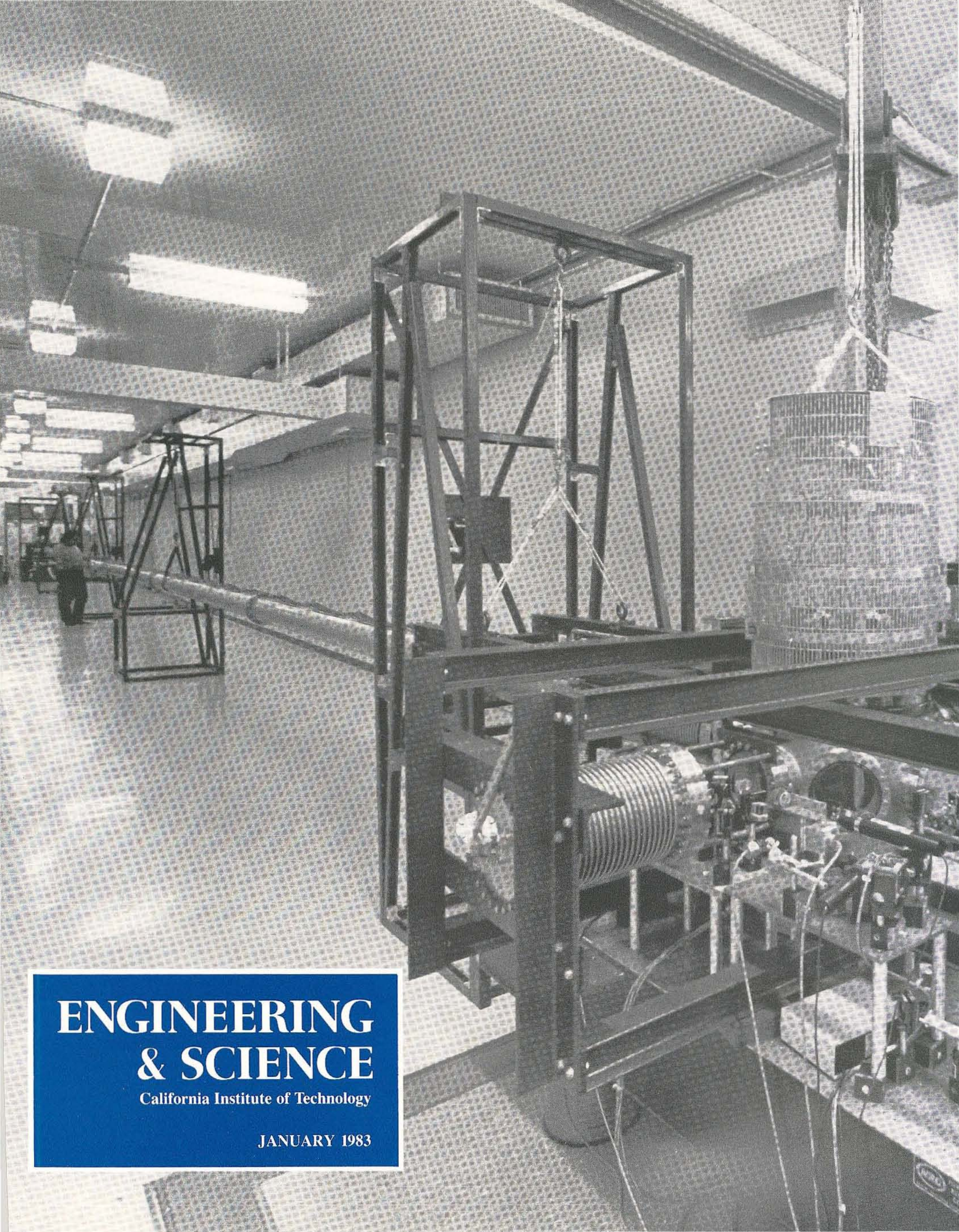
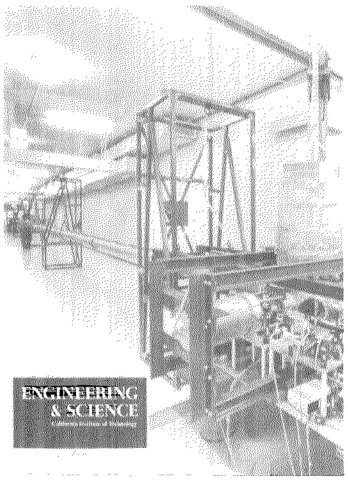


ENGINEERING & SCIENCE

California Institute of Technology

JANUARY 1983

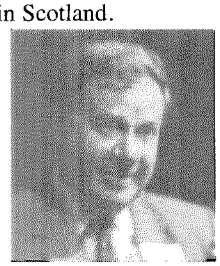
In This Issue



Ripples in Space-Time

On the cover — one of the 40-meter-long arms of Caltech's L-shaped gravity wave detector. Gravitational radiation is a propagating strain in space predicted by Einstein's relativity theory but as yet unobserved with any reliability. The almost complete laser interferometer, when its sensitivity is honed as sharp as it can go, will begin a tentative search for these very faint signals that would be produced by such violent astronomical events as a supernova explosion.

Actually, the Caltech instrument is only a prototype for an even more sensitive detector planned on a kilometer scale. And the forerunner of Caltech's prototype is a 10-meter instrument at the University of Glasgow in Scotland.



Architect of both prototypes and, he hopes, the third very large detector also, is Ronald Drever, whom Caltech has been sharing with the University of Glasgow since 1979. He is a half-time professor of physics at both institutions, although his connection with Glasgow goes back further. Drever received his BSc there in 1953 and his PhD in 1958 and has been on the faculty ever since (titular professor since 1975).

Much of his career has been spent looking for gravity waves. He cheerfully admits to not knowing whether he or anyone else will be able to detect this elusive radiation but claims, convincingly, that he's having a lot of fun trying. "The Search for Gravitational Waves," beginning on page 6, was adapted from Drever's Seminar Day talk last spring.

Light Fantastic

Technological problems have plagued the numerous attempts to generate electricity from sunlight cheaply. But a campus/JPL team led by Ahmed Zewail has been developing a very promising technique to increase the efficiency of photovoltaic solar energy conversion and reduce the effective cost of silicon cells. The encouraging progress on this work is described beginning on page 10 in "The Luminescent Solar Concentrator: An Illuminating Solution for Solar Energy" by Dennis Meredith, director of the Caltech news bureau. Zewail, whose research also involves laser-selective chemistry (*E&S*, January-February 1980), is professor of chemical physics at Caltech, where he has worked since 1976. He was born in Egypt and received his BSc in 1967 from the University of Alexandria. His PhD is from the University of Pennsylvania (1974).

Planetary Recipes

Despite the title of his article "Onions or Plum Puddings?" David Stevenson is not a chef but a theoretical physicist. And his gastronomical images (he goes on to include baked Alaska and, less appetizing, rubber ducks and oceans of cleaning fluid) serve as models for the structure and composition of planets in our solar system.

Stevenson became interested in planetary science at Cornell, where he received his PhD in 1976 in theoretical physics. Previously he had earned his BS and MS from Victoria University in his homeland, New Zealand. After two years as a research fellow at the Australian National University in Canberra and another two years as assistant professor at UCLA, he emigrated across town to Caltech. He has been associate professor of planetary science here since 1980.

The article for *E&S*, which begins on page 16, was adapted from his November Watson lecture. Actually, Stevenson does like to cook. He doesn't care much for plum pudding but does put onions in chili, his favorite recipe.

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Departments

ALUMNI FLIGHTS ABROAD

This program of tours, originally planned for alumni of Harvard, Yale, Princeton, and M.I.T., is now open to alumni of California Institute of Technology as well as certain other distinguished colleges and universities. Begun in 1965 and now in its sixteenth year, it is designed for educated and intelligent travelers and planned for persons who might normally prefer to travel independently, visiting distant lands and regions where it is advantageous to travel as a group.

The program offers a wide choice of journeys to some of the most interesting and unusual parts of the world, including Japan and the Far East; Central Asia, from the Khyber Pass to the Taj Mahal and the Himalayas of Nepal; the surprising world of South India; the islands of the East, from Java and Sumatra to Borneo and Ceylon; the treasures of ancient Egypt, the world of antiquity in Greece and Asia Minor; East Africa and Islands of the Seychelles; New Guinea; the South Pacific; the Galapagos and South America; and more.

REALMS OF ANTIQUITY: A newly- expanded program of itineraries, ranging from 15 to 35 days, offers an even wider range of the archaeological treasures of classical antiquity in Greece, Asia Minor and the Aegean, as well as the ancient Greek cities on the island of Sicily, the ruins of Carthage and Roman cities of North Africa, and a comprehensive and authoritative survey of the civilization of ancient Egypt, along the Nile Valley from Cairo and Meidum as far as Abu Simbel near the border of the Sudan. This is one of the most complete and far-ranging programs ever offered to the civilizations and cities of the ancient world, including sites such as Aphrodisias, Didyma, Aspendos, Miletus and the Hittite citadel of Hattusas, as well as Athens, Troy, Mycenae, Pergamum, Crete and a host of other cities and islands of classical antiquity. The programs in Egypt offer an unusually comprehensive and perceptive view of the civilization of ancient Egypt and the antiquities of the Nile Valley, and include as well a visit to the collection of Egyptian antiquities in the British Museum in London, with the Rosetta Stone.

SOUTH AMERICA and THE GALAPAGOS: A choice of itineraries of from 12 to 29 days,. including a cruise among the islands of the Galapagos, the jungle of the Amazon, the Nazca Lines and the desert of southern Peru, the ancient civilizations of the Andes from Machu Picchu to Tiahuanaco near Lake Titicaca, the great colonial cities of the conquistadores, the futuristic city of Brasilia, Iguassu Falls, the snow-capped peaks of the Andes and other sights of unusual interest.

EAST AFRICA—KENYA, TANZANIA AND THE SEYCHELLES: A distinctive program of 5 outstanding safaris, ranging in length from 16 to 32 days, to the great wilderness areas of Kenya and Tanzania and to the beautiful islands of the Seychelles. The safari programs are carefully planned and comprehensive and are led by experts on East African wildlife, offering an exceptional opportunity to see and photograph the wildlife of Africa.

THE SOUTH PACIFIC and NEW GUINEA: A primitive and beautiful land unfolds in the 22-day EXPEDITION TO NEW GUINEA, a rare glimpse into a vanishing world of Stone Age tribes and customs. Includes the famous Highlands of New Guinea, with Sing Sings and tribal cultures and customs, and an exploration of the remote tribal villages of the Sepik and Karawari Rivers and the vast Sepik Plain, as well as the North Coast at Madang and Wewak and the beautiful volcanic island of New Britain with the Baining Fire Dancers. To the south, the island continent of Australia and the islands of New Zealand are covered by the SOUTH PACIFIC, 28 days, unfolding a world of Maori villages, boiling geysers, fiords and snow-capped mountains, ski plane flights over glacier snows, jet boat rides, sheep ranches, penguins, the Australian "outback," historic convict settlements from the days of Charles Dickens, and the Great Barrier Reef. Optional visits can also be made to other islands of the southern Pacific, such as Fiji and Tahiti.

CENTRAL ASIA and THE HIMALAYAS: An expanded program of three itineraries, from 24 to 29 days, explores north and central India and the romantic world of the Moghul Empire, the interesting and surprising world of south India, the remote mountain kingdom of Nepal, and the untamed Northwest Frontier at Peshawar and the Punjab in Pakistan. Includes the Khyber Pass, towering Moghul forts, intricately sculptured temples, lavish palaces, historic gardens, the teeming banks of the Ganges, holy cities and picturesque villages, and the splendor of the Taj Mahal, as well as tropical lagoons and canals, ancient Portuguese churches, the snow-capped peaks of the Himalayas along the roof of the world, and hotels which once were palaces of maharajas.

THE FAR EAST: Itineraries which offer a penetrating insight into the lands and islands of the East. THE ORIENT, 30 days, surveys the treasures of ancient and modern Japan, with Kyoto, Nara, Ise-Shima, Kamakura, Nikko, the Fuji-Hakone National Park, and Tokyo. Also included are the important cities of Southeast Asia, from Singapore and Hong Kong to the temples of Bangkok and the island of Bali. A different and unusual perspective is offered in BEYOND THE JAVA SEA, 34 days, a journey through the tropics of the Far East from Manila and the island fortress of Corregidor to headhunter villages in the jungle of Borneo, the ancient civilizations of Ceylon, Batak tribal villages in Sumatra, the tropical island of Penang, and ancient temples in Java and Bali.

Prices range from $2,350 to $4,500 from U.S. points of departure. Air travel is on regularly scheduled flights of major airlines, utilizing reduced fares which save up to $600.00 and more over normal fares. Fully descriptive brochures are available, giving itineraries in detail and listing departure dates, hotels, individual tour rates and other information. For full details contact:

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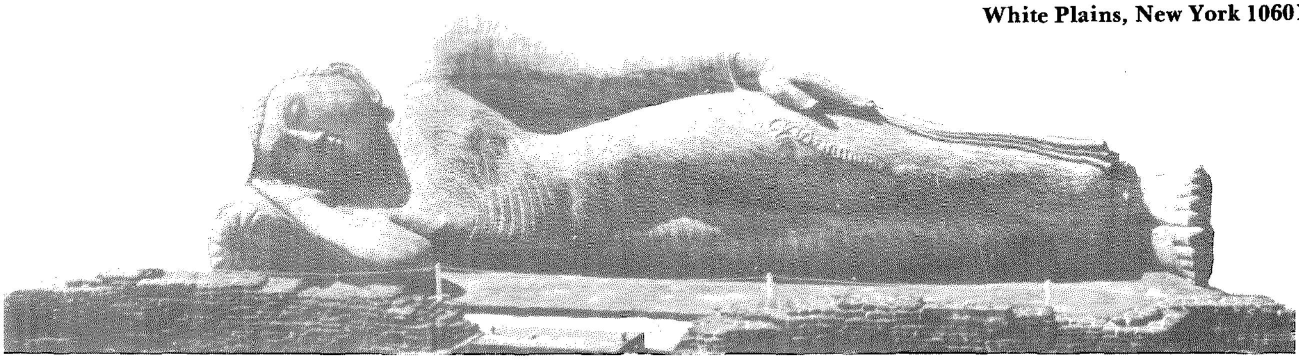

SCIENCE/SCOPE

For his pioneering contributions to geostationary communications satellites, Dr. Harold Rosen of Hughes has been given the prestigious Alexander Graham Bell Medal by the Institute of Electrical and Electronic Engineers. Rosen is credited with conceiving the first practical geostationary communications satellite, which orbits 22,300 miles high and covers over a third of the globe. Early satellites orbited lower and would have required a large fleet and complicated tracking procedures if continuous communications were to be provided.

Computers are being called upon to help create the "super chips" that will give military electronics systems a tenfold increase in data processing capability. Hughes is using computer-aided design programs to develop Very High Speed Integrated Circuits (VHSIC) and the systems in which these chips will be used. Computer help is essential because VHSIC chips are as complex as 100 Los Angeles street maps printed on a thumb tack, and they themselves are mere components of larger, more complex systems. Computer programs will help engineers design, lay out, and test a chip. They describe an entire system at many levels of detail simultaneously to predict performance under various operating conditions.

Landsat 4, the new second-generation Earth-watching satellite, is studying crops and other resources in greater detail than ever before possible. The spacecraft carries two primary instruments. One is a multispectral scanner like the ones on previous Landsat missions. The other is a thematic mapper, whose remote-sensing capabilities are a considerable improvement over the scanner's. The new mapper gathers different kinds of data and has a spatial resolution of 30 meters versus 80 meters of earlier scanners. Hughes and its Santa Barbara Research Center subsidiary built both instruments for NASA.

More than 4,500 men and women have furthered their professional careers through the Hughes Fellowship Programs since 1949. Those who qualify are given the opportunity to earn advanced degrees in scientific and engineering disciplines. Under full-study programs, employees study at selected schools and work at a company facility during the summer. Under work-study programs, employees work part-time and carry about one-half of a full academic load at nearby schools. More than 100 fellowships are awarded annually.

Scientists have tracked the ash plume from the Mexican volcano El Cinchon using a weather satellite. Daylight and infrared pictures from GOES-5 (Geostationary Operational Environmental Satellite) clearly showed the April 4 eruptions even from 22,300 miles in space. Subsequent images revealed the plume rising high into the stratosphere and across the Yucatan peninsula. GOES-5 was built by Hughes and is operated by the National Oceanic and Atmospheric Administration.

Hughes needs graduates with degrees in EE, computer science, physics, ME, and math. To learn how you can become involved in any one of 1,500 high-technology projects, ranging from submicron microelectronics to advanced large-scale electronics systems, contact: College Relations Office, Hughes Aircraft Company, P.O. Box 90515, Dept. SS, Los Angeles, CA 90009. Equal opportunity employer.

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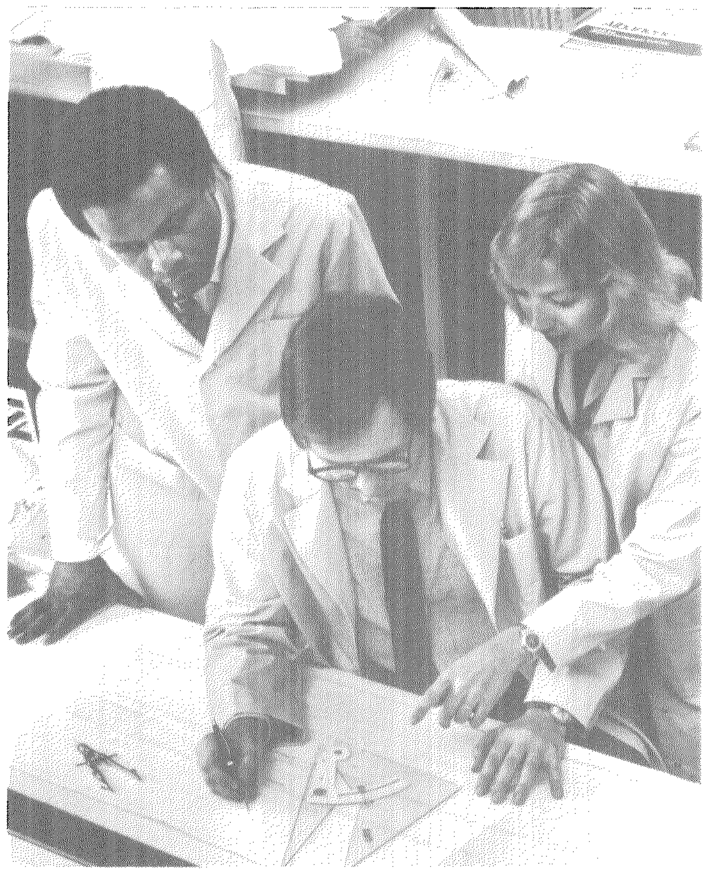
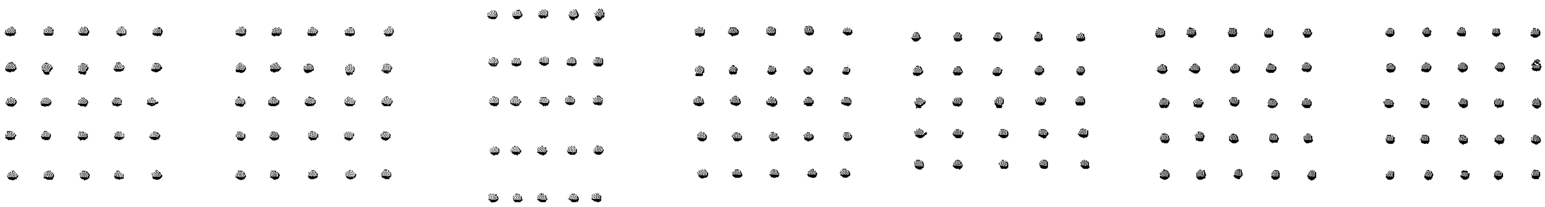




The Search for Gravitational Waves

by Ronald W. P. Drever

Illustrated above is a possible apparent effect of a gravitational wave pulse, traveling in a direction into the page, on a square array of light test particles floating freely in space. Seven successive snapshots taken at intervals of one-thousandth of a second might reveal the kind of relative particle motions indicated. The motions shown are highly exaggerated – by a factor of around a billion billion.

CALTECH's first prototype gravity wave detector, four years in planning and construction, is approaching completion in its initial form and is nearly ready for preliminary experiments. The sensitive instrument, with 40-meter-long arms, is housed in its own temperature-controlled and vibration-isolated "building" attached to the north and west sides of the Central Engineering Services facility. It may seem strange to be putting so much experimental effort into gravitational waves when it is not at all clear that anyone has ever even observed them yet. But if this project — or any of the others around the world — do actually find gravitational waves, it could lead to a new window on the universe. Right now we don't even know all the things we might see through that window; an entirely new area of astronomy would be opened up.

Gravitational waves are a form of radiation predicted by Einstein's relativity theory. Einstein showed that when masses move, the resulting changes in the gravitational field propagate out at a speed equal to the speed of light. An oscillating acceleration of masses would give a periodic effect, and it is quite reasonable to call this propagating strain in space a gravitational wave. Analogies can be made with electromagnetic waves, which are produced by accelerating charges — such as the electrons carrying the currents in the antenna of a radio broadcasting station. When thinking about gravitation, we can in some ways regard mass as analogous to electrical charge in electromagnetism, and it might not be too surprising that accelerating masses might produce gravitational waves.

But there are some basic differences between gravitational waves and radio waves. In electromagnetism, for example, we have both positive and negative charges; but in the case of gravitation, as far as we know, there is only one sign of "gravitational charge." Although in principle I might produce gravitational waves by shaking a heavy object up and down, when I make it accelerate in one direction, my body and the ground I am standing on would tend to accelerate in the opposite direction. And as my body and the ground would have effectively the same relative gravitational charge as the object being shaken, they would give an effect which would tend to cancel the waves from that object. In fact, generation of gravitational waves depends on the overall change in distribution of mass, or flow of mass, in a system. In principle the simplest gravitational wave generator might consist of a pair of massive objects made to oscillate with respect to one another, or rotate about one another.

How could we observe the waves from such a generator? In the radio wave analog we might set up an antenna and look for the relative motions of electrons and positive charges within it, detecting the resulting currents. In the gravitational wave case, with all masses equivalent, we have to do something different; and the simplest thing we might consider looking for could be relative motion of a pair of free test masses placed some distance from one another. And indeed this is a way of detecting gravitational waves, at least in principle.

So, to see a gravitational wave, we might set up two test masses, floating in space or suspended somehow so that they are free to move, and look for relative motions. It turns out that gravitational waves, like radio waves, are transverse in nature, and the maximum effect is obtained when the line joining the two particles is perpendicular to the direction of propagation of the wave, and is suitably oriented relative to its polarization. If the distance between the masses is small compared with the wavelength, then the change in separation is proportional to the separation, and the fractional change in separation may be taken as a measure of the amplitude of the wave. Another pair of test masses placed to reveal transverse motions in a direction orthogonal to that tested by the first pair will give relative motions of the same magnitude but opposite sign; and the usual definition of wave amplitude is in fact twice the fractional effect seen in either direction alone.

How big are these effects? Very, very small in most cases — and that is what makes experiments hard. If we tried to generate gravitational waves in the lab by making masses move, the radiated waves would be so weak that there would be no hope of detecting them by any method we can think of just now. There are, however, some violent astronomical processes that might generate detectable gravitational waves, such as, for example, a supernova explosion — the collapse of a normal star to give a neutron star.

When a star burns up its nuclear fuel, the central part can become unstable and start to collapse inward upon itself. As the parts get closer together, they're pulled more and more strongly by their own gravity, and the collapse becomes very rapid in its last stage. Sometimes a neutron star is formed — a star just a few miles in diameter with the extremely high density of nuclear matter. In the final stage of the formation of the neutron star the system may oscillate in shape from a pancake to a football shape, or bounce in other ways in times as short as a thousandth of a second, and these violent motions can produce a significant flux of gravitational waves.

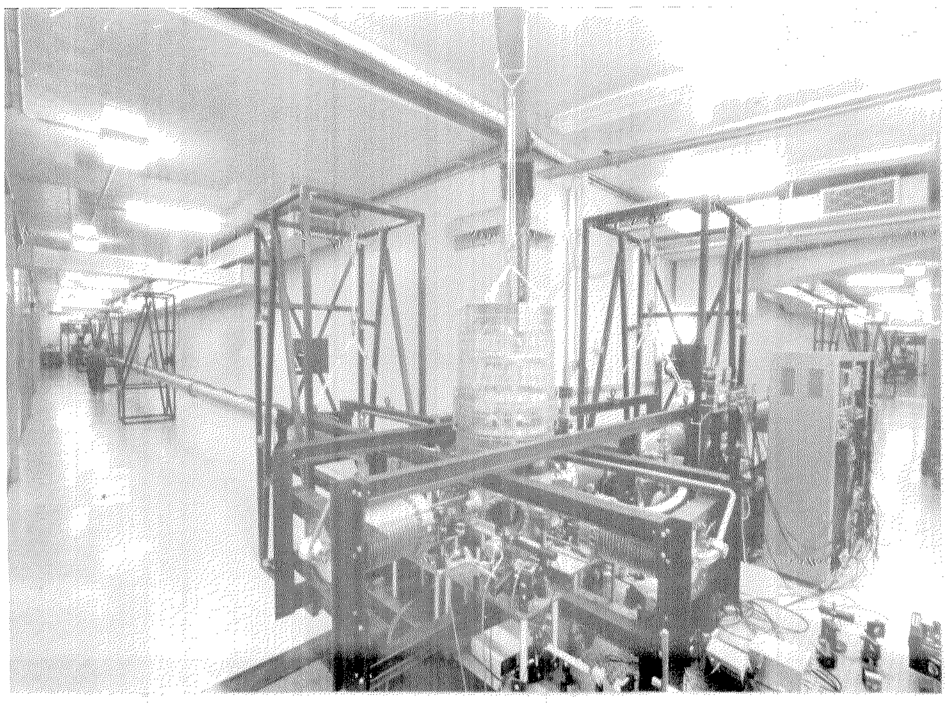
If the mass of the original star is rather larger than the mass of the sun, the collapse can proceed further to form a black hole — which has a density so high that the gravitational attraction prevents anything getting out of it — and this process may produce gravitational waves quite well too. Of course not even gravitational waves can escape from inside a black hole, but as pieces of matter cross over the boundary into the black hole, they're accelerating rapidly and could throw out gravitational waves just before they vanish.

The size of a gravitational wave signal from a supernova depends on how far away the supernova is. If it were in our own galaxy, that is, relatively close, the best estimates are that the amplitude of the wave might be about 10^{-17}. That means, for example, that if our gravitational wave detector had test masses a meter apart, the relative motion we would get from this supernova would be only about 10^{-17} meters. That's less than the size of the nucleus of an atom. If we imagine our detector expanded to the size of the earth itself, the opposite parts would move even then by a distance of only about one angstrom. So gravitational waves might not, at first, look a very promising field for experiment.

But nevertheless, Joseph Weber, of the University of Maryland, had the courage in the late 1960s to start some experiments to look for gravitational waves. It is generally considered that he did not find them, but it was extremely important work because it triggered many other experiments in the field. Weber's technique did not use two separate masses, but made the masses the two ends of a big aluminum bar a couple of meters long. The elasticity of the bar was such that it had a resonance frequency for longitudinal vibrations in the region of a kiloherz, which corresponds roughly to the frequency you would expect from gravitational waves from supernova collapse. As a gravity wave passes, it might set up oscillations in the bar, which would persist for some seconds and might perhaps be detectable.

Weber fitted bars like this with piezoelectric transducers connected to sensitive amplifiers, suspended them in vacuum tanks with isolation from seismic disturbances, and looked for changes in oscillation. He achieved quite good sensitivity, perhaps not far from 10^{-16} in gravitational wave amplitude, and, surprisingly, seemed to see many pulses he thought might be gravitational waves. They were, however, larger than expected, much more frequent than supernovae in our galaxy — which probably occur about once per 30 years on average — and indeed so numerous that they

The whole view (both arms) of the Caltech 40-meter prototype laser interferometer gravitational wave detector pictured on the cover. Test masses are suspended inside the vacuum tank at the center of the photo and in similar tanks at the far ends of the vacuum pipes. Laser beams within the pipes monitor relative motions of the masses.

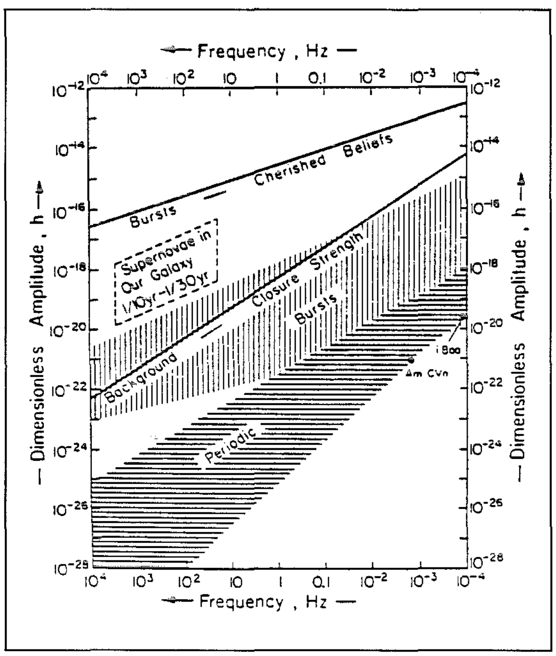


would correspond to a very puzzling loss of energy from the galaxy if they originated there. Of all those who got into the field after Weber nobody else found signals that seemed to correspond to gravitational waves at the level and rates suggested by Weber's results, and the consensus view is that he may have been seeing some other kind of disturbance. An important thing about this work, however, was that it did show that experiments could be carried out at a surprising level of sensitivity, and it brought many other researchers into the field.

Most of the gravitational wave experiments carried out so far have used bar-type detectors similar in principle to Weber's. Currently the most sensitive of these that have gone into operation is at Stanford, in which a large bar is suspended in a liquid helium cryostat to reduce thermal noise, and the vibrations are monitored by a superconducting accelerometer attached to one end of the bar. This instrument has had a sensitivity of order 10^{-18} to date — and achieving this has been a considerable feat, one that should be good enough to see supernovae in our galaxy. But these occur at such a low rate that observation is not very likely. Detection of unpredicted signals is not at all impossible at the level of sensitivity of this detector, however. Really critical experiments have not been possible yet due to the absence so far of another working detector of similar sensitivity with which to correlate data.

In order to do a really promising experiment, however, it would be good if we could aim at getting signals at a rate of around once per month. One way to do this would be to make a more

Estimates of the strengths of gravitational waves arriving at the earth over a range of frequencies. Regions where bursts or pulses at rates of order one per month (from black hole or neutron star formation) and periodic signals (from binaries and pulsars) might be expected are shown by shading. The lines indicate upper limits on bursts and stochastic gravitational wave background suggested by "cherished beliefs" such as mass-energy conservation, observed mass distribution in the galaxy and universe, and so on.



K.S. Thorne, Rev. Mod. Phys., 52, 285 (1980)

sensitive detector so that we could look further out and cover more supernovae. It looks as though we could expect signals at about once a month if we could detect supernovae events out into the Virgo cluster of galaxies, but the amplitudes of the signals from these distances would probably be of order 10^{-21} or so. That does not look very easy. It was hard enough to do the early experiments at sensitivities of about 10^{-16} or 10^{-17}, and now we are asking to do experiments four orders of magnitude better in amplitude sensitivity, which corresponds to eight orders of magnitude better in terms of energy flux.

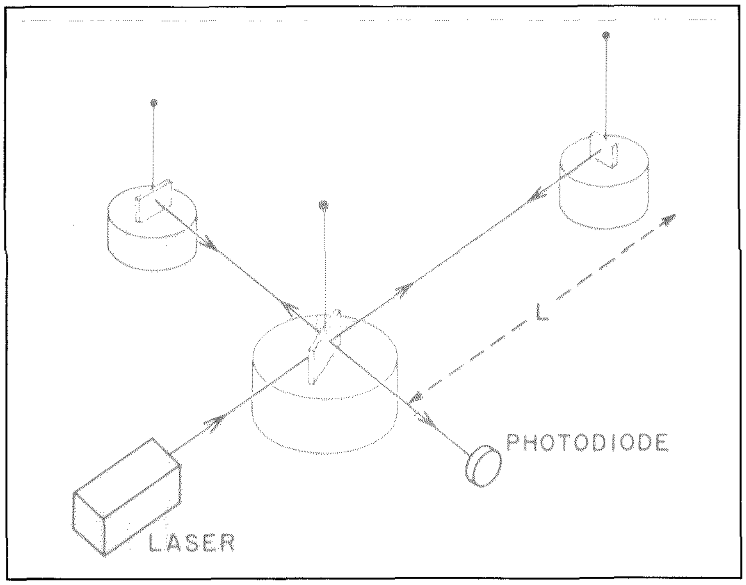
But, if we could achieve sensitivities of this order, quite a range of possibilities for seeing gravitational wave signals of different kinds might open up. In addition to supernova and stellar collapse signals at reasonable rates, we might see signals from collisions between black holes, from pairs of newly formed neutron stars rapidly rotating about one another, and from other possible sources. There are also continuous signals emitted by pulsars, known and unknown. A pulsar spins at a very steady rate — about 30 revolutions per second for the Crab Nebula pulsar, for example — and unless it is perfectly symmetrical about its rotation axis it will emit continuous gravitational radiation. In general, if the pulsar is precessing as well as spinning it will emit gravitational radiation at a frequency close to the repetition frequency of its radio pulses, and also close to twice this frequency. The strengths of the waves depend on the degree of asymmetry of the pulsar and so are hard to predict accurately, but the amplitudes are probably in the region of 10^{-26} for the Crab and the Vela pulsars. This is small but much easier to detect than a single pulse, since the signal is continuous and the frequencies known quite well. In fact I think that detection of pulsar and supernova signals presents problems of roughly equal magnitude, and when one is solved, the other will be near solution too. We would also expect a whole spectrum of gravitational wave signals at lower frequencies coming from more massive black holes — with masses up to a million times the sun's mass — in distant galaxies and quasars.

Can we build equipment sufficiently sensitive to pick up some of these signals? That's the task we set ourselves. The factor of improvement that we're expecting we may have to get over the previous experiments corresponds roughly to the difference in sensitivity between the human eye and the 200-inch telescope at Palomar Observatory, so the task may take some time.

The method that we've chosen to develop does not use bars at all. It goes back to the idea of watching free masses move relative to one another as the gravitational wave goes past. And if we use light to detect the motion, we can put the masses a long distance apart so that we get bigger effects to observe — an important advantage over the bar type of gravitational wave detector. Our experiments at Caltech are starting off with three test masses 40 meters apart — and maybe we'll make it several kilometers before we're finished. We hang each of the masses by wires, like a pendulum, so that it can make small movements in a horizontal direction fairly freely. We arrange the three masses in the form of an L, so that if a gravitational wave traveling in a vertical direction makes the two masses on one side of the L move apart it will at the same time make the pair forming the other arm of the L move together. Thus one distance gets longer and the other shorter. We need a way to measure that change, and the method we have chosen is based on an optical interferometer.

In principle we might use a Michelson interferometer. We could attach a partially reflecting beam splitter to the mass at the corner of the L, and illuminate it by a beam of light from a source such as a laser, so that half of the light passes through the beam splitter toward the mass at the end of one arm of the L, and the other half is reflected toward the mass at the end of the other arm. Mirrors on the two end masses reflect the beams back to the beam splitter, where they recombine and pass to a photodiode. The fringe pattern we get there depends on the relative phase of the light in the beams. If in phase, we get high intensity, if out of phase we get darkness. So if the masses move and make the difference in the path lengths change slightly, we may see a change in output from the photodiode. In principle this is fine, but once again the smallness of the effects causes problems. The wavelength of light is about 5 x 10^{-7} meters, and the gravitational wave motion is probably going to be smaller than that by a factor of 10^{10} or more, so we're not going to see whole fringes moving past. We can't even expect to see a motion of the fringe pattern by a reasonable fraction of the distance between one fringe and the next. We're going to have to look for changes corresponding to 10^{-10} of a fringe or less. And that's a bit difficult.

There are two fairly fundamental limiting factors for this kind of gravitational wave detector. One is the quantum limit to the sensitivity of the apparatus set by the uncertainty principle. If we try to measure the position of one of the test masses with very high accuracy, we make its momentum uncertain — giving it a little bit of a kick. If we look at the mass again a little later,



This drawing shows a possible arrangement of a simple, but insensitive, laser interferometer gravitational wave detector using three suspended test masses, with baseline L.

and we find it has moved, we don't know whether that's because we kicked it or because a gravitational wave went past. For test masses of reasonable size, and a gravitational wave pulse lasting a millisecond, this quantum limit corresponds to a wave amplitude of the order of 10^{-21} when the masses are 40 meters apart. So this is not a very serious limit in this case, and it becomes less important still if the distance between the masses is increased.

A much more serious problem comes from fluctuations in the output from the photodiode, arising from what might be called "photon counting error." The light detected by the photodiode can be regarded as made up of photons, and as they arrive essentially randomly at the diode, there will be fluctuations in the intensity of light recorded. These set a limit to the smallest change in relative phase of the interfering light beams which can be detected, and thus to overall sensitivity. This limit depends on the intensity of the light, and on the time available for the measurement — which for a gravitational wave pulse corresponds roughly to the pulse duration. For 1 millisecond pulses and a laser giving one watt of light, the sensitivity limit for detectable motions is about 10^{-15} meters. This is very good by ordinary standards, and indeed the first pioneering experiments on gravitational wave detection by laser interferometry were done using methods similar to this by Robert Forward of Hughes Laboratories some ten years ago. However we're now aiming at much higher sensitivity, and we have to reduce this photon noise by a large factor. If we tried to do it just by stepping up the laser power, we would need several megawatts of light from our laser continuously. This is hardly practicable, and

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The Luminescent Solar Concentrator: An Illuminating Solution for Solar Energy

by Dennis Meredith

THE TIME might be only a decade or so away, and you find yourself driving along a typical country road, with fields stretching away on both sides. Abruptly, however, you come upon a very atypical sight. Spread out in a multi-acre array is a series of large sheets of orange or green plastic, basking in the sunlight. Each sheet is bordered in silicon solar cells, with wires leading away into a network of power lines. These strange contraptions are harvesting electricity from the sun, using a combination of photovoltaic cells and a solar concentrator with seemingly magical properties. Such a scenario is a real possibility because of the work of a group of Caltech researchers.

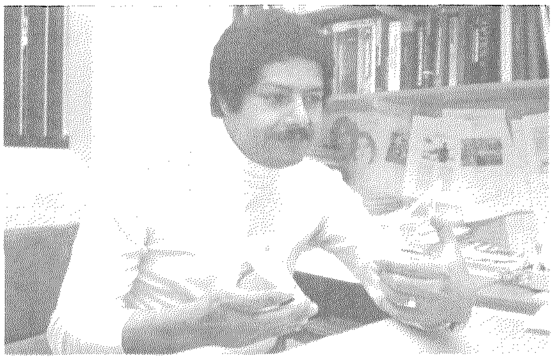
When illuminated with solar radiation, a sheet of the plastic glows brightly at the edges, not only concentrating sunlight but also altering its spectrum, transforming short-wavelength radiation into those longer wavelengths most efficiently used by photovoltaic cells. First conceived by Ahmed Zewail, professor of chemical physics, and his colleagues, these energy-cascade devices have developed rapidly, and now the scientists are highly optimistic that such concentrators will contribute significantly to the development of solar power.

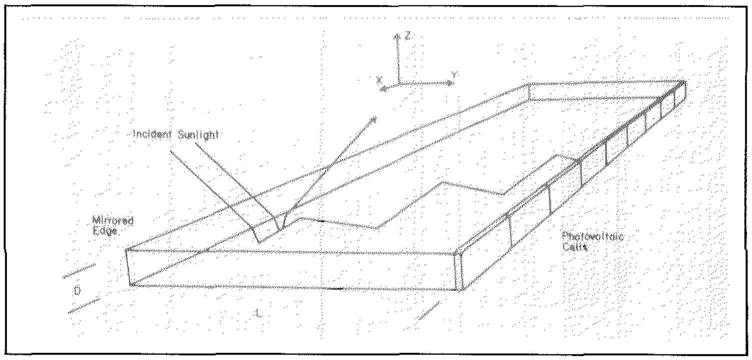
Even though solar energy has long been hailed as a clean, virtually unlimited energy source, the technological problems of generating electricity from sunlight cheaply have been considerable. Photovoltaic silicon cells, the most promising way of generating solar electricity efficiently, remain expensive compared to conventional methods of generating electricity. Reducing the cost of photovoltaic cells is one way to attack the problem. Another is to develop light concentrators that would increase the flux of sunlight impinging on the solar cell, so that fewer cells would be needed per watt of output.

When research on solar concentrators began at Caltech, the most widely studied devices were either Fresnel lenses or parabolic reflectors that focused solar radiation on photovoltaic cells. While these systems do effectively concentrate light, they have two drawbacks that designers have yet to overcome. First, they also focus heat on the cells, creating temperature increases that could reduce the cells' efficiency and lifetime. And second, to be effective, they must follow the sun, which requires expensive motorized tracking systems.

In 1977, however, Zewail, Terry Cole, who was then a Fairchild Scholar at Caltech, and graduate student Barry A. Swartz published a paper in the *Journal of Optics Letters* describing a new type of energy-cascade concentrator that promised to reduce the cost of silicon in solar electricity systems and to alleviate the tracking problem. It consisted basically of several dyes impregnated into a flat sheet of inexpensive Plexiglas. These laser dyes — so called because they are usually used as the lasing medium in chemical dye lasers — capture the sunlight as their molecules assume an excited state. They subsequently re-radiate this light at longer wavelengths. The dyes are matched so that radiation emitted by one kind of dye is at a wavelength ideal for being absorbed by another, producing a cascade in which short-wavelength solar radiation is funneled to longer wavelengths more usable by solar cells.

Because of total internal reflection, light entering a sheet of concentrator or re-emitted by the dyes tends to be trapped, creating a greenhouse effect as suggested by the Jet Propulsion Laboratory's John J. Lambe, who is also a lecturer in applied physics at Caltech. As a result of this "light-pipe" trapping, which is well known in physics, light emerges mainly at the edges of the Plexiglas as an extremely bright orange or green radiation, depending upon the dyes used. If a thin strip of solar cells is attached to these edges, the result is to greatly enhance the power that can be produced by a given area of solar cells. Such concentrators typically increase the solar flux on a





Ahmed Zewail (left) holds two samples of luminescent solar concentrator material, whose Plexiglas edges glow brightly. The concentrators (right) work by capturing incident sunlight, which reflects internally to the edges, where it is transformed into electricity by photovoltaic cells. In addition, laser dyes impregnated in the Plexiglas change the wavelength of the light, making it more suitable for use by the cells.

photovoltaic cell by four or five times that of a cell that has merely been pointed at the sun.

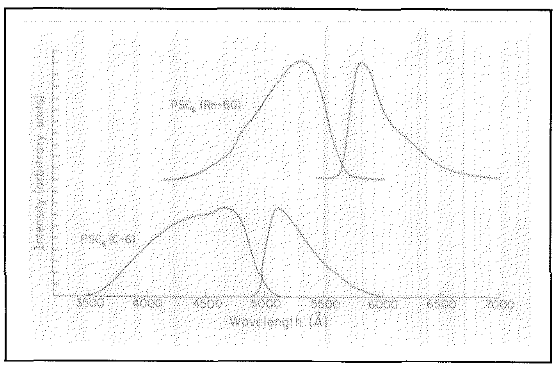
The idea was simple yet powerful, and in early experiments it showed significant promise. Because the concentrator diffused the sun's heat, it did not greatly increase the temperature of the solar cells. And because light could enter the plate at a wide range of angles and still be concentrated, expensive tracking systems were not necessary. The concentrators also worked well in diffused light, as might occur on a cloudy or hazy day. Nevertheless, if the devices were ever to be useful, their geometry, physics, and chemistry would have to be understood in detail. So, since publishing that first paper, Zewail and his group have made steady progress in optimizing the efficiency of the devices, which they have dubbed Luminescent Solar Concentrators, or LSCs. The physics behind the optimization of LSC efficiencies was published in two detailed papers in *Applied Optics* last year by Zewail, Cole (who is now at JPL and also a senior research associate in chemistry and chemical engineering at Caltech), and graduate student John S. Batchelder.

One important aspect of their work has been to understand how the geometry of LSCs governs their effectiveness as light concentrators. The trapping of light within the plastic depends basically on the principle that light entering a material with a higher index of refraction tends to be reflected internally if it enters at greater than what is called "the critical angle." In the case of a flat sheet of plastic, the critical angle can be rotated to make a "critical cone." Light rays emitted within this cone will escape, while light outside will be internally reflected, as shown above right. This internally reflected light eventually reaches the edge of the sheet through a series of internal reflections.

Of course, in the case of an LSC, the dye molecules within the plastic absorb a considerable amount of the light, subsequently re-radiating it. Because of this geometry of reflection, theoretically, the greater the ratio of plate area to edge area, the greater the amount of light concentration. Thus, the scientists could theoretically enhance solar energy concentration more and more by simply making the plate larger and larger. Unfortunately, this simple theory does not tell the whole story, and the scientists quickly found that the physics of the dye molecules would not allow the plates to be made arbitrarily large.

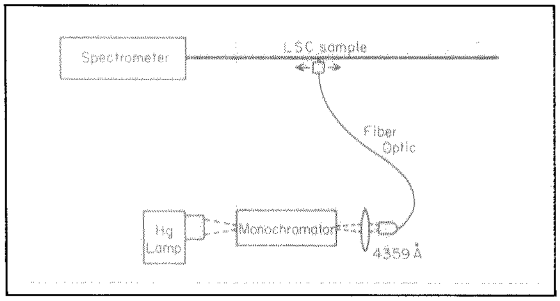
The light robber within the plate is called self-absorption, and it arises from the nature of the absorption and emission of light by the organic dyes. The basic phenomenon that allows these dyes to alter the wavelength of captured light is called the "Stokes shift," which means that when a dye absorbs light and then re-emits it, the emission is shifted to a longer wavelength by a certain amount. The figure below shows the difference in the curves.

If this Stokes shift is large enough, the re-emitted light is at a wavelength far from the absorption wavelengths of the dye. Under these circumstances, the emitted light would simply reflect to the edge of the concentrator, where it could be captured by the solar cells. Since laser dyes typically have high quantum efficiencies, re-emitting about 90 percent of the energy fed into them, the LSCs should be highly efficient in transporting light to the edge. However, in the dyes used in the early solar concentrators — Rhodamine-6G and Coumarin 6 — there is an overlap between the absorption and emission spectra of the dyes. Thus, there is a chance that emitted light will be reabsorbed before reaching the edge, and this likelihood increases as the con-



The absorption and emission spectra for two laser dyes used in the concentrators show that the dyes capture light at shorter wavelengths (left curves) and emit it at longer wavelengths (right curves). By combining certain dyes, concentrators can be made to "cascade" light into wavelengths most usable by solar cells.

To measure how light changes in spectrum and intensity as it travels through the concentrator, a long rod of the plastic is excited by light from a mercury lamp fed through an optical fiber. By moving the fiber along the rod, the distance light must travel to the spectrometer can be changed, and the effects on emerging light studied.



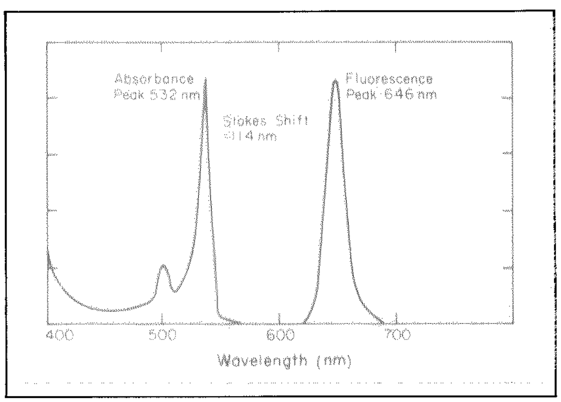
centrator is made larger. In taking this reabsorption into account, the scientists must limit the size of the concentrators.

To study this phenomenon, Zewail's group developed a number of basic methods of measuring self-absorption. For example, in order to measure the progress of light through LSC material, Batchelder performed an experiment in which a spot of light was used to excite a point along a rod of LSC material. In this experiment, the spectrum of light emerging from the end of the rod is measured. As the spot of light is moved along the rod (shown above) away from the end, the spectrum changes because the light has undergone more absorptions and re-emissions as its path length increases.

Besides self-absorption due to overlaps in absorption and emission spectra, other less important sources are scattering and absorption by the Plexiglas, reflection at the interface between the edge and the solar cell, and variations in output due to changes in solar radiation. All of these sources can be minimized by careful engineering. For example, methods have been developed for attaching solar cells to the edges of LSCs using adhesives with indices of refraction that reduce reflection.

The most important solution to the problem of self-absorption, however, is to find dye molecules whose Stokes shift is large enough that the spectrum of emitted radiation overlaps very little with the absorption spectrum. In fact, the researchers have recently done just that. Caltech undergraduate Lynne Hannah — working with Zewail, and Cole and Amy Gupta at JPL — has discovered that a porphyrin molecule and some other similar derivatives (below, left), when incorporated into a solar concentrator, display a Stokes shift that greatly reduces self-absorption. These types of molecules are widely employed in nature as energy trappers — chlorophyll is the most important example — so Zewail believes that such molecules offer considerable promise.

A promising new dye for solar concentrators is revealed in this set of absorption and emission spectra for a porphyrin molecule now being tested. Since the two spectra do not overlap, the dyes will not reabsorb emitted light, and the transformation of wavelengths in the solar concentrators can be much more efficient.



The degradation of dyes when exposed to the rigors of sun and weather is perhaps the most critical problem facing the developers of LSCs. By using a special weathering chamber at JPL, the scientists have been able to accelerate the aging of Rhodamine and Coumarin LSCs by exposing them to ultraviolet radiation, heat, and humidity. They found that heat and light seriously degraded the dyes, so that a typical LSC might have a useful lifetime of only about a year. Even though LSCs are quite cheap, a lifetime approaching a decade would be required to make them truly economical, say the scientists.

Zewail and his colleagues are attacking the longevity problems in a number of ways. For example, they are developing LSCs in which the dyes, rather than being simply dissolved in the plastic polymer, are chemically linked to the polymer molecules. This step could greatly enhance stability of the dyes.

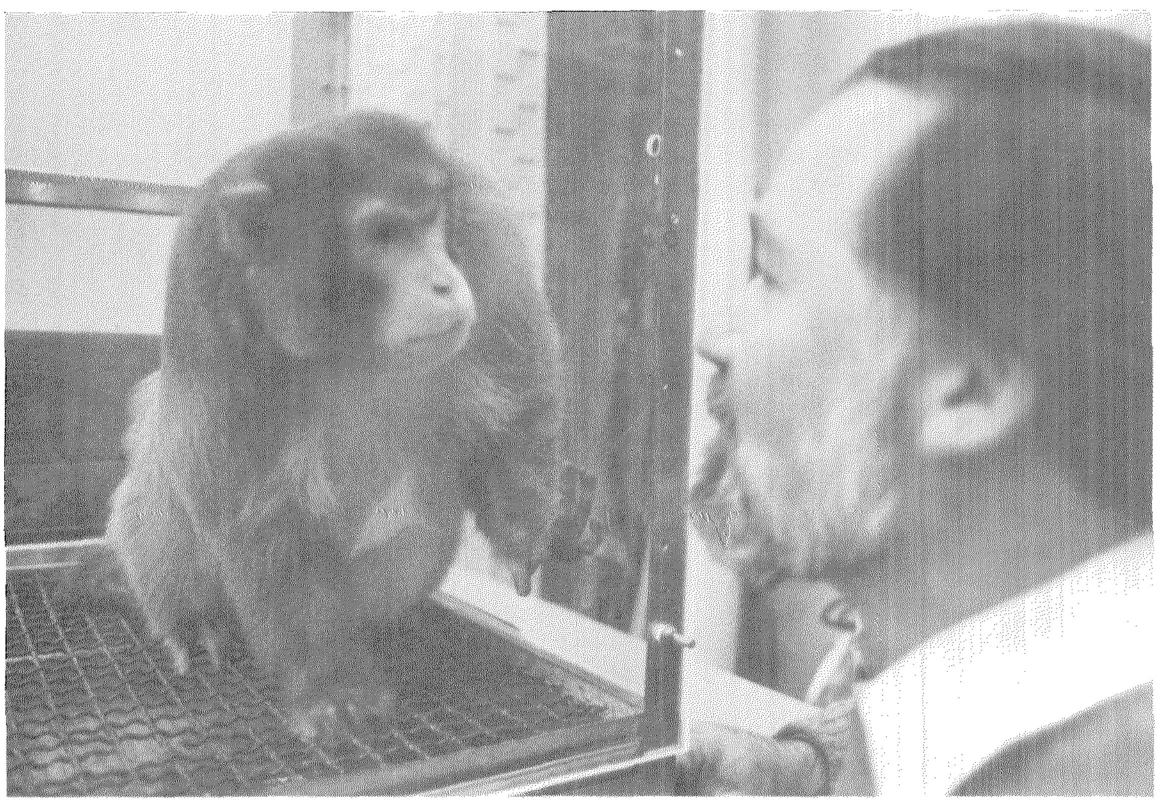
The researchers are also studying alternative forms of the solar concentrator which might offer longer lifetimes and higher efficiencies. They have, for instance, developed a liquid LSC in which the dye is circulated between two sheets of glass, one mirrored and one transparent. The dyes last far longer in such systems, and in fact can be easily replaced. Also, some important dyes in solutions show a larger Stokes shift than when embedded in a solid. The scientists also believe that a number of simple construction steps might help alleviate the degradation problem. Covering each LSC with glass to reduce ultraviolet radiation is one such example. And though the system development has concentrated on the LSCs themselves so far, the scientists expect significant increases in efficiency once they begin designing photovoltaic cells specifically to match LSC properties.

Clearly, much work remains to be done on the LSCs, but the Caltech researchers now have a thorough understanding of the factors governing the efficiency of the devices. This understanding, together with the wealth of ideas they have on improving the LSCs, brings closer the day when fields throughout the world will be adorned with gaily colored, and quite useful, sheets of electricity-producing plastic. □

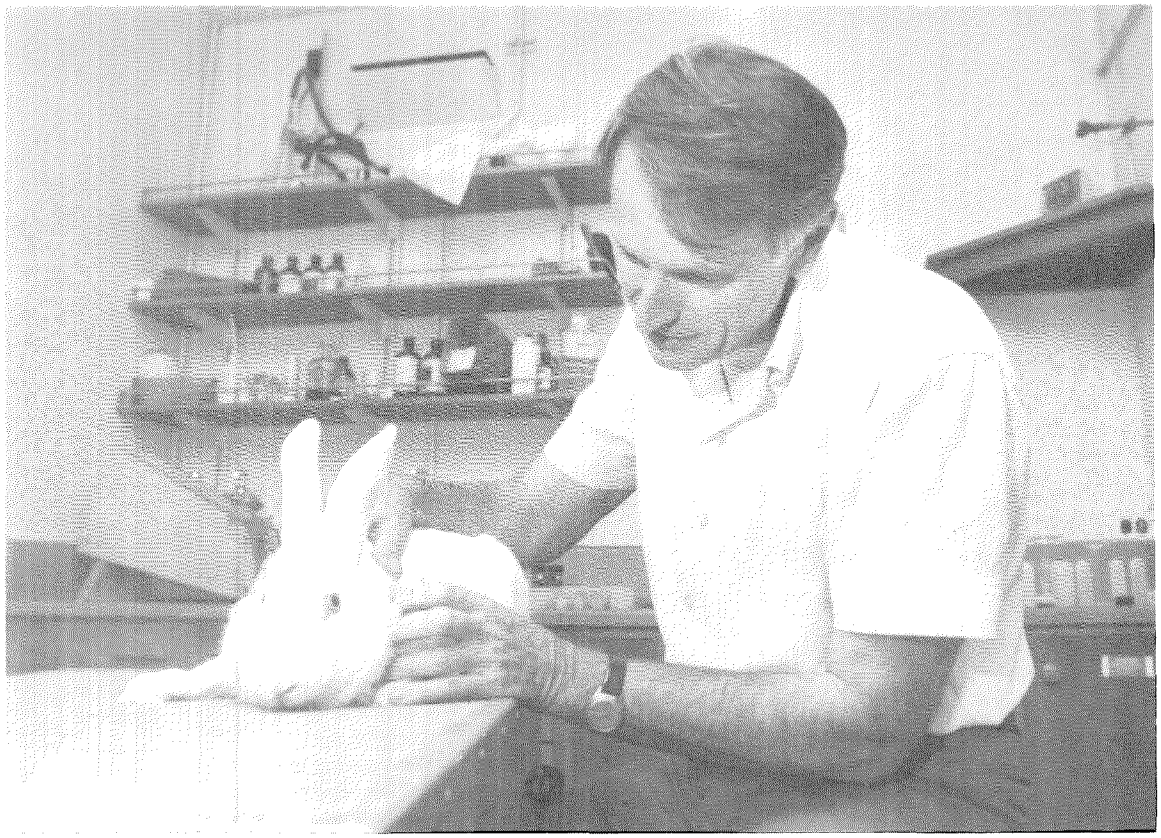
It's a Real Zoo

Although the versatile bacterium *Escherichia coli* is probably the most popular laboratory "animal" these days, Caltech is still home to a sizable menagerie of other beasts. Ranging from the familiar (and not just rats and mice) to the exotic, these creatures are an invaluable resource to scientists investigating how life works. Portraits of some of Caltech's animals, along with their human co-workers, appear on these pages.

Demon, a barn owl, lives in an office in Beckman Labs, where he was raised by hand from a hatchling. Mark Konishi, the Bing Professor of Behavioral Biology, and his group breed and raise their own owls for studies of how they respond to sound in space and how their brains use this information to locate prey.



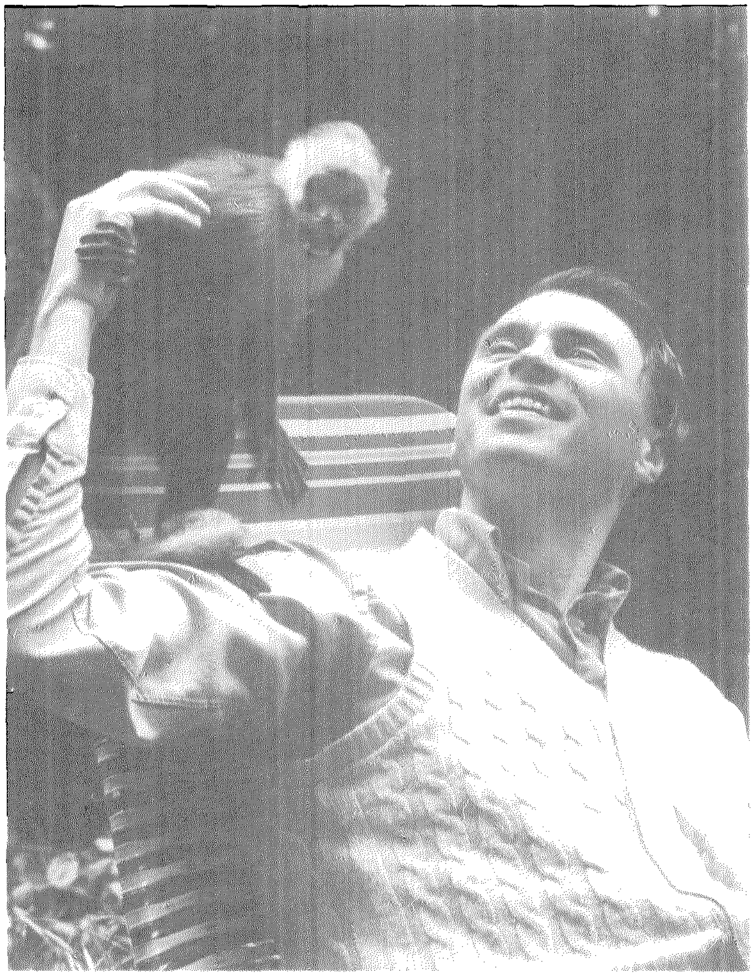
Dash, a macaque (one of a generation of monkeys born during the Watergate affair and named after the characters), works with Charles Hamilton, senior research associate in biology, in split-brain research. Hamilton is studying the behavior of macaques whose left and right cerebral hemispheres have been separated to see whether they have the same hemispheric specialization that humans have.



The immune system of animals can produce antibodies against an enormous variety of foreign substances. Thus rabbits, when injected with a particular foreign substance, conveniently produce antibodies that recognize that substance with quite exquisite specificity. John Richards, professor of organic chemistry, and his group use rabbits to generate antibodies against the enzyme beta-lactamase, which is responsible for penicillin resistance in an ever-increasing number of infectious microorganisms, and then study how the antibodies recognize slightly altered enzymes.

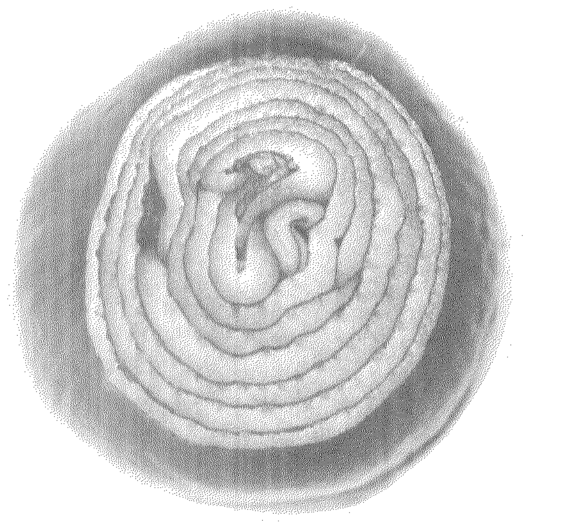
Rubber gloves are essential apparel when handling an electric eel that can generate a jolt large enough to knock you across the room. Henry Lester, associate professor of biology, is interested in the nerve-muscle synapse as an electrochemical machine. The electric eel, whose electricity evolved into a weapon from a navigational and prey-detection device, is "one giant synapse."

*This sea urchin (*Strongylocentrotus purpuratus*) has some characteristics that make it ideal for embryology studies. It lays enormous numbers of eggs that can be easily fertilized in the lab and that develop in seawater at a synchronized and rapid rate. Eric Davidson, the Norman Chandler Professor of Cell Biology, uses the sea urchin to study the mechanisms that turn an egg into an embryo.*



Associate Professor of Biology John Allman works with various kinds of primates – owl monkeys, tamarins, bush babies, lemurs, and macaques – in mapping the brain to determine how visual information is processed. Whole families of monkeys live under his care in Beckman Labs, but Sparrow, an eight-year-old capuchin, enjoys pet status and lives at Allman's home.

The marine mollusk Aplysia (a.k.a. sea hare because of its ears) has built into its eye a 24-hour biological clock, or neuronal circadian oscillator, which drives its sleep-waking rhythm. Professor of Biology Felix Strumwasser studies Aplysia to determine the mechanism of that clock – its biochemistry and the cell types involved – which serves as a model for the two types of circadian oscillators in the human brain.

Onions or Plum Puddings?

by David J. Stevenson

ONE RECIPE in the Betty Crocker guide to planets might feature the liliaceous herb of the genus *Allium* pictured above — the onion. This onion is layered, and it is possible that the concentric layers may be similar to the distribution of material within a planet dictated by gravity. An alternative planetary structure might be more like a plum pudding, which has a matrix with inclusions of a material of a different composition. If you have ever tried to make a structure like this, you know that if you make the mixture too runny, the raisins will settle out before the cooking process "lithifies" the matrix and causes the raisins to stay in place.

These gastronomical examples can serve as models for an age-old puzzle: What is the internal structure of planets? For thousands of years man has looked up to the heavens and pondered the nature of stars. Perhaps to a lesser extent, but more importantly, he has looked down and wondered what is below him. This wonderment is evident in both the scientific and popular literature throughout the ages. A typical example comes from a 1922 novel by Edgar Rice Burroughs, *At the Earth's Core* (recently made into a particularly bad movie).

> The earth was once a nebulous mass. It cooled, and as it cooled, it shrank. At length a thin crust of solid matter formed upon its outer surface as a sort of shell. But within it was partially molten matter and highly expanded gases. As it continued to cool, what happened? Centrifugal force held the particles of the nebulous center toward the crust as rapidly as they approached the solid state. You have seen the same principles practically applied in the modern cream separator. Presently there was only a small superheated core of gaseous matter remaining within a huge vacant interior left by the contraction of the cooling gases. The equal attraction of the solid crust from all directions maintained this luminous core in the exact center of the hollow globe.

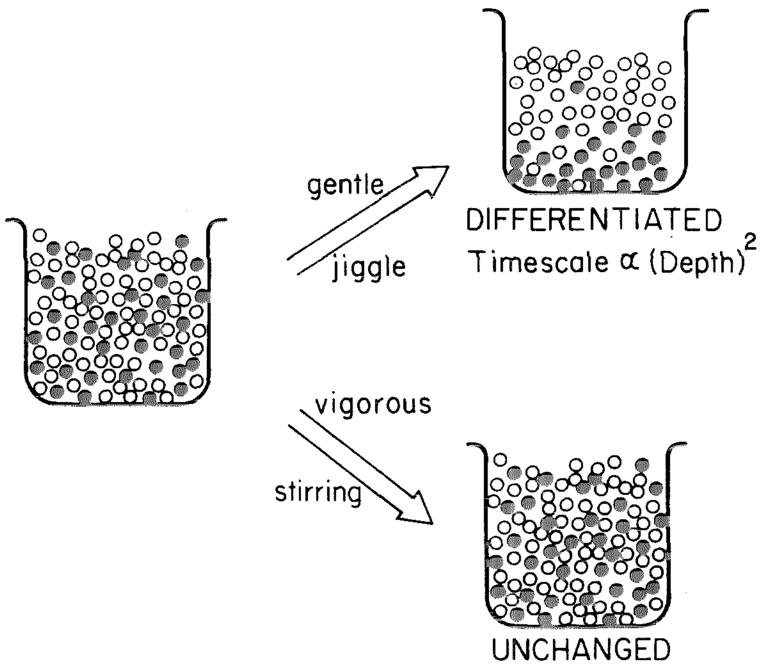
There are two interesting things about this extract. One is that it's complete nonsense, and could be said to be complete nonsense even in 1922. But it does mention two crucial issues for understanding the recipes of planets. One is the temperature and state of the material that goes into making the planet. The other is the extent to which the forces acting on that material (primarily gravity rather than centrifugal forces as Burroughs supposed) determine the distribution of the constituents within the planet.

This can be illustrated by several thought experiments (although the experiments can be and have been done in reality). Say you have a beaker containing a mixture of balls, or atoms, that are identical except that some are heavier than others. If you jiggle the system gently (that is to say that each one of these atoms has some kinetic energy associated with it) and then wait long enough, the system will tend to differentiate under the action of gravity. The heavier atoms tend to accumulate towards the bottom. But this process, called diffusion, is a random walk process, and as a consequence the atoms don't go down to the bottom of the system as quickly as they could. The time it takes to go from one state to the other is proportional to the square of the depth of the system. If you do this in a laboratory where the size of the system is quite small, the process doesn't take too long. But if you imagine trying to do it on the scale of a planet, you find that the time it takes for the heavier things to settle out is longer than the age of the solar system. It would take about 10^{12} years or more to do this process in a planet even if you set the conditions up right, that is, that you don't stir the system too vigorously. So the conclusion you reach is that you can't separate the heavy atoms from the light ones by a process that involves purely a simple diffusive process, because it takes too long.

Actually the situation is even worse because in many cases, including planets and including our own lower atmosphere, the stirring is sufficiently vigorous that the diffusive process cannot succeed for any time scale, and the system just stays well stirred. Therefore, in order to hypothesize that a planet actually manages to get its heavy constituents to the bottom under the action of gravity, you have to look at some other way of doing it.

There is a very simple way of doing it that unquestionably works. Let's suppose that the heavy atoms can stick to each other. They stick to other heavy atoms, but they don't stick to the lighter atoms, and the light atoms do not stick to each other. Then, with the same setup as before, when our beaker of atoms is jiggled, the heavy atoms will come into contact with each other. They will stick to each other and develop clusters that are more able to settle out through the system. And you can accumulate this mass of material at the bottom of the beaker on a shorter time scale than in the previous example.

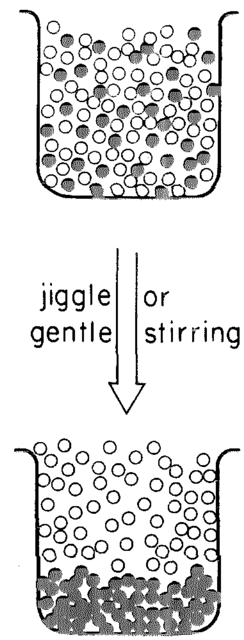
This is the same process that is responsible for getting water out of the earth's atmosphere onto the earth's surface in the form of rainfall. In fact, if the random walk process of the previous example applied to water, the water would go up because it's lighter than most of the other molecules in the earth's atmosphere. But when material accumulates into clusters, that is, undergoes a phase transition, then separation occurs.

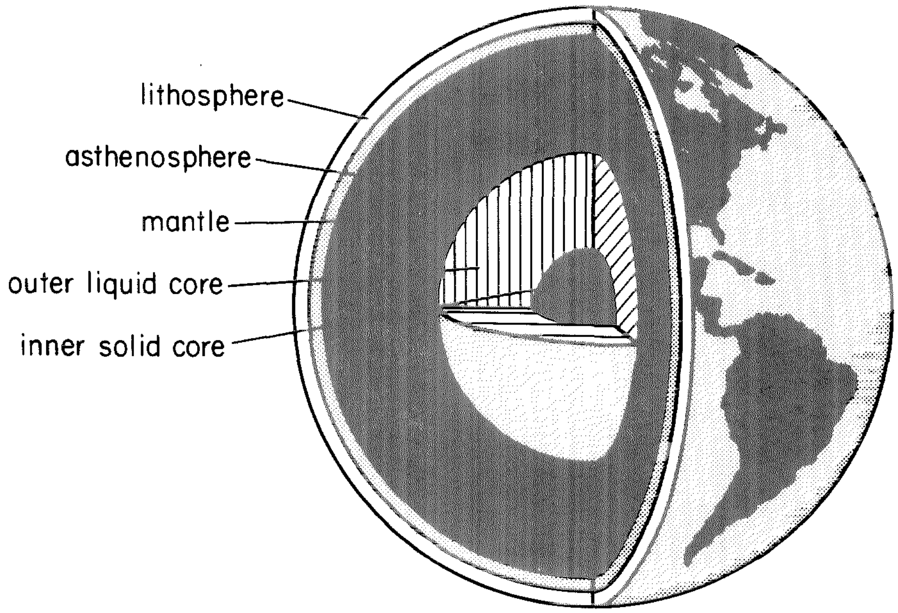


If the black balls, or atoms (above), are heavier than the white ones, jiggling the beaker will cause the black atoms to settle to the bottom by diffusion. This would take a long time if the beaker were a planet, and with vigorous stirring, which characterizes many planets, the heavier atoms will not settle out at all. If, however, the heavier atoms can stick to each other (below), they will form clusters and fall to the bottom relatively quickly.

If we move away from atoms and look at the way the system behaves macroscopically, there are two possible situations. One is an assemblage of solid particles with interstitial liquid. If the liquid is less dense than the solid, the solid can settle out of the system, and the liquid can settle up to the top. This is the process whereby melt is separated in a partially molten rock, which leads eventually to volcanic activity. The other situation involves snow or rain settling out to form a sedimentary layer. These processes can indeed happen in a time scale that is less than the age of the solar system. It can still be a very long time, but it will be much shorter than the time scale that relies on purely atomic processes.

Still another thought experiment illustrates what would happen if you had light material underlying heavy material. In general, gravity would prefer to have the heavy material at the bottom, because that is an energetically more preferable situation. How does the system try and adjust so as to go to the state where the heavy stuff is at the bottom and the light stuff is at the top? The answer depends on how the overlying material can deform. If it can behave as a fluid, the system can change through diapiric activity, that is, a large blob of light fluid moving up into the heavy material. This doesn't necessarily require the heavier material to be fluid like water; it could be deformable on a long time scale like the solid material inside the earth. If the heavy material does not behave like a fluid, a crack could form spontaneously. The fluid can rise up through the crack, and the crack can extend itself verti-





An onion? This cross-section drawing of the earth shows the small solid core surrounded by the larger, primarily iron, liquid core. The mantle overlying that consists of silicates similar to the rock of the earth's surface. Of the two outermost layers, the asthenosphere is a region of partial melting, and the lithosphere is the cold, rigid layer.

cally, allowing the light material to escape.

We've known for a long time that the earth has a dense core. Already at the turn of the century, rudimentary seismic data and other information had revealed that the central part of the earth was much more dense than the outer regions. It was suspected that this would be a region of iron, and the modern view is not very much different from this. Except for a smaller inner solid region, the central part of the earth is a primarily liquid core, which has iron as its major constituent. Overlying that is "rock," consisting of silicates, material very similar to that on the earth's surface. How was this state created? How did this heavy, iron material find its way to the center of the earth?

One possible hypothesis is that the core formed directly, and then the silicate outer material was added later. Based on what we currently understand about the way in which planets were put together, this is improbable. The solar system probably started out with a very large number of small bodies of iron and silicates orbiting the newly formed sun, or the region in which the sun was about to form. Because there were so many of them, they would frequently collide with each other. As a result of these collisions, the bodies would get larger and larger, and fewer and fewer, eventually reaching something like the present solar system.

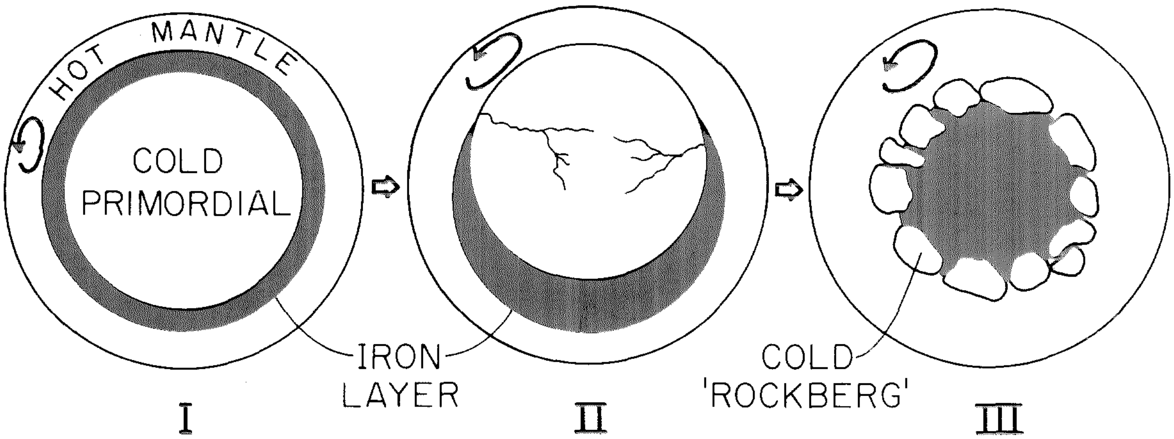
This sequence of steps is very efficient in homogenizing the material that goes into forming the planets. So you would expect that when you make a planet by this process, a planet like the earth, it will start out as a uniform mixture of silicate and iron. It will not have an iron core to begin with.

The other thing that we can expect on the basis of this sequence of steps is that the outer region of the earth is going to be very hot because of the collisions as it forms. The outer regions will actually be hotter than the inside, because the deeper regions are formed from bodies that collided at much lower velocities. So, before the earth reaches its final size, you can expect to get melting in the *outer* regions, sort of like a baked Alaska. As the iron in that hot outer region melts, the silicate and iron will separate into layers, and the iron will try to find its way down to the center of the earth. But it is going to have trouble doing so because the central, uniformly mixed part of the earth is much colder than the outer region and will be reluctant to let the iron pass through.

But we know that the iron *is*, in fact, at the center, so how does it get there? One possible mechanism, which was thought of primarily by the geophysicist Walter Elsasser of Johns Hopkins University, is that the material migrates down by deforming the cold inner region as though this cold region were behaving like a fluid. And in that way you might imagine a large blob eventually finding its way to the center of the earth. This process is a very slow one — on the order of a billion years. Another possibility is that silicate grains detach themselves from the cold primordial core and rise up through the liquid iron layer. As a consequence, the liquid iron layer slowly migrates down toward the center of the earth, eating away the material in the central part, the silicate portion of which then gets displaced upwards into the outer region. This would also take about a billion years. A billion years is a lot less than the age of the earth, which is 4½ billion years, but we still might wonder whether there is a faster way of doing it.

And there is. The process that I favor would take more like a million years. I call it a "catastrophic asymmetry," and it happens because there is a lower energy state. This state is reached when the central primordial region migrates spontaneously as a rigid body through the liquid iron layer. It will do so very rapidly in just the same way that a rubber ducky held down below the surface of the bathtub water and then let go would pop up to the surface. Since the material in the liquid layer can easily move out of the way of the core, the process can be very rapid. This spontaneous asymmetry makes the earth pear-shaped, which in turn creates very large stresses capable of fracturing the primordial core, which then breaks up into pieces. These pieces distribute themselves around the newly formed iron core. Basically what is happening here is that the earth's central region is turning itself inside out.

This process has important consequences for the origin of the earth's atmosphere, perhaps for the origin of the moon, and for the chemistry of the rocks that we see at the earth's surface. The core formation process can take place when the earth is a lot smaller than its present size. Subsequently, the earth continues to grow as bodies with iron in them hit the earth. That iron can separate out as blobs and drop down to the earth's core very rapidly. The mantle material, even though it's very hot, is compositionally similar to the present mantle of the earth, that is, the silicate outer region. This compositional similarity means that volcanic activity leads to the expelling of gases that are similar to the gases currently produced by the earth's volcanism. In particular, carbon dioxide would be the dominant form of expelled carbon.



"Catastrophic asymmetry" is one way for the heavy stuff to get to the center relatively quickly – about a million years. The central, primordial region could migrate as a rigid body through the liquid iron layer quite rapidly, creating an asymmetry that would fracture the core. The broken-up pieces of the old core – "rockbergs" – would then redistribute themselves around the new iron core.

D. J. Stevenson, Science, Nov. 6, 1981, Vol. 214, No. 4521, p. 612.

So the early atmosphere of the earth would have been rich in carbon dioxide, that is, in oxygen-bearing rather than hydrogen-bearing gases. This is very important for the origin of life. Until recently many scientists thought that perhaps the early earth had an atmosphere that was rich in such hydrogen-bearing gases as ammonia and methane. But now it seems more likely that the earth's core formed quickly in the way described above, with the early mantle and volcanic gases very similar to their present states. And it is indeed possible that life could form in that environment.

This model of the earth's formation also provides a scenario for the creation of the moon out of the mantle material, which is compositionally correct for the moon's observed bulk composition. There are a number of ways that a substantial amount of the mantle might have been persuaded to leave the earth's surface.

The moon as we see it from earth consists of dark regions and light regions. The dark regions are the maria, which are produced by the basalt flowing out from the interior of the moon and filling in the lows in the topography, quite often very large impact basins. The light regions are older rocks. They are the highlands of the moon, compositionally distinct from the lowlands. The *other* side of the moon, however, consists almost entirely of the light regions. This fundamental asymmetry of the moon can be explained by the spontaneous asymmetry mentioned earlier, which would occur with the separation of the primordial core moving through the liquid iron layer. Since the moon is a lot smaller than the earth and the amount of iron is a lot less, this state will last for a long time and could evolve in such a way as to produce an asymmetry between the near side and the far side, just as is observed in the moon today.

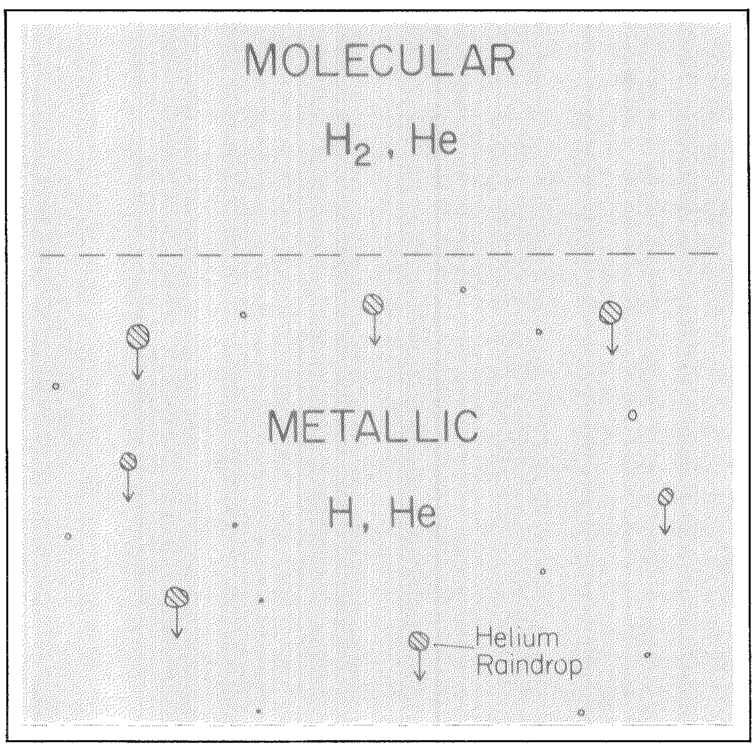
The behavior of the giant planets is completely different but still related to this theory of the earth's formation. When the two Voyager spacecraft flew by Jupiter and Saturn and measured the properties of these planets, they discovered a very important difference between them despite their superficial similarity. Jupiter can be understood simply as a large ball of gas, primarily hydrogen, which has been cooling off throughout geologic time. The heat coming out of this planet is exactly that which you would expect on the basis of starting from a hot state and cooling off. Jupiter's atmosphere is primarily a mixture of hydrogen and helium in the same ratio as existed when helium was created during the big bang that originated the universe.

Saturn is also a ball of hydrogen — hot and gradually cooling off, radiating excess energy into space, which we can measure. But Saturn is emitting an amount of energy larger than you would expect if it were just a hot ball of gas cooling down over geologic time. Furthermore, when we measure the composition of the atmosphere of

Saturn, we find that the amount of helium in the atmosphere is less than that in Jupiter by about a factor of two. These two facts together — too much heat and too little helium — lead us to suspect that differentiation is taking place. What is happening inside Saturn is directly analogous to the second thought experiment mentioned earlier, that is, the atoms are sticking together, resulting in a phase transition. In this case it's the helium atoms that are behaving as though they're sticky, and they do so because they find themselves in a metallic environment, where they would prefer to be with other helium atoms rather than mixed in with the hydrogen. That environment is metallic because of the very large pressure that occurs inside these planets. In the outermost region of these planets, the material we see in the atmosphere is molecular. The hydrogen is bound together in the form of molecules, and the helium is uniformly mixed in. But under higher pressures the hydrogen molecules break up into their constituent protons, and the electrons associated with these molecules get smeared out, distributed, as in a metallic state. This state is called metallic hydrogen, and it is an alkali metal just like sodium or potassium, except that the positive ions are bare protons.

In the outer atmosphere of a planet like Saturn, the hydrogen exists as molecules, and the helium atoms are uniformly mixed in. At the higher pressures closer to the interior, the hydrogen molecules break up, creating a metallic state. In a metallic state, helium atoms prefer to be with other helium atoms; they separate out as helium raindrops and fall toward the center.

Helium, on the other hand, prefers to retain its electrons, and so it doesn't like being in the metallic environment (helium gas is highly insoluble in any metal). What happens on Saturn, which is colder than Jupiter, is that the helium atoms stick together and then separate out into raindrops, and those raindrops settle down toward the center of the planet, depleting the helium in the uppermost region. Equally important is that, as these raindrops settle out, energy is released because heavy material is dropping through a gravitational field. That energy finds its way to the outside, and we observe it as an excess heat flow from the planet.

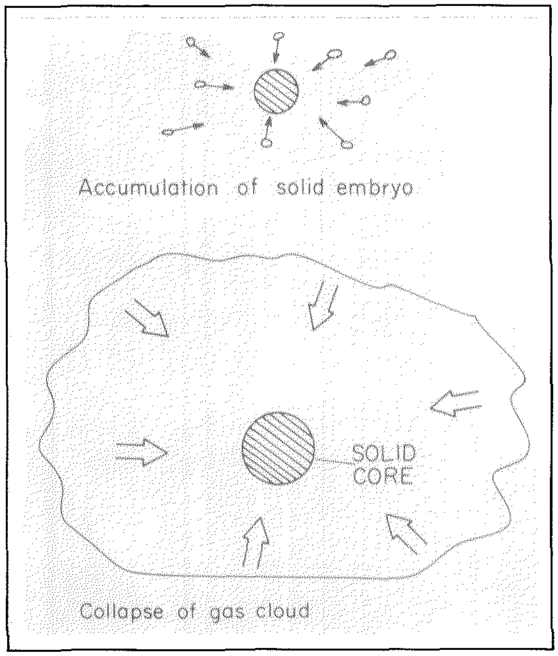


Jupiter and Saturn each have a very dense core equal to about 10 or perhaps 20 earth masses. We know that these cores exist from the observed gravity field external to the planets. The cores are very dense and consist of rock and possibly some water-ice at tens of millions of atmospheres of pressure. The temperature of this material is also very high — about 20,000°F in the case of Jupiter. But the interesting thing about the existence of these cores is that theoretically this material should get mixed upwards. If the atoms are not sticky, and if the material is being stirred by convection, then this core material should get dredged up. It has not been.

It turns out that the core in a giant planet like Jupiter or Saturn has to be made first. This is very different from the earth. In the case of the earth I argued that the core formed *after* the accumulation of the material that went into making the earth. In this case I'm arguing that because the material can mix, you have to make the core *first*. So in order to make a giant planet, you first have to accumulate a solid body in much the same way as you would accumulate the whole earth. And then you have to persuade the gas that resides everywhere in space during this process to collapse onto that solid core. It turns out that that is indeed possible if the solid core is massive enough — about 10 earth masses. If the earth had ever grown this large, and if there had been gas around, we would have ended up like Jupiter. But fortunately we did not.

Another member of the solar system that shows evidence of an interesting history is Titan, which is not a planet but a large satellite in orbit around Saturn. Titan's dense atmosphere makes it unique. From Voyager data we have some information about this atmosphere. The temperature at the surface is very cold — about 90 Kelvin or −300°F — and in the lowermost part of the atmosphere the pressure is similar to that on earth. The gas is primarily nitrogen but with a small amount of methane. How did this atmosphere come into existence?

When you put together a body, whether it is a giant planet or the earth or a satellite, you will always get very high temperatures. That temperature depends on the amount of energy released in the collision of the material that goes into making



The core in a giant planet is made first, as smaller bodies collide and accumulate. If this core is massive enough – about ten times the size of the earth – gas will collapse around it.

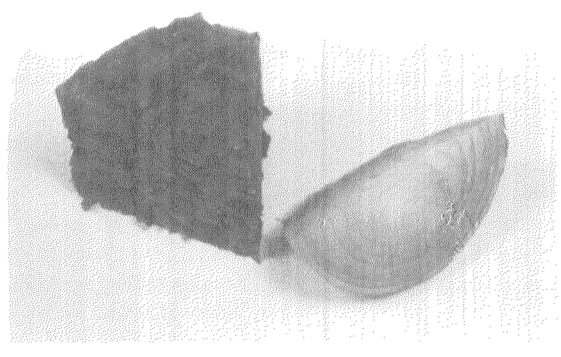
that body; in the case of Titan it would have been at least twice as hot as it is today — about 180 K or even hotter — for a period of time. Then you can expect to have a water-ammonia ocean — cleaning fluid — and an atmosphere that consists of a number of molecules — methane, ammonia, nitrogen, and some water vapor. This system too can undergo differentiation, which comes about because of a compound called clathrate. Clathrate is water-ice in which the structure of the ice has been modified so as to incorporate guest molecules, methane and nitrogen in this particular case. At about 180 K clathrate snow precipitates out of the oceans. Later on, when the ocean has mostly frozen, this material may become available for the outgasing of methane and nitrogen, which are the present constituents of the atmosphere. So this differentiation is a possible way of explaining the present atmosphere.

All these theories of planet composition are, of course, just theories, because we can't get inside planets to study them. But there are two new techniques that might lead to a better understanding of the interior of the earth. The primary technique currently applied is seismology. Seismology has many convenient attributes, but it also has a number of limitations in understanding composition. One new technique, which is already potentially available, although it is much more expensive than seismology, uses a beam of massless particles called neutrinos, which can be produced in a high-energy accelerator, such as Fermilab near Chicago. The neutrino beam goes in a straight line, and if you run it through the earth, you can measure the outcoming beam at the exact antipodes on the other side of the earth by placing detectors at the bottom of the ocean. By measuring the absorption of the neutrinos, you can learn something about the material inside the earth, because the absorption depends on the composition.

The other technique, perhaps somewhat bizarre from an engineering aspect, is to send a probe down into the interior. If you make a solid state probe (by which I mean something that is solid throughout with no cavities), and preferably quite large, say, 100 meters to a kilometer across, it can melt its way down into the interior of the earth and send information back up to the surface of the earth by seismic techniques or by very long wavelength electromagnetic radiation. With such a probe you would have in principle a way of sampling deep down within the earth, doing local measurements and sending the information back up to the eager people at the surface who would love to know what's going on down there.

This is a difficult engineering task and one not likely to come to pass in the very near future. But sending probes down into planets is potentially an important way of learning about their interiors. I'm even tempted to mention the idea, distasteful though it might be, of a new national agency. We already have NASA, which deals with outer space, and we have NOAA, which deals with oceans and atmospheres. Why not have NUA, which would be the National Underworld Administration?

So there is in fact a place for both onions and plum puddings in our solar system. Some of the planets (Jupiter is an example) are adolescent in the sense that they have not undergone the settling process; it has not yet separated except for the primordial core emplaced during the process of formation itself. The helium has not separated from the hydrogen; it is mixed in like the raisins in a plum pudding. On the other hand, the terrestrial planets, including the earth, do have something like the structure of an onion. □



William H. Corcoran
1920-1982

WILLIAM H. CORCORAN, the Institute Professor of Chemical Engineering, died on August 21 at the age of 62. A memorial service was held on campus on October 27, at which four of his colleagues reminisced about him. The service was opened by Harry Gray, Beckman Professor of Chemistry and chairman of the division of chemistry and chemical engineering. Gray was followed by John D. Roberts, the Institute Professor of Chemistry, provost, vice president, and dean of the faculty. One of Corcoran's graduate students, Murray Gray, spoke next. The final speaker was John Seinfeld, Nohl Professor and professor of chemical engineering and executive officer for chemical engineering. Michael Kong presented piano music both before and following the service. Excerpts from the tributes appear below.

HARRY GRAY: Bill Corcoran was a great teacher and scholar. He was a grand colleague and friend. And he was a superb human being. When I came to Caltech 17 years ago, I honestly thought that a chemical engineer was a person who slept through PhD exams in chemistry. Bill let me know very quickly and in no uncertain terms that that simply was not so. He felt very deeply that the training of every chemical engineer should include a strong component in pure chemistry. He also felt that chemists would not be hurt if they understood a little chemical engineering. I think it was this deep feeling and his expression of it that helped build our division into the close-knit group it is, a division with real cooperation between chemists and chemical engineers. This is not the pattern in this country, but it is at Caltech, and most of it is due to the devotion, the example, and the dedication of one man, Bill Corcoran.

I remember Bill as a person who wrote notes to me. Usually he wrote first, and usually I answered. But I have to tell you about one note that I beat Bill to. When I learned that he was to receive the highest honor in chemical engineering education in this country, the Warren K. Lewis Award for 1982, I quickly scribbled off a note to him expressing my delight. Just before he went to Hawaii last August, he wrote a little note to me in answer, as he always did. I could tell from it how much this award meant to him because it recognized his deep interest in education and his commitment to students. I am very pleased and honored to tell you that his award will be presented to Bill's family at the annual meeting of the American Institute of Chemical Engineers.

JOHN ROBERTS: The death of Bill Corcoran in late August deprived all of us of a wonderful friend, distinguished colleague, most loyal alumnus, and a staunch ally in the battle for excellence versus mediocrity.

Bill's career resumé spans six single-spaced pages in elite type, before one even gets to the nine pages detailing the titles and coauthors of 90 professional papers. Clearly, no one can do justice to such a career in a gathering like this one. Indeed, it is better not to even think of being comprehensive. It is better to mark the Corcoran era at Caltech by recalling the main features of the man and his efforts on our behalf.

Many at Caltech do brilliant research and brilliant teaching. These are Caltech's purposes, and Bill served those purposes well. But Bill's career was also featured by extraordinary service to the Institute. There may be others on the faculty who have records that compare with his service on 20-odd committees or boards, but I don't know of them. I think of myself as being a reasonably good Caltech citizen, and I have served on only four of these.

Two especially memorable jobs Bill did for the Institute, with real devotion and patience, were 19 years of service as chairman of the Sponsored Research Committee and 10 years (concurrently) as vice president for Institute Relations.

One can hardly believe with all of these Caltech responsibilities that Bill could possibly have much time for the outside world, but he served as an officer or committee member for some 50 different outside professional activities, as director of three corporations, on the board of Villa Esperanza in Pasadena, and he gave light years of truly outstanding and dedicated service to the Huntington Institute for Medical Research.

Perhaps, if each of us could bring ourselves to help others in a half, or even a third, as many ways, the world would be a far different place to live in.

MURRAY GRAY: During the 30 years that Dr. Corcoran taught at Caltech, he was research adviser to over 30 PhD students and a large number of MS and undergraduate students. Today I would like to describe what that meant to all of us.

In his contact with us, Dr. Corcoran

placed strong emphasis on several areas of professional and personal development. He encouraged good communication skills in our oral and written work. Biweekly reports and group seminars were opportunities to practice speaking and writing and to get helpful comments.

Dr. Corcoran always encouraged us to maintain a professional attitude toward our work and responsibilities. He strove for fairness in his dealings with us and encouraged ethical conduct.

He encouraged us to think of our research as a part of a larger framework of knowledge, making sure that we were up to date on related topics by sending a stream of material across our desks. His own research interests always had a well-defined social aim.

He worked to develop our self-reliance. Authority was always delegated to the students as much as possible. He treated our inevitable mistakes as part of the learning experience.

His impact on our professional conduct and attitudes was matched by his impact on us as a person. He was always a gentleman without necessarily agreeing with us.

He set standards of discipline and will power that few of us could match. He lived every day to the fullest. He carried such a massive work load that we always knew that he was working at least as hard as we were and probably much harder.

Dr. Corcoran always treated us in a fatherly way. He worked in our best interests. He was there when we needed him for help or advice. He strove to pass on the best of what he knew to us. We will do well to remember and build on the ideals that he taught us.

John Seinfeld: To describe the accomplishments and contributions of Bill Corcoran to chemical engineering, engineering education, and to his friends and colleagues would require many, many pages. During his life, Bill attained virtually every honor and recognition available to an engineering educator while, at the same time, truly touching the hearts and minds of all those with whom he came in contact. Perhaps no other individual had more influence on the course of engineering education in the United States over the last 20 years than Bill. Throughout a long and distinguished career at Caltech, and through his continued leadership in the American Society for Engineering Education and the American Institute of Chemical Engineers, Bill Corcoran maintained a vigorous, excellent program of teaching and research. One of his proudest moments was when he received a teaching excellence award from the Associated Students of Caltech.

I should like now to read an excerpt from a letter to Martha Corcoran from one of Bill's former graduate students, Malcolm Morrison (BS '64, PhD '69). It will remind you all of Bill's personality and character in a very special way. Morrison is recalling a softball game between faculty and students at a chemical engineering picnic that took place in the 1960s.

"Bill and I were on opposing teams. I was catcher. I think Bill played first base, but that doesn't matter. We were coming down to the end of a close game, and we were slightly ahead. His competitive nature had been thoroughly aroused, and for several innings he had been playing very aggressively, making plays deliberately and exuberantly, keeping the ball moving around the infield and keeping up the chatter. He was never laid back, but he was particularly hyper now, and he was exhorting the team relentlessly. His team was at bat, and for his "up" he laced a ball to right field which should have been only a strong single. But he turned it into a double with heads-up base running in all the speed a man in his late forties could muster.

So there he was, parked on second, when to my great dismay, the next man up hit a weak single to right field. Bill knew right away, and I knew right away, that he was tearing straight to home, come hell or high water, to get a run that was very important. And I as catcher had a reasonable chance to get him out if the throw was good. I am also quite combative, and by the time he had passed that shortstop I had determined that I was going to plant myself in front of the base and keep him from getting home if I had to break every bone in his — and my — body.

I have always wondered what he thought when he rounded third. He could see me finishing my burrowing in, and boy, was I planted! Dynamite could not have gotten me out. He could see the throw starting to come from the fielder, and it could not have taken long for his experienced eye to tell him that he and the ball would arrive at my location simultaneously. It was a perfect throw — the only kind that could have caught up to him.

So, for 60-odd feet, what did he think of? I know what I was thinking — pure fear. Here was a big guy with a humongous head of steam, coming straight in to cream me, and I had to hold on to the ball during the creaming. But what was he thinking? Was he thinking, as he saw me, that the only thing between him and possibly the game was a little "kid," six inches and 60 pounds smaller than him? A kid who, without that much problem could be totaled out of the base path so that even if he held on to the ball he would be too late with the tag? Was he thinking about the last several innings? Innings in which he had urged aggressiveness on his teammates? Innings in which he had shown them the right kind of go-get-'em, heads-up ball playing that won games? And how, now it had come to this, that winning the game meant putting it to me and counting the broken bones later?

But he could not. When our time came, he broke stride, slowed down, and tried to hook-slide around me. He failed, and when they untangled us, about five feet past the plate, I still held the ball, and he was out. Even trying to miss me, he almost killed me, and to this day I remember that hit. Jesus, the aches I had later!

After he had stood up and asked for, and received, the umpire's decision, he turned and jogged to his team without a word or a trace of facial expression. I am sure it hurt too much to tell me it was a good play, particularly when he had had the power, unused, to have prevented it. But he was too good a man to show disappointment and curse a little, as most everyone else would have done.

I forget who won the game. It was not important. Everything from which something could be learned was past. What Bill had said when he broke stride and tried to slide around me was that Yes, combativeness and controlled aggression is important to success, and that hustling and doing your heads-up best is important in life. But that when it all comes down to hurting someone to get the job done — then it is not worth it, even if your failure may cause a loss of face to those whom you have been guiding by your actions. He had been urging aggressive play, but when one spectacular aggressive play could have turned the game around, he could not do it. There were more important things than the game, and there always are, no matter what the "game" happens to be. And I remember this from that game, and from him." □

The Search for Gravitational Waves

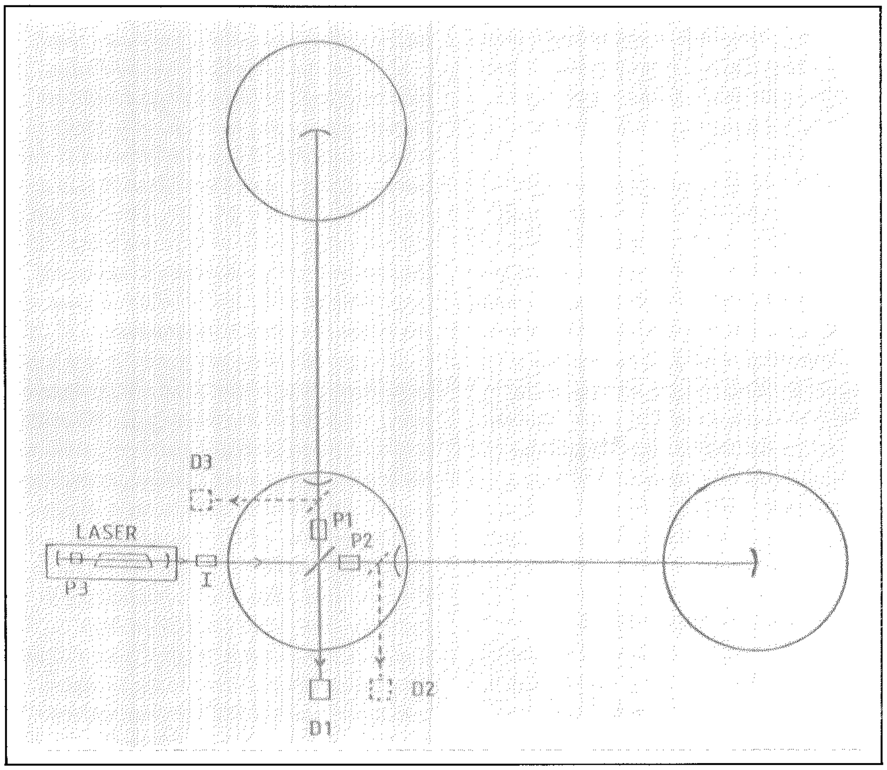
...continued from page 9

we would have difficulty paying the power bill.

But there are several other tricks which could make the system more sensitive. One is to make the light travel back and forth many times in each arm of the interferometer, making many separate reflections at curved mirrors on the test masses. If the masses move, there will then be a much bigger change in the total light path, giving a larger fringe shift to be observed. This idea was suggested by Ray Weiss of MIT, who is developing gravitational wave detectors of this type.

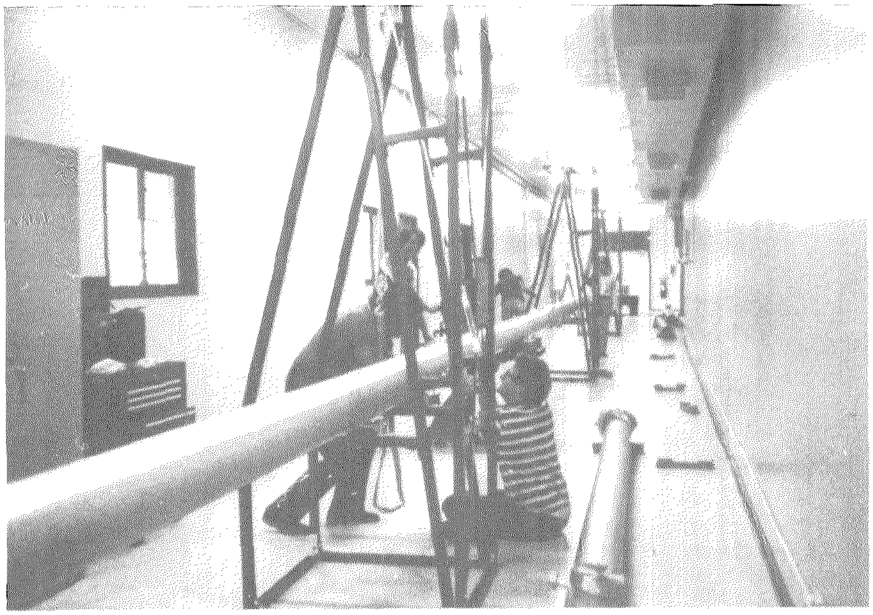
The number of times it is useful to make the light travel back and forth may depend on the losses in the mirrors, or, if losses are very small, on the time the light spends in the interferometer. If the light is kept in for too long, and the movement of the mirrors due to the gravity wave reverses its sign, there's going to be some cancellation of signal. In an instrument with 40-meter arms and mirrors allowing about 600 reflections of the light, the photon noise limit to sensitivity corresponds to a gravity wave amplitude of about 10^{-19} for 1 millisecond pulses and a laser power of 1 watt. With longer arms and lower-loss mirrors, so that light storage time is the limiting factor, the photon counting limit to sensitivity becomes of order 2×10^{-21} with either 4 km arms and 80 bounces of the light or 400 meter arms and 800 bounces. This would be getting somewhere near our target sensitivity — if there were no other problems.

Several technical difficulties with multiple reflection systems became apparent in early work at Munich and Glasgow, among them the finding that scattering at the mirrors can allow small but troublesome amounts of light to take unplanned paths through the system. There is also the simple fact that in a system with long arms the mirrors and the vacuum system containing them and the beams may have to be quite large — and correspondingly expensive. This led us to devise another approach. We use fairly small, highly reflecting mirrors on the test masses, arranged to form optical cavities between one another, in which the light bounces back and forth from a single spot on each mirror. If we arrange that the length of each cavity is precisely adjusted so that the light from the laser resonates within it, then there is a considerable buildup of light intensity. A slight change in the length of one of the cavities will change the phase of the light inside it, and we can observe that change of phase. In principle the system is somewhat similar to the previous one, except that here all the reflecting beams are superimposed on top of one another. With mirrors of equal loss this arrangement should give slightly better sensitivity than the multiple-reflection Michelson system, and it's potentially less expensive and more practicable on a large scale. The mirrors and beam pipes can be quite small. Even with 10-kilometer arms the mirrors would be only a few inches in diameter. The system does require, however, that the wavelength of the laser light be very well controlled to match the extremely narrow resonances of the long optical cavities.



The simplified diagram above illustrates an optical cavity gravitational wave interferometer. Reflection of light many times between curved mirrors mounted on the test masses (indicated by circles) increases phase difference in the light coming back from each arm caused by motions of the masses. The phase difference is measured by photodiode D1, aided by electro-optical phase modulators P1 and P2 driven at a high radio frequency. Signals from auxiliary photodiodes D2 and D3 measure small deviations of laser wavelength from resonance with the cavities and may be used both to control average length of each cavity and reduce fast fluctuations in laser wavelength.

How do we do all this in practice? The first problem was to stabilize the frequency of a fairly powerful argon ion laser sufficiently well. This led us to come up with a new way of stabilizing a laser — or at least one we had not heard of before. We phase modulate the light from the laser at a high radio frequency, and direct the light coming back from the first mirror of one of the optical cavities onto a photodiode. There are two components in this light: one of them light from inside the cavity, and the other light which has just come from the laser and has bounced off the first cavity mirror. If the laser is exactly in tune with a cavity resonance, these components will be out of phase with one another and there will be no signal from the photodiode at the modulation frequency; but if the laser wavelength lies slightly to one side of the resonance, the phase difference will change, and a signal will appear at this frequency. The amplitude of the signal is a measure of the error in the wavelength of the laser, and we can feed this back to an electro-optical crystal inside the laser itself to rapidly adjust the wavelength of the laser closer to the cavity resonance. This technique was first tested at JILA (the Joint Institute for Laboratory Astrophysics) in Boulder, Colorado, in collaboration with John Hall there, and very shortly afterwards, we had it operating at the University of Glasgow, where we had begun experiments on laser



Graduate and undergraduate students assemble one of the 40-meter lengths of vacuum pipe.

gravity wave detectors some years earlier. It worked extremely well. And in the complete gravitational wave detector we could use the same basic method to keep the length of the cavity between the second pair of masses adjusted to the wavelength from the laser — and use the error signals to sense the effects of the gravitational wave. With these encouraging results we set to work at Caltech to start up the new project here from scratch.

We wanted to make the detector a fair size, so the first thing to do was to persuade Caltech to make us a building to put it in. And they made us a very elaborate lean-to shed along two sides of an existing building, giving us two paths 40 meters long in nice, quiet, stable, temperature-controlled conditions. And inside that building we started to make up the system. It was put together mostly by students — undergraduates and graduate students — largely under the direction of Stan Whitcomb, assistant professor of physics.

One of the practical problems was how to suspend the test masses inside the vacuum tanks. Each mass has to be free to move in response to the gravity wave, and yet at the same time it must be controlled in its orientation so the attached mirrors remain accurately lined up to reflect the light beam. That's rather awkward to do without introducing additional disturbances, but we did it by detecting the orientation with small auxiliary lasers and moving the wires from which the mass is suspended. It is hung by three thin wires from a little metal block connected to the moving coil drives of small loudspeakers which can tilt or rotate the block in any direction. The mass follows the block like a puppet on its string. This enables us to line it up as accurately as if it were quite rigid, whereas actually it's almost totally free to move in the field of the gravity wave. This tricky job was worked out in detail mostly by graduate student Mark Hereld.

To cut down vibrations from the ground, the vacuum tanks are mounted on special isolation pads with foundations separate from the building. The suspension inside each tank is supported on a stack of alternate layers of lead bars and pieces of soft rubber. Little toy rubber cars, which were very inexpensive and of just the right resiliency, separate the lead bars. It would have been nice to use models of expensive cars like Mercedes Benzes everywhere, but we couldn't find enough of these, and toy dune buggies worked just as well.

We are fairly confident that this kind of apparatus will eventually achieve the kind of sensitivity mentioned earlier, though it will probably have to be made larger still to really see the gravitational waves from frequent events outside our galaxy. We regard this first Caltech detector largely as a prototype for future instruments with longer baselines between the masses. Even for larger detectors, the sensitivity estimates mentioned earlier for millisecond pulses might seem a little marginal. It is important to note that new ideas and new technical tricks that can improve performance significantly are still turning up. For example, just a short time ago an idea came up that may give us the last little twist that we need to do the job for gravitational wave pulses. If we take the case of the simple Michelson interferometer as an example, we would usually employ a phase modulation technique which operates best when the system is locked to a dark fringe, with minimum light coming out to the photodiode. In this situation most of the light from the laser has to be going somewhere else, and in fact it passes out from the other side of the beam splitter and is wasted. We now propose to use additional mirrors to bring this light back into the system again in just such a way that it reinforces the light coming from the laser. If we do this correctly, the light will build up in intensity inside the system to an extent limited only by the small losses in the mirrors and other components. Only a tiny amount has to come out to the photodiode — until a gravitational wave comes along, changes the phase condition, and allows the extra light to come out at just the right time to give us a signal. It sounds very nice!

Of course, it probably won't all work out quite as well as that, but when you estimate the possible sensitivity that might be achievable with very low loss mirrors and a large system, it looks pretty promising. With a detector with 10-kilometer arms we might be able to get a sensitivity of order 10^{-22} for millisecond pulses, even with currently available laser powers. For longer pulses sensitivity should improve. So we may have something in reserve. And we have also very recently come up with further possibilities for improving sensitivity for pulsar signals in the same basic kind of apparatus. There are still very many practical problems but I think we can overcome them one by one.

There are also other ways of looking for gravitational waves. At low frequencies, waves with periods in the range of seconds to hours or larger, laboratory experiments face a background of fluctuating gravitational gradients from nearby moving objects — or even from changes in distribution of air density in the atmosphere — which would limit sensitivity; and there are obvious advantages in doing the experiments in space. Indeed a lot of effort, at JPL and elsewhere, is going into the most direct kind of experiment, in which the radio signals used to track the motions of distant spacecraft relative to the earth are examined for effects of gravitational radiation bursts. Fluctuations in radio propagation velocity set limits to sensitivity, but there could be relatively strong gravitational wave bursts present, and these experiments are very interesting. Laser experiments done totally in space could be more sensitive, but are more complicated and expensive, and therefore further off. It has been suggested that one might put an interferometer somewhat like our ground-based ones into space. Very long baselines and high sensitivity could be achieved by using laser interferometric Doppler techniques to measure changes in distance between shielded test masses in widely separate spacecraft, and the possibilities for observing the definitely predicted gravitational waves from known binary stars this way are being seriously considered in several laboratories, including Caltech, JPL, and JILA. These are very interesting possibilities, but they will take time to materialize, and I think it is likely that we may find gravitational waves first on earth perhaps with the kind of apparatus that we are working on now.

Is all this effort worthwhile? I think so, and not just for the practical applications of some of the spin-offs, such as low-loss optical systems and new ways for stabilizing lasers. And not just to check the correctness of relativity theory in another interesting type of prediction — although that's certainly well worth doing in itself. But gravitational waves almost certainly exist, and if we can observe and analyze them they will give us a new window in astronomy. If we see gravitational waves from a supernova we will be seeing into the heart of stellar collapse, into a region hidden to radio and light waves by the surrounding material. We might be able to see what happens in the formation of a neutron star or a black hole, in a way that is impossible by other means. If, by slightly different techniques, we could see the gravitational wave analog of the big bang radiation, we should learn about very early stages in the big bang. And above all we may find things that we have never thought of yet. The future looks promising — but the experiments are certainly challenging ones. □

Acknowledgments

This kind of research essentially involves group efforts, and I would like to acknowledge the contributions to the experimental work described of my colleagues at Caltech, particularly Stan Whitcomb, Robert Spero, Dana Anderson, Mark Hereld and Yekta Gursel, and also colleagues at Glasgow including James Hough, Henry Ward, and Andrew Munley. The Caltech project is supported by the National Science Foundation.

Student Life

To Do Mathematics:

The Odyssey of a Soviet Emigré

GETTING INTO the Soviet Union's prestigious mathematics department at Moscow University is difficult enough (perhaps comparable to getting into Caltech for an American student), but for Jewish students it's virtually impossible. Moscow's reputation for anti-Semitic discrimination is not just an invention by disgruntled unsuccessful candidates. Over the past few years the fact that Jewish students must pass much harder entrance exams than other applicants has been carefully documented by two Soviet mathematicians. Last summer they were arrested and charged with anti-Soviet agitation.

Zinovy Reichstein, now a third-year undergraduate at Caltech, began his college studies as a statistic of this discrimination. In 1978 he was one of four or five Jews who actually passed the special math entrance exams, but he still wasn't accepted at Moscow University. Twice he had participated in the national mathematics Olympiad (as the third highest scorer in his home republic of Russia in 1977 and second in 1978), and he was recognized as one of the outstanding young mathematicians in the country. But he still wasn't accepted. "It's quite a common story," he says.

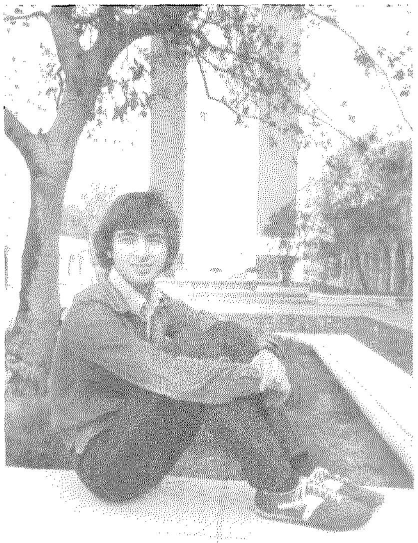
Reichstein was allowed to enroll in the Institute for Railroad Engineers, which had a small applied math department — not much of a consolation for an aspiring theoretical mathematician. But that institute at least had the advantage of being in Moscow, and for a semester Reichstein balanced a full curriculum there with studying on his own and sneaking into the informal evening seminars at Moscow University on the other side of town. These math seminars are led by some of the top Soviet mathematicians and, he says, were worth the risk of getting caught without proper university identification.

Even with these seminars on the sly, one semester of the railroad institute was enough for Reichstein. "I just had no choice. I was told I had to be a railroad engineer, and if I graduated from my college, they would probably send me to some place in Siberia or somewhere else for two or three years. I would be able to survive; I'd be able to eat every day. I'd have a job, but I wouldn't be able to do mathematics, and that's what I wanted to do. And I didn't think I would ever be able to be happy without doing it. My parents didn't think so either."

They felt so strongly, in fact, that they decided to try to emigrate. It was a difficult decision. Once a Soviet citizen applies for an exit visa, his professional life is over. Zinovy's father, a mathematics teacher, lost his job just one week after applying for a visa to Israel, the only officially allowed destination. His mother, a patent attorney, was fired a couple of weeks later.

"Once you apply there is no way back," Reichstein remembers. "It's one of the most irreversible things I've ever dealt with. If you get out of the country, that's fine, but if you don't, you just die there. If you are in Moscow, it's a little bit easier, because there are many people who are in the same situation, and they support each other somehow, at least morally. But in my city (Jaroslavl, 120 miles northeast of Moscow), most people just didn't want to deal with us."

The Reichsteins were lucky. Their timing was fortunate, and they got out during the peak of Jewish emigration in 1979, arriving in Vienna in August. They remained there for six months with little to do but learn English. In order to practice writing English and to develop any tenuous American contacts at all,



Zinovy's father wrote about his son to Hans Schneider at the University of Wisconsin, a friend of a friend to whom he had earlier sent some papers on linear algebra for publication. Schneider is editor of the journal *Linear Algebra and Its Applications*. Schneider immediately fired off a letter to *his* friend John Todd, professor of mathematics (now emeritus) at Caltech, about the "obviously gifted" young man —"I don't expect you to move mountains, but it occurred to me that Caltech might actually be on the lookout for people of his caliber."

Caltech was. Only a couple of weeks later Zinovy was rather startled to receive a "huge parcel of booklets and application forms" from the California Institute of Technology, a place he had never heard of. Since all Russian mathematics of note is concentrated in Moscow, he had presumed it was the same in the United States. And Harvard was the place he had heard of. Caltech sounded a bit technical, and he had already had enough of that sort of thing at his railroad college. He picked up on the American way of college applications pretty quickly, however, and when another friend of a Moscow friend (at Harvard, no less) informed him that he should lose no time applying to Caltech, he did so. He took the SAT exams with his minimum of English and thought he did "reasonably well on the math considering that I couldn't even read all the problems."

Actually he did very well indeed. Caltech sent Reichstein word of his acceptance in New York, where he was then supporting his family by working as a delivery boy. Reichstein entered as a freshman in the fall of 1980, a decision he hasn't regretted, since it turned out not to be a railroad college at all. He thinks now "that the Caltech undergraduate school is the best in the country, at least for the kind of training I would like to get."

It's very different from Moscow University though, which accepts 450 students per year in math alone. There is certainly some benefit to being at the national Mecca for mathematicians there. "They are all there together, and that's probably the main advantage — that you only have math majors around. In terms of mathematical education it may be very useful because people always discuss problems there. People can talk about mathematics whenever they want."

Although Reichstein probably wouldn't mind being able to talk about mathematics whenever he wanted, he also is aware of the disadvantages too. The Soviet curriculum is rigidly standardized — no electives at all — and it's almost all math, except for a few political and "history" courses. At Caltech he found the idea of having to take two years of physics initially unappealing, but in retrospect he is pleased about it. He even admitted to John Todd that going to physics class was sort of like attending a concert. Lab courses he still thinks he can live without, but the most positive new direction for Reichstein is the exposure to humanities. He has even considered a double option — math and literature.

A double option would be hard to accomplish in three years however, and Reichstein hopes to graduate a year early. He was exempted from freshman math and by mid-year was also excused from Math 2 and went on to abstract algebra and advanced calculus. Is Russian secondary school training so much better than American that he was that far ahead? No, says Reichstein, whose opinion seems to belie American fears that Soviet schools are turning out hordes of superscientists while American youth languishes in the age of permissiveness. In general, he says, most Soviet and American high schools are "equally bad — just terrible — at least in the way they teach mathematics and science." And American high schools are probably better than their Russian counterparts in the teaching of humanities, he thinks.

But there are specialized schools in the USSR with nonstandard curricula in certain areas such as math. Although "anything that's nonstandard is very difficult to do in the Soviet Union" and the government doesn't quite approve, mathematics "enthusiasts" have managed to establish special programs and seminars at certain schools and organize the Olympiad competitions. Most of this activity, and the best schools, are centered in Moscow, but there was one such specialized mathematics high school in Jaroslavl that Reichstein was able to attend.

Reichstein's experience with the Olympiad contests was welcome to Caltech's team in the national Putnam Mathematical Competition. In his freshman year he received honorable mention — approximately the 40 highest scores among the 2,000 contestants nationwide that year. This past year he just missed the honorable mention cutoff but was one of the top members of the Caltech team, which finished sixth. He feels he might be getting a bit too old for this sort of thing.

It's probably less a matter of age than of changing interests and involvement in more advanced math. During his first summer here he worked on a classic problem in algebraic geometry under Jack Conn, assistant professor of mathematics — work that was, according to Conn, somewhat more esoteric than what most undergraduates get into. This past summer, with a Richter grant, Reichstein worked under Professor Herbert Ryser on a problem in combinatorics. Although he is interested in "algebraic geometry — Lie groups, algebraic topology, differential topology — that sort of thing" and plans on going to graduate school, as an undergraduate he mainly wants to get a good general math education. "Now I'm just interested in doing mathematics and learning about it and thinking about it."

Reichstein is fluent in English now, and his father is teaching math at Susquehanna University in Pennsylvania. But adapting to a new country still presents problems. Zinovy's grandparents and an uncle have also managed to emigrate, but he misses his close friends in Moscow and writes long letters "home." Still he has no doubt that the decision to leave was the right one.

"In the Soviet Union I realized clearly that I couldn't do mathematics there, that I couldn't survive as a mathematician. But even more important, I didn't think I would be able to survive there as a human being. I really like this country; I feel it's the right place for me. Most of my moral values were formed in Russia, but they are so similar to those here I couldn't believe it. It was hard to explain in Russia. Here I don't have to." □ — *JD*

Research in Progress

Digital vs. Analog

DIGITAL RECORDING, which stores the shape of a sound wave in numerical form, is a technology new in the past few years. It has been heralded as superior to the conventional recording technique, which is now, in comparison, called analog, because the shape of the wave is stored as continuous variations in some analogous quantity — intensity of magnetization along a recording tape or the shape of the grooves of a record.

Once sound is put in digital form, the new technique can command all the resources of computer technology. A digital recording should be reproducible an infinite number of times without degradation in quality; there should also be no background noise. Theoretically, with sufficiently frequent sampling and high enough precision of each sample, a digital recording ought to be able to reproduce live sound perfectly.

But you don't buy a theory to listen to music on; you buy a machine. And ultimately the only way to test audio machines is to listen to them. So Jim Boyk, lecturer in music (in both engineering and humanities) and artist in residence, designed an experiment to find out just how good the digital machines sound and whether they are indeed better than the conventional recording technology. Undergraduates Larry Gross and Denes Zsolnay participated in the project from the beginning, and Gary Lorden and F. Brock Fuller, both professors of mathematics, also contributed to the experiment's design.

Perception tests are difficult to design, and Boyk's is the only one he knows of on recording that does not merely compare digital and analog but uses live sound as a simultaneous reference for both. Troops of musicians and listeners (''ideally someone who cares about live music rather than just technology'') were drafted for the study, which took place during several days spread over a number of weeks this past summer.

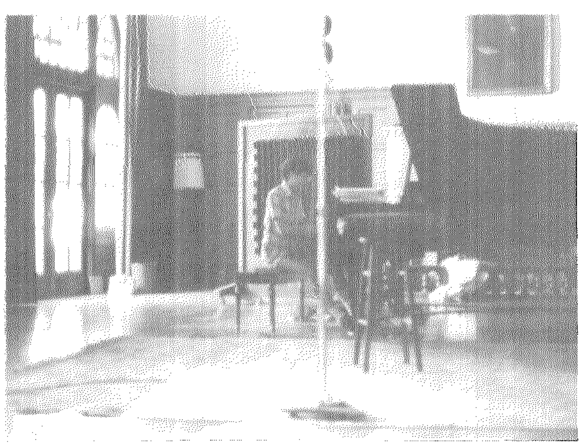
As the musicians — from pianists and other instrumentalists to vocalists — performed in live marathon sessions in Dabney Lounge, the sound was fed across the alley to Thomas Laboratory where it was split in three. One line led directly to the speakers in the listening room, where it could be heard essentially live. The other two were diverted to digital and analog recorders and then to the speakers.

By means of a switch the listener could choose among the direct feed, which was labeled and did not change, and ''apples'' and ''oranges,'' which represented the two unknowns — one of them digital and the other analog. The test was double-blind. From outside the listening room the apples and oranges were juggled randomly through an arrangement that kept even the operator in the dark as to whether, at any time, apples were analog and oranges digital or vice versa. Or whether both feeds were one or the other, which sometimes happened.

Seventeen subjects sat through 10 or 11 trials each (listening for from one to two and a half hours), switching back and forth among the three as they chose and answering two questions: Are the apples and oranges identical? And, if not identical, which comes musically closer to the direct feed? Listeners were also asked at the end if the apples and oranges were ever equal to the direct feed.

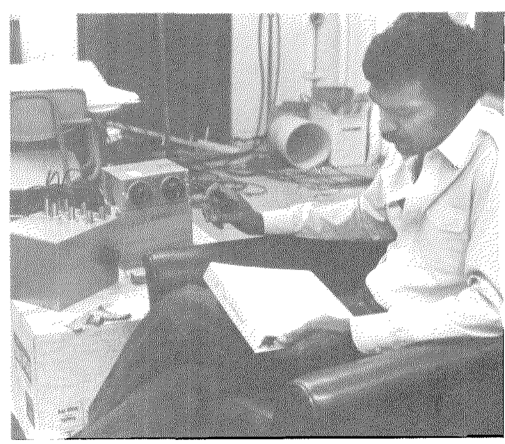
After unscrambling the apples and oranges and analyzing the data listener by listener, Boyk is now in the process of graphing the results. Although neither technique was a unanimous winner, the majority leaned toward analog. All Boyk will say right now is that the experiment clearly does not support the claim that digital recording machines are flawless — or even superior. This does not mean that they can't be improved and may eventually live up to predictions. Of course, proponents of analog recording claim that it too can certainly still be improved substantially.

Although the test was carefully stripped of any opportunity for bias, the results are not entirely surprising to Boyk, who has recently become something of a technological reactionary. His most recent recording (of Prokofiev's sixth piano sonata), which has been praised for its sound, was made with a tape recorder that is not only analog rather than digital but uses tubes instead of transistors. Boyk says this was not for ideological reasons but because the equipment sounded more ''musically accurate'' than anything else available. □ *—JD*



A microphone picks up the sound of the piano played by Mike Kong in Dabney Lounge.

Jim Boyk (left) and Larry Gross in Thomas Lab thread the tape on the analog machine.



In another room Robert Carr listens, comparing the live feed to ''apples'' and ''oranges.''

Communication Gap

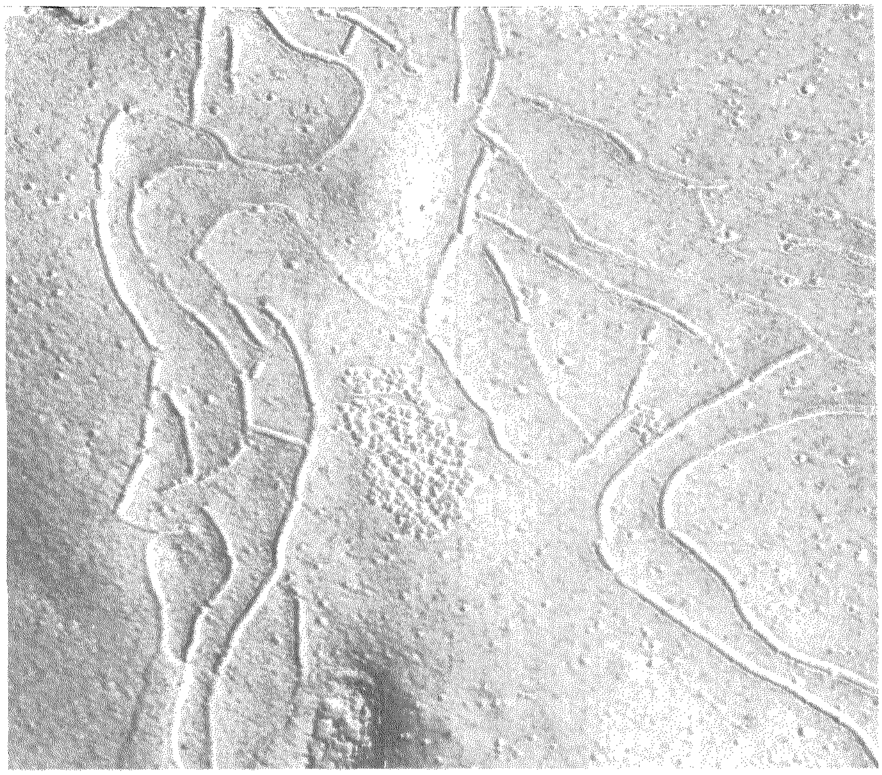
NEIGHBORING CELLS "talk" to each other over a communication system very much like a telephone. The cell's "Ma Bell" is what Jean-Paul Revel, the Albert Billings Ruddock Professor of Biology, calls the system, and for several years he, along with his collaborators, particularly senior research associate Barbara Yancey and graduate student Bruce Nicholson, has studied the intricacies of how this mechanism works.

Interaction between specialized cells — for instance, neurons communicating with each other — has been recognized for a long time. But research, including that in Revel's lab, has shown that all cells exchange information with their neighboring cells through "gap junctions" in their membranes.

The membrane surrounding a cell is a bimolecular film of phospholipids. These have a dual personality consisting of fatty acid residues (facing inward in the membrane) and a polar, hydrophilic end that faces the exterior of the membrane.

Because charged hydrophilic substances such as potassium ions (the most abundant charged ionic species in the cytoplasm of cells) don't dissolve well in the hydrophobic portion of the membrane phospholipid, the membrane has a high resistance to electric current. The cytoplasm inside the cell can be equated for present purposes to a salt solution rich in potassium ions, and it has a low resistance. When cells are touching, current passes easily from the inside of one to the inside of another, even though it has to cross two high-resistance membranes, one for each of the cells of the pair. There must be special devices where the cells touch to allow the current to cross the two opposed membranes.

Revel studies these membranes by freezing them in liquid nitrogen. They are then cracked open and a metal replica of the surface observed in the electron microscope. The micrographs reveal the presence of intra-membrane particles, or "imps," made up of protein molecules. Where cells touch, there are close-packed patches of very special imps. Six protein molecules, along with the phospholipid, form a flower-like structure with a hole in the middle; two of these arranged end to end, one in each cell membrane, form an aqueous path that allows ions to pass from one cell to another.



This electron micrograph shows a gap junction as a close-packed patch of IMPs. The sinuous strands are another membrane specialization not involved in communication. Each IMP is about 60 Å wide.

Not just ions go through this gap junction, but also molecules — not huge ones, of course, such as proteins, but a lot of interesting compounds that control the cell's behavior and metabolism. Researchers are very interested in figuring out what kind of molecules can pass through the junctions, since this exchange could play a role in a number of important functions. Communication through gap junctions is essential in getting organs to function harmoniously; for example, to keep the heart beating as a pump, cells must contract in the proper order after a proper delay. Potassium ions channeled through the gap junctions provide the signal at the right time. It has also recently been discovered that through gap junctions the differentiation of the female ovum is arrested until ovulation. And exchanges between cells can make up for cell deficiencies in certain genetic diseases.

Revel is also interested in figuring out how the gap junctions are put together. To isolate the junctions, the cells are put in a dilute medium; the osmotic shock causes them to blow up like balloons. When the insides leak out, you are left with the membrane, most of which will dissolve in detergents, leaving only the junctions. A gap junction is about half lipid, and the rest consists largely of a single protein species. With the protein sequenator recently developed at Caltech for research in molecular biology, part of the amino acid sequence of the protein molecule from the liver cell junction has already been determined. Knowing exactly how the protein is structured may lead to an understanding of how it is regulated, how its synthesis is determined, why and how it gets into the membranes, and how the gap junctions form.

A simpler and quicker (although not so precise) method of identification of proteins has yielded multidimensional "fingerprints" indicating that each organ may have its own unique gap junction protein; in other words, each organ has a different telephone system. It is not yet known but is under investigation why this is and to what extent these different systems can communicate with each other. Or, as Revel puts it: Can a princess phone talk to a Mickey Mouse phone? He will probably find out. □ *–JD*

Halley Heralded

HALLEY'S COMET, although still about a billion miles away, has been sighted on its return trip to the center of the solar system. Last seen in 1910-11 as it sped off on the outward leg of its elliptical orbit, this time the comet will reach its closest approach to the sun in 1986. Right now it's about 20 million times too faint to be seen by the unaided eye.

So it took extremely far-sighted instruments to spot it at its current distance. A Caltech team led by graduate student David C. Jewitt and staff member G. Edward Danielson was the first to do so — on October 16 — with the 200-inch Hale Telescope at Palomar Observatory and a sensitive electronic camera. The camera, known as PFUEI for Prime Focus Universal Extragalactic Instrument, consists of a charge-coupled device (CCD) developed by NASA for the Wide-Field/Planetary Camera of the Space Telescope. James A. Westphal, professor of planetary science, and James E. Gunn, formerly at Caltech and now at Princeton, designed and built the camera system for work at the Palomar telescope. The CCD, a tiny chip of silicon, is far more sensitive than usual photographic plates used in astronomy.

To see Halley's comet, the nucleus of which is only a few miles in diameter, at a billion miles, not only would the detector have to be very sensitive, but the searchers would have to know where to look. The Caltech team did, since the comet's position had been predicted by Donald Yeomans of the Jet Propulsion Laboratory. They took seven 480-second exposures about 10 to 15 minutes apart. After considerable computer processing, the very faint object was found near the predicted location and moving at the predicted rate.

Comet Halley has been moving back toward us since 1948, when it reached the outer limit of its orbit, 3.2 billion miles out — beyond the orbit of Neptune. When the comet nucleus, which has a mass of about a billion tons, gets closer to the sun and warms up from solar radiation, some of the volatile materials in the nucleus will vaporize to create the familiar glowing head, or coma. The brilliant tail, which always streams away from the sun and can reach a length of millions of miles, is composed of dust propelled by solar radiation pressure and ionized gas molecules accelerated by the solar wind. Comets are believed to be frozen bodies of gas and dust, leftovers from the formation of the solar system, that inhabit a vast cloud far beyond the outer planets (about one light year from the sun). Once in a while the gravity of a nearby star will perturb one into a sunward trajectory. There are hundreds of known comets with orbital periods ranging from 3.3 years to 2 million years, as well as hundreds of nonperiodic comets.

Halley's comet takes an average of 76 years to complete its orbit. That comets do return was discovered in 1695 by the English astronomer Edmund Halley, who used Isaac Newton's theories of gravitation to calculate the orbits of several comets. He observed that the orbit of a comet he had seen in 1682 was similar to ones seen in 1531 and 1607 and predicted correctly that it would return in 1758. It did and has roughly every 76 years since. Halley's comet has also been traced back to 240 B.C.

The Caltech team's confirmed sighting of Halley's comet on its latest approach is the first of a series of planned worldwide observations, which will be coordinated by the International Halley Watch from JPL and the University of Erlangen-Nürnberg in West Germany. The Caltech effort to spot the comet also included research fellow Donald P. Schneider; Alan Dressler of the Mount Wilson and Las Campanas Observatories of the Carnegie Institution of Washington; Caltech Professor of Astronomy Maarten Schmidt; and staff member Barbara A. Zimmerman.

Comets are interesting to planetary scientists and astronomers because they are thought to be samples of the primitive solar system. Data will be collected concerning Halley's orbit and velocity, its interaction with the solar wind, its physical and chemical composition, its possible magnetic properties, and every other aspect scientists can think of. It will be studied from ground-based observatories as well as from airplanes, balloons, the Space Shuttle, the Space Telescope, and several satellites. Five spacecraft (two Soviet/French, two Japanese, and one from the European Space Agency) will fly by the comet in March 1986. The European spacecraft, named *Giotto*, may come as close as 600 miles to the comet. Several American scientists are co-investigators on some of the experiments that *Giotto* will carry, since NASA's spacecraft plans were scrapped because of a tight budget.

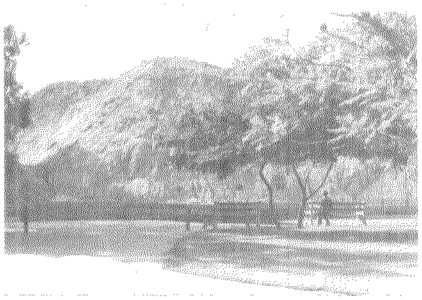
Halley's comet will be most visible to the average viewer at its closest approach to the earth in November-December 1985 and after it has rounded the sun and its tail is longest in April 1986. □ — *JD*

Giotto probably used the 1301 appearance of Halley's comet as a model for the Christmas star in his 1303 fresco in the Arena Chapel of Padua.

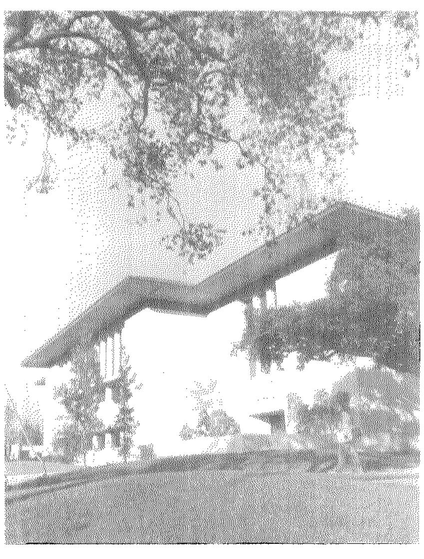
Random Walk

Scenery Changes

The area at the corner of Wilson Avenue and San Pasquel Street on the Caltech campus has seen a lot of changes in the past three years, beginning in 1979 with removal to new sites of two old houses. . . .



. . .Then the earth-moving machinery took over, and for a long time the view was dominated by a massive pile of dirt, referred to as Mt. Hood in honor of Leroy Hood, a many-titled biologist who will direct the cancer center in the new building about to emerge as . . .



. . . the Braun Laboratories in Memory of Carl F and Winifred H Braun. The building, which was dedicated on December 13, will house eight major research groups in cell biology and chemistry. E&S *plans to report on some of that work in March.*

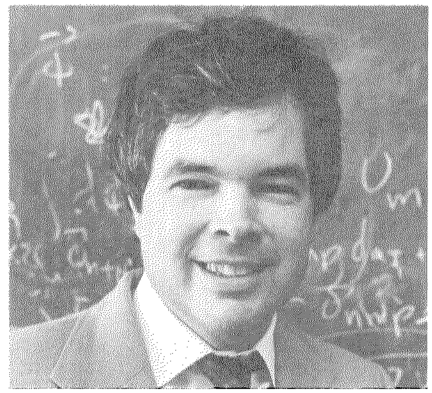
Kenneth Wilson

A SMALL PIECE of ice in a warm room doesn't remain solid very long. It soon turns into a structureless puddle of water that in no way resembles the hard crystalline substance from which it came. Such a transformation is called a phase transition, and Caltech alumnus Kenneth Wilson, PhD '61, who is now at Cornell University, has received the 1982 Nobel Prize in physics for his contributions to understanding how that transition comes about.

Coming to such an understanding has occupied the minds of physicists for at least a century, and in the search for a solution they have found many examples of the phenomena. The puddle of water, for instance, undergoes another phase transition if it is heated enough to turn to steam. And at no stage does the substance give any hint that it can assume other forms. Magnets are another example; they suddenly lose their magnetism when heated above a certain temperature and regain it when cooled below that temperature. Many substances change their ability to conduct electricity when cooled below a characteristic temperature. Moreover, the manner in which these substances change their properties in the course of phase transition shows remarkable regularities, which is not to say that the process is simple to describe. Obviously, these phenomena result from the movements of atoms and molecules and the interactions between them, but a theoretical explanation of what is going on has proved elusive.

Wilson went about solving the problem in a very ingenious way and was able to announce his results in several fundamental papers published in 1971. "Instead of a frontal attack," said the citation of the Swedish Academy of Sciences, "he developed a method to divide the problem into a sequence of simpler problems in which each part could be solved." This method, called "renormalization group method," uses mathematical concepts and techniques that, for the first time, permit detailed calculations from fundamental principles that correctly account for many of the experimental observations. Further, Wilson's theory provides an understanding of why the changes that occur in a phase transition show regularities that actually do not depend on the detailed properties of the substance in question.

At Caltech, Wilson did most of his



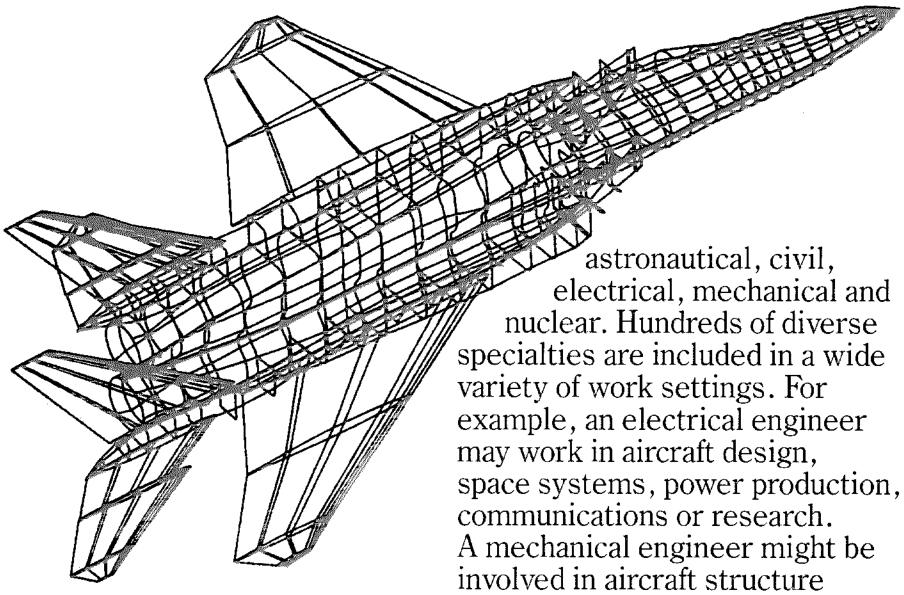
work under Murray Gell-Mann, now Millikan Professor of Theoretical Physics and winner of the1969 Nobel Prize, and some of Gell-Mann's insights played an important role in Wilson's thinking. While Wilson was a student, Gell-Mann and Francis Low (now of MIT) evolved a method for solving a problem totally unrelated to phase transitions, but Wilson was able to see that it was applicable. Wilson has, in fact, a reputation for mathematical ability amounting to genius, and it started early. He is reported to have been able to calculate cube roots in his head by the age of eight.

Benjamin Widom of Cornell and Leo Kadanoff of the University of Chicago also made important contributions to Wilson's thinking, and Michael Fisher of Cornell, a well-known authority on phase transitions, provided him with criticism and advice at all stages of his work. He collaborated with Fisher in one of the most striking applications of the new ideas, and in 1980 he and Fisher and Kadanoff shared Israel's $100,000 Wolf Prize in Physics.

An earlier — and continuing — contributor to Wilson's achievements is his father, Caltech alumnus E. Bright Wilson (PhD '33), who has been a distinguished professor of chemistry at Harvard, where Kenneth did his undergraduate work.

A member of the Cornell faculty since 1963, Wilson became a full professor in 1970 and the James A. Weeks Professor of Physics in 1974. He has won the American Physical Society's prestigious Heinemann Prize and the Boltzmann Medal in statistical mechanics from the International Union of Pure and Applied Physics. He was elected to the National Academy of Sciences in 1975. Wilson was a Fairchild Scholar at the Institute in 1976, and he received Caltech's Distinguished Alumnus Award in 1981. He is the 19th Caltech alumnus or faculty member to be awarded the Nobel Prize. □ —*JB*

ENGINEERING TAKES ON EXCITING NEW DIMENSIONS IN THE AIR FORCE.



Computer-generated design for investigating structural strengths and weaknesses.

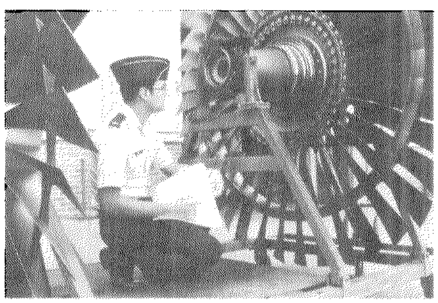
Developing and managing Air Force engineering projects could be the most important, exciting challenge of your life. The projects extend to virtually every engineering frontier.

8 CAREER FIELDS FOR ENGINEERS

Air Force electrical engineer studying aircraft electrical power supply system.

Engineering opportunities in the Air Force include these eight career areas: aeronautical, aerospace, architectural, astronautical, civil, electrical, mechanical and nuclear. Hundreds of diverse specialties are included in a wide variety of work settings. For example, an electrical engineer may work in aircraft design, space systems, power production, communications or research. A mechanical engineer might be involved in aircraft structure design, space vehicle launch pad construction, or research.

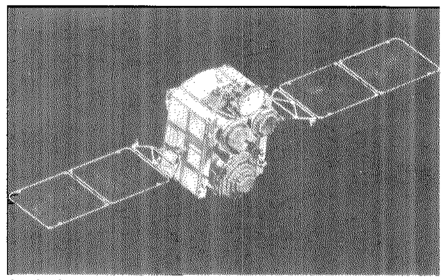
PROJECT RESPONSIBILITY COMES EARLY IN THE AIR FORCE



Air Force mechanical engineer inspecting aircraft jet engine turbine.

Most Air Force engineers have complete project responsibility early in their careers. For example, a first lieutenant directed work on a new airborne electronic system to pinpoint radiating targets. Another engineer tested the jet engines for advanced tanker and cargo aircraft.

OPPORTUNITIES IN THE NEW USAF SPACE COMMAND

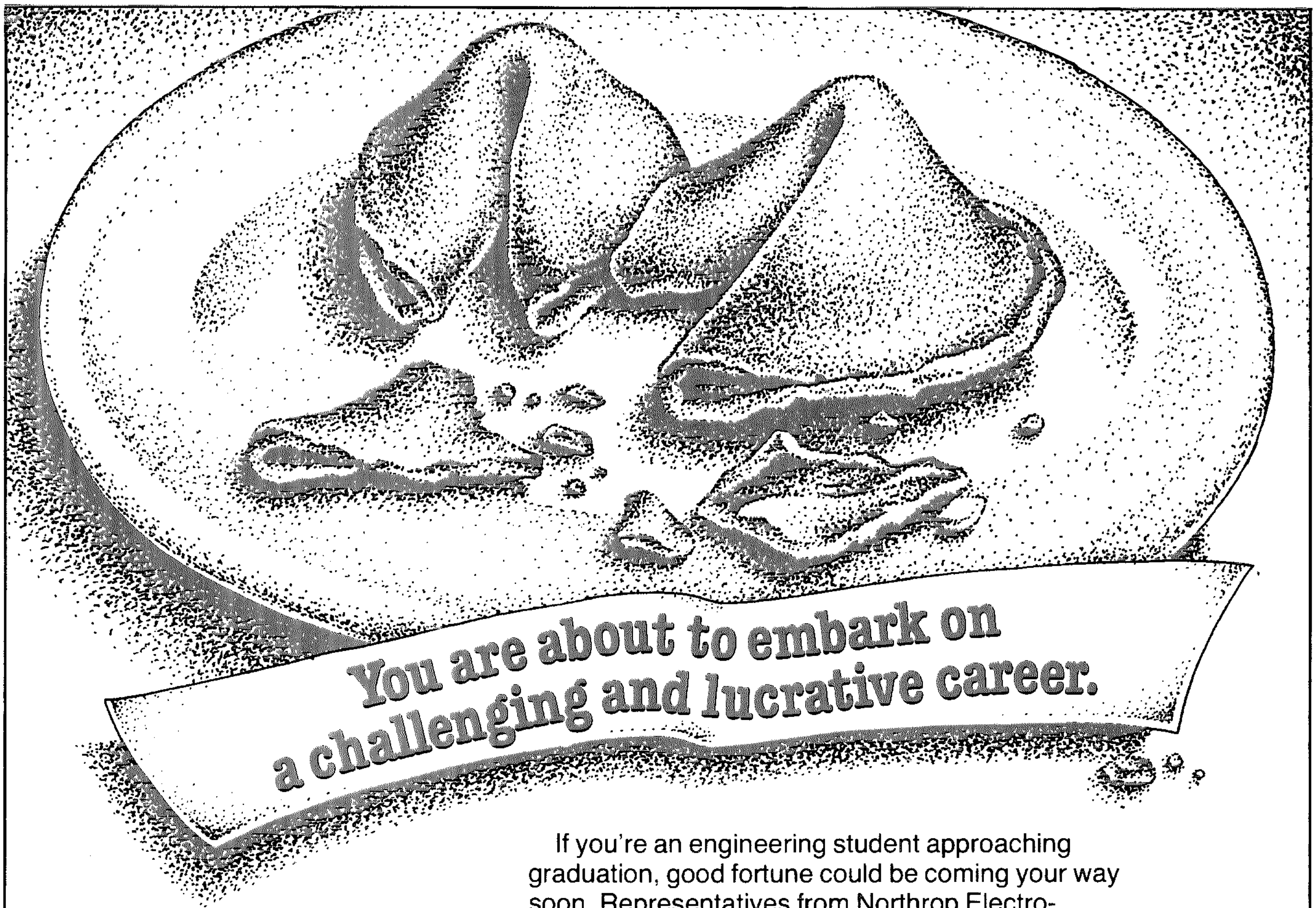


Artist's concept of the DSCS III Defense Satellite Communications System satellite. (USAF photo.)

Recently, the Air Force formed a new Space Command. Its role is to pull together space operations and research and development efforts, focusing on the unique technological needs of space systems. This can be your opportunity to join the team that develops superior space systems as the Air Force moves into the twenty-first century.

To learn more about how you can be part of the team, see your Air Force recruiter or call our Engineer Hotline toll free 1-800-531-5826 (in Texas call 1-800-292-5366). There's no obligation.

AIM HIGH AIR FORCE



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