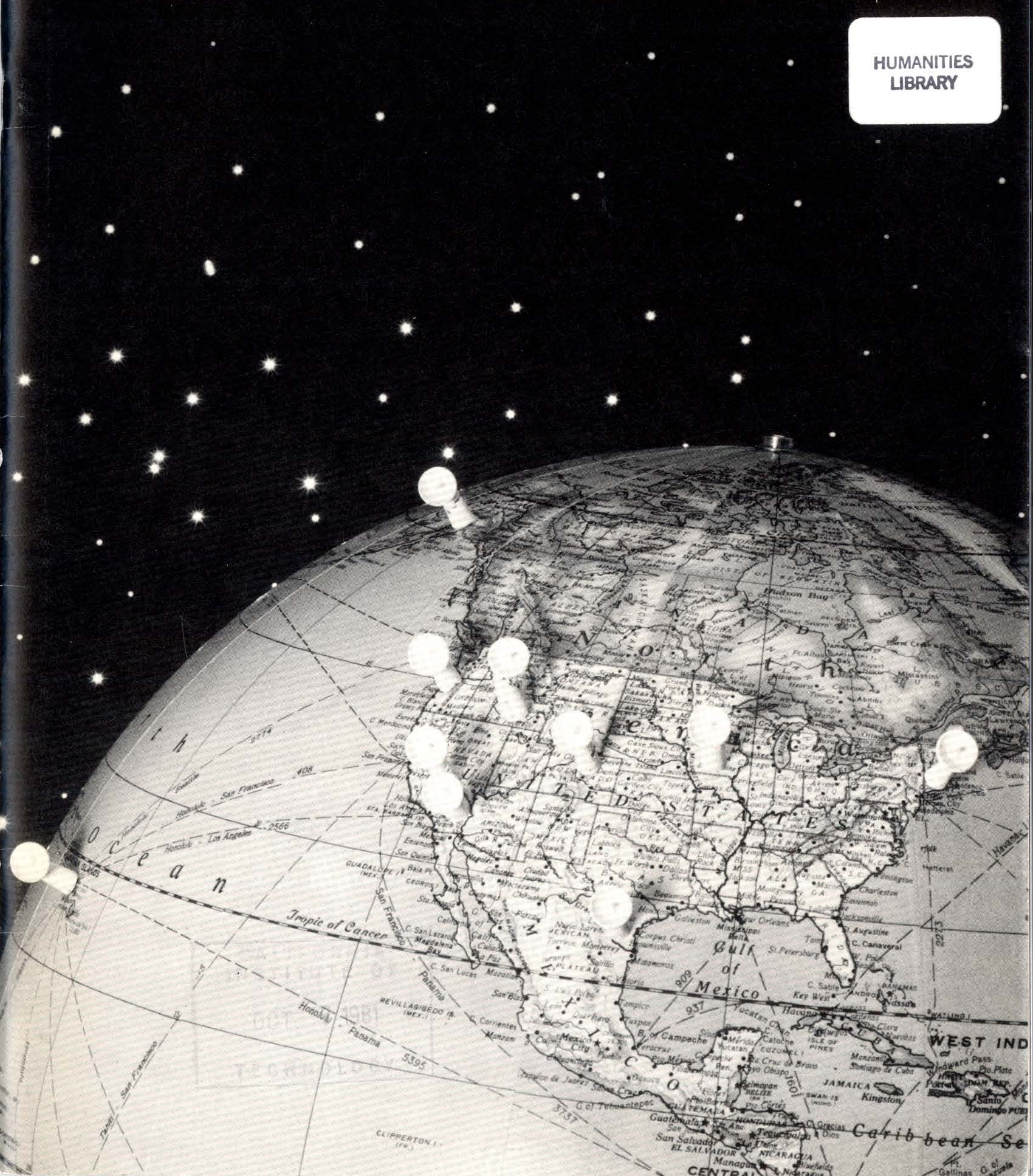
Engineering & Science

California Institute of Technology | February 1981



ALUMNI FLIGHTS ABROAD
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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.

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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.

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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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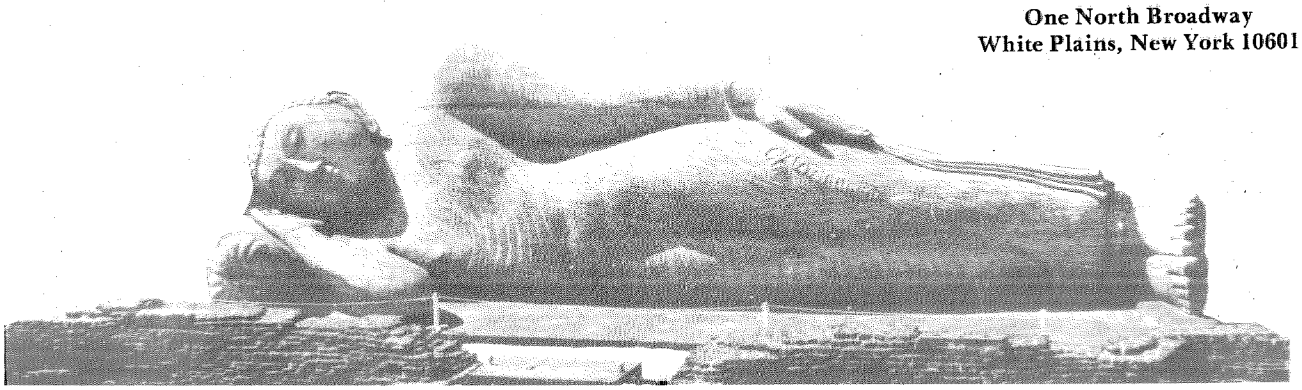

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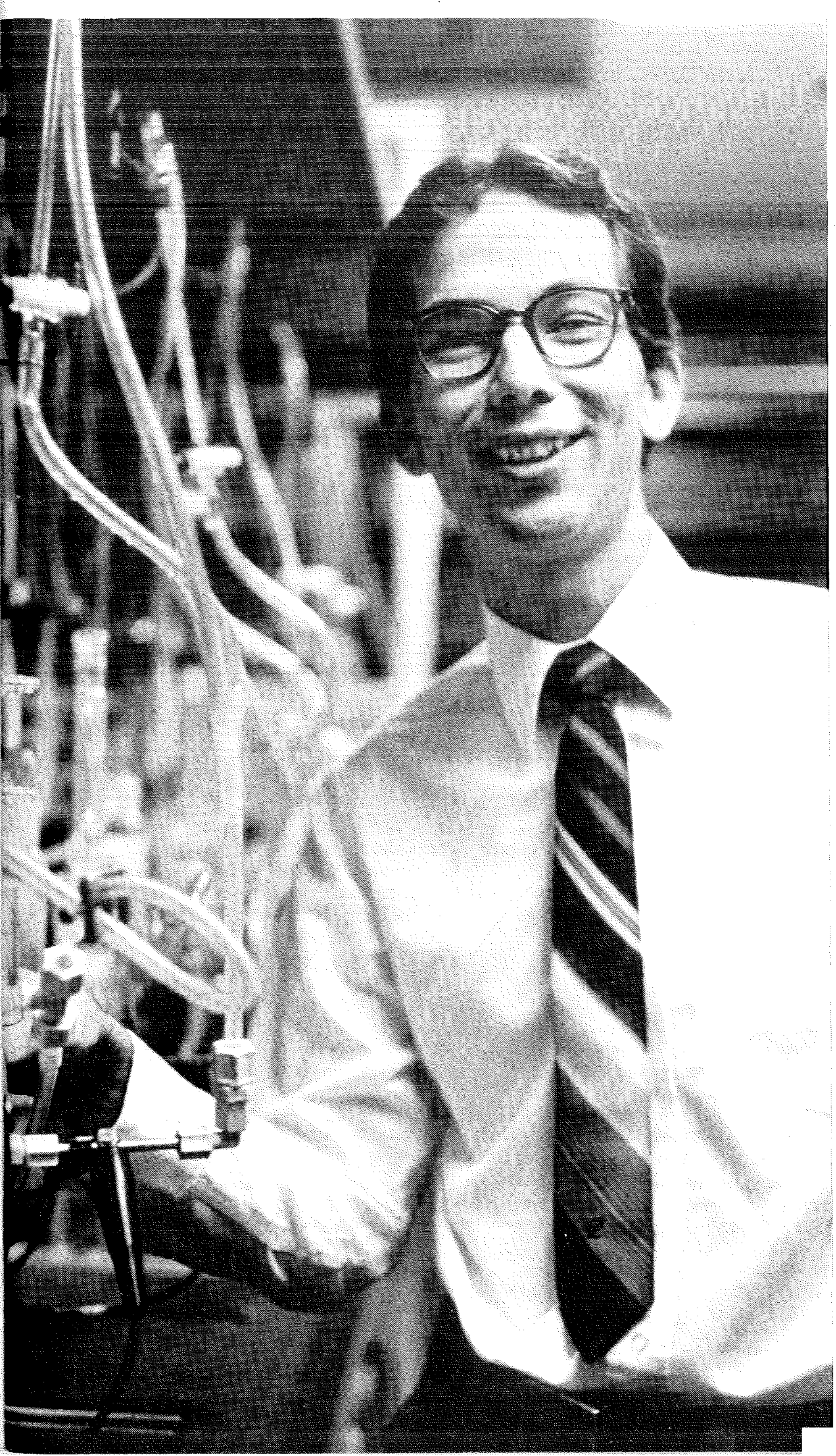

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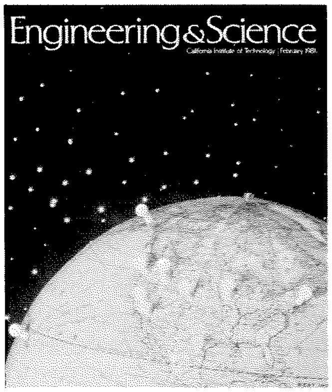


Global Outlook

On the cover — a glimpse of a projected network of ten radio telescopes, which together could synthesize a telescope aperture thousands of kilometers in diameter. With such a network, astronomers would be able to peer at galaxies and quasars up to 10 billion light years away with a resolution fine enough to see such relatively small details as features only a few light years in size! This achievement is made possible by a technique called very long baseline interferometry (VLBI). Although developed only in the past few years, VLBI has already revealed astonishing features of some distant objects that have a minimum mass of 100 million suns.

Caltech has been a leader in the development of this field, and this first attracted Anthony Readhead here in 1974. Originally from South Africa, Readhead received his BSc in theoretical physics from the University of the Witwatersrand in 1968. For his PhD he studied in Cambridge, England, under Sir Martin Ryle and Antony Hewish and then received a five-year fellowship from the Royal Society of London. It was during this period that he made an extended visit to Caltech, and he returned to the Institute as a senior research fellow in radio astronomy in 1976. He is now research associate and acknowledged to be a leading authority on VLBI.

Anthony Readhead

In addition to interpreting scientific results, Readhead has made important contributions to the technique of VLBI, that is, how it is actually done. His article, "VLBI — A New Frontier in Astronomy" on page 6, gives some examples of both.

Shirley Hufstedler

Educational Experience

The annual dinner of The Associates of the California Institute of Technology is always a festive affair, and never more so than when the speaker of the evening is an old friend of Caltech. Shirley Hufstedler, the first Secretary of Education, served on Caltech's board of trustees from September 1975 until her resignation in order to take up new duties in Washington in January 1980.

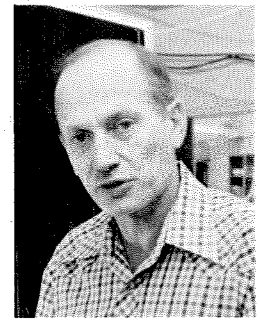
Secretary Hufstedler received her BBA from the University of New Mexico in 1945 and her LLB from Stanford University in 1949. After private practice in law in Los Angeles, she spent 18 years on the bench; first as a Superior Court judge; then as an Associate Justice of the California Court of Appeals; and then as the highest ranking woman jurist in the country when she became judge of the U.S. 9th Circuit Court of Appeals.

"A Report Card for American Education" on page 12 is adapted from her speech to The Associates.

Guiding Light

The story of learning to manipulate light to carry signals through tiny glass fibers over long distances is only a little over ten years old, but it now seems to have a happy ending. In "Integrated Optoelectronics" on page 17, Amnon Yariv traces the development of this field from the invention of the semiconductor laser to the achievement at Caltech of an integrated optoelectronic circuit on a single layered crystal. American industry, as well as Japanese and European, skeptical about the feasibility of integrated optoelectronics for most of this period, is now picking up the Caltech development — thus signaling the beginning of a new technology.

Amnon Yariv



Yariv was born in Israel but received all his degrees from UC Berkeley — BS '54, MS '56, and PhD '58. After five years at Bell Laboratories, where his interest in guiding light on semiconductor crystals was awakened, he came to Caltech in 1964 and continued this work. He is professor of applied physics, and in 1979 he was named Thomas G. Myers Professor of Electrical Engineering.

Harold McGee

Fruitful Idea

Harold McGee (BS '73) went to Yale from Caltech, earned a PhD, and taught for two years. While he was in New Haven, another Caltech alumnus, Sharon Long (also BS '73 and now Mrs. Harold McGee), gave a popular lecture-demonstration on crystal chemistry and fudge-making. It was out of this that Hal got the idea for the book he has been writing.

The Nature of Food and Cooking, which will be published late this year by Scribner's, explores the biology and chemistry of everyday food materials and culinary techniques, together with some cultural history — for example, the great impact of the 19th-century German chemist Liebig on the way we cook meat. "Ripeness Is All" on page 26 is one chapter in that book and originally appeared in *Horticulture*, which was published by the Massachusetts Horticulture Society in August 1980.

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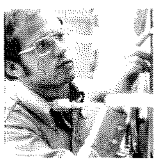

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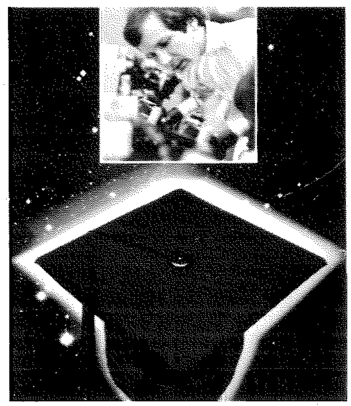
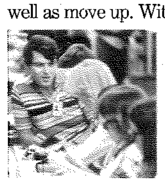


well as move up. Without changing jobs.



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SCIENCE/SCOPE

Field-effect transistors are emerging as strong contenders for microwave switch applications in communications satellites. Gallium-arsenide FETs are likely to replace PIN diodes due to advantages like higher speeds and lower power consumption. Using arrays of FETs, Hughes researchers built an 8x8 switch matrix for time-division multiple-access applications at 4 GHz. The device achieved a 1-nanosecond transition time at 10 milliwatts drive control power.

The unique method for ejecting Leasat satellites from the cargo bay of NASA's Space Shuttle -- a process that has been likened to flipping a flying disk -- has been proven in simulation tests. In a test designed to imitate the zero gravity of space, small explosive charges were fired to release a mock spacecraft weighing 15,000 pounds and measuring 14 feet in diameter. The simulated craft, hung from a 70-foot cable attached to a low-friction trolley, cleared its cradle and the bay as expected. Hughes is building five Leasat satellites to fill the communications needs of the U.S. Navy and other services.

A new weather satellite is gathering experimental data while continuing to provide conventional meterological information. GOES D, the fourth Geostationary Operational Environmental Satellite, carries a new sensor called a visible-infrared spin-scan radiometer atmospheric sounder (VAS). In addition to providing pictures every 30 minutes, VAS measures temperatures and moisture in the atmosphere at various altitudes. The data gives meterologists a more complete three-dimensional analysis of weather conditions. GOES D is the first of three spacecraft under contract to Hughes from the National Aeronautics and Space Administration, which is procuring the satellites for the National Oceanic and Atmospheric Administration.

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A revolutionary mosaic infrared seeker, which creates TV-like pictures of a scene's radiated heat to allow missiles to lock on and guide themselves to tactical military targets, promises to provide increased performance at reduced size, cost, and complexity. The seeker incorporates more than 1,000 infrared detectors mated to a corresponding number of charge-coupled devices used for signal processing. All these elements are located at the focal plane of the seeker. Unlike conventional sensors, which mechanically scan a scene, the focal plane array "stares" at an entire scene.

Engineering&Science
FEBRUARY 1981

VLBI

A New Frontier in Astronomy

by ANTHONY READHEAD

The contributions of radio astronomy to our knowledge of the universe have been impressive. They include the discoveries of quasars and radio galaxies, the largest and most powerful objects known; the discovery of the microwave background radiation, now widely accepted as confirming the Big Bang theory of the origin of the universe; and the discovery of pulsars, which provided impetus to studies of ultra-dense states of matter and collapsed objects. Without exception, these discoveries have been the result of technological innovations. *We are now witnessing a new technological breakthrough, in which Caltech is playing a leading role, which enables us to make images of objects only a few light years in size in the nuclei of the most distant galaxies and quasars.* The present methods and images are crude, but the full potential of these developments will be realized by means of a properly designed very long baseline interferometry (VLBI) telescope.

Galileo constructed the first astronomical telescope in 1609. His observations showed that a telescope performs two major functions:

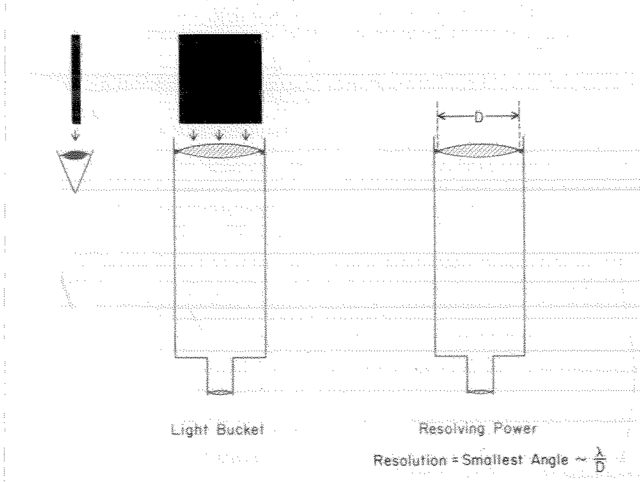
1) It is a light bucket, collecting more light than the naked eye and enabling us to see fainter objects.

2) It brings together light from points that are farther apart than the diameter of a pupil, and this enables us to see greater detail in the object.

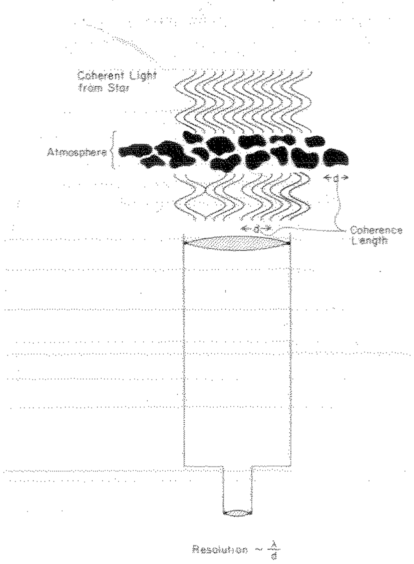
The second property is called the resolving power, or resolution, of a telescope. The resolution is given by λ/D, where λ is the wavelength of the radiation and D is the diameter of the telescope aperture. In order to see fine details in astronomical objects, we need to make D large and λ small.

Unfortunately the story is not quite this simple because the atmosphere interferes with the light on the way to the telescope. This is the same phenomenon that causes the twinkling of stars. When we look at a star with a large telescope, the light entering the telescope is not all in step, that is, it is not coherent. This corrupts the image, and the resolution we get is limited by the size of the refractive cells in the atmosphere — typically a few inches. The corresponding resolution is about one second of arc, which is not much better than the resolution Galileo achieved with his telescope. Thus, in one step Galileo achieved about the maximum resolution possible from the surface of the earth in visible light.

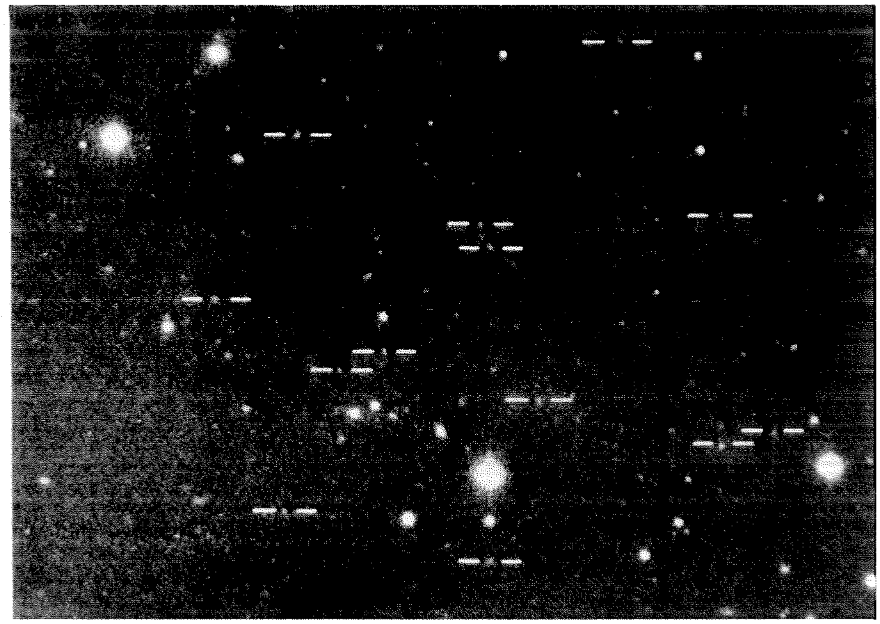
For 350 years this situation was unchanged. This meant that in the most distant galaxies, which are about 10 billion light years away, any details on a scale smaller than about 50 thousand light years — that is, roughly the size of a galaxy — were unresolved. At first sight the limited



Since a telescope collects more light than the naked eye, it enables us to see fainter objects; it also collects light from points farther apart than the diameter of the eye, allowing greater perception of detail. The resolution of a telescope is given by the wavelength (λ) of the light divided by the diameter of the aperture.



The resolving power of a telescope is limited by the size of the refractive cells in the atmosphere. Coherent light from a source is put out of step by these cells, whose size is typically a few inches, with the result that coherent signals are also only a few inches across regardless of the size of the telescope.



Galaxies more than a billion light years away (in brackets) are barely visible as unresolved blotches in this image from the 200-inch Hale Telescope. Because their resolution is limited by the atmosphere, optical telescopes cannot discern details smaller than 50 thousand light years at these distances. With very long baseline interferometry astronomers can now see details only a few light years in size — approximately the distance between individual stars in objects at these immense distances.

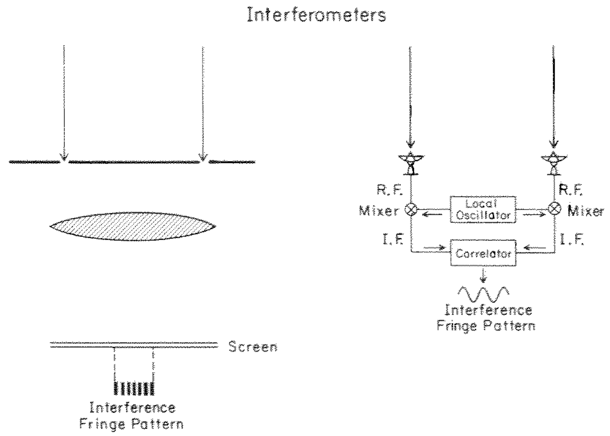
resolution of optical observations may not seem important. After all, there are plenty of nearby galaxies that can be studied in detail, so why bother about the more distant ones?

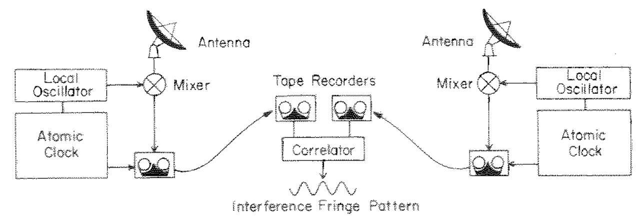
One answer is that in looking to great distances one is looking backwards in time and may therefore hope to unravel the story of the evolution of galaxies. But as we shall see, there is also another powerful incentive, which was initiated not by optical but by radio astronomical observations. By the early 1950s hundreds of celestial objects that emitted radio waves had been detected. They were thought to be stars in our own galaxy. Then, in 1953, Baade and Minkowski identified the optical counterpart of one of the strongest of these radio emitters, Cygnus A, as a distant galaxy (1 billion light years away). This was an astonishing discovery — if one of the brightest radio sources was actually a very distant galaxy, then the fainter radio sources are probably even more distant objects that might even be invisible on optical photographs. The discovery was also remarkable because it indicated that the total energy associated with the radio emission alone is 10^{61} ergs — equivalent to the yield obtained from the thermonuclear burning of a billion suns.

By the early 1960s it was known that there are essentially two types of radio objects: extended objects like Cygnus A and a class of compact objects that coincided with star-like optical objects. These were called quasi-stellar radio sources or quasars. In 1963 Caltech astronomer Maarten Schmidt interpreted the spectrum of one of these objects (3C 273) and showed that it was at a very great distance indeed — about 2.5 billion light years. This meant that 3C 273 is intrinsically 100 times brighter than the brightest galaxy.

There is no way to observe the structure of quasars with ground-based optical telescopes. However, the small scale atmospheric irregularities that limit optical resolution do not affect radio observations. Thus, it was thought, it might be possible to observe the structure of these objects with radio telescopes. This was bound to be difficult because even short radio waves are about 50 thousand times longer than light, so we would have to build a radio telescope much larger than optical telescopes to get reasonable resolution. To achieve a resolution of one arc second we would need a radio telescope five kilometers across. Of course, we cannot build a single telescope five kilometers across, but *it is possible to use interferometers to synthesize, or fill in, large telescope apertures.*

An interferometer is an instrument in which we add together light or radio waves from two points. A radio interferometer is an exact analog of an optical interferometer. In a radio interferometer the signals from the two telescopes have to be synchronized to within a fraction of a microsecond before being added together. This is usually achieved by making the connecting cables from the two telescopes equal in length. *In order to use an interferometer to synthesize a large telescope, we have to measure*





An optical interferometer (left) and a radio interferometer work on similar principles; the interferometer adds the signals from two telescopes together. Waves from the two telescopes that are in step produce constructive interference resulting in a bright region on a fringe pattern. Destructive interference, where the crests and troughs are opposite and cancel each other out, produces a dark region. The intensity of the gradations from bright to dark can be plotted as a sine wave, whose amplitude and position can be used to give an image of the signal's source. The relative positions of the interferometer elements can be changed so that the signals from each position fill in a piece of an aperture with a diameter much larger than that of a single telescope. Apertures up to thousands of kilometers can be synthesized (above) since the invention of atomic clocks, which make it possible to record and synchronize the signals with micro-second accuracy. So the signals can be added together at any location, freeing the two telescopes from the necessity of being connected.

both the size (amplitude) and the position (phase) of the sinusoidal output of the interferometer. For example, if we have a radio interferometer consisting of two radio telescopes linked by equal cables, we can make measurements with the telescopes in different relative positions and so fill in, or synthesize, an aperture that is much larger than the individual telescope. A variation on this theme makes use of the rotation of the earth to change the relative positions of the telescopes as seen from a distant celestial object. This technique was developed by Sir Martin Ryle and his colleagues at Cambridge, England. It has also been used successfully here at Caltech, in Holland, and at the Very Large Array (VLA), a group of 27 radio telescopes recently completed in New Mexico.

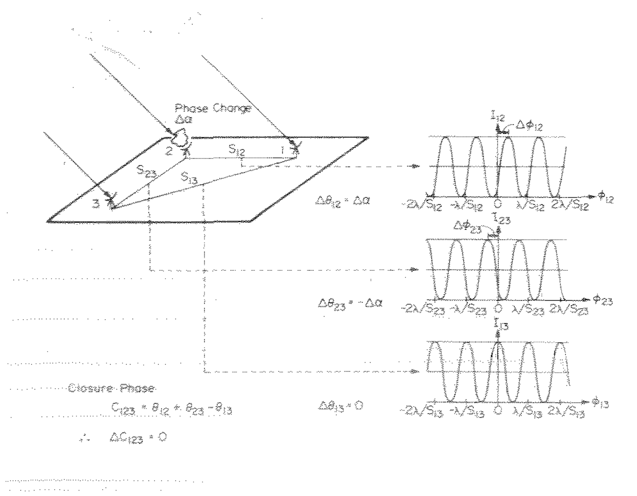
Early radio interferometry revealed some surprising images of radio objects; it showed that emission originates in two main regions, or lobes, roughly equidistant from the optical object. But these "aperture synthesis" telescopes are still limited in resolution. Even the largest of them has a maximum resolution of about one-third of an arc second — only slightly better than optical telescopes. In order to get substantially better resolution than this, the telescopes must be separated by much greater distances than a few kilometers. This is a problem because it is difficult to link telescopes over distances of, say, thousands of kilometers, and synchronize the signals to within a fraction of a microsecond.

Fortunately, by the late 1960s the advent of very accurate atomic clocks provided a solution to this problem. Using these clocks, it is possible to record the signals from two telescopes separately on videotapes with microsecond timing accuracy. The tapes are then shipped to a central processor where they are synchronized and the signals are combined. This is called very long baseline interferometry.

Here at Caltech we have had an active group practicing VLBI for the last ten years, led by Marshall Cohen, professor of radio astronomy, who was also one of the main founders of the field in the pioneering days of the late 1960s. Although VLBI looked promising at that time, it appeared at the start to be a limited technique, since, as in optical telescopes, all the waves must be coherent in order to make a proper image. Small scale atmospheric turbulence that upsets optical telescopes does not affect radio telescopes, but there are larger scale structures in the atmosphere that do affect radio telescopes. Ironically, these problems become severe over scales of a few kilometers at short wavelengths, that is, at just the scales and wavelengths at which radio observations begin to have resolution comparable to optical telescopes. The one-second resolution barrier applied to radio as well as optical ground-based observations!

The early VLBI observations were tantalizing — they showed that it was possible to achieve a resolution of 1/1000 of a second of arc, since interference fringes were observed, but due both to the atmosphere and to technical limitations, the position of the fringes jittered around in a random fashion. This made it impossible to add up all the signals coherently and hence to synthesize a large aperture and make a proper image. All we could do with VLBI was to make crude models of the active nuclei of quasars and radio galaxies, and face up to the fact that VLBI observations would never produce proper images (except perhaps in a very small number of special cases).

Or so it appeared in 1975. In that year we began ex-



Expanding to a network of three telescopes and interferometers (above) solved the problem of resolution limited by atmospheric interference. If the atmospheric cell over telescope 2 puts that signal out of step with the signals at 1 and 3, it does not affect the fringes of interferometer 13 (represented as a sine wave at bottom right), but it does shift the fringe positions on 12 and 23 by equal and opposite amounts. These cancel each other out, and the resultant closure phase gives a proper image of the source.

perimenting here at Caltech with a new approach to interferometry. Instead of considering *pairs* of telescopes, why not combine the signals from *three* telescopes simultaneously? With three telescopes — 1, 2, and 3 in the diagram above — there are three interferometers — 12, 13, and 23. If the atmosphere above telescope 2 delays the signal a bit, putting it out of step with the signals arriving at telescopes 1 and 3, this changes the position of the fringes on interferometer 12. However, it changes the position of the fringes on interferometer 23 by an exactly equal but opposite amount. The fringes on interferometer 13 are of course unaffected by what goes on above telescope 2. So, if we add up the fringe positions (or phases) around the loop, the shifts in position introduced by the atmosphere on 12 and 23 cancel exactly, and the "closure phase," that is, the phase summed around a closed loop, is unaffected. All the spurious contributions from the atmosphere and ionosphere, and from individual telescopes and electronics, cancel exactly. The closure phase reflects only the structure of the source.

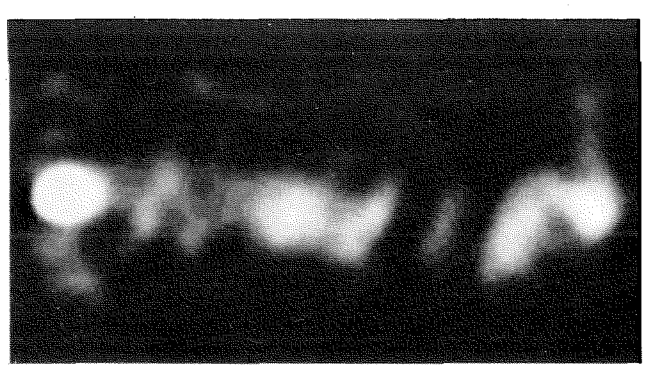
A generalization of this approach to a closed loop of four telescopes enables us to overcome difficulties in a similar way in measuring the size, or amplitude, of the sinusoidal signal, by measuring what we call the closure amplitude. These closure techniques use the object as its own phase reference and amplitude calibration, and we have developed a method for making proper images from completely uncalibrated and indeed uncalibratable data.

This breakthrough makes it possible now to synthesize telescopes thousands of kilometers across. For example, we would like to build a ten-telescope system that would reach from Hawaii and Alaska to the East Coast, using the earth's rotation to fill in an aperture 7,500 kilometers in diameter. Unfortunately, we do not yet have an instrument expressly designed for this function, but there are a number of telescopes built for other purposes scattered across the globe, and they can be used to test the feasibility of this scheme.

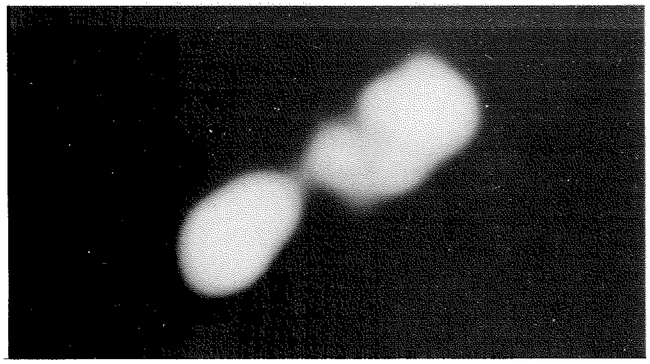
Using such a network of existing telescopes, we first applied this new approach in 1975 on the quasar 3C 147 (7 billion light years away) and succeeded in producing the first proper image of an astronomical object with a resolution of 1/100 of a second of arc. The next year we observed 3C 147 with a network of five telescopes. The jet in the image we obtained in 1976 is 2/10 arc seconds long, so the optical image would be an unresolved point one second across, that is, five times the size of the jet. We see that the quasar has a bright core and a one-sided jet about 5,000 light years long. We were very excited by these results for two reasons: First, they showed that it was technically possible to make proper images with VLBI — that is, we really can synthesize a telescope of global dimensions and make images with the full resolution that we would obtain in the absence of any atmosphere. Second, the results themselves were unexpected. We knew from initial work with aperture synthesis telescopes up to a few kilometers in size that the large-scale structure of radio galaxies and quasars is generally *symmetric*, consisting of two lobes roughly equispaced on either side of the optical object. In this distant quasar that we first mapped with VLBI we have an *asymmetric*, one-sided jet with a very bright core at one end.

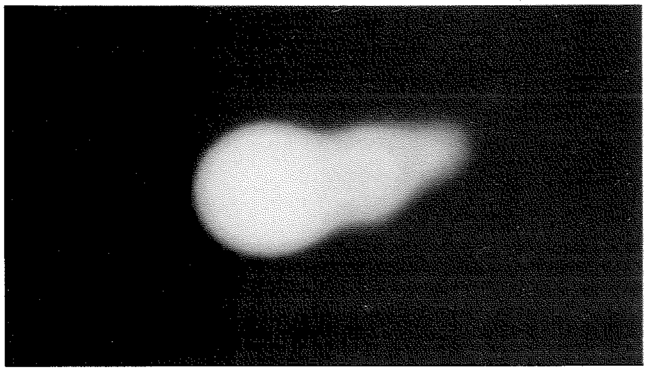
The VLBI picture (below) does not show the full resolution of these observations. We can use the full resolution of 1/400 arc seconds on the core; and we find that it is a double source, which is aligned with the large-scale jet, with a separation between the two features in the core of only 50 light years.

Since 1976 we have observed a number of quasars, and



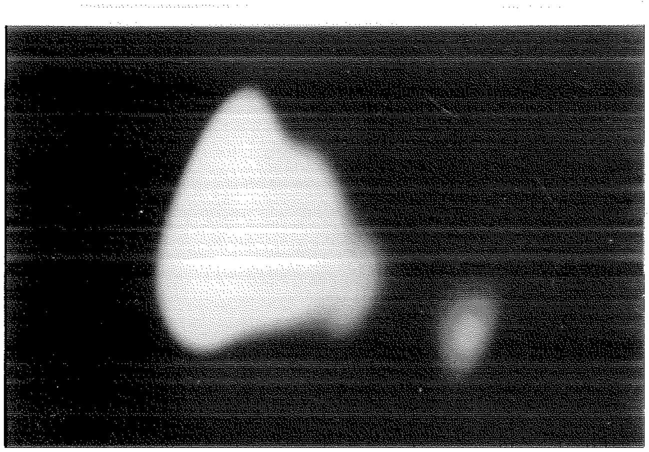
The first radio object to be mapped by VLBI was quasar 3C 147 — 7 billion light years away. This 1976 image with a resolution of 1/100 of an arc second showed a bright core with a surprising one-sided jet 5,000 light years long. The resolution of an optical telescope would have yielded an unresolved point one second across — five times larger than this jet.





Quasar 3C 380 (top), 8.2 billion light years away, is also a one-sided jet, although at this particular frequency the western knot in the jet is almost as bright as the core. The distance between the knot and the core — the two bright blobs — is 400 light years. In quasar 3C 345, seen here (bottom) with a resolution of 1/1000 of an arc second, the one-sided jet is about 50 light years long and is changing rapidly with time. Bright blobs are continually moving out toward the west and then fading away — at speeds apparently greater than the speed of light.

These images of quasar 3C 273 were made three years apart. In 1977 (top) the distance between the two blobs was 65 light years; in 1980 they were 92 light years apart. They appear to have moved 27 light years in three years or nine times the speed of light. This is called superluminal motion and is only an apparent speed, perceived because the blob is moving almost directly toward us.

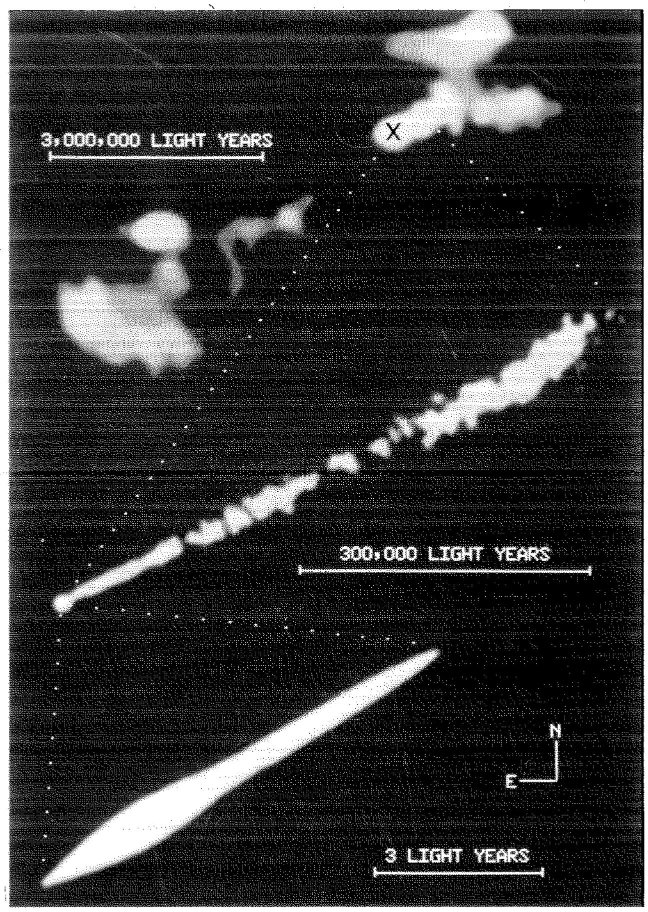


VLBI has revealed some extremely interesting features. We have seen 3C 345, also a one-sided jet, with a resolution of 1/1000 of an arc second. The jet is about 50 light years long and is changing rapidly with time. We continually see blobs moving out toward the west and then fading away. In an image made of another object — 3C 273 — in 1977, the distance between the two blobs was 65 light years. But in an image made this year, that distance is 92 light years. We also have observations from 1978 and 1979 that show the blob steadily moving out from the quasar nucleus. The extraordinary thing about these blobs in both 3C 345 and 3C 273 is the speed at which they *appear* to move. If the separation of the blob from the core of 3C 273 has changed from 65 to 92 light years, this is a distance of 27 light years in three years. So this blob is moving at an apparent speed of nine times the speed of light.

But this is only an *apparent* speed. The most likely explanation is that the blob itself is actually moving at slightly less than the speed of light, but close to it, and almost directly toward us. Because of the finite speed of light, this motion shows up as an apparent speed greater than the speed of light; Roger Blandford coined the term "superluminal motion" for this phenomenon. There is now a lot of other evidence that supports the above interpretation of this phenomenon.

It is remarkable that these quasar nuclei eject blobs of matter at nearly the speed of light and always in the same direction. What about the nuclei of radio galaxies? The best image we have obtained thus far of the nucleus of a radio galaxy is from a galaxy called NGC 6251 situated in a small cluster at a distance of 400 million light years. This object is by no means unique, but it provides a very good example of what we see in a number of extended radio galaxies and quasars. Optically this radio galaxy looks like a normal elliptical galaxy; however, radio observations reveal some fascinating properties of this object.

At right is a composite of three pictures of NGC 6251 made with three different radio telescopes giving three different resolutions. Note the different scales and the nesting of the two lower sections. The top image was made with the half-mile telescope at Cambridge, England. The optical galaxy itself is situated at the cross and occupies only a very small portion of this picture; the radio structure is similar to that of other typical radio objects. There are two major components straddling the galaxy, and the total size of the object is 6 million light years — about 60 times the diameter of a large galaxy. The region of the beam has also been observed at Cambridge with the five-kilometer telescope at higher resolution — about eight arc seconds — as shown in the middle picture. Here we see the beam along which matter and energy are transferred to the outer components. The length of this visible part of the jet is about half a million light years. The nucleus of the galaxy is coincident with the bright core at the eastern



Three views of radio galaxy NGC 6251 with different telescopes, different resolutions, and different scales. The entire radio galaxy (top) is about 60 times the diameter of a typical large optical galaxy. The center picture shows just the nucleus of this galaxy and the jet that carries matter and energy to the outer lobes. The lower frame shows only the core of the nucleus, which mimics the larger jet.

end of this jet. The galaxy itself only reaches out to about one-tenth the length of the jet in the middle portion. The core is unresolved by the Cambridge instrument, but using VLBI we have observed this nuclear source, as shown in the bottom portion. We see that the nuclear source mimics the structure of the larger jet on a scale 10^5 times smaller. The width of this jet is about one ten-thousandth of a second of arc — that is, equal to the width of a human hair seen at a distance of 50 miles. The visible part of the jet is about five light years long, and the brightness temperature is about 10^{12} K.

We can deduce some interesting properties of the galaxy from these observations. First, the total energy in these outer lobes is about 10^{61} ergs, that is, equivalent to the total annihilation of 10 million suns. In other words, the absolute minimum amount of matter that could give rise to the energy we see here has a mass of 10 million suns. On the other hand, if we consider ordinary thermonuclear burning, rather than total annihilation, we would have to increase this mass by a factor of 100.

Next there is the remarkably good alignment between this outer jet and the inner jet. This alignment, to within a few degrees, has persisted over at least the last million years — the time it would take matter traveling at the speed of light to reach the end of the jet. It only takes matter traveling at this speed a few years to traverse the inner jet. Thus, while an amount of matter comparable to a small galaxy has been expelled from the nucleus along this narrow beam, the alignment has not been disturbed. Physical arguments suggest that material is moving along the inner nuclear jet at nearly the speed of light. So the situation is similar to that in the quasars 3C 273 and 3C 345. In addition, the pressure required to collimate and confine a jet like this is very large.

Thus we have four stringent requirements of the object in the nucleus that is responsible for these radio features:

1) The object must produce a huge amount of energy to account for the energy in the outer lobes.

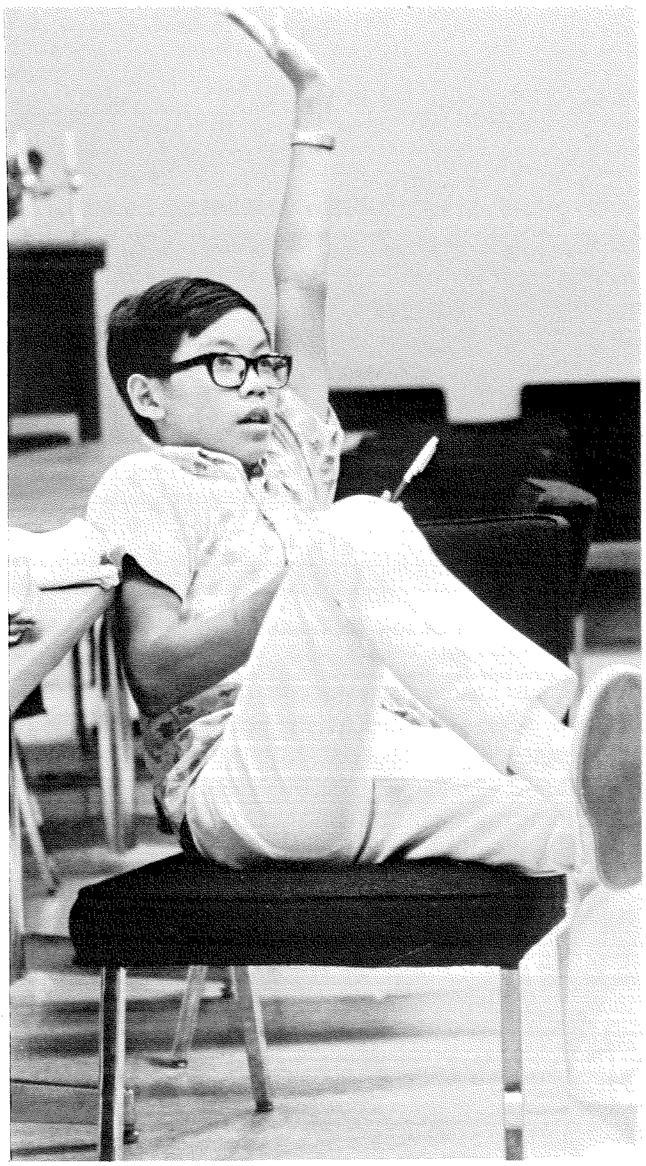
2) It must be very stable to account for the good alignment persisting over millions of years.

3) It must be able to eject matter at nearly the speed of light.

4) It must channel vast amounts of energetic matter into a narrow beam and withstand the high transverse pressure of the jet.

We know of only one class of objects that could satisfy all of these requirements, namely a spinning supermassive black hole of about 1 billion solar masses. We require it to be spinning so that gyroscopic action would make it very stable. If we imagine jets as coming out along the spin axis, this would account for the persistently good alignment. As we have seen, the object is required to produce enormous amounts of energy. A black hole in the galactic nucleus would use gravitational energy to power the radio source, and this is about 100 times as efficient as nuclear energy, so we do not need as much mass as we would if it were powered by nuclear energy. Finally, the high pressure and ejection of matter at nearly the speed of light would be most easily achieved in a relativistically deep potential well surrounding a black hole. Thus a 1 billion solar mass black hole is a conservative answer to what is going on in the nucleus of this galaxy. In a sense it is the minimal solution that can explain the observed properties of this remarkable object.

If this conclusion is correct, and there are indeed supermassive black holes in the nuclei of galaxies, then it is important to see if the observations allow us to learn anything about the space-time continuum around gravitationally collapsed objects. By pushing VLBI observations to higher frequencies, it appears very likely that we could achieve ten times the resolution that we have here. At this tremendous resolution of considerably better than a ten-thousandth of a second of arc, we would be able to look at the structure of some of these galaxies on a scale not much bigger than the size of the black hole itself. This would surely tell us whether the central object is indeed a black hole or some other beast as yet undreamed of. □



A Report Card for American Education

by SHIRLEY HUFSTEDLER

I have recently completed my first year of service as Secretary of Education — and also my last — and so it seems appropriate to offer my version of a report card on the state of American education as it relates to science, mathematics, and engineering. I also want to make a few suggestions about some trends I think can be of importance in the next decade. Like all gazers into crystal balls, I am not passing out warranties along with my predictions, but I don't have any hesitancy about proposing some courses of positive action by the nation's great universities and by the private sector because there must be action from both if we are to avoid unpleasant consequences from some of the trends that I foresee.

I'll begin with some good news. Contrary to popular belief, American public education in the elementary schools is in very healthy condition. Today's elementary schools are better by far than those of 30 years ago, or even 20 years ago. That is likely to be lost sight of in a place like Los Angeles, which is going through the turmoil of an integration order. It is also likely to be lost sight of in many other major urban centers in which all kinds of problems are evident in education — as they are in every other sector of the society in the large cities.

The report card with respect to those elementary schools is high, even though schools are being asked to perform today a simply extraordinary number of nontraditional tasks as well as to serve a much more diverse and less affluent population than ever before. During my tenure as Secretary of Education, I was in classrooms all over the United States, and I made it my business — because that *was* my business — to learn what was happening in classrooms that I could not visit personally. Seeing is believing, and accordingly I have become a believer. Our elementary schools are not as good as they can be or as they ought to be, and therefore I cannot give them the highest possible mark. But they certainly deserve a solid B+.

The contrary view is shaped not only by the American addiction to bad news as a daily portion of one's news diet but by the needs of the media for dramatic stories. Neither bad news nor drama has been lacking in American education, especially in the large cities. Prevailing negative attitudes about schools have also been shaped by the fact that today only 28 percent of our population has children in school, and the proportion of students from upper- and middle-income families has declined dramatically. As a result, fewer and fewer of those families ever visit the public schools, and that accounts in large part for their estrangement from what is really happening there.

Educational success is not limited to elementary schools; I have also seen some outstanding secondary schools, even under the most difficult environments. But that, alas, about ends the good news story about the state of American education. The nation's junior and senior high schools as a whole are experiencing very severe difficulties, not only in the inner cities where you might expect it, but in many other areas as well. While there are some very bright spots in the report for secondary education, not many of them are in the areas of science and mathematics. In October the National Science Foundation and the Department of Education sent to the President a report on the state of science, mathematics, and engineering education in the United States. It is a very detailed report, and the conclusion was that we have good reason to be alarmed — not simply about the state of education at this instant but about the kinds of nationwide trends that threaten scientific and technological decline within a generation.

The position of power and leadership in the world, as well as the amazing prosperity that the United States has enjoyed in this century, has many foundations, but no one could deny the significant role that has been played by the scientific and technological supremacy of this country. I am not suggesting that we are in imminent danger of losing that advantage. American science remains the envy of the world, and no other nation will soon match the brilliant constellation of research universities in the United States. Ultimately, however, those universities and our entire structure of scientific research and high-technology industry are based on the quality of education provided in the elementary and secondary schools.

We have failed to maintain the momentum in science and mathematics that we gained in the post-Sputnik era. I don't need to remind anyone of the galvanic effect of the space race upon science and technology throughout American society, particularly in the schools. Alas, it is sad but true that when the nation's priorities shifted from extensive space exploration and the development of the aerospace industry, support for science and mathematics education in the schools began to erode.

The number of science courses offered and required has dropped all over the nation. This decline in our standards and efforts has occurred at a time when our international rivals for technological supremacy have raised their standards and redoubled their efforts. While fewer and fewer American students are being exposed to rigorous scientific and mathematical curricula, more and more students in Germany and Japan and the Soviet Union are pursuing very difficult and sophisticated courses of study. Every year more than 3 million students graduate from Soviet high schools with two full years of calculus under their astrakhans. By contrast, barely 100,000 American high school graduates have taken even one year of calculus. American performance improves during the early years of college, but it is not improving fast enough to keep us abreast of our counterpart students abroad.

These problems of secondary education are not remote, as they might seem, from the concerns of Caltech. It is true that the quality of higher education in the United States is outstanding, rating a full A in university after university. That is particularly true at the very top levels of science education. Caltech is still an A+ institution at the pinnacle of that structure. There is at the present time no dearth of highly qualified applicants for every available spot on the campus, but if we don't act now to shore up our secondary school system, that state of affairs is unlikely to continue either for Caltech or — perhaps even more importantly — for less distinguished institutions that nevertheless will play very significant roles in the training of scientists, mathematicians, and technologists for the rest of this century.

Because our great colleges and universities have experienced no shortage of intellectual riches even in an era of declining youth populations, there has been a temptation to be rather complacent. A number of highly respected leaders in science, math, and engineering have remained aloof from the serious problems brewing in the secondary schools, in part I think because they have not fully appreciated what is happening. Aside from sheer love of science (and who is to love science and to guard its health if not those who practice and teach it?), there are some eminently practical reasons for institutions like Caltech to become more involved than they already are in secondary education.

In the first place, we have to consider the quality of future students. Even when one takes only the top one-tenth of one percent from the pool of potential students, the quality of the freshman classes will still depend on the size of the pool and the abilities of its members. Yet today hundreds and thousands, even millions, of potentially brilliant scientists are being turned away from science at a very early age. The most critical age today is the seventh grade, where youngsters, once fired up by high-quality elementary schools, begin to see that their futures are not expanding as they should. They are not being adequately challenged; they are not being asked to persevere for rigorous academic training at a time when their natural talents might be permitted to mature.

Entire minority communities and an enormous portion of young women never even consider the possibility of careers in science. And even among white males, the number of students giving short shrift to science, math, and engineering is not encouraging. Though they have no way of knowing it, some of these youngsters belong in the Caltech freshman classes of the eighties and the nineties, and they are not going to be there. Because of that, their lives as well as the lives of Caltech and the nation will be far poorer.

Outstanding students are not the only ones who are going to be in short supply if we don't reverse this trend. Faculties and the whole array of practical researchers and engineers who sustain our scientific establishment are decreasing. Already there are spot shortages of qualified people in areas of computer science and certain other fields. Because the demand in computer science, for instance, is growing at an astonishing rate, these shortages will get worse. Even in fields that have not experienced overt shortages, intense private sector competition for talented and well-trained people often skims the most able young men and women from the campuses before they are willing or have had an opportunity to undertake serious doctoral and postdoctoral work. The general scarcity thus undercuts the vital work of regenerating our teaching faculties at both the secondary and the postsecondary levels. Someday we may be in the ironic position of having piqued dramatically the interest of students in high school, only to find that the college-level distinguished faculty does not exist to teach them. We are already facing very serious teacher shortages at the secondary level in science and math.

Ultimately, however, the greatest risk for institutions like Caltech is that we will produce an entire generation of young people who are not only ignorant about science and math, but who are actually alienated from both. Over the course of a generation, Americans convinced themselves — incorrectly, to be sure — that science and technology could accomplish anything and everything. Disillusionment was, of course, inevitable. It should come as no surprise that there is now an almost equally incorrect strain of thought that contends that science and technology can accomplish nothing — or at least, that every gain is outweighed by costs and the dangers of its unintended consequences.

In a sense science has been both oversold and undersold. Relentless change did not bring us the nirvana that Madison Avenue told us we should have, and it had heavy and pernicious effects upon our environment. Yet the long-term solutions to so many of our problems — from cleaning up polluted air to producing an adequate food supply for our country and the world — can only be found through recourse to the very same science and the very same technology. When I say *same,* of course, I do not mean that it should not undergo improvement.

Some people within American society have been slow to recognize this. There is increasing evidence that our own people are rapidly becoming divorced from any real understanding of the machines and the ideas that routinely govern enormous portions of their lives, both at home and abroad. We face the dangerous possibility of increasing isolation of the scientific community from the rest of humankind. All of those connected with Caltech know very well how many symposia over the years have been devoted to sounding warnings against the propagation of distant scientific elites who deal with problems incomprehensible to the rest of the nation. Such a state of affairs is dangerous to those who do not share in the scientific and mathematical knowledges because they are likely to find themselves permanently confined to an underclass of society. In the past, illiteracy formed the underclass; in the future, it is extremely likely that scientific and technological illiteracy will be the mark of the underclass of America.

Isolation and alienation may be even greater for the scientific and technologically literate. The rising generation will, after all, ultimately control political and economic levers of our entire society. Individually and collectively, they will make decisions that will govern the fate of the whole scientific community. Even without the gifts of Cassandra, I can easily foresee the very unpleasant consequences that may arise if scientists are estranged from the great majority of our people. It is the most natural of human instincts to be suspicious, to be anxious, and to be angry about things that are outside our own understanding.

At best, we may predict that money will be shorter for science in the next few years than it has been in some of the past years. It is perfectly true that money is not everything, but in science it is also true that no money is very nearly nothing. Research support has already suffered in an era of inflation and its necessary budgetary constraints. If the politics of inflation should be wedded to the politics of alienation from science, institutions like Caltech could enter an era of permanent austerity. Experimentation, as all of us know, is not always immediately cost-efficient. It is rarely tidy, and it is virtually never straight-line. Its worth is not always intuitively obvious. Considered in that light, it is genuinely remarkable that such an activity as science has been funded so well for so long by those who are not directly participants. But if the holders of tomorrow's purse strings lack understanding of and faith in scientific inquiry, then all research will suffer, and pure research will become an endangered species.

Anti-intellectualism is never very far below the veneer of any civilization, including our own. We should not delude ourselves that Galileo's trials and the Luddite rages were merely historical oddities. At present we are seeing a growing movement toward return to some persons' notions of fundamental biblical verities in rebellion against the scientific and social uncertainties of our time. When that movement is combined with fears (whether or not legitimate) about nuclear power, as it is in our society today, an unmistakable element of active hostility toward science is created.

We can't let ourselves become the victims of ideological mood swings; we have already seen in China what happens when emotional fervor is wedded to political zealotry. The convulsive upheavals of the Cultural Revolution locked out a whole generation of science and scientists and effectively foreclosed schools and universities from replacing them. China is only now beginning a slow and exceedingly painful recovery. Such an anti-intellectual exposure to popular rage is all but unthinkable in the United States, but it is most surely not impossible. If we do not act now to curb the growth of technological and scientific illiteracy, there may come a time when the unthinkable can indeed be thought right here.

Furthermore, the ideological perils to science are not limited either to the left or to the ill-informed. Some proposals emanating from other directions are almost as disturbing. Dr. Milton Friedman, for example, has suggested that the National Institutes of Health and the National Science Foundation should be disbanded. He believes in effect that federal support for scientific research should be

The children of this nation are not simply part of the future; they are the whole future

eliminated and that future decisions and future funding should be left to private initiative, wherever and under whatever circumstances it may be found. I don't think I need to spell out how potentially disastrous such a policy could be in American science. Our pluralistic society and our mixed economy are simply not very well suited to sudden, drastic, and sometimes doctrinaire solutions.

There's always a danger in making public lists of potentially troublesome things because if the list is long enough and discouraging enough some people may react by simply throwing up their hands, and I don't believe in pessimism at all. My indications of what is troubling do not mean that I think the problems are insolvable; it does not mean that there are not a lot of good things going on that are working to resolve those issues. There are many counterforces to the centrifugal forces that have moved us apart from one another for a significant period of time.

As a matter of fact, the United States has the resources to do all the jobs that need to be done with respect to education, as long as we appreciate that we can no longer engage in tiresome turf wars with one another. We must, instead, begin to put our resources together in new, creative, cooperative ways. Those resources, then, can do positive things toward reversing these trends.

Let me just give you a few examples from the many I have. Johns Hopkins University is attacking the problem of poor scientific and mathematical education at the secondary level and doing so head on. The University is administering a unique program designed to identify junior high school students (remember, I said those are the youngsters who are most at risk today) who are gifted in math and to make sure that every one of them has an opportunity to develop his or her talents. Johns Hopkins uses the Scholastic Aptitude Test for college admissions to identify these gifted youngsters, and then puts them in touch with various public and private programs offering advanced instruction in mathematics. In just a few years, more than 1300 students in Maryland have been rescued from school curricula that were too limited and simple to challenge them or even to hold their interest. Instead of tuning out in the seventh grade, they have now taken the first steps to*ward very exciting careers in math and science.*

Johns Hopkins is also responsible for another extremely energetic and interesting program. It has adopted Dunbar High School in Baltimore. Dunbar is 84 percent black, and it has only 3 percent white students. The University has produced a program in which these young people prepare for careers in both health and science at every single level from learning entering basic skills through sophisticated technology. Johns Hopkins does this by using its own personnel to teach in the high schools and to bring youngsters into the hospital for training from the time they are in the eighth grade. The results have been remarkably good.

Our neighbor to the north, the University of California at Berkeley, is working intensively on extremely imaginative programs in the Bay Area secondary schools. Other universities are working in the field of educational television to fire the imaginations of the young and to instruct the general public. Such efforts at public education both for children and adults should be an integral part of the scientific community's approach to improving scientific curricula in the schools. I welcome programs like *Cosmos*, which is now reaching an enormous audience, to begin to turn the excitement of *Star Wars* into the reality of what is *basic to scientific information. It is only by communicat*ing the joy, the mystery, the excitement, and the truths of science that we can effectively counter the propaganda of some zealous anti-intellectuals and unknowledgeable radicals who are taking dead aim at the scientific base.

Another great set of resources that need to be moved in new ways for the support of education is the private business sector. I am aware of many exciting programs in which private businessmen in the United States have become involved intimately in secondary schools. They have learned an enormous amount; they have brought a great deal into those institutions; and they can make important contributions toward turning around the inadequate scientific, mathematical, and engineering education in this country.

Education is in some ways very much like a natural resource, like coal, or oil, or timber. It fuels rapid economic growth and progress; indeed much of America's prosperity and incredible growth in the postwar years has been due to the extraordinary quality of the educational system. But natural resources are not different in some respects from human resources. They have to be taken care of appropriately and effectively over a long period of time before their true productivity can ever be realized.

The flourishing private business sector has been the result of the coming together of educational, scientific, financial, and management resources into a synergism — a whirl of activity in which the whole is greater than the sum of its parts. Out of that synergistic whirl has emerged tremendous prosperity for this nation, but (if you'll forgive a pun) there cannot be any synergism when no one is feeding the sinners. And there can be no future profitability or even survival of American business if it does not have a healthy and secure relationship with the American public school system.

Now in the past, business has not shirked its obligations to education in many respects. Support has been generously extended to postsecondary institutions, but the time has come to extend that regard and help into the area of the secondary schools, without abandoning the postsecondary institutions. I want to mention a few of the things I have seen effectively done in the junior high schools and high schools by American private business — things that are really important to go on feeding those sinners. Some of these things are really quite simple; others take a great deal of effort. For example, some of the systems that have been very effective involve no more than an industry finding a junior college, a community college, or a high school that is now clanking along with equipment that is wildly out of date and making a donation of equipment that is just a little bit out of date. That is an instance when business can do both good and well at the same time — doing something very good for those schools and at the same time giving itself a perfectly nifty tax writeoff. I don't mind at all if people do well by doing good; and I don't mind appealing to lesser sensibilities than conscience if cupidity will get me what I need for the children.

There are also things that involve a great deal more; for example, there are severe shortages of teachers of mathematics in the secondary schools. Secondary school teachers are paid miserably, and they lead a hard life. To ask somebody of more than ordinary sense — let alone of extraordinary intelligence — to work at a rate of pay that is significantly less than for those who do routine blue-collar labor is to ask him to do things that are contrary to economic and personal good sense. We still have dedicated teachers who do that because they take teaching as a calling, like becoming a member of the clergy, but you cannot expect to populate the schools with teachers who are all seeking roads to canonization.

We need real help for these teachers, and so I have encouraged people in the private sector to consider taking some of these dedicated science and math teachers and arrange for them to spend a year's sabbatical in the private business sector, during which they will finally be paid a decent salary. This should not only give them a new enthusiasm about what they do, but also give them an opportunity to have greater outreach and thus to bring back more into the classroom.

As Secretary of Education, I have been developing a whole recipe book of similar projects. I don't mean to suggest that it is the federal government's business to preside at shotgun marriages between the private sector and secondary schools. Not at all. But I don't think there's anything wrong with inviting the two groups to a courtship ceremony. If they get together, fine.

In short, there are many things that American businessmen can do, and that a number of them are already doing. But it must not be too little and too late. I don't need any elaborate study to know who are going to be the entry-level workers, the graduates, and those who are going into postdoctoral work in the late eighties and nineties. All I need to do is to go into any junior high school in the United States. There they are. That's the population we have; that is *all* of them. And that is why I am not only extolling the virtues of getting involved, but I am also saying that getting involved is survival. The children of this nation are not simply part of our future; they are the whole future. That is why it has been such a wonderful opportunity for me to begin to work with and for education on a much broader scale than was ever possible before.

One other aspect of my report card for American education that I want to mention is the marvelous diversity and intricacy of our educational system. We need to understand and think carefully about what the American public elementary and secondary schools mean to this country because we can never simply abandon them. We can never leave the poor behind. Brilliance and talent do not come simply in one color of skin, in one gender, or in one group of people in one economic sector. Talented people appear at all economic levels and in all colors of skin, and though some of them may have fewer advantages, they are just as necessary a part of a bright future as our more traditional students.

I believe firmly in setting national goals and undertaking bold missions — like those of the early days of our commitment to science, to space, to exploration beyond the limits of our immediate grubby sense of instantaneous territorial concerns. We do not do anything that really counts for the future unless we are willing to take a soaring leap of the imagination — to set not only a hilltop as a goal but a margin in outer space, saying "We shall go there. We shall go together; we are going to make the investment. We are going on a great trip for all humankind."

I hope in the years to come we shall see a renascence of the spirit, not simply of going across the street to help our neighbor — though that trip must always be made — but that we shall set our sights and our minds and our spirits for the whole nation to continue that great voyage of exploration of the human mind. □

Integrated Optoelectronics

by AMNON YARIV

A new information era, which will cause a fundamental change in the way we go about our daily lives, is about to dawn as the result of a major technological development now under way in the United States and Japan. We may even call it a revolution in communication.

Three separate technological breakthroughs, almost simultaneous but independent of each other, are responsible for this revolution. The first is the incredible advance that has taken place in the last 10 years in the very large scale integration of semiconductor circuits. This technology, which in 15 years has condensed the calculating power of a room full of computers into a box that fits in a pocket, makes it possible to store and process vast amounts of information at high speeds, using small and inexpensive hardware. Major advances now in the works, aimed at making basic transistors and circuit elements with submicron dimensions, will cause a further increase within the next 10 years of several orders of magnitude in the number of electronic functions that can be packed onto a semiconductor chip one centimeter square.

This vast and rapidly increasing capability for data handling would be of limited usefulness if it were not possible to transmit the data from one location to another at very high rates; otherwise the transmission link would form a bottleneck. It is also important for the cost of transmission to be low enough to be afforded by the average household. This brings us to the second technological breakthrough — optical fiber communication.

Up to now, the mainstay of modern man's communication has been transmission systems based on copper. Coaxial cable and twisted wire pairs still carry the vast majority of telephone conversations and communication data within cities. These installations, however, are the last dinosaurs of the communication field, and they are already on their way to extinction. The new and more agile predators causing this demise are inauspicious in appearance. They are tiny ("hair-thin" as the ads say) silica glass fibers with diameters between 5 and 50 microns (1 centimeter equals 10^4 microns).

Glass fibers have been used since the 1950s for specialized applications involving short-distance transmission of light (less than a few meters). Originally they were not considered as serious contenders for long-distance optical communication because of the huge losses, of the order of magnitude of 3000 decibels per kilometer (db/km). A loss of that amount causes the intensity of light propagating in a fiber to be halved during each meter of path length.

What changed this situation was the realization in 1968 by researchers at the Standard Telecommunication Laboratories in Great Britain that these high losses were not intrinsic to the fibers but were due to impurities incorporated during their fabrication. Two years later scientists at the Corning Glass Works succeeded in pulling a fiber with losses of only 20 db/km. Further advances have resulted in fibers with losses down to the intrinsic level of about 0.1 db/km, due to Rayleigh scattering from the frozen-in thermodynamic inhomogeneities of the glass. At this level we can consider the prospect of propagation links with lengths of a few hundred kilometers between repeater stations, where the attenuated signals are reamplified.

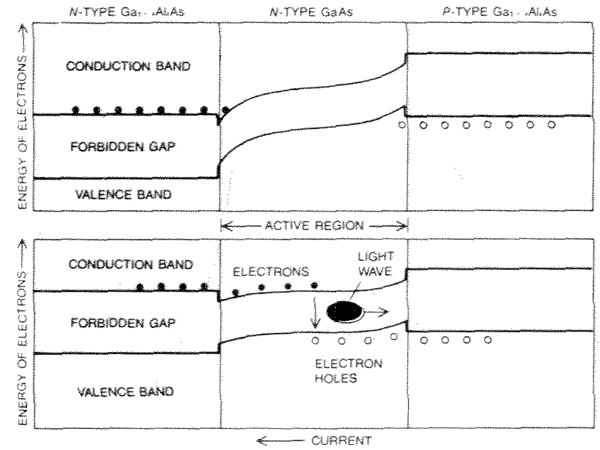
An important property of these fibers is their extremely large bandwidth, that is, the ability to transmit very short (about 10^{-12} seconds) optical pulses; this makes them capable of carrying vast amounts of information. A single glass fiber a few microns in diameter can carry the entire FM and television channel spectrum with plenty of room to spare, or the equivalent of one hundred thousand telephone conversations. Fibers can transmit, conservatively, at speeds of billions of bits (gigabits) per second (bits are the measure of the number of pulses carried by the wave); this is a tremendous increase in data-transmission rate over other forms of communication. At these rates it will take approximately 1/100 of a second to transmit the information contents of an average book, or about four hours for the entire collection of a major library of one million books.

So, someday this "hair-thin" glass fiber entering an average home will be able to put at the disposal of its occupants huge amounts of information, which at present may be available only at special, often remote, sites. It will be much cheaper then to transport data than to transport ourselves. Our grandchildren will find it difficult to believe that back in 1981 we were so primitive that an engineer in Los Angeles had to board an airplane (and the price of fuel at this future time will probably reach $100 per gallon) and spend three days on a trip to New York just to discuss some blueprints for a new project with a client.

But the fibers only *transmit* light at gigabits per second; first the light has to be launched into the fibers. This brings us to the third partner in this technological troika — the semiconductor diode laser — a device less than a millimeter in size, which, when energized with a small voltage (about 2 volts) emits a coherent infrared beam that can carry the information "piggyback" as it propagates in the fiber. These lasers, invented simultaneously in 1962 by researchers at IBM and General Electric Research Laboratories, are still undergoing intensive development, and some of their properties are still topics of current research.

The principles of operation of these semiconductor lasers involve semiconductor physics, quantum electronics, and optics. With later modifications, the laser consists basically of a number of layers (transparent thin films a few thousand molecules deep) of gallium arsenide (GaAs) and gallium aluminum arsenide (GaAlAs) and takes advantage of the fact that the former has a smaller energy gap than the latter. When voltage is applied, electrons from the n-type layer of GaAlAs combine in the central GaAs layer with electron vacancies (holes) from the p-type layer of GaAlAs, producing a photon, which becomes part of the laser beam.

When the GaAs semiconductor laser appeared in 1962, I was working at Bell Laboratories, where it was *not* invented, so we were, of course, eager to see what our competition had done. As we were studying the physics of it, to try to discover the reason for its low light loss, we realized that dielectric waveguiding was going on at the p-n junction of the laser — that the layered structure trapped light as well as electrons. Light guiding, or waveguiding, confining and channeling a propagating beam of light (even a laser beam eventually spreads out), was first demonstrated in 1870. It involves the optical principle of total internal reflection, propagating a beam of light without any loss when an inner layer of the waveguide has a higher index of refraction (the degree of retardation with respect to the velocity of light in air) than the outer layer. In the original GaAs lasers, the waveguiding resulted fortuitously from the p and n doping of the different layers, causing a



In the layered structure of the semiconductor diode laser, the electrons (black dots) of the n-type GaAlAs and the holes (open circles) of the p-type GaAlAs have the same energy but are separated by the central GaAs layer (in the top diagram). When voltage is applied (lower diagram), the energy of the electrons is raised, allowing both the electrons and the holes to flow into the central well where they can jump the energy gap and annihilate each other. The resulting photons are confined in the central trap, which also acts as a waveguide.

single light ray to zigzag back and forth across the inner layer by total reflection.

Even before coming to Caltech, I became convinced on theoretical grounds that it would also be possible to guide light at the surface of semiconductor crystals as well as at the p-n junction. This would make the light more accessible to launching and removal as well as to manipulation by surface techniques, and thus much more adaptable to practical use. I asked David Hall, one of the first graduate students to join my group at Caltech, to undertake this problem as his doctoral thesis project. He also attempted to use the electrooptic effect in the same crystal to make a light valve (modulator), in which an applied electric field turns the light on or off. At the time we did not have the facility for growing the crystals, so it was a rather frustrating experience for David, who had to depend on the generosity of a few industrial laboratories to supply us with gift crystals (a generosity that later stopped altogether as the donors became our competitors). Fortunately, David persevered and succeeded in 1969 in observing waveguiding and switching in a dielectric waveguide in a GaAs crystal.

Up to this point, research on the semiconductor lasers and waveguides had been proceeding without any particular direction — it was a nice thing to play with. But shortly after David's experiment, the first low-loss glass fibers were announced, and it became obvious that the era of optical communication via fibers was almost upon us. All of a sudden there was a need for a whole new technology to generate and manipulate the light that the fibers could transmit. You couldn't use conventional lenses, prisms, and the like because they are just too big and clumsy compared to the micron-size fibers (picture a watch assembly line where the workers are elephants). We needed a new approach to making optical systems that include miniature lasers, the modulators to impress the information on the light beam, the detectors to recover the information, and electronic amplifiers — a whole system to couple to the microscopic fibers and take advantage of their high data rates. Thinking about all this back in 1970, it suddenly dawned on me that the GaAs and GaAlAs crystals that we were already working with were a material system capable of performing all the functions needed to feed and retrieve information from the fibers. It's a very versatile material in both its electrical and its optical properties. GaAs/GaAlAs was already the material of choice for making lasers; field-effect transistor amplifiers in GaAs had just been demonstrated, and we had just shown how to make waveguides and modulators in these crystals. The variety of problems to be solved was large, but the technology definitely feasible.

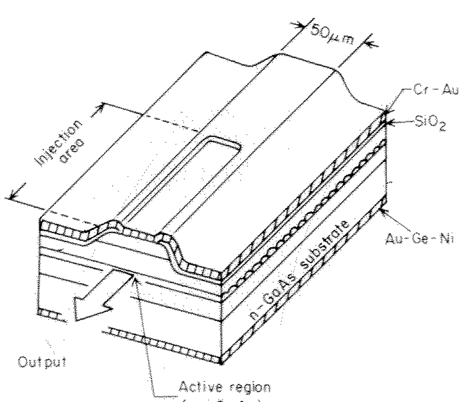
So, almost exactly 10 years ago, in March 1971, we proposed that it should be possible to construct complete single-crystal monolithically integrated optical circuits, consisting of lasers, waveguides, modulators, detectors, and amplifiers, that would function as transmitters, receivers, and repeaters in fiber communication systems.

What is amazing is that we were then left alone for eight years to work on the problem by ourselves — despite frequent proselytizing on my part. The giant communication and computer companies in the United States were not convinced by our initial arguments and didn't pick up the idea (although the Japanese started watching us very closely). This afforded us the opportunity to pursue our goal at a fairly leisurely pace with the tolerant support of the Office of Naval Research and the National Science Foundation. Thanks in large part to the ingenuity of our graduate students and postdocs, Caltech succeeded where American industry, with its great resources, balked.

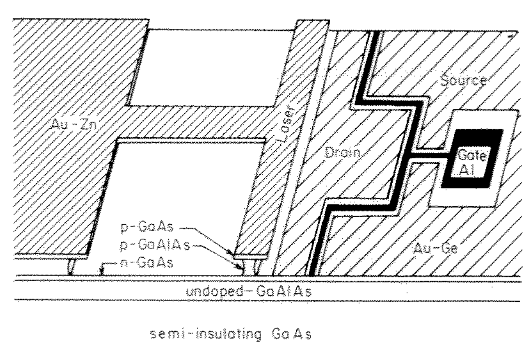
Before attempting the integration of all the functions in the "mother crystal," GaAs, we wanted to demonstrate that they could all be performed individually — as separate building blocks. A string of talented graduate students and postdoctoral fellows attacked many of the individual problems. One of our first tasks was to become self-sufficient in growing our own crystals. We do this with a liquid epitaxy (crystal-growing) system, starting with a semiconductor substrate, such as GaAs, and then bringing it in contact with successive wells of molten gallium saturated with the desired compound, for instance GaAlAs. When the temperature is lowered, a thin layer of that substance is grown on the crystal. Since GaAs and GaAlAs have the same crystal structure, the many-layered sandwich will act essentially as a single crystal. Impurities to create the p-type and n-type layers can also be added to the melt.

Many researchers contributed to the overall effort. Harold Stoll, PhD '74, and Sasson Somekh, PhD '74, demonstrated waveguiding in ion-implanted GaAs and developed the basic analytical and experimental tools to describe propagation in periodic waveguides. Shlomo Margalit, on leave as professor of electrical engineering at the Technion in Israel, added his enormous understanding of semiconductor device physics.

A great deal of our work has involved making lasers, and our lasers at Caltech are superior to those from any U.S. firm. Graduate students Huan-Wun Yen, PhD '76, and Willie Ng, PhD '79, and postdocs Michiharu Nakamura and Abraham Katzir, developed the distributed feedback laser, in which a fine surface corrugation, or grating, with a period of a fraction of a micron, replaces the end



The distributed feedback laser uses a built-in corrugation for reflection (feedback) instead of the conventional end mirrors. The light generated in the active region by electron-hole combination is continuously Bragg-reflected back and forth by the corrugation, whose period determines the oscillation wavelength with great accuracy and stability.



In this integration of the main electronic and optical elements, a field-effect transistor (FET), consisting of a source, gate, and drain, is grown monolithically along with a semiconductor laser on a single crystal of GaAs. The FET acts as a gate, which is capable of interrupting the laser current, turning it on and off at rates of a few times 10^9 per second.

mirrors in creating laser feedback by Bragg reflection of light (like x-rays in crystals). The gratings, produced by lithographic techniques, can also act as optical filters and multiplexers, since they discriminate among wavelengths. Along the way they also demonstrate field controlled coupling of light between adjacent waveguides.

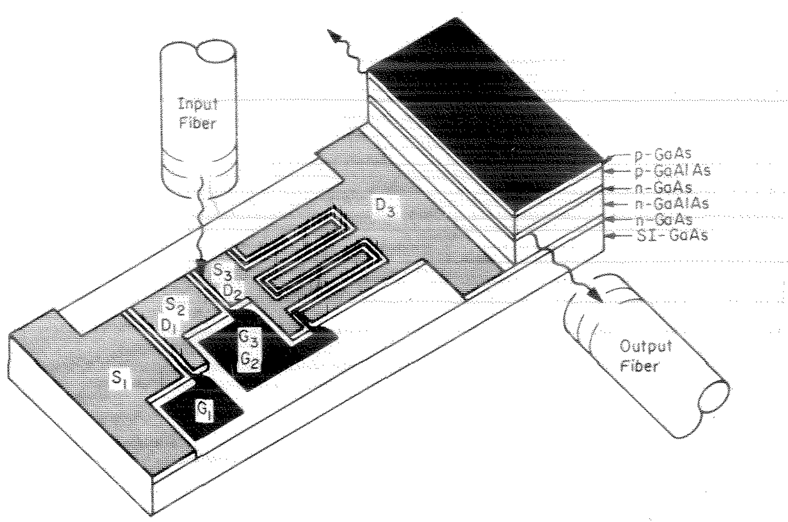
At about that stage, in 1975, we felt ready to begin integrating a number of optical devices on a single-crystal chip. One of the first examples involved, naturally, bringing together the two main actors of optics and electronics — the laser and the transistor. Taking advantage of the basic similarity in the epitaxial layer structure of these two building blocks, Israel Ury, PhD '80, grew them together on a single crystal.

Another interesting example involved the monolithic integration of a microwave oscillator (Gunn oscillator) with a diode laser. The oscillator current, which flows through a crystalline channel directly into the laser, oscillated in our first experiment at a rate of 10^9 Hz, causing the light output to turn on and off at this rate.

The world's first completely integrated optoelectronic circuit was an optical repeater consisting of a light detector, electronic field-effect transistor, current amplifier, and semiconductor injection laser fabricated on a single chip of GaAs. The attenuated light pulses (as a result of long-distance propagation) enter the repeater from the incoming fiber at the detector. The current pulses are translated by the detector into voltage pulses, which are applied to the current field-effect amplifier. The output current pulses are fed into the laser and converted into large output light pulses that make their exit via the output fiber on their way to their ultimate destination. The technology is now available for long-distance communication over tiny optical fibers.

What happens next? At this point the biggies in industry have seen the light and are entering the game. At home, giant Ma Bell has finally picked up her skirts and waded in. In Japan, Hitachi already has a big effort, headed by our ex-postdoc Nakamura. The Japanese government has also established the Optoelectronic Collaboration Laboratory, which, as its name indicates, involves the cooperation of the large electrical companies there (Nippon Electric, Hitachi, Toshiba, Mitsubishi, and Fujitsu) with a charter to do research and basic development in optoelectronic integration. Further advances in this field will involve large expenditures of manpower and money — both more available in industry than in academia.

Our own effort has already changed direction. When we were trying to convince industry of the advantages of optoelectronic integration, we had in some cases to become more practical and technological than is our custom. Our research group is now moving back into a more basic pursuit of the material and electromagnetic aspects of the field. We are looking at the effects of the properties of the layer interfaces on the carrier lifetimes. Graduate students Tom Koch and Liew-Chuang Chiu are doing this with the aid of picosecond lasers. We are planning on growing synthetic crystals by molecular beam epitaxy, which makes it possible to control the thickness of the layers within a few angstroms. Chris Harder and Kam Lau are considering the ultimate frequency response of semiconductor lasers, while Dan Wilt has developed what is probably the first realistic numerical model of a semiconductor laser that allows for the interdependence of the optical and electronic properties. Hank Blauvelt and Joseph Katz are cooking up lasers with radically new layer structures and properties, and P.C. Chen is now working with a new "mother crystal" — indium phosphide — which holds a great deal of interest. This should keep us happy and busy for some time to come. □



This complete monolithic optical repeater station regenerates the weak pulses from the input fiber. Current generated by FET 1 (source S_1, gate G_1, and drain D_1) flows through FET 2, whose source-to-drain resistance is modulated by the incoming light pulses. The resulting small voltage pulses are then fed to the gate of FET 3. The resulting large drain (D_3) current pulses enter the laser (raised mesa at right) through the common n-GaAs layer, causing it to turn on and off, feeding the regenerated optical pulses into the outgoing fiber.

Frederick C. Lindvall

—How It Was

Frederick C. Lindvall, professor of engineering emeritus, was interviewed by Ann Underleak Scheid for the Oral History Program of the Caltech Archives. E&S *has made a shortened version of the original transcript and presents here Part Two (of two parts).*

Ann Scheid: Could we talk about what you did during the war years?

Frederick Lindvall: Well, shortly before Pearl Harbor, I got involved with Dr. Charles Lauritsen's group. He was much impressed with what rockets might do. He had a chance to learn something of the English experience with rockets, and he came here and got projects started on them. It was all very hush-hush. I was asked to help on this, and I started devoting part time to it. Then when Pearl Harbor came, I went full time on it.

My particular responsibility was rocket launchers, and at that time we had them for land use, ships, and aircraft. Later on, Carl Anderson, who was also working on the project, took over the aircraft-type launchers, and I continued with the shipboard launchers, particularly those for landing craft and some for land and amphibious vehicles. We would get up early in the morning, drive out to Goldstone Lake and do our test firing, and then drive home again, getting home after dark.

Then the Navy came to Dr. Lauritsen with torpedo problems. The Mark 13 aircraft torpedo was not performing as it should. I was asked to form a group to work on the torpedo, so I dropped out of the rocket business. The big problem with the Mark 13 aircraft torpedo was that it was dropped from aircraft, but there were such limitations on the speed at which it could be dropped and the altitude from which it could be dropped that the torpedo planes were virtually sitting ducks for the anti-aircraft fire from the ships being attacked. Also the torpedoes wouldn't run properly after they got into the water. They would suffer internal damage and would broach the surface of the water and run in a crazy path. We built a launching facility behind Morris Dam to simulate water entry. It was literally a long tube down the hillside, and we blew the torpedoes out with compressed air so they would enter the water at whatever speed we wanted, depending on the amount of air pressure we put behind them. We would study the underwater trajectory and examine the works afterward to see what the internal damage was. We also developed instruments to determine the kind of accelerations that were occurring in different parts of the torpedo at water entry. We explored various head shapes too, to see if anything better for water entry was possible. It turned out that the existing head shape was pretty fair, but we discovered that the tail structure exerted quite an influence in controlling the entry. The more tail structure we had on the torpedo, the better it behaved. So we came up with the idea of a shroud ring that went on the tail of the torpedo.

Another group at Caltech was working in the water tunnel, and they found a good profile for this ringtail. We machined these, put them on torpedoes, and stabilized the water entry. We also made certain improvements in the way of the mounting of the equipment that kept things running, as the term goes, "hot, straight, and normal." Then we conducted tests at sea from a carrier that let us use its planes. We loaded them with these modified torpedoes, and then the torpedo planes fired them at their own ship. Of course, there was no explosive in them. They were set to run deep, so if they ran properly, they would run under the ship. The performance so impressed the skipper that he wanted all the modified ringtail torpedoes he could get his hands on to take out to Pearl Harbor, which he did. He demonstrated them to Admiral Nimitz, and Nimitz ordered the Bureau of Ordnance to modify some thousand Mark 13 torpedoes. Since the Bureau of Ordnance hadn't heard much about what we were doing, it was quite upset, but we were able to work directly with the fleet here at Caltech and not have to go through the cumbersome Washington machinery.

Later, I was asked to split my engineering group to assist the Manhattan Project people. So we divided the group and added some more engineering people to it and took over part of the manufacturing facilities we had acquired for rocket work out on East Foothill Boulevard. Our principal mission was to develop a backup fusing system for the A-bombs. Our version didn't have to be used because the Los Alamos version worked, but nobody knew until it was tried, and they had to be sure.

AS: So actually Caltech was involved in manufacturing at this time?

FL: Oh, yes. We modified several hundred torpedoes before the Navy got its own production going, and Caltech manufactured well over a million rockets that went into service. It was done in shops all over the place; wherever we could get any machine time, we would contract for parts. The Caltech people — principally our chemical engineers Bruce Sage and Will Lacey — set up the powder extrusion facility in Eaton Canyon to make powder grains for the rockets, and that was a big operation.

AS: Were you getting contracts from the government?

FL: Yes, we worked under the National Defense Research Committee (NDRC) and later on for something called OSRD,

Fred Lindvall and students at the weekly Winnett Center coffee hour in 1964

which was the Office of Scientific Research and Development. At that time, Richard Tolman was one of the principal people in that operation in Washington, along with Vannevar Bush.

AS: What was happening to the regular activities of the Institute?

FL: Well, there were special war training programs, in which people taught things that were perhaps a little elementary — drafting, elementary electronics, and the like. We got instructors wherever we could, people who were teaching in high schools and junior colleges.

AS: So the training became less academic?

FL: Yes, but there were, of course, a few of our regular students, and then we got the Navy V-12 program, and a whole group of students transferred from Stanford to Caltech, so there was a sudden increase in the student body. The V-12 program was mostly engineering with some work that was relevant to Navy things — some on ordnance, some on navigation principles, things of that sort. These students were going to be commissioned directly into the Navy.

AS: How did this affect your teaching?

FL: I wasn't doing any. I was working on rockets and torpedoes at this time, but Professor Sorensen kept on teaching, and Professors Maxstadt and Robert Daugherty, and a number of other people who, for one reason or another, didn't want to or didn't fit into what was going on in the Caltech contracts. They kept on teaching and doing almost double duty.

AS: Did you do quite a bit of traveling in this period?

FL: Oh, yes, to make installations of rocket launchers on support boats that were going to take part in the African invasion. I went to Norfolk, Virginia, for that. We conducted some test firings with these special rockets — barrage rockets. They were quite inaccurate as far as trying to hit a target, but for barrage purposes — bombarding a beach prior to landing — they were quite effective.

AS: Did you really go out on a carrier for your torpedo testing?

FL: Well, actually, we were in a Navy blimp looking down to watch the torpedoes running. That was off the coast of southern California. And there were lots of trips to Washington and some to Los Alamos.

AS: Were you at Los Alamos when the bomb tests were made?

FL: No, but one day while I was on the Manhattan Project I got a call from a Caltech graduate who had been a Naval reserve officer and was back in uniform. He was with Navy procurement in Los Angeles, and he wanted to know if I knew a Dr. Benioff in the Seismological Laboratory. "Oh, yes," I said, "I know Benioff." "Well, I have a secret dispatch to deliver to him, and would you mind coming along and identifying him to me?" So we rode up to the lab in his Navy car; he, incidentally, was wearing side arms. He made me describe Benioff before we got there. Fortunately, this was one of the times Benioff was wearing a mustache.

AS: He kept shaving it off and growing it back?

FL: Off and on. But the officer delivered the message and got the signature for it. Actually, the message was a request for Benioff to watch at the time of the Trinity shot to see if there was a recordable bump on the seismological record. And there was. And that's as close as I got to the actual blast.

One of the things we were asked to do at Caltech was to make replicas of the A-bomb, and we built them from scratch. They were simply TNT bombs, which would be dropped as decoys, and the real one might come down right along with them — if they wanted to play it that way. We manufactured quite a bunch of those, and they turned out to be pretty potent TNT bombs in their own right.

AS: Millikan was still head of Caltech. Was he really running things in this period?

FL: He began to sort of lose touch with things because the business office was so filled up with contracts. After all, we were handling millions of dollars worth of procurement contracts, and scads of non-Caltech people were on the payroll. Right after the war a couple of business types that had come in on the rocket procurement moved over into the business office and began to bring order out of things. Originally, Millikan and Ned Barrett, the secretary-treasurer, ran things pretty much out of their pockets. There weren't good records or good systematic dealings with the faculty. Once in a while I might get a letter saying that my salary had been increased, but a couple of times without a letter I discovered that I had had an increase because the deposits they were making for me at the bank were bigger than they had been.

Shortly after the war was over, Dr. Millikan asked me if I would become chairman of the engineering division. My major responsibility was to build up graduate work in civil and mechanical engineering, which had not had the kind of development that electrical had had; nor had they gone the way aeronautics had under von Kármán. Von Kármán was then director of Guggenheim Laboratory, and he certainly didn't need me for a boss. Aeronautics ran practically as a little division by itself, though I had to see to it that they got their salaries, come budget time.

So there was the building up of mechanical and civil engineering, and, of course, in the meantime electrical engineering was growing, particularly in the direction of applied science. It became fairly clear to me that if engineering was going to survive at Caltech, it could not be second-rate. It would have to be pretty close to science. So I tried, rightly or wrongly, to steer things in the direction of applied science, and tended to appoint people whose research was of that nature rather than nuts-and-bolts engineering.

AS: I'd like to talk about engineering education a bit. You were president of the Society for Engineering Education, so you were quite involved in devising the engineering curriculum. When did you become interested in that?

FL: Well, on the campus it was a gradual transition as some subjects ceased to be of interest or relevance. We gradually shifted our emphasis here to put more stress on the theoretical and fundamental background of engineering. So one course after another was introduced that carried on this shift.

AS: Could you be more specific about the kinds of courses that were dropped?

FL: Well, for example, it was traditional over many years for engineers to take surveying. That was dropped. Mechanical drawing was also considered necessary, but we gradually phased it out as a requirement and made it optional. Engineering design, which was really machine design, no longer seemed to have a place here, so it was gradually phased out except as an elective subject.

Over the years undergraduate work absorbed more and more of what had been graduate work 15 or 20 years earlier. So the general level of mathematics competence had to be built up in the undergraduate work. Another aspect of the undergraduate program that eventually disappeared was shop work. Many engineering schools hung onto it much longer than Caltech did, but while it is good to know about manufacturing methods, how to run a lathe, build a machine, know a little something about a foundry, there isn't room in the curriculum for teaching it.

AS: Did the caliber of the students change?

FL: The level of the entering students was improving all along, particularly in mathematics. Many of them were able to start in with advanced placement. In the engineering curriculum we introduced some applied mathematics, which would carry on from the usual calculus and differential equations into applications of these subjects. We also introduced some new elements, such as La Place transforms and functions of a complex variable.

AS: Did you ever have trouble as head of the division recruiting faculty to Caltech?

FL: No, no. Always there was the problem of whether it was the right man. And, in general, we tried not to recruit a man for a specific teaching responsibility but to find a good man in a general area and then let him work out his own set of courses and his own research program. We've always wanted to look for outstanding people first because they turn out to be quite flexible.

AS: What did you see as your basic responsibilities as division head?

FL: To encourage people who came in with good ideas or a line of research that seemed promising. I tried to act in a permissive and encouraging way rather than trying to direct anything. There were a few key faculty people whose judgment I trusted, of whom I would ask questions. We didn't usually get together as a faculty and meet formally on things, nor did we have very many meetings of the division as a whole. And when we did, to talk about some curriculum or policy matter, we never voted. I would listen to the discussion and make up a kind of consensus.

AS: Is that typical, do you think, of the divisions here?

FL: Some were much more formal. But the more formality you have, I think, the more chance there is for divisiveness.

AS: You took a trip to the Soviet Union, I believe, and looked at their engineering education system. When was that trip?

FL: In 1958, right after Sputnik. In fact, as we were finishing up our visit, we had a session with the minister of higher education. I asked him, "What is the curriculum that trains people to produce Sputniks?" He shrugged his shoulders and said, "People like that just emerge."

AS: You didn't find that their curricula were that different or their method of selection was that different from ours?

FL: At that time they had their engineering broken into about 160 named curricula — as specialized as, for example, diesel engineering for stationary power plants and diesel engineering for locomotives; there was railway engineering, railway civil engineering, railway mechanical, railway electrical; there was also power engineering — the whole gamut of things. Students would try to get into the options that were the most glamorous — that is, communications and electronics, but only the very best students were selected for those. So there was a kind of built-in screening process, and the students who knew they weren't really tops would opt for one of the less rigorous disciplines. And each year the overall planning would specify that they needed to have so many new places in the curriculum in nonferrous metallurgy, for example. So the word would get around that there would be some openings in nonferrous metallurgy, and somebody who might have wanted to be in the steel business would decide, "Well, maybe I can get into nonferrous and maybe later on I can make a shift," or something of that sort. We also found that the schools we thought would be good, bad, or indifferent, were indeed that way. The farther from Moscow or Leningrad we went, the lower the general quality. The top professors wanted to be where the action was, namely, Leningrad, Moscow, or Kiev.

AS: Were there significant differences in the Russians' preparation before they got to the university?

FL: They had been pushed along a little more in mathematics than some of our engineering schools required. A foreign language was something that was encouraged. Of course, some of them automatically got two languages — their native language, which was, say Lithuanian, but they also had to have Russian for college. They had more training in drafting, shop work, and things of that sort. And they usually had to have at least one year of practical work in agriculture or factories before they could even go to college. Also the engineers had a design project, a design thesis. They would work part of the year in an industry, and then at the college they would work on completion of the project that they had started in industry. Then they would have to defend that design before a committee of faculty and outside engineers.

Their curricula were essentially five years long rather than our typical four-year program, and also the system provided carefully programmed correspondence work. It was possible for students in the correspondence courses to shift into regular academic programs at various stages in their development. The correspondence work might cover certain elementary things, such as basic physics, chemistry, and mathematics. And when a student had passed suitable examinations in those, he would be admissible to one of the colleges in a particular option.

AS: What was the group you went over with?

FL: After I retired as president of the Society for Engineering Education, I selected some people who were keenly interested in engineering education — a group of about eight — and we went on what was called a State Department Exchange Mission. It was funded by the National Science Foundation.

I might point out that the engineering in the Soviet Union was at that time, and I think is still, taught in engineering schools and not in universities. There were three or four engineering schools in Moscow, but not at the University of Moscow. That school had science and certain fundamental subjects, mathematics and so on, but not engineering. They had an engineering school for electrotechnics, for power, and for telecommunications, but I understand that since then some curricula have been developed that are quite broad and would be comparable to what we have in, say, Caltech and MIT. One thing was quite evident — all the engineering schools had excellent libraries of foreign books and current magazines, from the U.S. and the U.K. particularly. English was taught quite generally to engineering students.

AS: Was there anyone in your group who knew Russian?

FL: Yes. Leon Trilling, who was one of our Caltech PhDs, had grown up in Poland and had learned Russian as a young man. He was very helpful because the rest of us were dependent on interpreters. We'd sit around a table and talk, and if the interpretation was coming out the way Leon thought it should, he would sit quietly. On the other hand, if there was a misunderstanding or a misinterpretation, he would begin to fidget and burst in. But in general, we found that it was better to play down the fact that we had a fluent Russian speaker in our group.

AS: At Caltech you were also involved in committees on cooperation with industry and patents, weren't you?

FL: Yes, and in the early days of the patent committee, we had some real problems. This was because some interesting propositions were made to us by industry that would have tied us up in terms of secrecy. The people who would be working on some such project would not be able even in lunch table conversation to talk about what they were doing. It was almost as bad as having secret military work going on. So we established a policy that we would not take work that required any inhibition of what is normally called freedom of discussion. We wanted our students who'd worked on this research to be able to present it in seminars, write it up in their theses, and so on.

Also we had to work out a policy. We never had a patent policy before we had a patent committee. Was there any way in which a discovery of some sort could be assigned to the sponsor of the work? At first it seemed awfully difficult, and we were very stiff-necked about it, but over the years I believe that has relaxed somewhat. At that time our biologists were very strong in the belief that since many of their discoveries were health-related they really didn't want anybody to make a profit out of them — which was a little difficult to reconcile with the fact that the biologists would happily accept research grants from pharmaceutical houses.

AS: Do the patents ever accrue to Caltech as an institution rather than to a private individual?

FL: Yes. Under government contracts, the government has the option of first refusal. If the government agency decides it does not want to prosecute a patent application on a particular discovery, the college is free to do so if it wishes. And in some instances, that has been done. Originally, there were patents on a vacuum switch of Professor Sorensen's, which were assigned to the college with certain rights granted to General Electric Company because it had sponsored some of the work. There was an orthodontist here in town who made a lot of inventions on his own — things that were useful in orthodontics — a little tiny spot welder and various braces and things of that sort. He turned those patents over to Caltech with no strings, and a company was organized on the outside that made these things and sold them to dentists. Royalties were collected over quite a few years on these particular patents. The vacuum switch patents just lay dormant until the state of the art in vacuum technology and materials developed to the point where the vacuum switch could be a commercial product. But by that time the basic patents had expired.

We tried to encourage industry to suggest lines of investigation that would have some value to them, preferably in a broad rather than in a specific sense. And we tried in all ways to improve relations with industry on recruitment, getting industry to send its representatives over here, encouraging seminar talks, encouraging student-society talks with industrial representatives. We did all of those things, recognizing that most of our engineering students went to work for industry. And, after all, we were always passing the hat to industry for funds for general purposes, such as the Industrial Associates program.

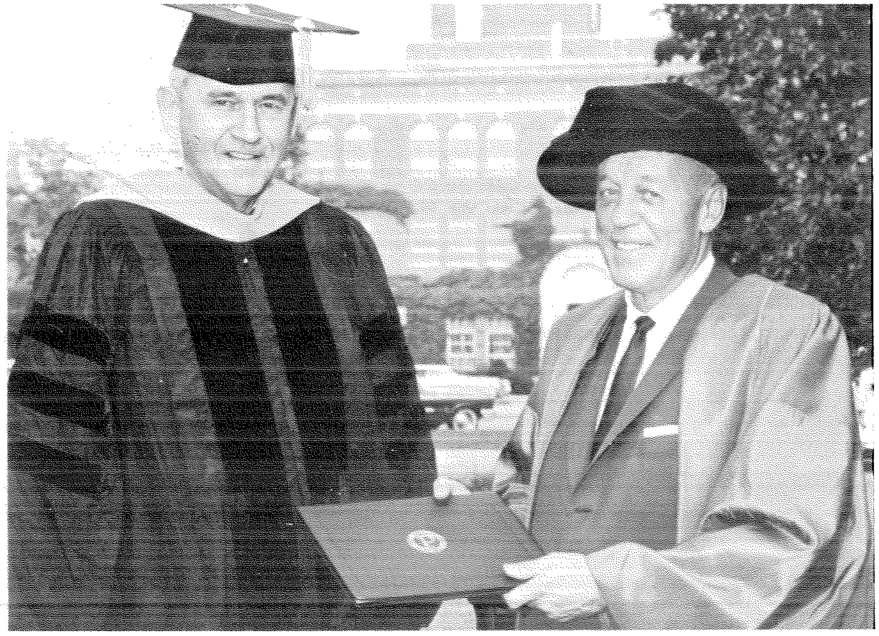
AS: You made a couple of other trips, particularly one to Africa, which sound interesting. What was your purpose there?

FL: I went along to see what the engineering education situation was in the countries we visited and to try to assess to what extent that kind of education and research was helpful in their economic development. We spent a lot of time in South Africa, where they were taking care of themselves quite nicely; but in some of the other countries what was going on was too much patterned on the old British colonial schemes.

Many of the engineering students were being taught an advanced type of engineering that was not immediately useful in their countries. Most of the developing countries needed a lot more of the how-to-do-it kind of engineering. They needed roads, railways, drainage systems, and safe water supplies — all the things that are just the necessary infrastructure of a country. Over there, the universities felt that they were a little above that sort of thing. They were teaching engineering with the object of having their students pass professional engineering society examinations that were set by people in London.

AS: Did they have trade schools too?

FL: They had some vocational type schools. In Kenya at that time, there was a quite good training school operated by the Department of Telecommunications, to train people to service telephone, telegraph, and radio systems as well as the signals of the railways. The man who showed me around there said, "One of our big problems is that our students are grabbed up by private industry to service radio and computer equipment, and we



Recipient of an honorary doctor of engineering degree from Purdue University in 1966

don't get them into the government service for which they've been trained."

AS: You were with a group of people from Caltech who were in different fields?

FL: Let's see, we had Professor Munger, who was really our leader. He's a political geographer. And there was Horace Gilbert, in business economics; Robert Oliver, who was more in general economics; Thayer Scudder, who is a student of African culture and anthropology; and I went along to look at engineering and as much of industry as I had an opportunity to visit, and at industrial-type labs and research labs sponsored by governments in developing countries.

I found in two or three countries efforts being made to use waste materials to get by-products. I believe it was the waste material from the cashew nut that was capable of producing a fair amount of alcohol that was adequate for industrial purposes, and they were trying to make that economic. But it was very difficult to have people accept the concept of making do with what they have rather than hoping for money to buy something like equipment. Everywhere there was a big desire on the part of the ruling people to have a steel mill, for example. That was a big symbol, and often that kind of thing took priority over the infrastructure that was needed to support the economy.

AS: You also traveled to India, I think.

FL: Yes. Caltech was one of a consortium of about eight engineering schools that got together and established, and for a time helped staff, an engineering institute of technology at Kanpur, India. This was a program of the Indian government, and our own AID organization was backing it financially. Caltech had two or three people who were there over a period of time helping build labs, organizing and teaching courses. After about five years, the consortium thought that several people who had not been part of the Kanpur operation should go there and see how it looked, whether any progress had been made. I was asked to go on that mission.

AS: What did you try to evaluate?

FL: Basically, whether they were doing a good job. Had they been able to recruit and hold good faculty people or were they still too dependent on faculty from the States, and too dependent on the U.S. for equipment and supplies? We felt that Kanpur was capable of doing a somewhat better job than they were, but they were held down by the Minister of Education, who didn't want Kanpur to be better than any of the other institutes of technology. They couldn't get out of line with the others on salaries or equipment appropriations.

We were also interested in what they were doing to develop worthwhile relationships with industry. Where did their graduates go to work? Did industry employ them? Did industry sponsor any kind of research activities or specialized education? To a considerable extent, industry and the universities were miles apart, but we saw signs that they were coming together. Efforts were being made, at least at Kanpur, to make the work relevant to industrial needs. But there was always the problem of whether they should be helping on today's problems in industry or the problems industry will be facing later.

AS: You retired in 1970. What have you done since then?

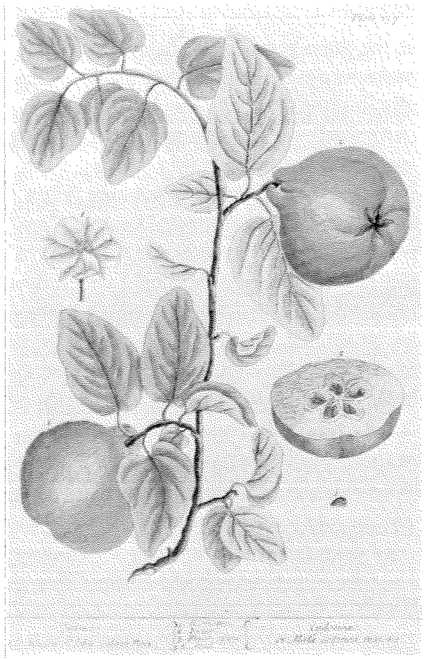
FL: At the time I reached the age of administrative retirement here, I was offered the opportunity to go to Deere & Company to establish the position of vice president of engineering at the corporate level. In the three years I was there, I tried to make recommendations that would generally improve the engineering situation, particularly the interchange of engineering ideas among the different factories. Each factory did all its own engineering, even keeping secrets from other Deere & Company factories. Now at Deere they have a central engineering laboratory, which does not design new products or tell the factories what to do, but it solves problems that the factories have and are not equipped to handle, such as in materials or methods or design details, fracture mechanics, better methods of planting seeds — things of that kind.

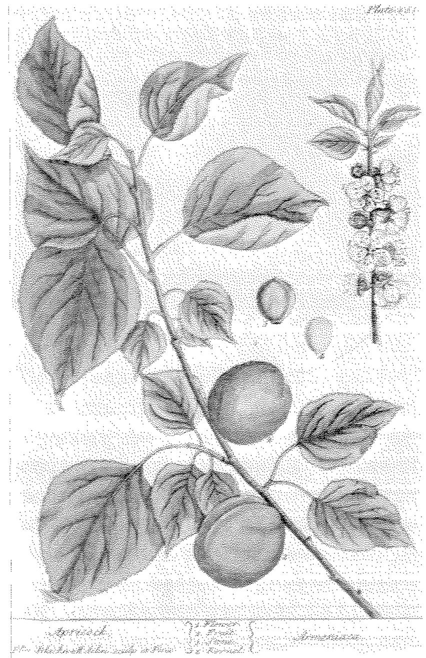
AS: That was just a temporary position?

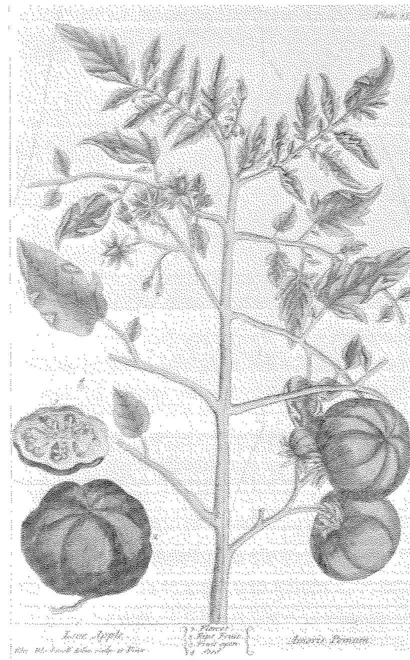
FL: Oh, yes. The chairman there, Mr. Hewitt, who's a Caltech trustee, said to me, "Fred, you're at an age when you would be retiring from Deere, but by just coming on board now, the young fellows won't regard you as a threat." And that was helpful because they did cooperate with me, knowing that I was not a threat to them in the internal corporate politics.

AS: What have you done since you came back from Moline?

FL: Well, my son started a consulting firm — Lindvall, Richter, and Associates — that advises its clients on the ground motion that can be expected in the event of an earthquake of a given size and location. Then the client can have his designers check out a proposed building design or dam design to see whether the specifications are adequate to meet the postulated design earthquake. We analyzed the Big Tujunga Dam for the Los Angeles Flood Control District, for example, and we've looked at other dams for the Metropolitan Water District. The Richter of the company is Charles Richter, also retired from Caltech, and nominally I'm the president. Since I don't pretend to be a structural engineer or a geologist or seismologist, about all I can do is talk with them along general lines. And I provide a shoulder on which people can cry, but I always did that when I was division chairman at Caltech. □







Ripeness Is All

by HAROLD McGEE

Like petrified wood or amber-preserved ants, linguistic fossils — clichés, dead metaphors, ancestral forms — can, if we listen to them, speak to us of conditions buried in the past and yet bearing on our present. Consider these specimens of all-too-common food metaphors. On one side: "That job is a real plum." "What a peach of a dress!" "Life is just a bowl of cherries." "She's the apple of her father's eye." And on the other: "That show was pure corn." "Your offer isn't worth a hill of beans." "Nuts!"

The difference is clear: Fruits convey praise, other plant products serve to disparage. Of course, this is too neat. Figs, raspberries, and the word *fruit* itself can all be used to express derision, while a carrot can mean a reward or inducement, though at the cost of turning its object into a quadruped. A lemon is perhaps the most obvious exception, but it proves the rule, as we shall see. Unlike vegetables or grain, meat or dairy products, fruit generally enjoys special status as an emblem of the ideal or the desirable.

The very fact that we distinguish between fruits and vegetables is noteworthy. As anatomical structures, green beans, corn, eggplants, peppers, and zucchini are the functional equivalents of grapes and peaches: They are all organs derived from the flower and surrounding the seeds. And to the botanist, they are all fruits. But in everyday usage we place many fruits with root, stem, and leaf foods and call them *vegetables*. This word has no anatomical reference and is based solely on culinary custom. Vegetables are usually eaten as a cooked accessory to the main course; fruit, usually raw, alone, and — at least since the Greeks — at meal's end. The special role of culinary fruit in our figures of speech is a reflection of its place at our table: the ultimate dish.

We can trace this underlying hierarchy even in the etymologies of the terms. A very early addition to the English language, the word *fruit* derives from the Latin *fructus*, the past participle of the verb *frui*, meaning to enjoy, to delight in, to have the use of. *Fructus* denoted enjoyment of or pleasure in something, a reward, or a useful product of any kind, but especially produce from the earth. The word was largely evaluative and implied desirability, as it has continued to do in English. Our word *vegetable*, on the other hand, is only about 300 years old. It derives from the Latin *vegere*, meaning to animate or enliven, and is relatively neutral (the Latin for vegetable, *holus*, came from the Greek for "green"). This etymological distinction and the figures of speech that parallel it vindicate the judgment of most children and probably not a few adults: Vegetables may be good for us, but it is fruit that tastes good.

What is it about fruit that gives it this privileged status? In essence, the single trait of sweetness, or a favorable balance between sweet and sour. Studies of newborn humans and other mammals indicate that of the four basic tastes, only sweetness is innately preferred. The plant parts we call fruits and treat as such generally have a much higher sugar content, and often more acid, than those we call and treat as vegetables. It is a rare vegetable that can match the 10 percent average sugar content of most temperate-zone fruits, to say nothing of the 20 to 60 percent characteristic of tropical fruits like the banana, date, or fig. It is on this count that the lemon is wanting and so has become a synonym for *dud*: Its 1 percent sugar content fails miserably to match its acidity.

There are other differences between culinary fruits and vegetables. Most vegetables are especially prized when young; let carrots, asparagus, or beans go too long, and they become tough, coarse, and dry. But most fruit can only be eaten just this side of rotten, at the very end of its development. The edible stage is often signaled by the sudden changes in color, flavor, and texture that constitute ripening. Other plant parts do not ripen, and this is why, unlike fruit, vegetables are usually cooked: Heat is needed to soften them and bring out their flavor.

Unexamined fruit is surely worth the eating. But once held at arm's length and interrogated, this commonplace object becomes more and more mysterious. What exactly is a fruit? Why does it differ so from the rest of the plant? What is going on as it ripens? Why does it ripen? Why does it, more than any other food, please us with its sweetness? Not all the answers are known, and each answer has its own set of exceptions. But a combination of cellular, chemical, and evolutionary perspectives can give us a fairly coherent picture of the nature of fruit.

First, what is a fruit? In botanical terms, it is a distinct organ that develops from the ovary and encloses the maturing seeds. Most fruits are simply the thickened ovary wall. Others incorporate nearby tissues as well. The apple, pear, fig, and strawberry, for example, are all composed principally of the "receptacle," or stem tip, in which the flower parts are embedded. The pineapple is a composite of many flowerlike structures and the central stalk. The fruit usually develops into three distinct layers: a protective skin, a seed coat, and an intermediate layer which in nuts and grains is thin and dry, but in the fleshy fruits is thick and succulent. Since the fruit does not support the plant structurally, like a root or stem, or nutritionally, like a root or leaf, it is composed primarily of storage cells, with a minimal complement of vascular and photosynthetic tissue.

The development of fruit can be divided into four distinct stages. The first is fertilization of the female ovule by male pollen, an event that initiates the production of growth-promoting hormones and leads to the expansion of the ovary wall. Some plants, called "parthenocarpic," can develop fruit without fertilization. Bananas, seedless grapes, and navel oranges are the most common genetic carriers of this trait, but many other plants can be tricked into setting fruit without seed by abnormal temperatures during flowering, or by such chemical manipulations as the application of growth hormones.

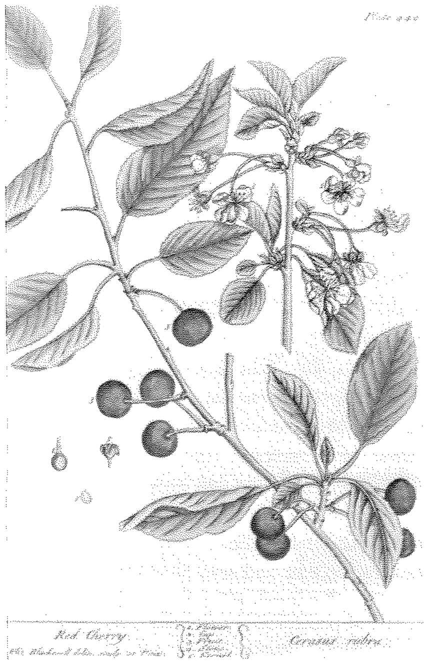
The second stage of fruit development is the multiplication of cells in the ovary wall. This phase is surprisingly short. In apples, cell division is over a month after flowering, though it takes about four months for the fruit to mature. And in the tomato, cell division is virtually complete at the moment of fertilization. An exception is the avocado (a vegetable to us, but with sugar added, a fruit in Brazil), whose cells continue to divide until it ripens.

Most of the increase in size we notice during fruit maturation is the expansion of a fixed number of storage cells. In this third stage, growth can be astonishing. Melons at their peak put on better than five cubic inches a day. Pumpkins average 12 ounces, with some daily gains of 20 ounces. Most of this expansion is due to the accumulation of water-based sap in cell vacuoles. Storage cells in mature fruit are among the largest in the plant kingdom, in the watermelon reaching up to 350,000 times their original size, or about a millimeter in diameter. Actually, we should speak of nightly gains in size. Fruit grows faster — as much as 25 times faster — during the night than during the day, and some will even shrink when the sun is up. Daytime temperatures and humidity cause large losses of water from the rest of the plant, so less can be spared for storage in the fruit. In fact, fruit may act as a reservoir for the plant, supplying water during the day and storing it at night.

What is happening as the cells enlarge? Water and minerals from the roots and sugars newly synthesized in the leaves are translocated to the fruit, where they are put to various uses. As each cell expands, its surface area increases, and new cell wall material, which takes the form of cellulose fibers embedded in a cementlike layer of pectic substances, must be laid down. Sugar provides energy for the cell's metabolism, and excess supplies are stored in the vacuole as sugar or organic acids, or are converted into the more compact, less reactive starch granules (the avocado forms oil rather than starch). So-called secondary compounds, among them poisonous alkaloids and astringent tannins, are synthesized in order to deter infection or predation. And the many enzymes, hormones, and other intermediate molecules necessary to run these processes are continually replenished.

The gradual work of cell enlargement proceeds for weeks, even months, and compared with what goes on in the rest of the plant, it is not very remarkable. But the fourth stage of fruit development, ripening, is unique. It is a sudden, rapid, and drastic change in the life of the fruit that merges into its death and decay. While cell expansion will stop if the fruit is cut off from the plant, mature fruit will go ahead and ripen as if by remote control, and at times even faster than fruit left on the plant. (The anomalous avocado will not ripen *until* it has been picked — the tree appears to supply some inhibiting substance — with the result that storing avocados means leaving them in the orchards.)

Ripening consists of several simul-



taneous events. Skin color changes, usually from green to something else. Starch and acid contents decrease, and sugar increases. Cell walls weaken. Secondary compounds disappear. A characteristically fruity odor develops. Translated to the consumer's perspective: Fruit becomes sweeter, softer, safer, tastier, and gives us a visual advertisement of the fact.

What brings on these changes? The single largest cause is the action of many different enzymes, which break down complex molecules into simpler ones. Color shift, for example, is due primarily to the destruction of chlorophyll, together with some synthesis of other pigments. The membrane surrounding the chloroplast is weakened and permits an enzyme called chlorophyllase to reach and destroy the green pigment, which is normally so intense that it masks the presence of others that invariably accompany it.

Enzymes also convert starch into sugar and so make the fruit more palatable. An extreme example is the banana, which goes from a 25 percent starch, 1 percent sugar ratio to 20 percent sugar, 1 percent starch after ripening (the missing 5 percent is used to provide energy for the cell's metabolism). Several common fruits, however, do not store starch, and this fact has practical significance. Their final sugar content will depend on the time they spend attached to the sugar-supplying leaves. Melons, citrus fruits, and pineapples will not get any sweeter once they are picked; in these cases, we are left at the mercy of the growers.

Even these fruits will, however, improve in texture after picking. Fruit softens because pectic enzymes convert the cell wall cement into more soluble forms, which then dissolve away and weaken the entire network. For reasons that are not entirely understood, this change is so extensive in tree-ripened pears that they become unpleasantly mealy; pears turn out best if they are picked prematurely.

All secondary compounds do not follow this trend of enzyme degradation. Alkaloids do, but tannins bind to each other to form unreactive polymers. And fruity odors are a complex combination of the many volatile compounds that result from the general breakdown of storage tissue.

It was long thought that ripening is in fact nothing more than the progressive breakdown of cellular structure, which results in the mixing of reactive compounds normally segregated from one another, and so in eventual chemical chaos. Today, however, ripening is seen as the final, carefully programmed stage of fruit development, a directed process that involves the synthesis of new materials rather than mere destruction. The key piece of evidence for this view is the role of the gas ethylene.

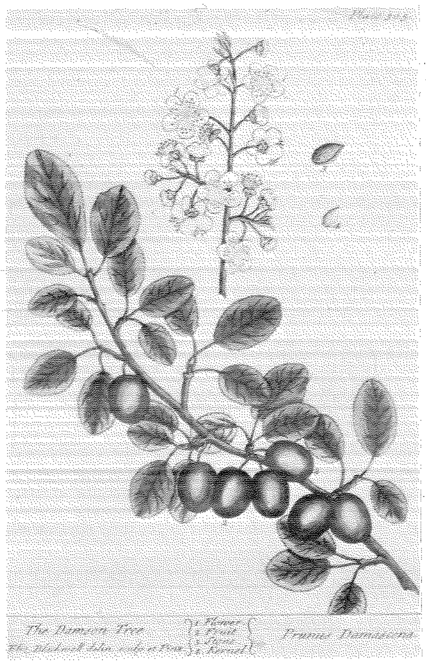
In the Caribbean islands, around 1910, it was reported that bananas stored near some oranges had ripened earlier than others. In 1912, California citrus growers noticed that green fruit kept near a kerosene stove changed color faster than the rest. What secret ripening agent did fruit and stoves have in common? The answer came two decades later: ethylene, a simple hydrocarbon gas ($H_2C=CH_2$) which, when applied to mature but unripe fruit, triggers ripening. More recently, it has been determined that the fruit itself produces ethylene in advance of ripening, an event called "autostimulation." Ethylene is not merely a byproduct of cell disorganization, then, but a specific hormone that initiates this process in an organized way.

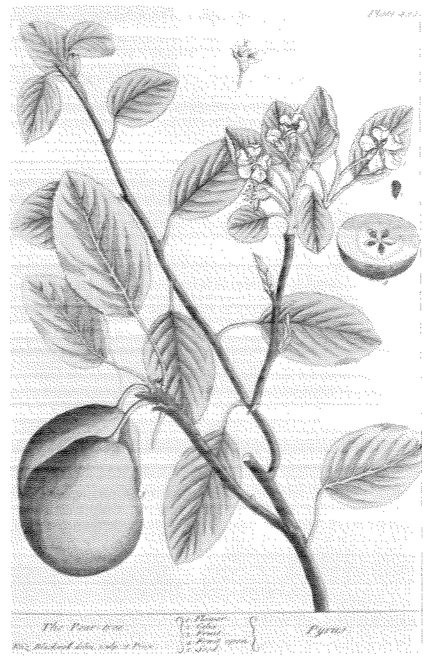
This knowledge has found widespread commercial application. Bananas, tomatoes, and other fruit are shipped hard and unripe to reduce the damage caused by picking, packing, and transport, and then are gassed on arrival. Oranges are treated simply to improve their color; their flavor and texture do not change. But the control of ripening is hardly an invention of the supermarket era. In the fourth century B.C., Theophrastus, a student of Aristotle's and author of the first known botanical treatise, wrote of the Egyptian fig: "It will not mature fully unless it is cut and anointed with oil. . . . For the excess juice is drawn off by the wound, and the oil, like the sun, warms the open fruit and accelerates its maturation." This practice of "oleification" for the purpose of ripening figs about a week early continued well into this century in the Mediterranean region. Research in the Yale laboratory of Bruce B. Stowe (Caltech BS '50) has shown that long-chain fatty acids in the oil, given the compact name "oleanimins" by the investigators, stimulate the fruit to produce the ripening hormone ethylene. Today, most growers say that the gain of a few days is not worth the trouble and that treated figs are not as tasty as the untreated — a familiar remark about supermarket produce.

Exactly how ethylene works is not known. It probably increases the permeability of cell membranes, and triggers the synthesis of enzymes that are immediately responsible for the series of changes that constitutes ripening. It is known that once ethylene reaches a certain concentration in the fruit, the cells suddenly begin to respire — to use oxygen and produce carbon dioxide — from two to five times more rapidly than before. This respiration rate is a sign of furious biochemical activity. The cells are not simply dying away and disintegrating, but are living a last, intense phase of life. As it ripens, the fruit actively prepares for its end, organizing itself into a feast for eye and palate.

That may explain what fruit is and what ripening is. But why such an elaborate ritual of passage for something that is in the process of falling apart? Here we must shift perspective drastically.

Arguments abound about how many kingdoms of organisms there are on the planet, but plants and animals are assuredly two. Plants are generally "autotrophic," or self-nourished. Given a supply of water, minerals, oxygen, carbon dioxide, and sunlight, they can thrive, independent of other organisms. But animals are unable to synthesize from such primitive materials the complex proteins, carbohydrates, and other compounds necessary for life. They are "heterotrophic," or other-nourished, and depend on the ingestion of other organisms, plant or animal, to meet their needs for energy and building materials. And while land-dwelling autotrophs need access only to





the soil, atmosphere, and sun — sources which, once located, are rather reliable — the heterotroph must worry more about the availability of food, and will have a distinct advantage if it can control its access to prey. Hence the animal's unique combination of sensory organs, central information processor, and locomotive power, which empowers it to perceive its situation, choose an appropriate response, and act accordingly.

The plant, cradled at the constant breast of Mother Earth, seldom does without nourishment, and so has no need for eye or muscle or brain. But this versatile system does multiple duty for the animal, and in some areas of life plants have had to develop special strategies for which the animal has no need. Lacking the power of movement, plants defend themselves from predators with unpleasant or poisonous chemicals. The tannins and alkaloids in unripe fruit are two such chemical weapons. And pollen and flowers are structures designed to make use of mobile middlemen — the wind, insects, birds — in joining male and female in the process of reproduction. Then there is the subsequent task of seeing the next generation off to a good start. If a plant's seeds were to fall straight to the ground, then they would have to compete with each other and with their overshadowing progenitor for the limited resources of a small area. Most seedlings would die, and the population would grow very slowly, if at all. Successful plant species have tended to develop mechanisms for dispersing their seeds over as wide an area as possible. These mechanisms include seed appendages that catch the wind, containers that pop open and spray their contents in all directions, burrs that catch on passing fur . . . and structures that manage to hitch a ride *inside* passers-by.

Fruit is in essence a device of seed dispersal, the result of long coevolution between plants and animals. One needs food, the other a transportation service, and fruit is the compromise, the medium of exchange. Different animals have called for different inducements, and while we are a long way from being able to say exactly how particular fruit characteristics have evolved, some generalizations are possible. Reptiles are not generally climbers, and reptile fruits are usually borne near the ground or dropped at maturity. Birds are sensitive to color contrasts and can easily reach heights, and typical bird fruits are accordingly brightly colored and remain attached. Fruit bats are color-blind, attracted to their own odor, and have trouble negotiating leaves; their fruits are drab, smell musty, and hang exposed below the foliage. Mammals are generally color-blind, have a good sense of smell, and possess teeth; their fruits develop odors and can have tougher skins. Primates, relative latecomers to the mammal family, can climb and see colors and have invaded the birds' territory.

Of course, the plant will have gained nothing at all if its embryonic offspring do not survive the animal's attentions. Seeds can escape being consumed along with the fruit in several ways. They may be too large and hard to be eaten with the fleshy covering, or else small and numerous enough that some will be spilled during feeding and not be worth the trouble of searching after. They may remain distasteful, even poisonous: Apple, pear, peach, and citrus seed coats all contain cyanide compounds, though the fruits are perfectly edible. Or the seeds may be constructed so as to pass through the animal's digestive tract uninjured and finish their journey in a pile of fresh manure. In such cases the animal both transports and unwittingly nourishes the new generation of plants.

We can understand fruit's special place in our language and our cuisine as a consequence of the special roles it and we play in the plant's life. Unlike the rest of the plant, edible fruit is meant to be eaten, and this is why the complex of taste, odor, and texture is well matched to our animal predilections. And so it is that, in everyday language, fruit tends to suggest desirability. But fruit is meant to be eaten only when its seeds — its whole reason for being — are mature and viable. This is why ripening occurs: Vegetables can be eaten any time, and the earlier the tenderer, but we must wait for fruit to indicate that it is ready to engage our services.

In its conjunction of death and new life, of purposefulness and disintegration, ripeness too has metaphorical power. It is perhaps most sweepingly invoked by Shakespeare, toward the end of *King Lear*. Old, loyal, cruelly blinded Gloucester rests on the ground beneath a tree. He hears of Lear's defeat in battle, and, weary of life, wishes aloud for death: Like the tree's own fruit, "a man may rot even here." But he is as yet unreconciled with his devoted son Edgar, whom his other, treacherous son Edmund has successfully accused of planning parricide. For Gloucester to die now would be to leave his and his sons' lives incomplete, to escape the painful and joyous truth rather than accept it, not to know the good seed from the bad. Edgar, as yet unrecognized, tells his father as much in words that transcend the particulars of the play.

Men must endure
Their going hence, even as their
coming hither:
Ripeness is all. Come on.

Jon Mathews
1932-1979

Jon Mathews, professor of theoretical physics, was lost at sea in December 1979 during a sailing trip around the world with his wife, Jean, in the 34-foot sloop Drambuie II. *A memorial service was held at Caltech on October 30, at which tributes were paid by colleagues, friends, and his son Richard. Below is an adaptation of remarks made on that occasion by Robert Walker, professor of physics and executive officer for physics.*

Jon Mathews had a long association with Caltech, beginning in 1953 when he came here as a graduate student and continuing as a faculty member after 1957. Because he was not a specialist but had wide interests and knowledge in a number of fields, he was able to fill faculty roles that are now difficult to fill in his absence. He is greatly missed by his colleagues and friends.

Jon was not like most of the other people on the physics faculty at Caltech in his motivations and his approach to science. He had great versatility — as do some of the others — but I think his most outstanding characteristic was that he was a scholar, and his scientific motivations stemmed from that. In *The Canterbury Tales,* Chaucer describes the various characters traveling together on a pilgrimage to Canterbury. Among them was a scholar, about whom he said:

> A Clerk ther was of Oxenford also,
> That un-to logik hadde longe y-go. . . .
> Of studie took he most cure and most hede.
> Noght o word spak he more than was nede,
> And that was seyd in forme and reverence,
> And short and quik, and ful of hy sentence,
> Souninge in moral vertu was his speche,
> And gladly wolde he lerne, and gladly teche.

I think the last line describes Jon particularly well. What really interested him was learning a new subject, which he did with great intensity and remarkable intellectual power, but he was never so involved with his own long-range research that he was unwilling to be diverted and give attention to a new problem — provided you could get him interested. Then he would be of great help.

The best example of my association with him occurred some years ago when I found a theoretical prediction of a surprising experimental result that my students had just observed. This prediction was in a preprint of a theory paper in which the quark model of hadrons was applied to pion photoproduction. I struggled for a few days to try to understand the theory, but without success, so I went to Jon with the experimental results in one hand and the theoretical preprint in the other. Luckily, I succeeded in getting him interested. In a week or two he had understood all about the theory, worked out a simpler and far more elegant method of calculation, and checked all the results. He then explained it to me in a way that was easy to understand.

In addition to teaching his colleagues, as the story of the solving of my problem illustrates, Jon was one of our most valued teachers of students. First of all, he was valued by the executive officer, namely me, who has the task of finding teachers for all of the physics courses. Jon was willing and able to teach a wide variety of courses, and professors with those qualities are a great asset. More important, he was valued by the students because of his well-prepared and substantive courses. Several times I had self-appointed delegations of students come to me with requests that Jon be assigned to some course that they wished to take in the following year.

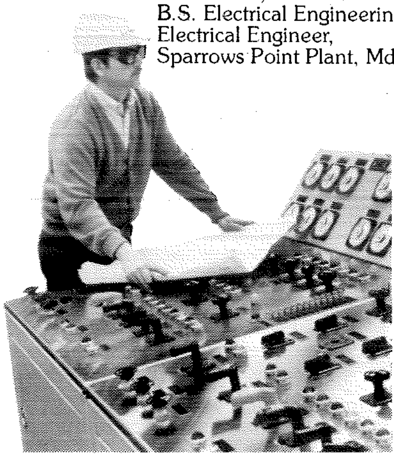
Before he left on his trip, I asked Jon if he would be willing to teach our graduate course in relativity during the year after his return. With some trepidation he agreed and said he would take along for study the big, heavy black book *Gravitation* by Misner, Thorne, and Wheeler. But, he added, "if I get into trouble, that's going to be the first thing thrown overboard."

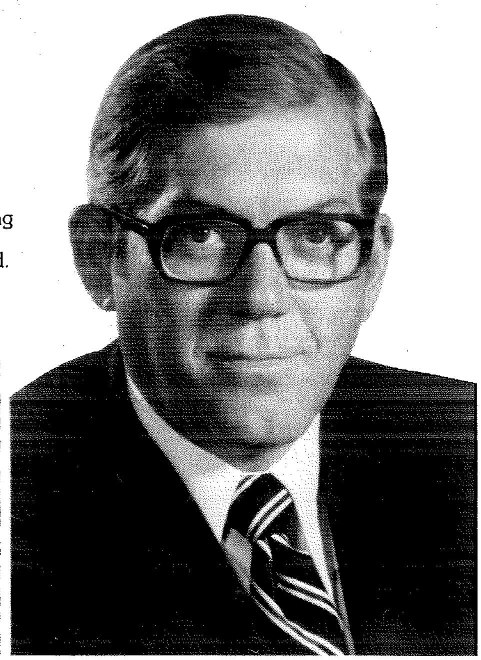
Sometime around 1963, Jon and I wrote a book together, *Mathematical Methods of Physics*. He was a great co-author, and we also had a fine typist. So writing the book was not a pain as it is supposed to be; it was actually enjoyable. Not only that, I learned a lot from Jon in the process.

In conclusion, I want to read a cablegram from two people who would certainly have attended this memorial service if they were not far away in South Africa: "In Kiswahili, which Jon learned at Pasadena City College, there is a saying that the wealth of a country is in its people. Jon exemplified that. The more of a man is shining spirit, the more of him lives beyond the grave. From the shore of the Indian Ocean, which claimed him, we salute him. (Signed) Chris Engelbrecht, Jon's first PhD, and Ned Munger, tennis buddy." □

"Will you find a rewarding career in the steel industry?

Charles Anderton
Penn State, 1976
B.S. Electrical Engineering
Electrical Engineer,
Sparrows Point Plant, Md.



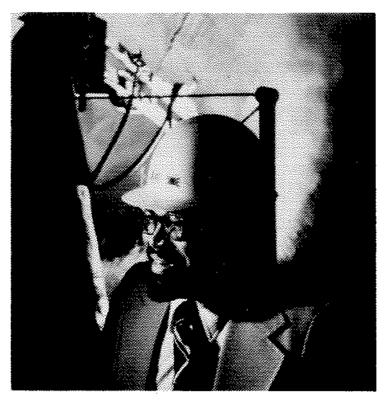


Pat Posbergh
Lafayette, 1977
B.S. Metallurgical Engineering
Turn Foreman
Bethlehem Plant, Pa.

"I did–at Bethlehem. And so did these engineers."

**Walt Williams, President
and Chief Operating Officer
Bethlehem Steel Corporation**

Claire Van Matre
Duke, 1977
B.S. Mechanical Engineering
Staff Engineer,
Buffalo Tank
Division, N.J.



Juan Giscombe
Polytechnic Institute
of New York, 1976
B.S. Operations Research
and Systems Analysis
Industrial Analyst,
Burns Harbor Plant, Ind.

"When I joined Bethlehem Steel's management training program back in 1951, I wanted challenges and I wanted opportunities. As a civil engineer in a company that was growing and modernizing, I was given my share of both.

"Today the challenges and opportunities at Bethlehem Steel have never been greater. Sure the steel industry has problems. But here at Bethlehem we're hard at work solving those problems. We're strong financially. We're strong in raw materials. We're strong competitively. We're strong technologically. And we're strong in people.

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"I invite you to join us and grow with us. Pick up a copy of our Loop Course booklet at your Placement Office or ask us for one. See for yourself what we've got to offer you. Write: Director—College Relations, Bethlehem Steel Corporation, Bethlehem, PA 18016."

Mr. Williams joined Bethlehem Steel's management training program (The Loop Course) in 1951 upon graduation from the University of Delaware with a B.S. in Civil Engineering.

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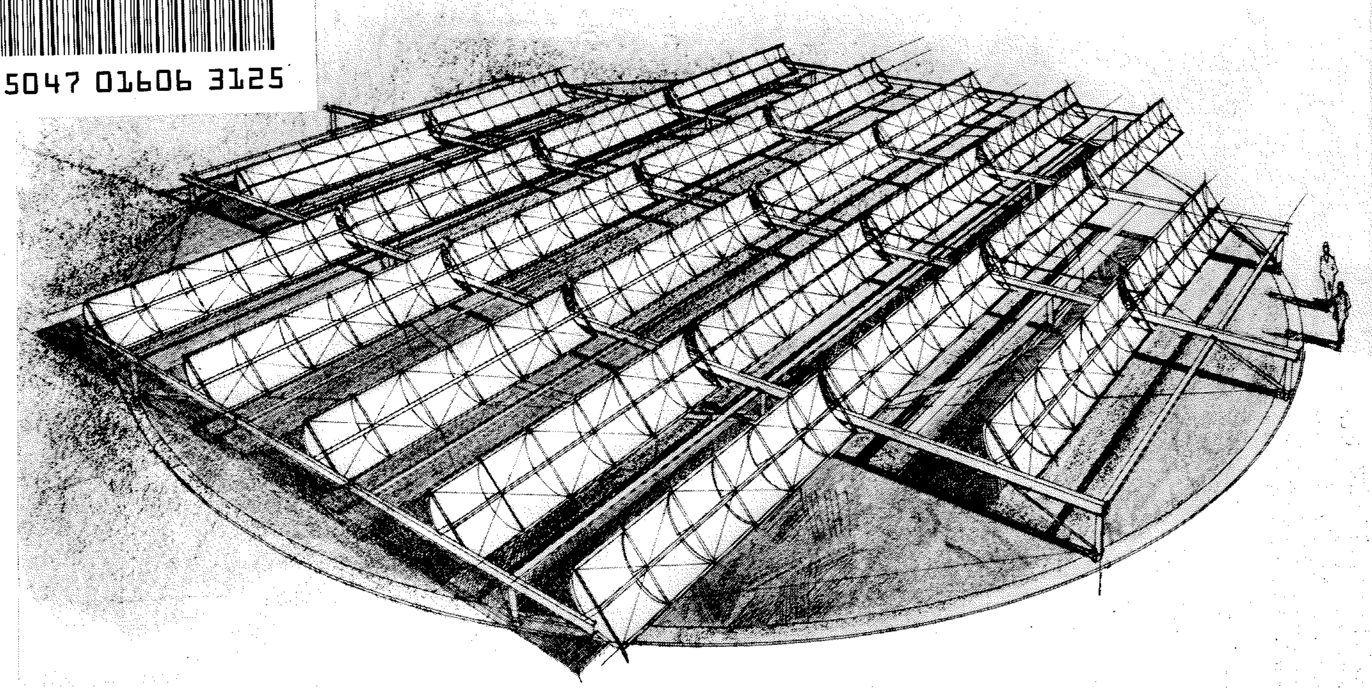
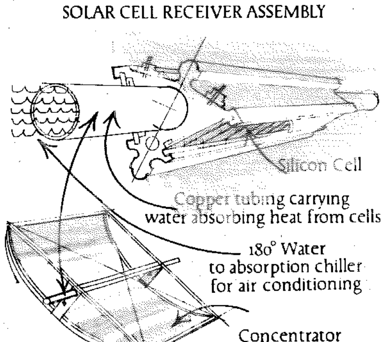


8 years ago, we designed turntables to track records. Today, we're designing turntables to track the sun.

What you're looking at is a turntable that measures 146 feet in diameter — a turntable programmed by computer to track the sun's azimuth while concentrators track the sun's elevation. Nine of these turntables are being designed to power marine-mammal life-support systems at Sea World in Florida.

The photovoltaic concentrator system uses high-intensity silicon solar cells to convert sunlight into electric power and is under study by General Electric for the U.S. Department of Energy. Parabolic troughs on each turntable are formed of aluminum sheets covered by a reflective film laminate. They are angled to concentrate energy on a focal line of solar cells. DC power generated by the photovoltaic cells will be converted to AC power providing up to 300 kw of peak electricity—enough power to service about 40 average homes.

SOLAR CELL RECEIVER ASSEMBLY



Water circulated through copper coolant piping in the solar cell assembly and carried to absorption chillers would be used to air-condition a shark exhibit. The generation of electricity and simultaneous ability to air-condition makes the GE system unique.

Our Sea World application is a test project. It will include researching ways to reduce costs to make photovoltaic systems practical for commercial or industrial-scale use.

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