every two or three years the IRS conducts a series of 50,000 totally random audits. These are the horror-show audits you hear about. They're the line-by-line audits, the ones you just don't want to have to deal with. For example, if you claim you're married, they want to see the marriage certificate. If you claim dependents, they want to see birth certificates. It's just unbelievable."

The information from TCMP audits is compiled to produce the Discriminant Income Function (DIF), a scoring rule that is later applied to all other tax returns. Tax returns that receive high DIF scores are those that are most likely to be subject to large adjustments after an audit. These returns are then audited, but this third type of audit is far more selective than the TCMP audits — the auditor may just be interested in verifying a single line on the return; he may ask for proof of a claimed capital loss, for example. Since the DIF-based audits are conditioned on information taxpayers supply to the IRS, and since the IRS keeps the DIF formula a closely guarded secret, there is no precommitment, and for that reason Graetz, Reinganum, and Wilde have moved away from the principal-agent framework.

They have also added a number of other features that make their model richer and more realistic. For example, they take into account the fact that most taxpayers are risk-averse. In addition, they include in the model two groups of taxpayers — habitual compliers and strategic players. As their work proceeds, they expect to add several other types of taxpayers as well. These may include people who don't fully "game the system," but who avoid feeling like dupes by lying only as much as they think other people are lying. And future versions of their model may incorporate people who can't report their true income since it is derived from illegal activities.

Another realistic assumption in the new model is that the IRS is only allowed to set audit policy, not tax rates or penalties, which are imposed on the IRS by Congress. But in the initial version of this new model, Graetz, Reinganum, and Wilde assume that taxpayers have only one of two incomes — either high or low. This was done for simplicity of exposition and the authors have included additional income levels in subsequent versions.

In the basic model, a low-income taxpayer has no motive to lie, but a high-income taxpayer may find it in his interest to claim low income, thereby reducing his tax burden. The IRS, for its part, has no reason to audit a taxpayer who admits high income, but since there's a chance that someone who claims low income may be lying, it is in its interest to audit some proportion of these people. By applying the mathematics of game theory to this setup, the authors are able to determine the best response of each of the players to the other's strategy. This simultaneously determines an equilibrium level of auditing and compliance as a function of a number of underlying parameters. These parameters include the cost of an audit, the probability that a taxpayer has a high income, the percentage of strategic taxpayers, and the level of taxes and fines.

This approach can yield some counterintuitive results. "Suppose that the percentage of people who are willing to act strategically goes up," says Wilde. "On average, one of the low-income reports will be more likely to come from a strategic taxpayer with high income who lied, and less likely to come from someone who actually had low income. So, at the first cut, the IRS ought to want to audit more often. But if it audits more often, then strategic taxpayers are going to want to lie less often. Countervailing forces are present here, and it turns out that in this simple model those forces exactly balance each other out. In this framework, at least, changes in the percentage of strategic taxpayers have no effect on the number of audits the IRS will conduct or the number of people who actually lie."

Another surprising result has to do with the effect of tax rates on compliance. It is widely believed that there is currently a "crisis of compliance" in the American tax system, with more and more people underreporting their income. Although this belief, according to Wilde, is not supported by solid data, many commentators are quick to assign causes to this perceived increase in the compliance gap, and just as quick to offer solutions. The dominant belief is that when marginal tax rates go up, underreporting increases since the gain from underreporting also goes up. If this is true, then a lowering of tax rates should be accompanied by an increase in compliance and an increase in revenue to the IRS. The model says that this received wisdom is exactly wrong.

"An *increase* in the marginal tax rates

"Other folks have to pay taxes, too, Mr. Herndon, so would you please spare us the dramatics!"

should increase compliance," maintains Wilde. "The reason is two-fold. When you increase the marginal tax rate it's true that you increase the gain from underreporting, but you also increase the penalties for being caught, since fines are proportional to the amount of taxes evaded. And on top of that you increase the IRS's incentives to audit." The model predicts that a taxpayer's increased incentive to underreport is more than balanced out by the increased number of audits the IRS would be conducting and the larger fines they would be collecting from the cheaters who were caught.

Some evidence for Wilde's assertion that lower tax rates will actually *increase* cheating comes from the example of the tax on capital gains. Although capital gains are taxed at a much lower rate than normal income, evasion of capital gains taxes is one of the biggest compliance problems the IRS has. "This is not what we would call hard evidence," admits Wilde, "because there are a lot of confounding factors. Capital gains also happens to be an area where there's a lot of opportunity to evade. But nonetheless it suggests that lower rates alone aren't enough to get us out of the 'crisis of compliance.'"

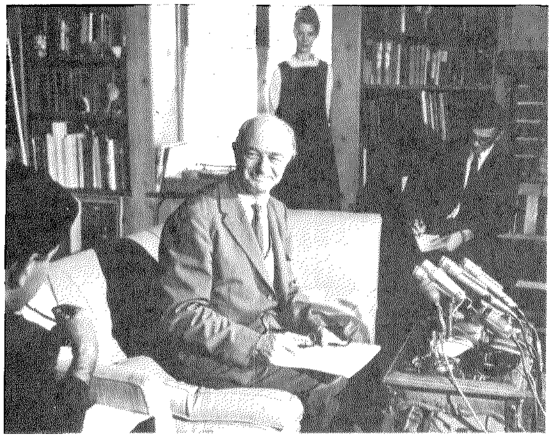
The model has other implications for tax policy as well. For example, it predicts that the IRS's revenue would increase if there were additional third-party reporting requirements. The IRS's best strategy is not to fine-tune the game, but to eliminate the opportunity of many taxpayers to play it. The research has also yielded some negative conclusions, according to Wilde. "It says that moral suasion — TV ads telling people that they ought to be good citizens, courses in elementary school to teach children that 'the IRS is your friend' — may not be to the point at all. The game is a tough game for the government to play. The enormous resources it would take to give the IRS a really fair advantage are not likely to be forthcoming in an era in which budget cuts are the rule. You've got to change the nature of the game instead of fine-tuning it." □ — *RF*

Pauling at 85

LINUS PAULING'S 85TH BIRTHDAY was the occasion for a day-long seminar in the Division of Chemistry and Chemical Engineering February 28. "A Salute to Linus Pauling," organized by Ahmed Zewail, professor of chemical physics, featured scientific sessions (held in 22 Gates, the scene of Pauling's Chem 1 lectures), celebratory remarks by a large number of faculty and administration — and some reminiscing. Among the latter was Ed Hutching's after-dinner talk on "The Pauling Era at Caltech." Hutchings, who was editor of *Engineering & Science* from 1948 to 1979, had gathered for his talk a vast collection of photographs of the Pauling years — from 1922, when Pauling came here as a graduate student, to 1964, a period during which the two-time Nobelist (one for contributions toward understanding chemical bonding, the other for his peace efforts) left a singular stamp on the Institute. A few of the photographs from that remarkable era (and one *not* from that era) are reproduced here. □

Above right: Pauling tries lecture experiment to be used in Chem 1 (1942).

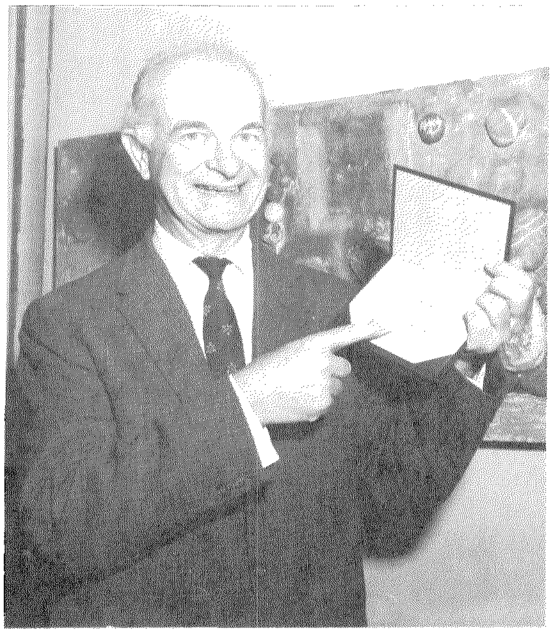
Right: Pauling's office was crammed full of molecular models.

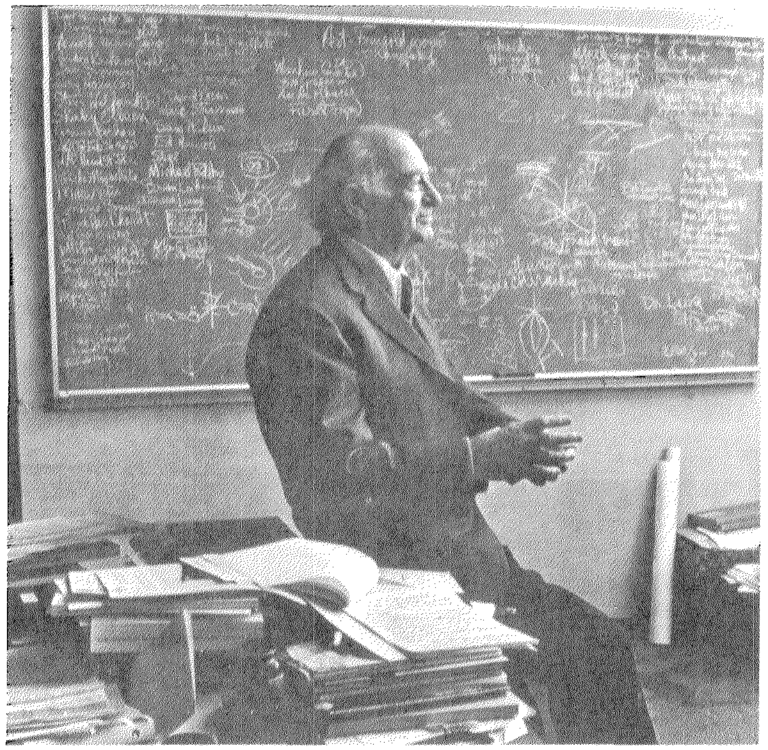


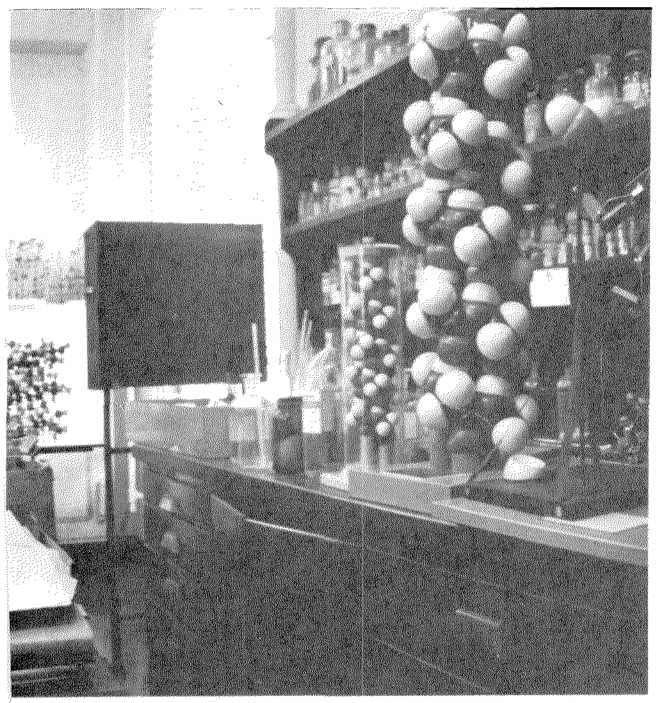
Left: Pauling is besieged by reporters after winning the Nobel Peace Prize in 1963. Behind him is daughter, Linda Kamb.

Below left: Although he didn't officially graduate from high school, Pauling finally received his high school diploma 45 years late (1962).

Below: The blackboard in Pauling's office was always covered with notes, rarely erased.







After the Pauling era at Caltech, he relaxes at his Big Sur ranch. Pauling's latest book is How to Live Longer and Feel Better.

Particles in Motion: The Case of the Loaded Die

by Bradley T. Werner

*"Iacta alea est!"**
— Julius Caesar

*" *The die is cast!*"

PROBLEMS IN THE BASIC SCIENCES can be divided into two categories: those that have been around for a long time and have only been brought to a stage of partial solution, and those that were posed as a result of recent innovations or discoveries. A subset of the former category consists of problems that were investigated in the past but were not solvable by available methods. The development of new tools, particularly modern high-speed computers, has reawakened interest in many such questions. You can discover abandoned problems by venturing to a dark corner of a library and browsing through dusty volumes of a past era, but it often turns out that there is a strong relationship between the original question and current investigations and applications.

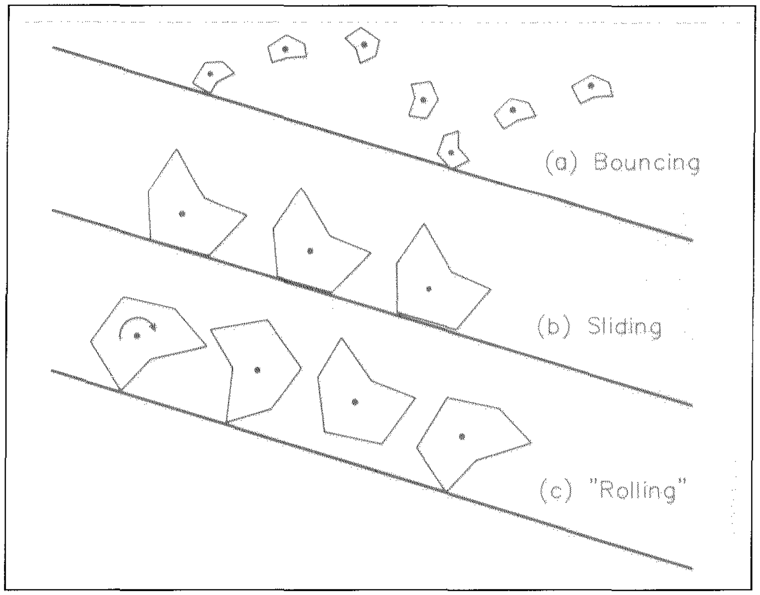
A group in the Division of Physics, Mathematics and Astronomy at Caltech (composed of graduate student Gary Gutt, Senior Research Associate Peter Haff, Professor of Physics Tom Tombrello, a passel of undergraduates, and myself — supported by the National Science Foundation) has been studying a problem of this nature: the dynamical behavior of granular materials. A granular material consists of a number of extended objects that interact through very strong compressional forces, as well as through friction, and that move according to Newton's equations for linear motion and Euler's equations for rotational motion. Examples of dynamic granular systems include rock slides, sand dunes, planetary rings, snow avalanches, icebergs in an ice jam, and dry dogfood. Our aim is to derive the general behavior of these systems starting from the level of the properties of individual grains, in a manner similar to the derivation of the kinetic theory of gases and fluids from a consideration of the properties of the basic molecular constituents. The desert environment is the home of many granular systems, and much of our work depends on observations made, ideas and information gathered, experiments performed, and inspiration acquired on trips to the Mojave Desert.

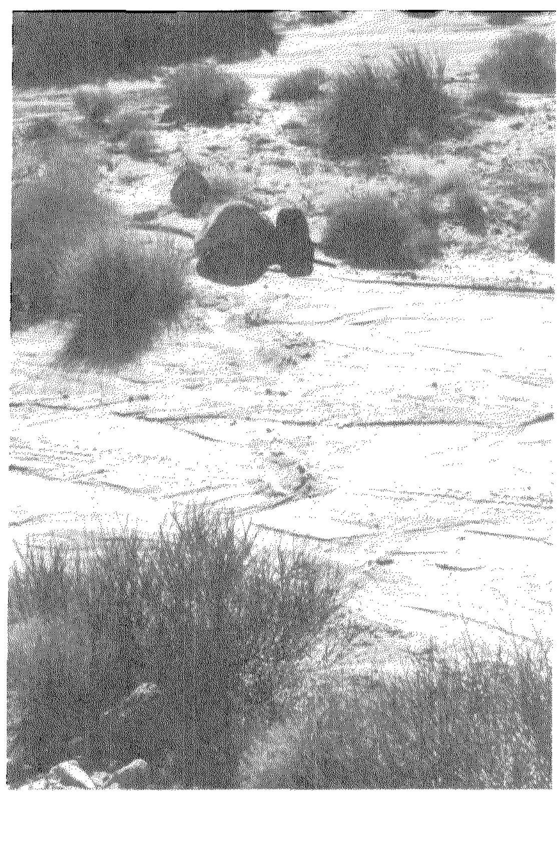
A fundamental problem in grain dynamics is to describe the interaction of a single particle with a flat plane in the presence of a gravitational field. The feeling is inescapable that if this problem is not amenable to solution, understanding a sand dune, composed of many trillions of grains, is beyond hope. A common reaction to hearing of the single-particle case is that surely the solution may be found in some freshman physics text. In fact, the motion of a single particle on a plane inclined with respect to gravity is far from simple to analyze, particularly if the particle is allowed to have arbitrary shape, and if the collisions between plane and particle include collisional energy loss and friction.

From a simulation study of a two-dimensional particle moving down an inclined plane, I concluded that such particles exhibited three types of motion: sliding, bouncing, and "rolling." As illustrated in the bottom figure at right, an irregularly shaped particle rolls in a rather peculiar manner, with the points farthest out from the center of mass (about which the particle rotates) being the only ones to contact the plane. I found that for sufficiently high friction and energy loss per collision, those particles that went far enough down the plane would eventually move predominantly in this rolling mode, with the bounces perpendicular to the plane being damped out by the energy loss at each collision; particles that engaged in sliding over a significant distance came to rest. Subsequent work by undergraduate Chris Chen on the motion of an ellipse on an inclined plane supports these ideas and highlights the critical importance of the incline angle on the mode of motion. In a practical vein, researchers at the Laboratorio di Fisica Terrestre in Switzerland have used computer simulations to study the motion of rocks that tumble down upon highways in the Alps.

Last year I embarked on a field excursion to investigate the movement of single rocks downslope. In a lonely canyon in the Mojave, just off the Old Spanish Trail, I found a slope covered with rocks ripe for rolling. I scrambled to the top and began sending massive boulders tumbling down the mountainside, with the sharp retorts resulting from rock hitting rock echoing off the canyon walls. Almost every rock that was dislodged either went into the rolling mode or slid rapidly to a stop. When the tumbling rock hit a rock of comparable size or larger, it would be propelled upwards, but the motion perpendicular to the slope would quickly diminish as the rock settled back to rolling. Having exhausted the supply of rocks at the top, I descended the mountain to be pleasantly surprised that the tumbling boulders had implanted "rock-prints" in the sandy wash at the base of the slope, illustrating that these rocks were engaged in rolling.

I was sufficiently inspired by this desert trip to begin the study of single three-dimensional particles. A cube is a simple, yet interesting example. Graduate student Tobi Delbrück suggested that I paint dots on the six faces of the cube and call it a die, and further, that I study the motion of a die that has been altered so that the sides have





Above: The three primary types of motion for a particle moving downslope are: (a) Bouncing — the particle possesses a large amount of energy normal to the plane; this mode of motion usually decays into either sliding or rolling. (b) Sliding — the particle slides without rotating and is often brought to a stop by frictional forces. (c) Rolling — the particle rotates as it moves downslope, with the center of mass staying at roughly a constant height above the plane and only the points farthest from the center of mass contacting the plane.

These "rock prints" were made in a sandy wash in the Mojave Desert by a rock in the rolling mode.

unequal probabilities of landing face-up at the end of a roll: the case of the loaded die.

Being unknowledgable about the world of gambling, I decided to delve into the history of gambling with dice to obtain some background. By far the most authoritative guide is *Scarne on Dice*, written by John Scarne, who saved American soldiers in World War II millions of dollars by teaching them how to detect the tricks of gambling dens. According to Scarne, the ancient civilizations of Egypt, Greece, Rome, and Korea all used dice for gambling. The first written record of modern-appearing dice is found in a 2,000-year-old Sanskrit manuscript. These dice were loaded, suggesting that cheating was present from the start of die history.

Modern dice are cube-shaped, generally three-quarters of an inch on a side, and are made of cellulose. Gambling establishments use "perfect dice," which are square to a tolerance of roughly 1/5,000 of an inch. In contrast, the dice used in my investigation, borrowed from a worn-out Monopoly game, are far from perfect. Yet simply by throwing such a die across one's office floor, it is possible to observe many of the phenomena that make dice interesting. You get to observe a few other things too, including the puzzled stares of passing secretaries and the enthusiastic encouragement of dedicated craps players.

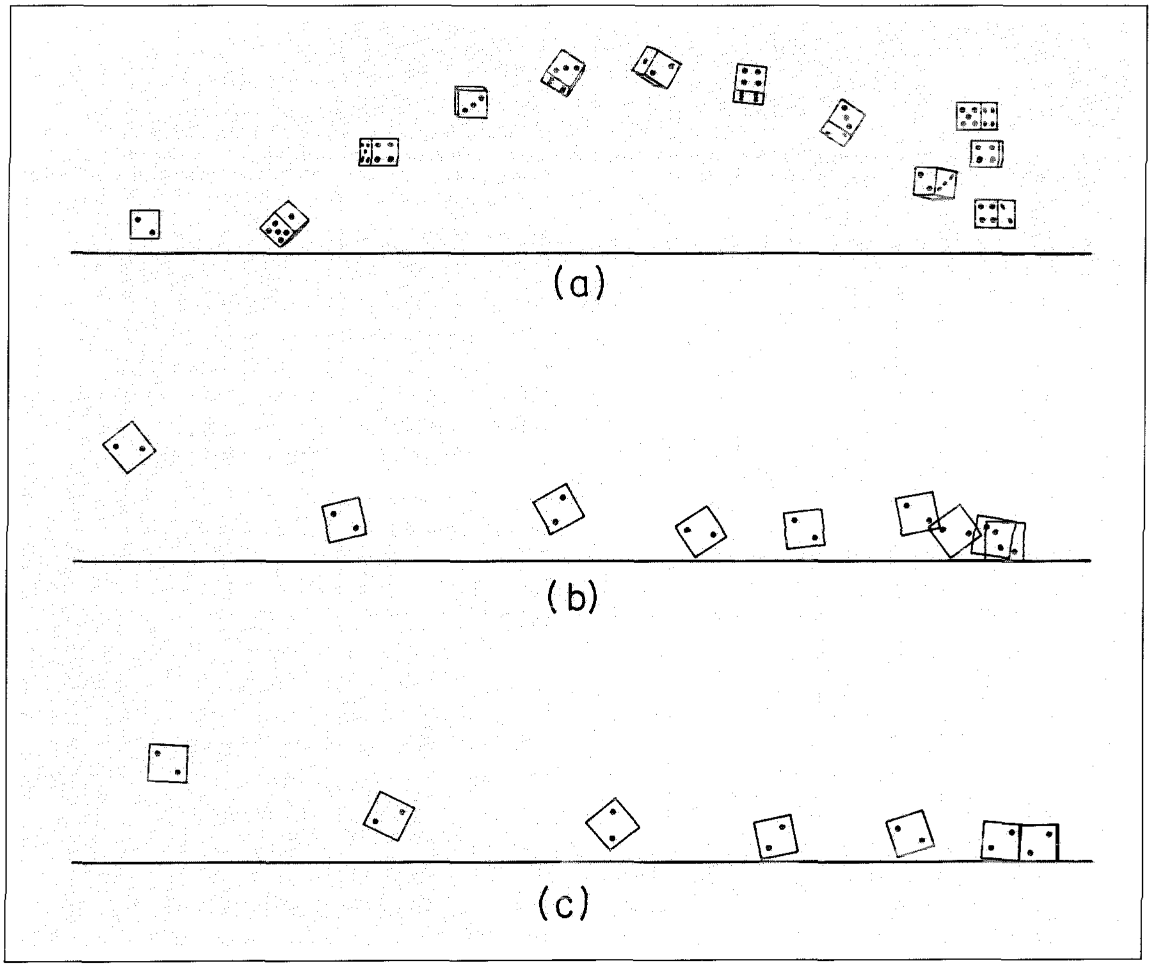
Eventually, when the crowd cleared out, I set about classifying the behavior of the die. It was clear from the start that, at least when interacting with a typical Caltech office floor, the die-floor collisions are rather elastic; that is, only a small fraction of the die's energy is lost in each collision. Related to this is the apparent unpredictability of the value of the die (the number of dots on the top face). When dropped from a distance equal to the die's own height, despite much concentration on keeping the bottom face parallel to the floor, the die will often turn up a different face. This instability makes the value of the thrown die essentially random, and it is no doubt appreciated by casino operators and honest gamblers. Talented cheaters can throw the dice in such a way as to influence the outcome, but such a skill is acquired only through years of practice.

There are a variety of ways to alter a die so that one or more faces have a larger probability of being on top when the die has come to a stop. The most popular method is to change the distribution of mass within the die in order to shift the center of mass away from the center of the cube toward one of the faces, edges, or points. Gambling lore then says that the one, two, or three faces (respectively) closest to the new center of mass will land face down with enhanced probability. With the transparent dice that are currently in common use, the cheating gambler is generally forced to place small weights behind the dots. Casinos detect loaded dice by dropping them carefully in a glass of water; a loaded die will tend to turn with the loaded side down while descending through the fluid, whereas a fair die will fall with little rotation. Scarne states that "Newton doped out the law of gravitation and dice players began to admit that the fall of dice is controlled by gravity rather than by psychic manipulations. . ." My goal is to add some physical detail to Scarne's basically sound explanation for the dynamical behavior of dice.

In my studies of a loaded die in motion, as well as in other granular materials problems, I have found that dynamical simulations are crucial to formulating and verifying a model. Many of the die simulations, including this one, were performed on an Apple MacIntosh; each simulation requires several hours of MacIntosh time. In these simulations, the motion of the die is stepped forward in time according to the laws of Newton and Euler. When one of the eight points on the die begins to penetrate the plane on which it is tumbling, a force is applied, which increases rapidly with the amount of penetration. Frictional forces are also applied at this point. Each collision between the die and the plane results in a loss of a fraction of the die's energy of motion, or kinetic energy.

This simulation picture embodies all of the important characteristics of a real moving die: a nearly rigid particle and energy loss during collisions and friction. I can adjust these characteristics, as well as the mass distribution within the die, at will. In the top figure (a) on the opposite page I show a succession of images of a fair (unloaded) tumbling die.

Using the simulations I have constructed two models for predicting the probability of each side landing face up. These models represent a starting point to which I hope to add refinements as the investigations progress. Both models make the simplification that the die rotates in such a way that only four of the faces can turn up: in other words, it tumbles as if it were a square rather than a cube. Therefore, when the center of mass is located

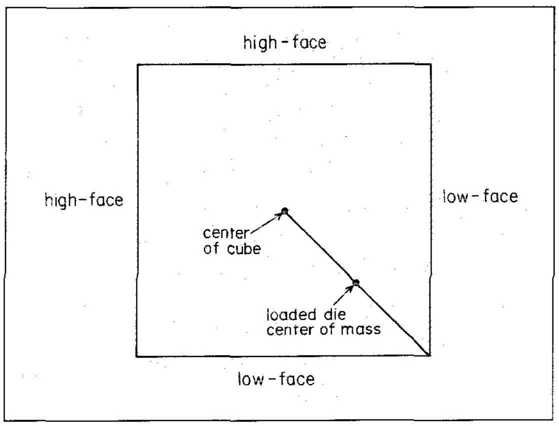


Time-sequenced images of simulated dice moving from left to right: (a) A fair die tumbling on all six sides. (b) A loaded die constrained to tumble on just four sides. (c) A fair die constrained to tumble on just four sides.

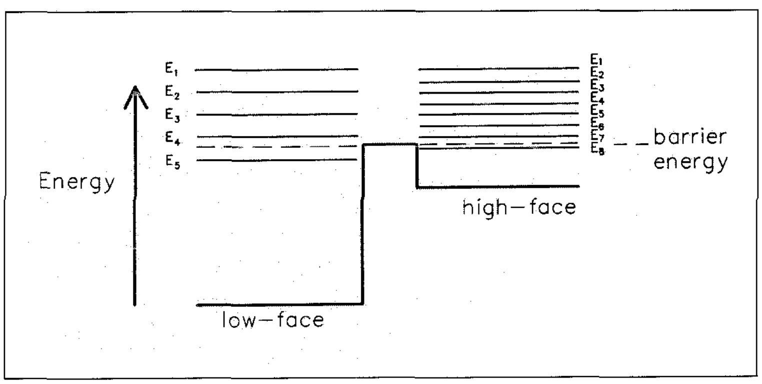
along the diagonal from the center of the cube to an edge (the face diagonal), there are two types of faces: those adjacent to the center of mass, termed "low" faces, and those farthest from the center of mass, or "high" faces. I picture the tumbling die as "progressing" from face to face and continually losing energy until it is finally "captured," with one of the faces resting on the plane.

The first model ignores the order in which faces come up. The idea is schematically illustrated in the bottom figure at right by plotting the energy barrier that must be overcome for a die to transit from a state where a low face is down to a state where a high face is down and vice versa. As the die tumbles around on the plane losing energy and approaching the barrier energy, if it is in a low-face-down state, the behavior of the die is more sensitive to the presence of the barrier, which acts like a brick wall for the die to hurdle over, than if it is in the high-face-down state, where the barrier appears like a mere crack in the sidewalk.

The second model introduces a correlation in the order of the faces hitting the plane; the

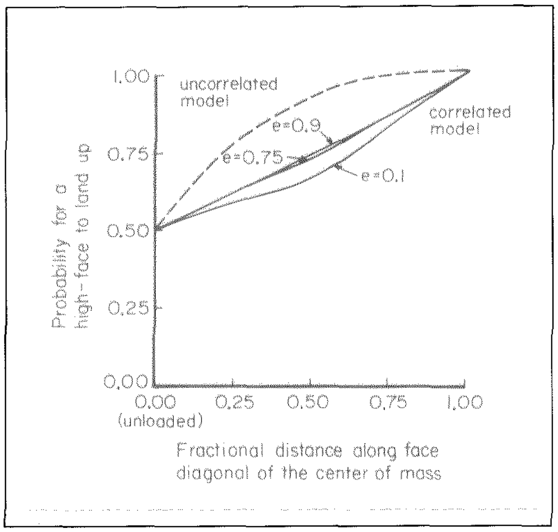


Left: The die in this investigation was loaded in such a way that the center of mass was shifted halfway along the diagonal connecting the center of the cube and the middle of one of the edges (the face diagonal). This creates two types of faces: two low faces, close to the center of mass, and two high faces, far from the center of mass. The models described here ignore the other two faces of the cube.



Below: For the model that does not consider the order in which the die faces can be turned up, a low face can be captured face down much more easily than a high face can.

The probability for a high face to land up is plotted against the fractional distance along the face diagonal of the center of mass. The results for the model that does not consider the order of impact are plotted as a dashed line and are valid for collisions in which most of the energy is retained by the die. The correlated (rolling) model results are plotted as solid lines. These results depend on e, the fraction of the energy retained at each collision.



die is assumed to roll. In the figure above, the predictions of these two models for the probability of a high-face landing up are plotted as a function of the fractional distance along the face diagonal, through which the center of mass has been moved in the process of loading the die. The second model predicts somewhat less advantage to be gained by loading a die, basically because with the enforced correlation there are fewer opportunities to get "captured" in the desired state (a low-face-down state). It is also of interest that when the collisions with the plane become less elastic, the probability of being captured in the low-face-down state decreases. This happens because the system doesn't have the chance to explore all of the available states, in a manner similar to the way in which rapidly quenching a metal from the melt produces an amorphous or unstructured material, whereas slow cooling results in a crystal.

The center of mass of the die was moved to halfway along the diagonal connecting the center of the cube with one of the edges, as shown in the middle figure on page 23. The motions of a die so loaded and of an unloaded die are compared in (b) and (c) respectively at the top of page 23. Note that the motion of the loaded die is slightly more erratic than that of the unloaded die, which is the trend seen in the simulations. Sixteen simulations of this tumbling loaded die started with random initial orientations (but with the constraint that the cube roll as a square) were performed, with the result that for 75 percent of them the die stopped with the high face up. This compares with a prediction of 93 percent for the first model and 72 percent for the second model. The agreement between the simulations and the second model is encouraging.

For the purpose of accurately verifying and refining the second model, it will be necessary to provide better statistical definition of the simulation results, and therefore I expect the MacIntosh to be chugging away at odd hours in the coming months. I hope to be able to consider several additional aspects of a tumbling loaded die in the models, including the effect of the free rotation of a cube (rather than a square). In addition, it would be of interest to investigate other methods of altering dice, including shortening some of the faces and altering the collision characteristics of one or more of the faces. I also plan experiments with loaded dice. Perhaps a few trips to Las Vegas will be necessary to investigate fully all aspects of this complex problem.

But, unlike the group of physics students from UC Santa Cruz who, while betting at a casino, covertly used a computerized shoe to predict where a roulette ball would land, I have no plans to use my knowledge of loaded dice to enhance my meager earnings as a graduate student. The roll of a die, the power of avalanches and rock slides, and the sand-grain ripples on a sand dune have intrigued man for ages. It is wonderful to be alive at a time when a detailed physical understanding of such phenomena appears to be attainable. □

Speaking of Communication

by Edward C. Posner
Rodney M. Goodman
Robert J. McEliece

As communication systems have become more extensive on earth and in space, what are the limits of their energy and complexity? What are the means of protecting transmitted information from error and theft, and what will prevent a logjam of data bits or an infinite queue of waiting telephone calls? While much of the information theory that underlies today's high-performance communication was formulated 40 years ago, it is only recently that very large scale integration (VLSI) has made such electronic communication practical commercially — generating further opportunities for communications researchers.

The communications research group in Electrical Engineering is trying to solve some of these problems and is gaining an international reputation in the process. Caltech is now one of the leading academic institutions world-wide in information and coding theory and in error correction for data storage. We are also, with support from Pacific Bell, one of the very few academic institutions in the country doing teaching and research on circuit switching and, together with other departments on campus and at the Jet Propulsion Laboratory, are at the leading edge of research on associative memory.

The communications group has close interactions on campus with computer science, mathematics, neurobiology, and chemistry and biology, as well as with JPL. Such interactions are beneficial to all, because the techniques of information and communication theory, involving probability and combinatorial reasoning, apply widely in other areas of information processing and networks, and in statistical physics.

John R. Pierce (BS 1933, PhD 1936), professor of engineering emeritus, started the communications group at Caltech in 1971. The Pierce Lab in 214 Steele is named in his honor. We three have been involved with it

This portrait of John R. Pierce by Sylvia Posner hangs in the Pierce Lab.

for varying lengths of time — Posner, a holdover from the Pierce era; McEliece since 1982; and Goodman, the newest arrival, since 1985. The research projects of the communications group are also varied, and we would like in this article to give an overview of this exciting field.

McEliece's research specialties are information theory and error-correcting codes, subjects that have developed from Claude Shannon's important work first published in 1948. This research concerns the problem of communicating reliably over unreliable channels and has wide-ranging applications. One subject his group is investigating is anti-jam communications — devising efficient strategies for communication in the presence of intelligent and adaptive interference. This problem can be viewed as a game with two power-limited players — the communicator and the jammer — and McEliece and his group have been able to combine game theory with information theory to develop several new classes of anti-jam communication strategies using error-correction concepts. Some of the results have been quite surprising and may find application to protecting communications.

McEliece is also interested in the application of information theory to the problem of reliable storage and retrieval of information from computer memories. Here the communication is the transmission of data not in space (from here to there) but in time (from now to then), and the transmission medium is not the electromagnetic "ether" but rather a storage medium, such as semiconductor RAMs, magnetic tapes, and magnetic disks. As device physics technology pushes these storage media toward their physical limits, the reliable retrieval of the stored data becomes more and more difficult. For example, as RAMs become larger and feature sizes shrink, soft (non-permanent) error rates rise due to background alpha particle radiation, circuit noise, and other effects. Error-control coding has become essential if the computer's memory system is to have a reasonable mean time between failure. McEliece and Goodman have developed theories for estimating the mean time between failure of coded systems, which are actually being used by system designers in specifying coded RAM systems. Back in 1948 Shannon's theorems predicted with uncanny accuracy that in most high-performance communication systems it is better in the long run to correct errors (and that is what we are doing here) than to try to prevent them by overwhelming the noise with signal.

Particular research projects in the data-storage area concern the design of error-correcting codes for magnetic tapes and the reliable storage of data on semiconductor RAM chips. The latter involves both the ultimate physical limits of data storage density (combining semiconductor physics with Shannon's theorems) and practical methods for incorporating error-correcting codes right on the high-density RAM chips themselves rather than by adding extra chips.

VLSI can also be used to build powerful decoders for both space and time communication. Recently the communications group developed a single-chip VLSI implementation of a decoder for the important class of Reed-Solomon codes. These codes have applications ranging from deep-space communication (Voyager at Uranus) to cellular radio to high-density data storage on magnetic tapes and computer disks.

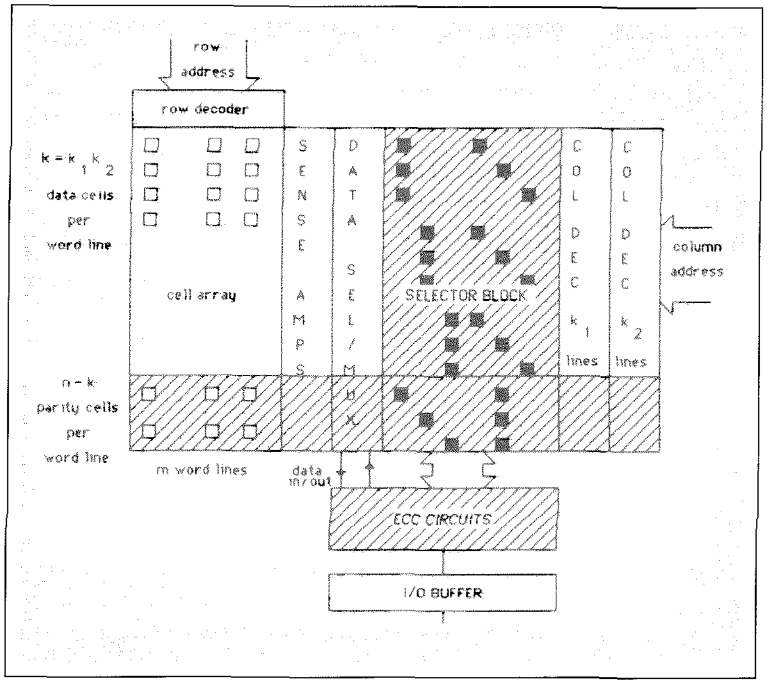
Some very exciting recent work of McEliece, Posner, and Eugene Rodemich (JPL), with both students and faculty in the Electrical Engineering Department and others, involves the asymptotic storage capacity of the associative memory network concept developed by John Hopfield, the Roscoe G. Dickinson Professor of Chemistry and Biology. Information theory and pattern recognition are involved because the concept of an associative neural net has close ties to both fields. John Lambe of the Electronics and Control Division at JPL heads the design and fabrication effort. The group is also working closely on neural nets with James Bower, assistant professor of biology.

Goodman's interests, like those of the communications group in general, lie in digitally getting the information from A to B through space (communications) or time (storage), with minimal distortion (coding), without it being ripped off (cryptography), via the fastest route possible (intelligent computation-intensive algorithms). More specifically, he's interested in digital communication and computer networks, error control and public-key cryptography for data transmission and storage, digital signal processing for speech and vision, VLSI architectures for decoding and signal processing, expert systems, and high-level computer language hardware implementations.

Although diverse, these interests have two strong themes that are fundamental to the digitization of communications networks: information theory (to give us a sound theoretical path to follow), and computation (to give us the most efficient method of implementing algorithms). Computation cannot be divorced from VLSI, because VLSI is changing the way we think about algorithms and their efficiency. For example, it is now possible to build considerable intelligence into even the smallest communications system, and, in fact, intelligence in networks, and our understanding of it, are key requisities for the all-digital public and private networks of the future.

Widespread acceptance of public-switched, all-digital telephone networks will rest partly on the ability to guarantee secure point-to-point communications. The user must be confident that the information cannot be tapped or altered without his knowledge. Authentication is also important in a digital system: How do you know whom you are talking to? On the telephone we recognize a person's voice, but "bits is bits" and a digital bitstream can be impersonated much more easily than an analog signal. This fact puts cryptography, in the form of secret coding and authentication, firmly into the civil communications arena. Public-key cryptosystems (PKCs) offer a means to provide both these features automatically, but there are many practical and theoretical questions that need answering before such systems can be implemented. Indeed PKCs still seem very much the ultimate party trick — it turns out that two people can openly exchange numbers and quickly establish a secure common key, while the eavesdropper has to do an almost impossible amount of computation to get the same result.

Goodman and research fellow Tony McAuley are doing research in three main areas of public-key cryptography. First, they are trying to develop new practical PKC algorithms; they and McEliece have invented some as-yet-unbroken PKCs. They are also developing new "broadcast" PKCs for transmitting a message securely to a number of users. Conventional PKCs are one-to-one systems and cannot handle this. These broadcast systems have great potential application in direct broadcast satellites and in packet-switched data networks, where the number of packet hops can be reduced significantly by using group-addressed packets. Goodman and McAuley are researching



One-megabit RAM with on-chip error correction. The cost is extra chip area needed to store and select the check bits (shaded). The particular coding scheme shown, however, saves area by using the same column and row decode structure as needed in an uncoded chip.

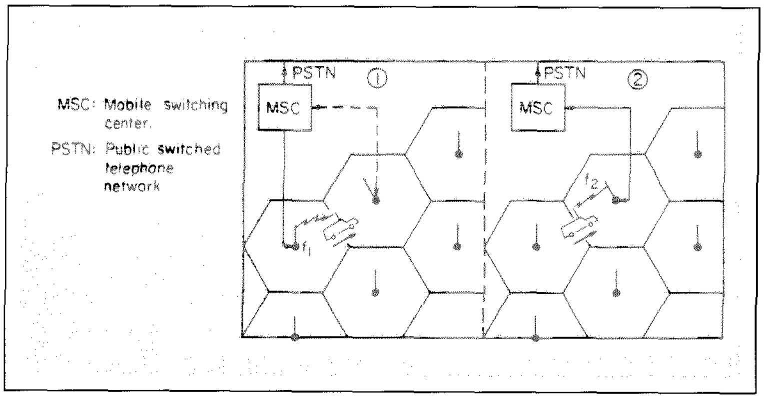
several broadcast PKC methods that can trade security for fewer packet hops (useful for data that need to be secure only for a short time). They are also looking at broadcast PKCs that use such network topology as ring local area networks, tree hierarchies, and layered communication systems. Goodman's PKC research also concerns the practical implementation (on VLSI chips) of particular algorithms involving the modular exponentiation of large (e.g. 512-bit) numbers.

More recently Goodman has been investigating the use of on-chip error correction required by the new ultra-large RAMs. Soft (non-permanent) errors occur so frequently (in terms of the high reliability one demands from computers) that the chip mean time between failure would be very low without error correction. In addition, coding to avoid hard (permanent) errors can be used to further increase lifetime and to increase yields without having to reconfigure spare memory rows by a process known as laser trimming. The main questions to be answered are: How can we implement powerful error-correcting codes on the chip, while using the minimum number of redundant (non-data) cells? And how can we make these systems fast so as to not degrade RAM access time? Goodman and colleagues have developed coding schemes that are intimately linked to the actual RAM structure and will be investigating these algorithms practically using the chip fabrication facilities of the digital communications lab that Goodman set up.

Another application of the digital communications lab is in space communications. A project is currently under way in collaboration with F. Pollara of JPL's Telecommunications Division to examine the applicability to deep space communications of a convolutional code decoding algorithm developed by Goodman. In order to send back high-quality pictures from the outer planets with the low-power spacecraft transmitters, the information is encoded on the spacecraft and decoded back on earth. Extremely low error probability is needed because video compression cannot tolerate errors. Long convolutional error-correcting codes are among the most powerful known but have been impractical to decode optimally. Goodman's algorithm uses the structure of these codes with a pre-computation to significantly improve decoding speeds and hence make decoding long codes a practical possibility.

Somewhat more down to earth is Posner's research on communications traffic and switching. New telephone services make many of the traditional models of communication traffic inapplicable, and advances in queueing theory are needed to model them. Some of the more popular of these new services are cellular radio, alarm reporting and monitoring, electronic messages with images and voice annotation, and interactive services such as home banking and games. In order to cope with the problems of accomodating large numbers of users in these new services, and because of the need to share system facilities efficiently, the development of intelligent systems and networks is essential. One of the most important problems in these systems is the automatic and intelligent allocation of a small number of communication links, channels, or paths among the relatively large number of users. This is indeed a main theme of research in switching and traffic.

Handoff in cellular radio. When a car moves from one cell to another, as determined by signal-strength measurements, the central mobile telephone switching office hands the call off to the new cell site at a new frequency. This is done without any user involvement. If there were no free frequency channel in the new cell (a rare event), the handoff would be blocked and the call disconnected.

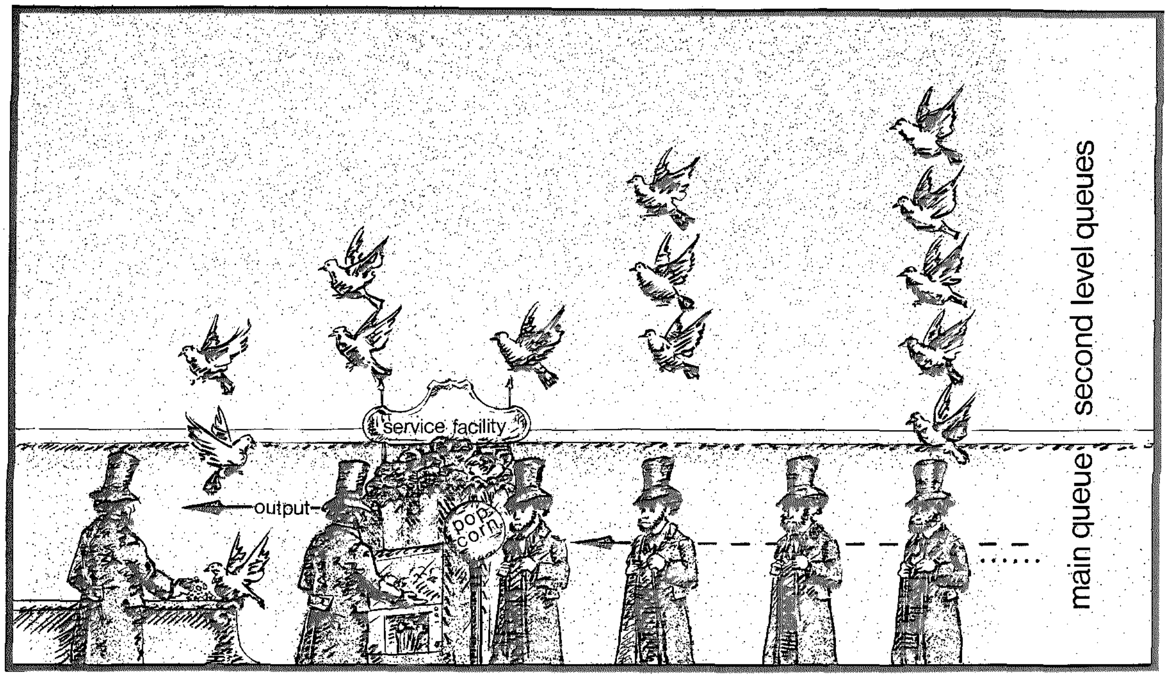


Cellular radio, which has recently been successfully introduced in the greater Los Angeles area, enables a much larger number of subscribers than before to have mobile telephone service. In the past, communication with mobiles was achieved in a way similar to broadcast radio. A high-power transmitter is positioned at a high point (on Mt. Wilson for the bulk of the LA area) allowing coverage of virtually an entire extended metropolitan area. The transmitter would then serve any mobile wishing to initiate (or receive) a call from the public switched telephone network. The main problem of this approach is the small number of frequency channels available for the service — only 11 for all of Los Angeles. This means that as soon as 11 calls are taking place over the old system, which still exists, it would be saturated and no new call could be accepted. Long delays then ensued.

Cellular radio solves this problem by dividing the service area into a large number of smaller cells, currently with centers about 10 miles apart, each served by its own low-power cell-site transmitter. Due to the faster-than-inverse-square drop in signal power in the urban environment (because the propagation is not line-of-sight), a frequency channel used in a given cell can be reused in another one located fairly close-by while still avoiding co-channel interference (self-jamming). Each frequency channel can be reused dozens of times in the whole service area, so the total number of subscribers that can be simultaneously served increases by that factor. (Some of the increased capacity is due to the use of a higher UHF frequency not previously available to mobile radio.)

The problem of subscribers moving from one cell into another is solved by the handoff concept — disconnecting from the frequency channel of the old cell and switching to a frequency channel of the new cell. The whole process is unnoticed by the subscriber but requires a high level of automation and intelligence at a base switching office. Although the cellular concept was invented by AT&T in 1947, cellular radio first became practical only in the mid-1970s because of advances in integrated electronics. And VLSI makes it extremely practical and affordable now.

With the electronic circuit problems by now largely solved, most of the few remaining difficulties that cellular radio faces deal with traffic. One of the Posner group's first tasks in attacking the problem was to estimate the probability distribution of the occupation



Queue of servers. Each man here has his own loyal queue of pigeons waiting to be fed as soon as the feeders buy popcorn. The pigeons wait in turn to be fed on a first-come, first-served basis. Recent experimental work in front of Steele Laboratory has shown that real pigeons don't behave this way.

time of a frequency channel in a cellular system. This parameter is vital in determining the number of channels needed in each cell. It is also needed to derive policies that maximize the number of customers actually served. An analytical model was derived under simplified assumptions and a computer simulation written for the more general case. The main result of this work was to establish, both theoretically and by simulation, that in most practical situations the simplifying memoryless assumptions (negative exponential service time distribution) used in classical telephony could still be applied without too many modifications. This is an encouraging result because traffic theory is much simpler if we can forget about memory.

Other traffic problems Posner's group is investigating involve the protection of handoff calls from being blocked and disconnected when all new frequency channels are busy, and setting priorities in channel assignments when a mobile telephone system (a modification of the old type) shares the frequency spectrum with mobile dispatchers.

Queueing has always been an intimate part of traffic theory and becomes especially important for these new services. One familiar problem in service management (from supermarkets to banks) has to do with situations in which we are forced to wait for a certain facility shared by a large group of users to become available. Posner's group is considering an interesting case in which these customers themselves constitute service facilities. (They also serve, who only stand and wait.) The initial service facility can be considered as no more than one of the multiple subscribers in the network. That is, any one of them can provide service to other customers, as in the illustration above. Such a multi-level situation can arise in intelligent networks with a hierarchy of computing facilities or when data service providers must wait for data from remote data bases in order to provide service to their customers.

In the context of today's multiple options for residential or business telephone service — a far cry from plain old telephone service (POTS) — we can also think of this situation as a "camping" system. Camping means that a calling subscriber can wait for a busy subscriber to become free and then be automatically connected. When several levels of camping are allowed, what happens when a third customer tries to call any of the camping customers? Dealing with machines rather than people, we might be willing to tolerate some delay and wait for our call to be completed, instead of continuing to call and hoping that eventually we will reach the intended party. A new camping queue can be repeated for each new customer arriving, giving rise to a series of new queues served in an overall first-come-first-served basis. Once a unit or terminal becomes free, it will respond in sequence to all those calls waiting for it. Thus, any call can become a new service facility itself. The study also realistically allows reneging (leaving the queue).

A number of questions arise in this kind of problem: Is it possible for deadlock to occur, with everyone ending up waiting forever? And if deadlock can arise, how can it be avoided? How long are the delays? How do we minimize the average waiting time? Solutions for some of these problems have already been found for particular camping systems under the memoryless constraint for the customer arrival and service processes. In the memoryless case, closed-form solutions have been found for the steady-state probability distribution of the queue sizes, which in turn provide tools to understand this and other related traffic problems. And such solutions will be helping people to communicate better as the integrated services digital networks of the future become available.

In addition to those faculty members mentioned in the article, others whose work is allied to the communications group include Yaser Abu-Mostafa (PhD 84), assistant professor of electrical engineering and computer science; Eric Baum, research fellow in chemistry; Charles Elachi (MS 69, PhD 71) visiting lecturer in electrical engineering from JPL; Dale Harris, visiting lecturer in electrical engineering from Pacific Bell; Carver Mead (BS 56, MS 57, PhD 60), the Gordon and Betty Moore Professor of Computer Science; Vera Pless, visiting professor of mathematics from the University of Illinois-Chicago; Demetri Psaltis, associate professor of electrical engineering, and his student Santosh Venkatesh; Lawrence L. Rauch, recently retired professor of electrical engineering from the University of Michigan and JPL; David Rutledge, associate professor of electrical engineering; Laif Swanson, visiting lecturer in electrical engineering from JPL; P. P. Vaidyanathan, assistant professor of electrical engineering; Henricus van Tilborg, visiting professor of electrical engineering and computer science; and Richard Wilson, professor of mathematics, and his student, Pierre Baldi.

Graduate students involved in the communications group include Khaled Abdel-Ghaffer, Mark Bell, Mario Blaum (Phd 85), Li Fung Chang, Kar-Ming Cheung, Yurdaer Doğnata, Roch Guérin, Enrique Hernández, Eric Majani, Phil Merkey, Patrick Smyth, Kumar Swaminathan (PhD 86) and Doug Whiting (PhD 85). Research support has come from the Air Force Office of Scientific Research, AT&T Bell Laboratories, the Defense Advanced Research Projects Agency, Garrett Corp., IBM, NATO, Pacific Bell, the Pacific Telesis Foundation, and Caltech's Program in Advanced Technologies, whose communications company is GTE Laboratories. □

Research in Progress

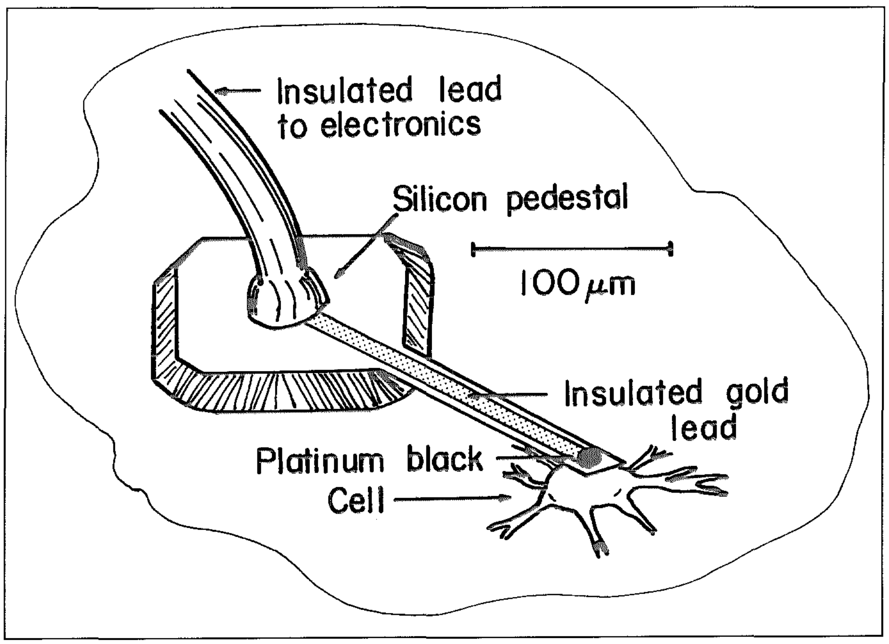
The Neuron-Silicon Connection

NEUROPHYSIOLOGY is a tough business. If you want to study the electrical activity of nerve cells, you're placed on the horns of a dilemma. You can insert a fine glass electrode into a neuron to get detailed information on a single cell, but the electrode often kills the cell after a short period, and it's very difficult to insert two intracellular electrodes into neighboring neurons to study their interactions. Or you can use an extracellular electrode, which can be left in the brain of an active animal for much longer periods without doing harm and which can record the activity of neighboring neurons simultaneously. But an extracellular electrode is too distant to provide detailed information on the inner workings of any of the neurons in its vicinity.

Resolving this dilemma is the project of two Caltech researchers: Jerome Pine, professor of physics, and David Rutledge, associate professor of electrical engineering. Pine, a physicist turned neuroscientist, and Rutledge, an expert in microfabrication techniques, are collaborating on the development of microdevices that might eventually allow researchers to stimulate and record from dozens of individual neurons hooked up into complex networks. And beyond that, the devices might be implanted into humans to form an element of a high-precision neural prosthesis.

For now, the researchers would be happy to build a device that would allow long-term intracellular monitoring of a single neuron kept alive in a culture dish. Graduate student Wade Regehr is constructing a prototype "diving board electrode," illustrated here, using techniques developed for etching silicon surfaces in the fabrication of computer chips. A silicon pedestal will support a fine gold electrode suspended just 20 μm off the surface, less than a third the width of a human hair and just about the thickness of a cultured neuron. The electrode will be insulated with a mixture of silicon dioxide and silicon nitride, except for a contact hole about 5 μm in diameter. Regehr will electroplate the gold in this exposed area with platinum black, a material that looks something like cauliflower under a scanning electron microscope, to greatly increase the electrode's effective surface area.

Conventional intracellular electrodes are made of glass micropipettes, drawn down to extremely fine points and filled with conductive fluid. Such an electrode is gently poked into a cell, the cell membrane seals around the glass and, if things go well, researchers can stimulate the cell and record from it for periods ranging from minutes to hours. But a glass electrode requires bulky and expensive equipment to keep it steady so it doesn't rip open the delicate cell membrane. The diving board electrode should avoid this problem. Using a micromanipulator, an experimenter will position the diving board over a cell, glue the pedestal to the culture dish, and, with a brief burst of high voltage, blast a hole in the cell's membrane. The membrane may then seal itself around the silicon insulation, forming a stable intracellular connection. The $64,000 question is just how stable this connection will be. Says Pine, "We don't know whether the cell will tolerate it for a minute, an hour, a day, or for weeks." Even if a stable intracellular connection cannot be formed, an electrode just outside the cell membrane would form an intimate extracellular connection, still very useful for two-way com-



Pine and Rutledge hope that the diving board electrode will allow long-term recording and stimulation of a neuron maintained in cell culture.

munication with a neuron.

But the researchers, operating under the assumption that they *will* learn how to achieve a useful connection with a single cell, are already starting on the next stage of the project: building "neurochips" that will house at least 16 cultured neurons on a silicon wafer. Immature neurons will be injected into tiny wells, which will have electrodes at their bases. Undergraduate Heidi Langeberg is working on the delicate task of constructing the neurochips. One problem she's facing is that the thin, delicate silicon wafers must be etched from both the top (to produce the well) and the bottom (to produce the electrode). In addition, she must overcome the tendency of cultured neurons to migrate out of their wells. She's dealing with this by etching the top of the wafer into a fine gridwork of silicon dioxide bars that will overlay each well. The bars have to be far enough apart to allow for the injection of an immature cell and the outgrowth of axons and dendrites. But the bars have to be close enough together so that the cell body, after a day or two of growth, couldn't "walk" away from its electrode.

Since the wells in the neurochip will only be 100 μm apart, the axons and dendrites growing from the developing neurons should easily find each other and form connections. The ability to stimulate and record from all the neurons in the resulting network will be an important tool for neuroscientists. One of the most perplexing questions in neurobiology is how the brain changes in response to new information. Learning is thought to involve synaptic change — either the formation of new connections or the change in strength of existing ones. Says Pine, "It's hard to study that kind of question in an active animal because you can't record from many individual cells over a long time. We've chosen to answer the technical problem by recording in culture where we can easily have access to the same cells as time goes on. So that's the name of our game — to study synaptic change."

If the neurochips can be made to work, Pine and Rutledge are eager to try an idea, suggested by graduate student John Gilbert, that sounds like the stuff of science fiction. Says Pine, "We'd like to put a probe like this into the nervous system with cells in it that have been preselected to ask a specific question." For example, the probe could be loaded with the type of cortical cells that normally receive inputs from other brain regions. If these inputs hooked up to the neurochip cells, researchers would have a powerful means of studying the development and function of those connections.

And the neurochips might also be used to help create neural prostheses, perhaps for the control of artificial limbs. "People know how to make beautiful artificial limbs," says Pine, "but getting the appropriate control signals from the amputee is very difficult." The difficulty is in the interface between a person's desire to make a movement and the limb's machinery. A neurochip loaded with the proper cells could be implanted at the site of the amputation. This might then receive the same signals the brain uses to move a natural limb, and send those signals on to the artificial limb. Pine and Rutledge caution that this is highly speculative and, even if possible, is certainly many years away. But they may overcome the major hurdle on this road — a long-term neuron-silicon connection — within the next year or two. □ — *RF*

Travels of a Terrane

The residents of Juneau, Alaska might be surprised to learn that they live on land that was once part of eastern Australia. But the Australians will have trouble asserting property rights; the 70,000 square kilometers of what geologists call the Alexander Terrane broke away from Australia 375 million years ago. The terrane traveled across the Pacific and stopped off the coast of Peru. Then it turned northward, brushed past California, and finally came to a halt only after it slammed into the North American continent.

This, at least, is the sequence of events pieced together by Jason Saleeby, associate professor of geology, and his former student George Gehrels, who is now on the faculty of the University of Arizona. By reading the stratigraphic, paleomagnetic, and fossil evidence plastered on the terrane like labels on an old steamer trunk, Saleeby and Gehrels have constructed a detailed history of this highly peripatetic land mass.

Gem-quality zircon was the key to understanding the detailed history of the Alexander Terrane. This mineral, which is found in small quantities in igneous rock, can be dated with great precision. When zircon is formed it contains rather high levels of uranium and virtually no lead. Radioactive isotopes of uranium turn to lead as they decay, so the amount of lead that has accumulated in a zircon sample is a reflection of the host rock's age. Since zircon has such a low proportion of lead contamination to begin with, Saleeby and Gehrels were able to provide a stratigraphic time line with a high degree of precision.

Using this time line, the researchers determined that the Alexander Terrane started its existence over 500 million years ago as a long chain of volcanoes much like the present-day Mariana, Solomon, or Tonga island chains. Such "island arcs" leave distinctive lava flows. The lava flows on the Alexander Terrane turn out to be the remains of volcanoes far older than volcanoes anywhere else in western North America.

The history of mountain building also indicates that the Alexander Terrane could not have originated in its present location. Geologists infer mountain building by evidence of major faulting, by the metamorphism of rocks, and by a distinctive type of sedimentation resulting from coarse rocks shed from high elevations. This sort of information has led to the conclusion that the Alexander Terrane has been the site of two major mountain uplifts, one 520 million years ago and one 430 million years ago. Eastern Australia had periods of mountain building at just those times, but western North America was quiescent then. On the other hand, western North America underwent a series of mountain-building episodes starting about 350 million years ago, a time when there's no evidence of such events in the Alexander Terrane.

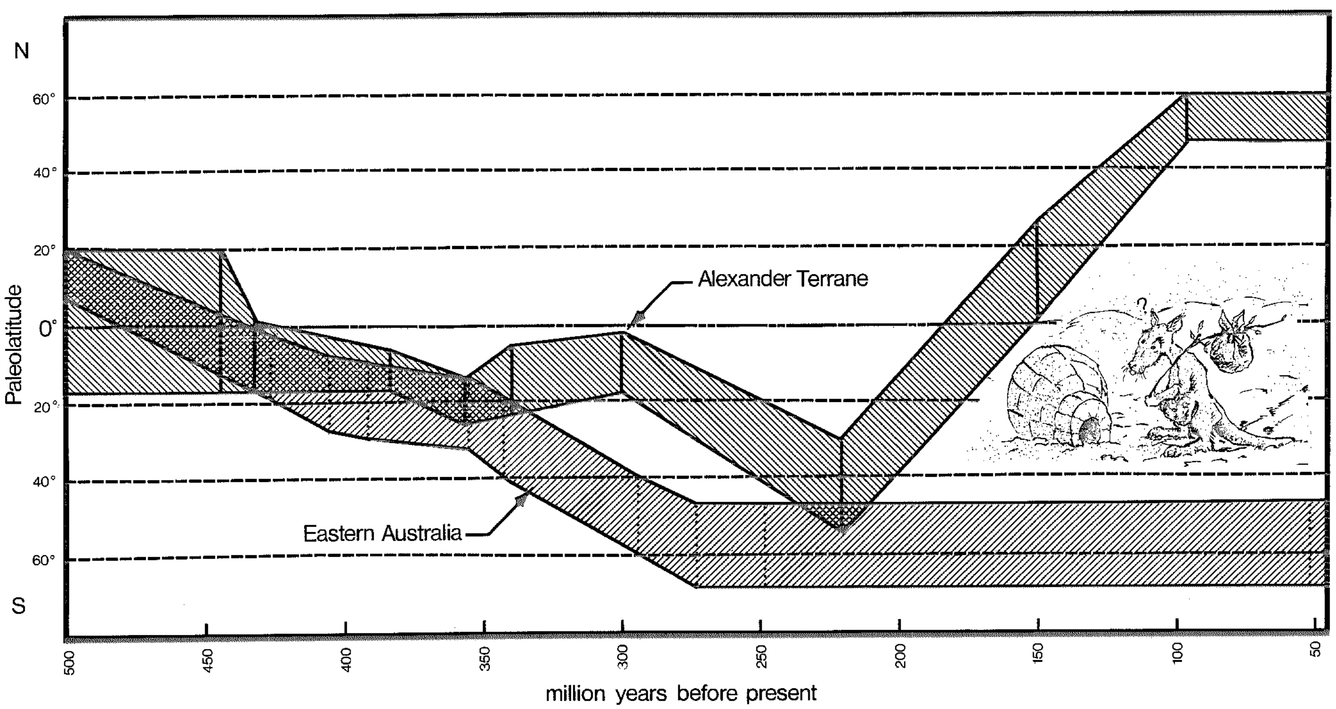
Paleomagnetic data provided the next piece of the puzzle. When a rock solidifies from the molten state, it contains many tiny magnets, all of which line up in the direction of the earth's magnetic field. Geologists can take cores from these rocks and determine the orientation of the magnetic material with the use of a magnetometer. By correlating this information with information on the rock's age, its original position on the horizontal plane, and the history of shifts in the earth's magnetic field, geologists can deduce the latitude at which a rock formed. Such information was used to construct the accompanying illustration, which indicates that the Alexander Terrane started out at the same latitude as eastern Australia, but started diverging some 375 million years ago. About 225 million years ago it began moving northward at 10 centimeters a year. This continued for 135 million years, at which time the terrane collided with the North American continent at its present latitude.

When it separated from Australia, the Alexander Terrane stretched like a piece of taffy, forming a subsurface ocean plateau. It remained an ocean plateau throughout nearly all of its travels, floating freely on the underlying mantle until it collided with North America. After the terrane was firmly welded to the continent, glaciers scoured fjords and channels, forming Prince of Wales Island and the other islands of the Alexander Archipelago.

The fossil evidence found on the terrane is consistent with this history and provides a third piece of the puzzle. The earliest fossils are land plants and animals with affinities to those of eastern Australia. When the terrane first became an ocean plateau, many small planktonic creatures called foraminifera settled out, forming small reefs. When the paleomagnetic evidence shows that the terrane moved south toward the coast of Peru, various marine bivalves begin appearing in the fossil record. The fossil bivalves proceed in a neat sequence from southern hemispheric species, to equatorial species, to species characteristic of northern temperate zones. Finally, about 100 million years ago, North American fauna began appearing.

The geological community has expressed much interest in these views of the Alexander Terrane's history, and the hypothesis is now in a state of rigorous testing. Saleeby and Gehrels are trying to determine whether the terrane traveled along with a neighboring land mass known as Wrangellia. They're trying to refine their dating of the collision and are attempting to determine the means by which much of the terrane was shoved underneath the North American cordillera.

The researchers are also testing some ideas that are more speculative. Saleeby believes, for example, that the renegade terrane may have snatched some of the host rocks of the California Mother Lode gold belt as it grazed the North American coast. "This is something that's going to draw a lot of debate because it flies in the face of established ideas of California geology," says Saleeby. But if the speculations are confirmed, these rocks would have formed the host for the Juneau gold belt. So the Alaskan gold rush may have actually been the California gold rush, just displaced 1,500 miles to the north. □ — *RF*



According to the paleomagnetic evidence, the Alexander Terrane broke away from eastern Australia 375 million years ago. It traveled across the Pacific, stopped briefly off the coast of Peru, and then moved northward at about 10 centimeters per year. It reached its present latitude about 100 million years ago when it became welded to the North American cordillera.

Books

QED: The Strange Theory of Light and Matter

by Richard P. Feynman

Princeton University Press........$18.50

"While I am describing to you *how* Nature works, you won't understand *why* Nature works that way but you see, nobody understands that. I can't explain why Nature behaves in this peculiar way."

So the author introduces his attempt to make understandable the theory of quantum electrodynamics — QED — a theory that allows physicists to calculate the results of interactions between light and electrons; and this includes chemistry and biology, materials and structures, mirrors and lenses, rainbows and sunsets — in short, ourselves and our world. In fact, the only things not included are gravity (a stubborn outsider, resisting the efforts to bring together the forces of nature) and interactions within the atomic nucleus, although the last chapter explains the frustration physicists have encountered in their seemingly reasonable attempts to extend QED to this latter domain.

The book is based on a series of four lectures — the Alix Mautner Memorial Lectures at UCLA — and is intended as an explanation of QED for a non-technical audience. How well does it come off? Indeed, there is little demand placed on the reader's technical or mathematical knowledge. Addition, subtraction, and multiplication are all that are required. The word "vector" is left unused. Instead we are told about arrows and how to manipulate them: how to point them (rotate them) in the right direction; how to add them, nose-to-tail like circus elephants, making sure that we slide them across the paper without changing their direction; and how to find the result, connecting the tail of the first to the point of the last.

He tells us how to analyze an event, how to look at all the possible ways in which that event might have happened, how to calculate an arrow for each way and then add them up for the final arrow. And then comes the magic of quantum mechanics: We measure the length of that final arrow and square it. What do we get? The probability that the event we were looking at would actually happen; for example, the percentage of light particles (photons) that would go through a piece of glass versus the percentage that would be reflected back. He then goes on to explain how to put together the arrows for events that happen in succession and once again calculate — from the length of the final arrow — the probability of the sequence.

The next step is to look at interactions between two different kinds of things: photons and electrons. There are special ground rules for adding up all the different ways that such interactions could take place. The very useful technique of "Feynman" diagrams is brought in, although the author doesn't call them that.

It is a beautiful demonstration of how the mathematically complex can be made mathematically simple; but not intellectually simple. You may find yourself frequently putting your finger in the book to mark the page and staring off into space. The theory is, as the title states, "strange." Beams of light and material objects don't *really* behave that way, do they? It seems to defy common sense, which Einstein is purported to have described as the set of prejudices we acquire by the age of 18. Why isn't it more sensible, like the theory of gravity, for instance? But then, the theory of gravity is simply a technique for determining the motion of two bodies pulling on each other — the moon and the earth, the planets and the sun, and so on. We have become so accustomed to it that we seldom stop to think that this theory is really only a set of rules for making calculations — whether we use Newton's rules or Einstein's update. The theory of gravity doesn't tell us what gravity *really is.* In fact, when it was first put forward there was much objection to the apparently nonsensical notion of "action at a distance." Somehow, over the centuries, we've gotten used to that. But most of us aren't quite ready for QED.

So, when you have gone through this delightfully written book (complete with footnotes expanding on some of the simplifications), you may feel somewhat frustrated. You have learned how to use simple mathematics, and a considerable amount of careful thinking, to calculate the outcome of the most basic processes that control the material world you deal with on a day-to-day basis. But you don't understand why it works that way. Well, he warned you. □

Al Hibbs
Senior Scientist
Jet Propulsion Laboratory

Letters

New York, NY

EDITOR:

Prof. John D. Roberts's informative article on "Biomedical Applications of NMR" laudably uses the initials for the term Nuclear Magnetic Resonance. But NMR has become a no-no in the medical profession, as patients are frightened by "nuclear." The term employed is MRI for Magnetic Resonance Imaging.

Although the MRI euphemism is at worst technically meaningless, or at best incomplete, users of NMR equipment in the medical field know what MRI means and are comfortable with it.

"To Shop or Not to Shop" is a theoretical and lab-experiment confirmation of what I have learned empirically over the last 35 years. I have been managing a small family business of importing frozen seafood. Some of our customers are "shoppers," while others will always pay our asking price (assuming it is within reason). When the product is in short supply, even the shoppers will pay full price, after some demurring. When the market is "soft," then, as Grether, Schwartz, and Wilde indicate, an equilibrium results, with an array of prices.

Further, information brokers develop automatically, these being the sales brokers used by importers to sell in markets nationwide. The sales brokers provide to the *sellers* information about competitors' prices, and the sellers must then develop their *marketing* strategies. Shipments arrive once per month, and the seller must determine how best to maximize profits, i.e., sell large quantities to a few shoppers, or hold out over the month and hope for many buyers of small quantities who will pay the higher price.

VICTOR WOUK, PhD'42

Mars: Myth and Reality

continued from page 9

by viewing the planet at different angles) should provide a way to estimate atmospheric pressure. Furthermore, since scattered light is polarized, polarization measurements should provide a check on the result.

But scattering depends not only on the wavelength of the light and the mass of the atmosphere but also on the atmospheric composition and the presence or absence in it of dust and other suspended particles, and therein lies the snag. In order to allow for these and other complications, such as polarization by the planetary surface, investigators before 1963 had to make some unverifiable assumptions before they could derive the atmospheric pressure from their data. The result, in the words of Claude Michaux and Ray Newburn of the Jet Propulsion Laboratory (JPL), was that "Each successive worker pointed out the 'unwarrantable assumptions' of his predecessors and proceeded to make a new set of his own."

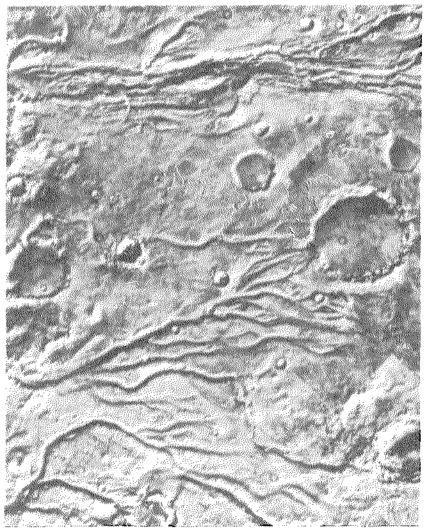
Despite the difficulties, a dozen or so attempts were made after Lowell's time to apply photometric and polarimetric methods to the surface-pressure problem. Their generally concordant results were reviewed by the French astronomer Gerard De Vaucouleurs in an influential book on Mars, the English edition of which appeared in 1954. De Vaucouleurs concluded that the most probable value for the Martian surface pressure was 85 ± 4 millibars. (This was the perfect Lowellian result. In *Mars as the Abode of Life*, published in 1908, Lowell had applied photometric arguments to the problem and arrived at a pressure of 64 millimeters of mercury, or 85 millibars!) After reexamining the evidence, the panel of experts quoted above gave its judgment: "It is unlikely that the true surface pressure differs by as much as a factor of 2 from 85 millibars." Actually, the true surface pressure differs from 85 millibars by a factor of more than 10.

Vegetation

Lowell based his belief that the dark areas of Mars were covered with vegetation on their blue-green color and on their observed seasonal color changes. In the springtime, what he called a "vernal progression" or "verdure wave" moved through these areas and along the canals, starting near the edge of the dark collar surrounding the shrinking ice cap and proceeding toward and beyond the equator. He estimated the speed of the wave at 51 miles per day. In Lowell's scheme, the wave of deepening color proved the sprouting of vegetation as water became available at lower latitudes in its regular swing through the atmosphere from one pole to the other. Lowell recognized that the direction of this wave of darkening, as it came to be called, was opposite to that seen on the earth, where the springtime growth of plants starts in temperate latitudes and moves poleward. But, he argued, this was just what one would expect on a planet where life is limited by the availability of water.

Telescopic observations made after Lowell's time confirmed the existence of the dark polar collar and of seasonal changes in the maria. These phenomena are now thought to result from redistribution of dust by seasonal winds. Or perhaps the polar collar is simply an optical effect produced by a glazed layer of frozen carbon dioxide exposed by sublimation of the overlying carbon dioxide frost. For decades following Lowell's death, however, the vegetation scenario reigned, and, by 1960, it seemed close to being proven.

The story began modestly in 1947-48 when, following the conclusion that the Martian polar cap was composed of water ice, G. P. Kuiper turned his attention to what he called the "green areas" of Mars. His plan was to compare the light reflected from these areas with the spectra obtained from higher plants, lichens, and mosses. Lichens are symbiotic associa-



Dendritic flow channels on Mars are shown west of the Viking 1 landing site in this Viking Orbiter shot. Old impact craters, formed before the flooding and eroded by it, and younger craters are visible. (National Space Science Data Center)

tions between a fungus and an alga. They are green or greenish in color and, like higher plants, they carry out photosynthesis by means of chlorophyll. Extremely hardy, these organisms inhabit cold, dry, forbidding places where few other living things survive.

Kuiper found no resemblance between the higher plant and lichen spectra. Whereas the plant spectrum showed a dozen or so peaks and valleys in its visible and infrared regions, the lichen spectrum appeared featureless and nearly flat over the same spectral range. Dry mosses produced a spectrum like that of lichens. Kuiper did not, for technical reasons, obtain a complete spectrum of the green regions of Mars. Instead, he measured their reflections at four different wavelengths. These observations convinced him that the Martian spectrum was unlike that of green plants and similar to that of lichens and mosses. A featureless spectrum hardly constituted strong evidence for the existence of either of these life forms on Mars, and a nonbiological explanation for the wave of darkening had been proposed. According to this hypothesis, the seasonal changes occurred when inorganic materials on the Martian surface absorbed water vapor from the atmosphere as it moved across the planet in the spring, then lost it in the dry fall atmosphere. Many such absorptive substances are known, and some of them do change color with the uptake and loss of moisture. Ernst Öpik, a noted Estonian-British astronomer, disposed of this hypothesis in 1950 with the argument that dust storms, recognized telescopically as yellow clouds that sometimes obscure the entire planet, would have covered the dark areas long ago if they had been simply inorganic deposits. The fact that the same areas always reappear after such storms, Öpik said, shows that they have regenerative powers.

Considering all the evidence and giving due weight to Öpik's argument, Kuiper concluded that the case for living things in the dark areas "appears very good." He thought it improbable, however, that Martian lichens were identical to those on the earth, because this would imply a highly unlikely parallel evolution — and besides, our lichens do not change color in the fall.

Kuiper's case was, at best, only suggestive, but it was soon strengthened by a spectacular result obtained by W. M. Sinton, a young American astronomer. As Kuiper had done, Sinton investigated the light reflected from Mars, but instead of scanning the whole spectrum, he concentrated on a narrow region in the infrared — in the neighborhood of 3.5 micrometers — where carbon-hydrogen bonds absorb strongly. Since all organic matter contains such bonds, Sinton argued that if plant life were responsible for the wave of darkening, that fact should be revealed by absorption in this region. Tests performed on lichens, mosses, and dried leaves confirmed that the light they reflect does show this absorption feature. Sinton then examined Mars over a period of four nights and found an absorption band centered at 3.46 micrometers, exactly where the tested plant material had absorbed. Two years later, in 1958, he repeated the observations, but with better equipment and with the 200-inch telescope of the Palomar Observatory. This time, he was able to analyze the light from the dark and bright regions separately. He found three bands near 3.5 micrometers — all attributed to organic compounds — in the light that came from the dark regions. The absorptions were weak or absent in light from the bright regions. On the face of it, a stronger confirmation of Lowell and Kuiper could hardly have been imagined.

The Space Science Board panel was not convinced by the Sinton absorption bands, stating that "the possibility that they arise from a combination of inorganic substances does not seem to have been explored sufficiently." On the question of Martian life, however, it concluded:

> The evidence taken as a whole is suggestive of life on Mars. In particular, the response to the availability of water vapor is just what is to be expected on a planet which is now relatively arid, but which once probably had much more surface water. The limited evidence we have is directly relevant only to the presence of microorganisms; there are no valid data for or against the existence of larger organisms and motile animals.

. . .

(A chapter section on the initial "delowellization" of Mars — the work between 1963 and 1969 — is omitted here)

. . .

MARINER 9 AND PRE-VIKING MARS

Once begun, the unraveling of Lowellian Mars proceeded swiftly, and by 1969 the delowellization of Mars was complete. In place of a harsh but recognizably earthlike planet, a Mars came into view that was almost moonlike in its hostility. This new Mars had a thin atmosphere, composed predominantly of carbon dioxide, that provided little protection against solar ultraviolet radiation which penetrated to the surface of the planet almost unfiltered. Furthermore, all attempts to detect the life-essential element nitrogen, the most abundant gas of the earth's atmosphere and the one that was supposed to compose the bulk of Mars's atmosphere in the Lowellian era, had so far failed. It now appeared that nitrogen made up less than 5 percent of the Martian atmosphere, and the possibility that the planet had no nitrogen at all had to be considered. Most ominous of all from a biological viewpoint was the dryness: the low surface pressure meant that water could not exist on the surface of Mars in liquid form, but only as ice or vapor.

The television pictures returned by *Mariners 4, 6,* and *7* were just as discouraging as the atmospheric results. Mars looked more like the moon than an earthlike planet. With a few exceptions, even the familiar surface markings disappeared on close approach, and none could be identified with particular surface features. Even the boundaries between classical bright and dark regions — so clear when viewed from afar — were invisible in pictures that otherwise showed Mars in greater detail than had ever been seen before. It now appears that the bright areas consist of relatively smooth and level ground that has accumulated a more or less continuous cover of light-colored dust. The dark areas, on the other hand, correspond to steeply sloping or heavily cratered regions where the dust layer is not continuous and where the darker bedrock shows through. Of Schiaparelli's and Lowell's canals, the only traces are possible chance alignments of craters and other natural surface features that the eye connects up to form lines.

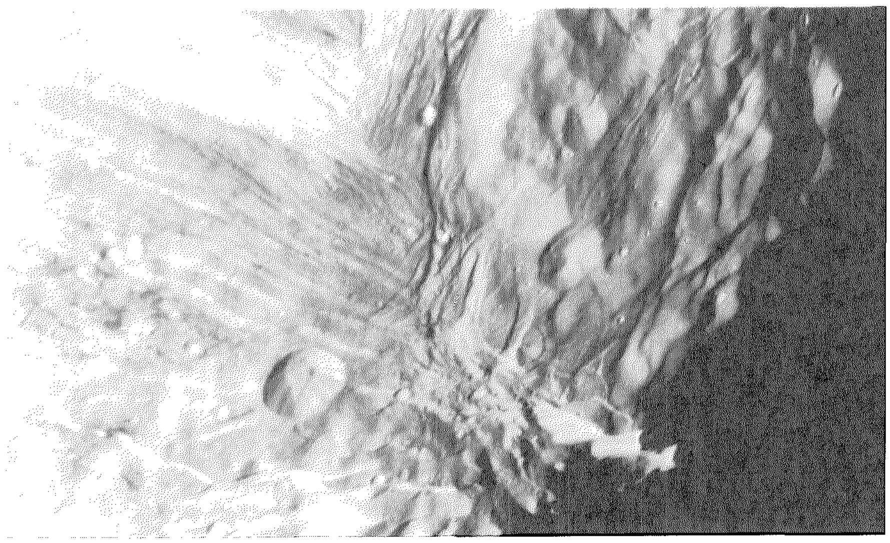
The prospects for life on Mars seemed so dim by 1970 that there seemed little good reason to emphasize biological questions in planning the spacecraft that would land there in 1976. A radical reversal took place in 1971, however, when another Mariner mission was sent to Mars. Of the two spacecraft launched in 1971, one — *Mariner 9* — achieved orbit around Mars, the goal of the mission, and it operated there for 11 months. Its most important accomplishment was to photograph the entire planet, and as large regions not previously seen by spacecraft came into view, it soon became obvious that Mars was not just another version of the moon, as earlier Mariner pictures had led one to expect, but was a planet with its own complex history.

Several spectacular discoveries led to this conclusion, among them four gigantic, inactive volcanoes, one of which is the largest in the solar system. But the aspect of Mars that has attracted the most attention is undoubtedly its multitude of channels, some of them hundreds of kilometers in length and apparently cut in the past by running water. (These channels, which are invisible from the earth, have no relation to Lowell's canals.) A number of morphologically distinct channel types are seen, but not all of them require running water to explain their origin. Some may have been eroded by glacial movement, for example, and some by flowing lava, to mention two possibilities. Many, however, and perhaps most, were very probably formed by water. Among these are sinuous, meandering streambeds that, with their tributaries, form typical drainage patterns. The source of water for these systems could have been subsurface ice (permafrost) that was melted by geothermal activity and seeped through the surface, but other sources — even rain — have not been excluded. Other Martian channels start abruptly as very large features, as if caused by sudden, catastrophic flooding. Unlike typical drainage systems, however, they frequently diminish in size downstream. It is less certain that these channels were eroded by flowing water, although it is not impossible.

None of this streambed cutting happened in recent times. The evidence indicates that the channels are ancient — billions of years old in most cases, judging from the number of meteoritic impact craters that overlie them. Nor is there any clear evidence that lakes or oceans ever existed on Mars. The rivers did not flow into seas, but — from the evidence that remains — simply petered out, either disappearing into the ground or evaporating.

The possibility that liquid water once flowed on the surface of Mars improved the biological outlook considerably. If conditions during the early history of the planet were so temperate that water could exist on its surface, then life may have originated. If so, it was conceivable that, by adapting to gradually deteriorating conditions, Martian life had managed to survive and was still surviving on the planet. The probability that this was so did not seem very high, but in such matters, *a priori* judgments do not carry much weight when an empirical test can be made. Such a test became the major objective of the Viking mission, the next and climactic chapter in our story of the search for life on Mars. □

Random Walk



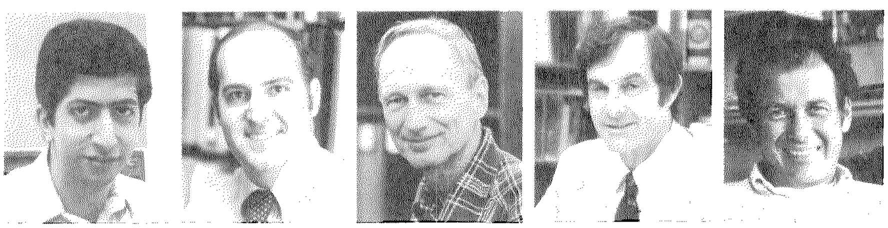
This Voyager 2 image, taken January 24, 1986, shows part of Miranda, innermost of Uranus's large satellites. Voyager was some 36,000 kilometers from Miranda when this shot was taken. Miranda is an amazing place, comprising quite a number of terrain types juxtaposed closely. At least two of those terrains are visible here. The rugged, higher-elevation terrain to the right contains numerous craters, indicating that it is older than the lower, striated terrain to the left. Several scarps, probably faults, cut the different terrains. The large crater at left center in the image is about 25 km across. In its September 1986 issue Engineering & Science *will publish an article on Uranus by Professor of Physics Edward Stone, who is also division chairman as well as Voyager project scientist.*

Harrison Dies

THE CALTECH COMMUNITY recently lost a close friend with the death on February 7 of Dr. R. Stewart Harrison. Harrison, 79, was born in England and received his undergraduate and medical degrees from Oxford University. He specialized in radiology and, in the early 1930s, wrote a definitive work on the radiation therapy of cancer of the larynx. In 1936 he was invited to Caltech where he worked with C.C. Lauritsen, then professor of physics, who had built the world's first supervoltage radiation therapy machine in his lab next to Kellogg.

After service in the U.S. Army during World War II, Harrison returned to Pasadena where he held the position of Chief of Radiology at Huntington Memorial Hospital until his retirement in 1974. But he always maintained close ties with Caltech. In 1954 the Trustees appointed him Consultant in Radiology and he served for many years on the Institute's Radiological Safety Committee. He was instrumental in the establishment of the Health Center and served as its assistant director from 1960 to 1970. In recent years he spent most of his time at his home in Solimar Beach, CA. He is survived by his wife, Helen.

Teachers Honored



FIVE FACULTY MEMBERS have received ASCIT awards for excellence in teaching. These awards are based on survey responses and represent the sentiments of the entire student body.

The honored faculty members are from left: Yaser S. Abu-Mostafa, assistant professor of electrical engineering and computer science, for the course, "Information and Complexity;" Glen R. Cass, associate professor of environmental engineering, for the course "Engineering Problems of Man's Environment;" Eugene W. Cowan, professor of physics, for the course "Classical Electromagnetism;" Fred E.C. Culick, professor of applied physics and jet propulsion, for the course "Vehicle Performance and Dynamics;" and Jerome Pine, professor of physics, for the course "Introduction to Biophysics of the Nervous System."

IBM Gives Grant

PRESIDENT MARVIN GOLDBERGER has announced a new $1 million grant to the Institute from IBM. "This grant helps meet some of the most vital needs of Caltech," said Goldberger. "For example, a portion of the funding will be used to establish the IBM Research Fund to support research initiatives by both new and established faculty. These funds are absolutely necessary if we are to attempt untried research approaches that would normally be supported by traditional sources." The IBM Research Fund will also be used to bring outstanding young scholars to the Institute as visitors. In addition, the IBM grant will help support the Summer Undergraduate Research Fellowship (SURF) program and the Secondary Schools Science Project.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