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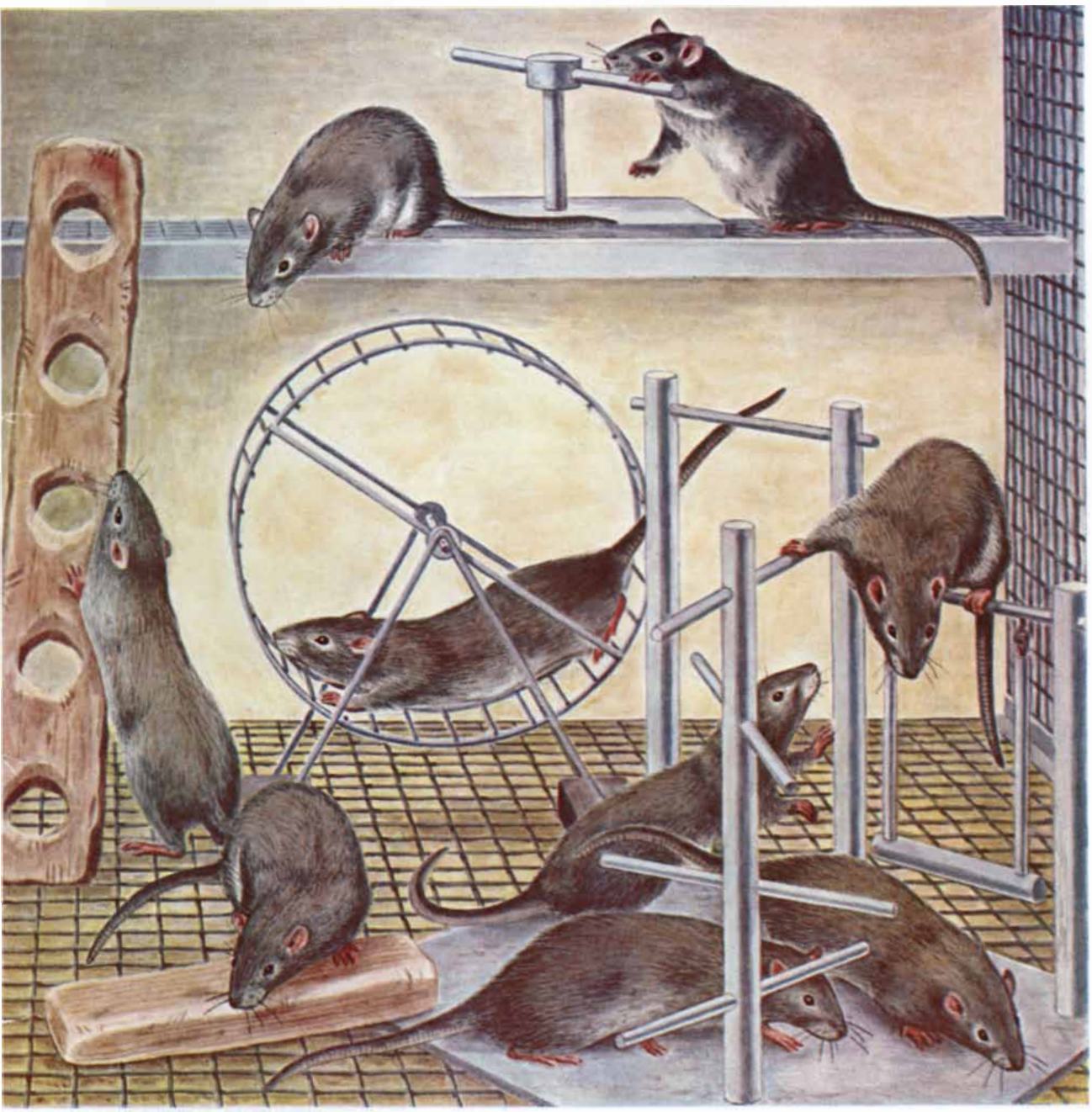

EXPERIENCE AND THE BRAIN

ONE DOLLAR

February 1972

Nobody knows electronics like North American Rockwell.

Strong statement? Maybe. But when it comes to sensing, processing, storing, displaying or transmitting data, nobody can match our experience. Or capabilities. Look at our background in commercial applications alone.

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Your new Monte Carlo.

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Chevrolet

1972 Monte Carlo at historic Houmas House, Burnside, La.

There's so much to see, make sure you're around to see it. Buckle up.

Established 1845 **SCIENTIFIC AMERICAN** February 1972 Volume 226 Number 2

ARTICLES

DEPARTMENTS

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THE COVER

The illustration on the cover shows rats at play in a large cage furnished with a variety of objects. The play objects and the company of other rats provide an "enriched" environment. Rats placed in such an environment for four weeks or more develop a heavier and thicker cerebral cortex than littermates that live in isolation or in standard laboratory colonies (see "Brain Changes in Response to Experience," page 22). Alterations in the chemistry of the brain as the result of experience, such as changes in the RNA/DNA ratio and in the activity of the enzyme acetylcholinesterase, have also been discovered. How these various cerebral changes are related to the functions of learning and memory is currently being investigated.

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SCIENCE/SCOPE

The U.S. Army's M-60A1 main battle tank will have a new fire-control system built around a ruby laser rangefinder and a solid-state ballistic computer, both developed by Hughes. It will enable the crew to fire its first round more quickly and will greatly increase the probability of scoring a first round hit. The laser rangefinder will utilize hardware assemblies developed earlier for the Army's M60A1E2 tank and M551 Sheridan armored reconnaissance airborne assault vehicle.

A long-life solar cell power supply system for orbiting satellites, now being developed for the U.S. Air Force by Hughes, will be capable of operating at altitudes between 200 and 22,300 nautical miles, or higher, for at least seven years. It will incorporate technology which Hughes developed for USAF's FRUSA (Flexible Rolled-Up Solar Array) program, a system of extendible solar cell panels unfurled like windowshades in space to convert the sun's energy into electrical power.

The first of five U.S. Navy F-14A Tomcat air superiority fighters has been flown to the Pacific Missile Range, Pt. Mugu, Calif. for installation of the AWG-9 weapon-control system and testing of the Phoenix missile, both developed by Hughes. When the twin-engine F-14A becomes operational it will be the Navy's most sophisticated fighter for both offensive and defensive missions. It will carry a 20mm cannon and various combinations of Phoenix, Sidewinder, Sparrow, and Agile missiles.

Two new series of lightweight digital computers have been developed by Hughes for central avionics, ECM, missile guidance, RPV, and other military applications. The HCM-230, latest of a line of Hughes airborne computers spanning 20 years, is a 24-bit, 92-instruction, truly modular computer with a throughput of 400,000 operations per second. The Mini-HDP is a low-cost minimal unit. Though very small (20 cu. in. including 8K of memory), it is a 19-instruction, 16-bit-word-length LSI computer of about 600,000 operations per second.

Hughes needs electro-optical system analysts to work on surveillance and precision tracking systems. Requirements: MS or PhD in Physics or EE and 3-8 years experience with E-O sensor systems, infrared physics, and computer techniques for analysis. Also mechanical engineers for conceptual design of complex E-O systems. Requirements: BS or MS in EE or Physics, 5-10 years experience. Please send your resume to: Mr. Robert A. Martin, Hughes Aerospace Engineering Divisions, 11940 W. Jefferson Blvd., Culver City, CA 90230. An equal opportunity M/F employer.

Digital display systems for the U.S. Navy's future fleet of 30 Spruance-class destroyers are now in production at Hughes under a subcontract from Litton Industries. They will be part of the Naval Tactical Data Systems (NTDS) which provide instantaneous presentation of the action within tactical combat zones. Within seconds, NTDS can evaluate a potential threat, assign and control countering weapons, and perform other command functions. The Spruance class will be the backbone of the Navy's destroyer forces in the mid-1970s and beyond.

LETTERS

Sirs:

In my recent article "The Measurement of the 'Man-Day'" [SCIENTIFIC AMERICAN, October, 1971] I failed to notice the work of Leonardo da Vinci (1452–1519) and thus missed the fact that important aspects of the study of manpower, whose origins I placed in the 17th and 18th centuries, had been anticipated by Leonardo in the late 15th and early 16th centuries.

In spite of the care he lavished on his exceptionally lifelike drawings of human anatomy, Leonardo saw clearly the mechanical aspects of limbs and joints. Probably because of his interest in muscle-powered human flight he studied the forces and movements of parts of the body considered as a system of levers. In so doing Leonardo anticipated Giovanni Borelli's mechanical anatomy that was published in 1680, nearly 200 years later.

Furthermore, he considered in some detail the most effective ways to employ human muscle power in raising weights. He decided first that maximum force could be exerted by a man's weight on a lever end, augmented by his pushing upward with his arms and shoulders against a fixed bar. "This will raise at the other end of the balance," wrote Leonardo, "a weight equal to his own, and added to that as much weight as he can carry on his shoulders."

He then designed a pile driver whose arrangement of motive power was similar to that of John Théophile Desaguliers' water-lifting machine of 1744, illustrated in my article [*page 99*]. Utilizing the weight of their bodies, the men who lifted the pile driver's "monkey" (ram) climbed ladders and stepped into stirrups on ropes running over pulleys at the top of the contrivance. The monkey was raised as the men rode the ropes down to the bottom of the ladders.

Finally, Leonardo argued convincingly that the conventional man wheel, in which men tramped inside a drum somewhat like a modern "squirrel cage," was inherently less efficient than one that employed the men's weight on the outside of the drum, as in the British workhouse treadmills of the 19th century.

All this has been pointed out to me with admirable restraint by my friends Ladislao Reti and Bern Dibner. I say "with admirable restraint" because not only had Professor Reti published an article that treats fully the matters sketched above, but also he and Dr. Dibner had sent me, on publication, a copy of their attractive *Leonardo da Vinci: Technologist* (Burndy Library, 1969), which contained Professor Reti's article. This is not the first time that I have been reminded by a distant correspondent to look on my own bookshelves, and it is probably not the last if my correspondents continue to be as forbearing as they have been thus far.

EUGENE S. FERGUSON

University of Delaware
Newark, Del.

Hagley Museum
Greenville, Del.

Sirs:

I shall comment on "Multistability in Perception," by Fred Attneave [SCIENTIFIC AMERICAN, December, 1971]. I direct your attention only to those aspects of the article concerned with "reversible perspective."

Professor Attneave suggests that reversible perspective may be explained by the Gestalt principle of *Prägnanz* (or simplicity of figure). I suggest that reversible perspective may be explained by ancient principles describing three-dimensional representation in two dimensions. These principles of linear perspective were described by Albrecht Dürer in 1525.

According to Dürer, an observer effectively portrays three-dimensional objects somewhere in space on a theoretical picture plane suspended between the eye and the objects; Dürer's splendid representations of the picture plane are well known and often reproduced. Further, observers infer depth by analyzing collections of lines (or imagined lines) on the picture plane. We have just two rules: (1) Parallel lines are interpreted as being "real" lines parallel to each other *and* parallel to the picture plane. (2) Converging lines are interpreted as being real lines that are parallel to each other but nonparallel to the picture plane. (These lines converge to a "vanishing point.")

Now, the important point, and one that I believe Professor Attneave fails to make, is this: A drawing exhibiting reversible perspective is *not* drawn according to Dürer's rules for perspective. The Necker cube, for example, is an isometric drawing and not a perspective drawing; in the Necker cube no line systems converge.

When the Necker cube appears on the picture plane, we can suppose the visual mechanism interprets its depth by the usual Dürer rules. If no converging lines are seen (as is in fact the case), the visual mechanism interprets the representation as being two-dimensional. The visual mechanism, however, is a notoriously imperfect optical system. As the optical system is in constant flux, first one set of parallel lines is portrayed as very slightly converging and then another set of parallel lines is portrayed as slightly converging. Successive interpretations are the apparent oscillations of the isometric drawing.

I suggest a simple explanation for the progressive loss of perspective in the Necker cubes at the bottom of page 67 in Professor Attneave's article. I submit that it is not progressive "simplicity" that accounts for the loss; it is only a progressive loss of parallel-line (or converging-line) information—information on which all perspective judgments are made. In the first Necker cube there are three sets of four parallel lines. In the second Necker cube there are two sets of four parallel lines and one set of three parallel lines. In the third Necker cube there are only three sets of three parallel lines. Loss of parallel-line (or converging-line) information would reduce linear three-dimensional information in *both* isometric drawings (as in Professor Attneave's Necker cubes) and true perspective drawings.

JOZEF COHEN

Professor of Psychology
University of Illinois
Champaign, Ill.

Sirs:

The rules of "linear perspective" to which Professor Cohen refers are entirely consistent with a *Prägnanz,* or minimum, principle. Parallel lines are simpler (to describe) than nonparallel lines. If this is not self-evident, consider the fact that a single number can represent the slope of a million lines if they are all parallel to one another.

Just as things tend to be seen in depth in such a way as to make *slopes* equal, so do they tend to be seen in such a way as to make *angles* and *lengths* equal. For some experimental support of this generalization see Fred Attneave and Robert Frost, "The Determination of Perceived Tridimensional Orientation by

Minimum Criteria," *Perception and Psychophysics,* 1969, Vol. 6B, pages 391–396. If Professor Cohen will read this article, I think he will agree that the two rules he takes from Dürer are insufficient to account for the way perspective is handled by the perceptual system. Incidentally, these two rules do not explain why scalene triangles such as those on page 69 of my *Scientific American* article are seen as isosceles or right triangles in depth.

However, what Professor Cohen calls "the important point" is indeed important: one must typically display an orthogonal projection of an object, in which parallel lines do not converge, to get a reversing figure that is as stable in one orientation as in the other. The introduction of "linear perspective" biases the perception more or less strongly in favor of the "correct" aspect, because certain inequalities of slope are eliminated in that aspect, whereas they are exaggerated in the other.

FRED ATTNEAVE

Professor of Psychology
University of Oregon
Eugene, Ore.

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NAME

NEW ADDRESS

OLD ADDRESS

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

FEBRUARY, 1922: "The widespread introduction of motor vehicles has done much for highway transportation, so that today it is a powerful rival of the railroads of this country. But with the ever-increasing use of motor vehicles the highways of the nation have become more and more taxed until now there is an overcrowded condition on many of our highway systems. This condition is really acute in large centers of population, such as New York and its surrounding cities and suburban districts. It goes without saying that such an increase in street traffic in large cities has called for rigid and effective traffic regulation. In the case of New York's Fifth Avenue a signal system of traffic regulation has been evolved. Signal towers have been erected for the control of traffic on Fifth Avenue and on cross streets in the most congested areas. These towers make use of signaling lamps. The system has been successful beyond a doubt and has accomplished much in the way of eliminating annoying and costly delay. Even on remote rural roads traffic has become exceedingly heavy. It seems that this condition could be relieved if the state highway departments widened these roadways so as to make it possible for four lines of vehicles to be operated over them at one time."

"An ancient skull has recently been found at the Broken Hill Mine in Northern Rhodesia in a cave some 140 feet below the original top of the hill. The skull was found at the far end of the cave by a New Zealand engineer, whose trained eye immediately recognized the importance of the find. It is perhaps premature to say that these are the oldest human remains extant, but it seems assured that the skull is more ancient than the Neanderthal man, and the question is opened up of whether the human race may not have originated in Africa."

"That the atoms, those smallest bricks of nature, of which chemistry teaches us all material is but a combination, are the seat of unbounded energy one may say has only been discovered by the appearance of radio-activity. For instance, it is proved that a very tiny particle of bromide of radium suffices to raise and keep the temperature of its nearest surroundings by several degrees, continually throwing out into space a vast number of very tiny particles charged with electricity. Scientists are today of the opinion that radio-activity is not only a property of radium, uranium or thorium atoms; it is common to all atoms whatever, only that in other atoms this power is latent. If it were possible to start the decomposition of the atoms, which in the case of radium takes place by itself, artificially, the radio-activity must needs also appear. The quantity of energy that could be won by such means is enormous and infinitely greater than that attained by chemical reaction or combustion. Perhaps there will come a time when we shall use the energy in the atoms to drive our machines, cook our food and heat our rooms."

SCIENTIFIC AMERICAN

FEBRUARY, 1872: "Working men and working women ought not only to perform their daily tasks faithfully but also be so circumstanced that they will perform them cheerfully. In so far as lies within our power, we ought to remove every just cause of complaint. The fact that there is unrest and dissatisfaction when man is confined to unremitting toil is one of the brightest and most healthy omens of the times. We must fairly and honestly examine the conditions of the laboring classes, upon whom the whole superstructure of the social organism rests. The question raised by them and in their behalf can never be adjusted by the two extremes—those anxious to secure the greatest possible amount of pay for the least possible work, and those anxious to obtain the greatest possible amount of work for the least possible pay. Nor will relief come with the determination of how many hours shall constitute a legal day's work. The great *desideratum* is to determine what would be a fair division of profits between the employer and the employee."

"At a recent meeting of the Royal Geographical Society, Sir Bartle Frere explained the grounds on which the Council had determined to despatch an expedition from England for the search and relief of Dr. Livingstone. He said it

was now more than two years and a half since anything in the shape of written communication had been received from Livingstone. In one of his last letters he had described himself as in great want of men, stores, clothing and medicine, in short, of everything that was necessary to enable him to continue his explorations. That Livingstone was alive, and had been pursuing the great plan of exploration which he had marked out before leaving England, was to be concluded from the rumors that had reached Zanzibar from the interior. His latest letters gave a vivid picture of his destitution as regards the commonest necessaries of a traveler. It would be in the last degree disgraceful to the assistance despatched, not only as a body of geographers but as Englishmen, if they allowed him to perish without making an effort to relieve him."

"Genuine truth being uncontrovertible, the truths taught by religion and by science must agree in the end. Where discrepancy appears to exist, it is only because either the theologian takes the individual opinions of a certain class of scientists for the teachings of science itself, or the scientist, in his turn, takes the individual opinions of certain theologians for the teachings of religion. In this way a kind of antagonism is cultivated; the unwise antagonism displayed by many religious teachers against scientific pursuits has reacted on several of the prominent leaders of science, and in their writings and teachings they accordingly ignore religion. It is not only our stock of knowledge that has increased; its diffusion has increased in still greater ratio; and if our religious teachers and leaders only take this into account, and provide such measures as will cause their profession to be at the head of civilization, scientifically as well as in other respects, there is no doubt that their useful and necessary influence will become greater than ever before."

"The successful completion and operation of the Mont Cenis railway tunnel through the Alps has given new impetus to the project of establishing railway communication between England and France by means of a tunnel under the English Channel. The distance is 22 miles. If a railway tunnel can be carried seven miles through the hard schist and quartz of the Alps, why not for three times seven miles through the softer chalks under the Channel? It is reckoned that the work, if it is practicable at all, could be completed within five years and for $25,000,000."

THE AUTHORS

RAYMOND BOWERS and JEFFREY FREY ("Technology Assessment and Microwave Diodes") are at Cornell University; Bowers is professor of physics and deputy director of the interdisciplinary Program on Science, Technology and Society, and Frey is assistant professor of electrical engineering. Bowers, who was born in London and educated at the University of London and the University of Oxford, is spending the first half of this year as a visiting fellow at Clare College of the University of Cambridge. He has been at Cornell since 1960, except for 14 months in 1966 and 1967, when he was on leave to serve as a member of the staff of the Office of Science and Technology. His research has been in solid-state physics and the physics of very low temperatures. Frey, who was graduated from Cornell in 1960, received his master's and doctor's degrees from the University of California at Berkeley. He spent the years 1966 to 1969 in England, first as a postdoctoral fellow and then as a researcher with the United Kingdom Atomic Energy Authority. His current work is in the fields of microwave integrated circuits, semiconductor technology and transit-time microwave devices.

MARK R. ROSENZWEIG, EDWARD L. BENNETT and MARIAN CLEEVES DIAMOND ("Brain Changes in Response to Experience") are respectively professor of psychology at the University of California at Berkeley, associate director of the Laboratory of Chemical Biodynamics at the Lawrence Berkeley Laboratory and associate professor of anatomy and associate dean of letters and science at Berkeley. Rosenzweig was graduated from the University of Rochester in 1943 and obtained his master's degree there in 1944. After service in the U.S. Navy he did additional graduate work at Harvard University, receiving his Ph.D. there in 1949. He joined the psychology department at Berkeley in 1950. In addition to his research and teaching he has been active in the Berkeley faculty's special scholarship program to prepare economically disadvantaged high school students for college and to aid successful university careers. His avocations are travel and photography. Bennett was graduated from Reed College in 1943 and received his Ph.D. in chemistry from the California Institute of Technology in 1949. He has been with the Laboratory of Chemical Biodynamics since 1949. His outside interests are gardening, skiing, hiking and conservation. Mrs. Diamond received her bachelor's, master's and doctor's degrees in biology and anatomy at Berkeley between 1948 and 1953 and has been on the faculty there since 1960. She writes that she and her husband derive "special pleasure" from taking one of their four children at a time on a trip to a place of his or her choice. "So far Russia, Peru and Alaska have been chosen. The whole family travels together under other circumstances." The investigation the authors describe has received support from the National Science Foundation and the U.S. Atomic Energy Commission.

C. FRED FOX ("The Structure of Cell Membranes") is associate professor in the department of bacteriology and in the Molecular Biology Institute of the University of California at Los Angeles. He was graduated from Wittenberg University in 1960, took his master's degree at Ohio State University in 1961 and then did further graduate work at the University of Chicago, receiving his Ph.D. in 1964. After two years as a postdoctoral fellow at the Harvard Medical School he served on the faculty of the University of Chicago until he moved recently to Los Angeles. He writes: "If anyone is interested in such things, I am a fanatic skier and a tennis nut. This may not be very scientific, but it at least identifies me as being human."

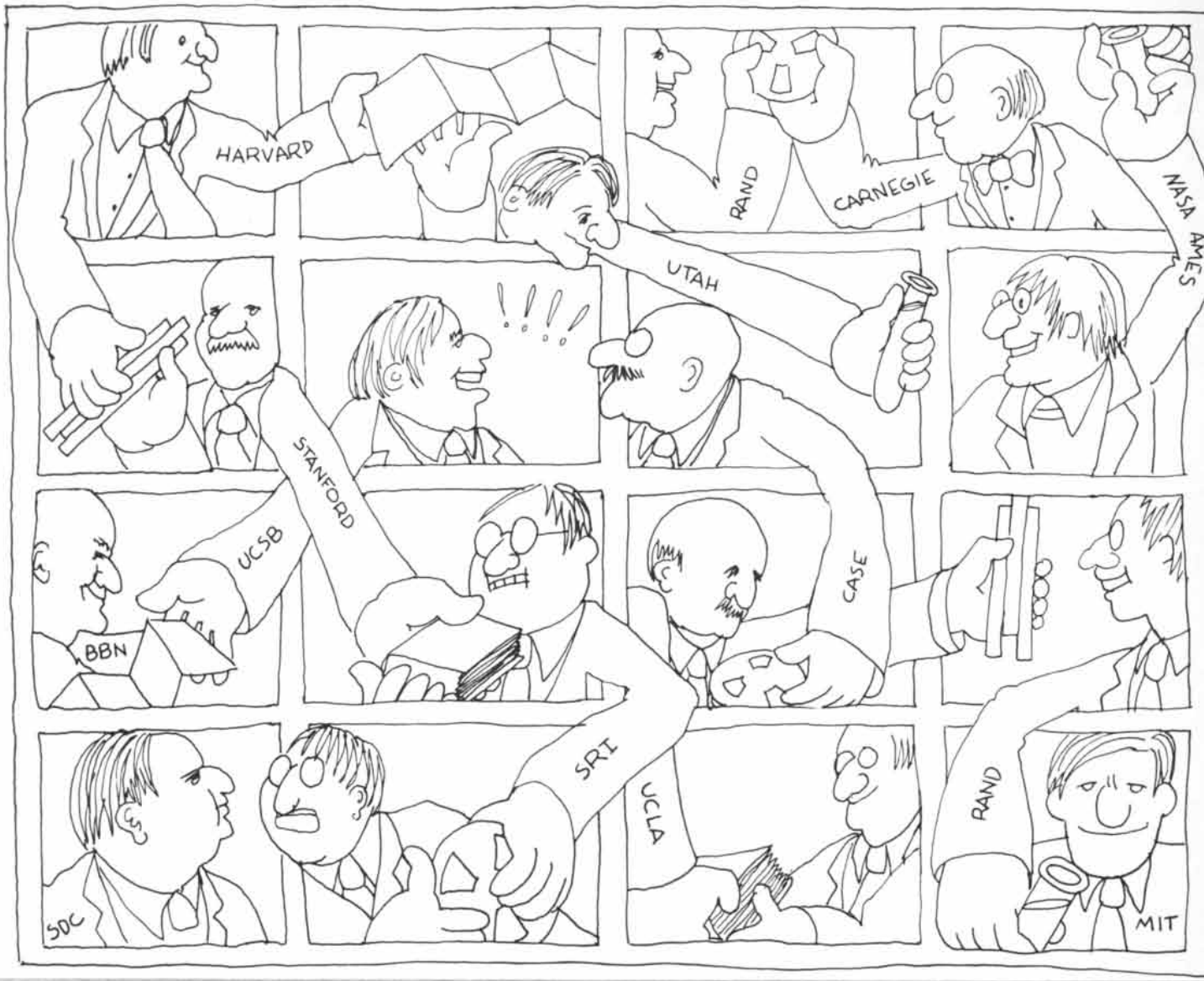
JAMES L. FLANAGAN ("The Synthesis of Speech") is head of the acoustics research department at the Bell Telephone Laboratories. He joined the laboratories in 1957 after receiving his D.Sc. in electrical engineering at the Massachusetts Institute of Technology. He is the author of many technical papers and a book, *Speech Analysis, Synthesis and Perception.* Flanagan writes that he "swims year-round (indoors in the winter)," his "usual drill" being 20 regulation laps of crawl and backstroke. He adds that he is "an avid, though infrequent, saltwater fisherman" and that his reading for pleasure includes biographies and science fiction.

ARTHUR ASHKIN ("The Pressure of Laser Light") is head of the physical optics and electronics research department at the Bell Telephone Laboratories. He writes that he became interested in electromagnetic phenomena when, as an undergraduate during World War II, he worked on microwave magnetrons at the Columbia Radiation Laboratory. Receiving his bachelor's degree from Columbia College after a period of military service, he did graduate work at Cornell University, where he obtained his Ph.D. in 1952. He has been at Bell Laboratories since 1952 and has worked on electron beams, microwaves, lasers, nonlinear optics and radiation pressure.

K. I. KELLERMANN ("Intercontinental Radio Astronomy") is a member of the staff of the National Radio Astronomy Observatory in Green Bank, W.Va. After obtaining his bachelor's degree in physics at the Massachusetts Institute of Technology in 1959, he went to the California Institute of Technology, where he took his Ph.D. in physics and astronomy in 1963. He then spent two years in Australia with the Radiophysics Laboratory of the Commonwealth Scientific and Industrial Research Organization.

ROBERT KEITH WALLACE and HERBERT BENSON ("The Physiology of Meditation") are respectively an independent researcher and assistant professor of medicine at the Harvard Medical School. Wallace, who obtained his Ph.D. in physiology from the University of California at Los Angeles in 1970, has since been collaborating with Benson, who was graduated from the Harvard Medical School in 1961. Their work has been supported by grants from the National Institutes of Health.

WILLIAM L. LANGER ("Checks on Population Growth: 1750–1850") is Archibald Cary Coolidge Professor of History emeritus at Harvard University. His active association with Harvard extended over many years: he received his bachelor's degree there in 1915, his master's in 1920 and his Ph.D. in 1923 and was a member of the faculty from 1926 to 1964. From 1950 to 1952 he served as assistant director of the Central Intelligence Agency, and from 1961 to 1969 he was a member of the President's Foreign Intelligence Advisory Board. Langer was director of the Russian Research Center and the Center for Middle Eastern Studies at Harvard from 1954 to 1959. In 1957 he was elected president of the American Historical Association. He is the editor of *An Encyclopedia of World History,* which was first published in 1940 and is now in its fourth edition, and of the series "The Rise of Modern Europe," of which 17 volumes have been published to date, including his own volume, *Political and Social Upheaval, 1832–1852.*



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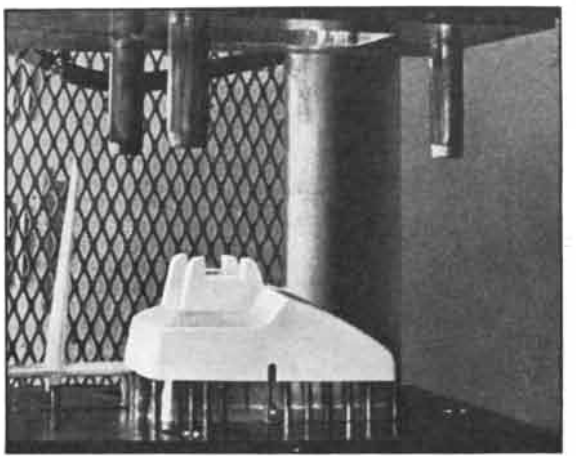
WESTERN ELECTRIC REPORTS



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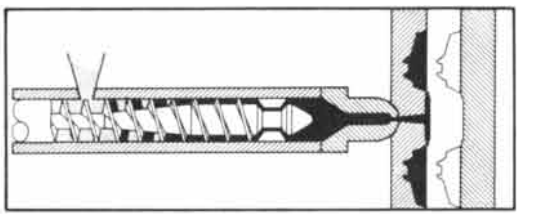

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Some of their recent investigations have brought forth new and highly useful information about a relatively unexplored area: the melting behavior of plastics in the injection molding process.

One result of these studies is the mathematical formula, or model, above.

The model helps us predict melting behavior along the length of the injection screw molding machine used to mold telephone housings and other parts. Melting behavior is extremely important, because plastic pellets should be completely melted but not thermally decomposed before injection into the mold.

This information on melting is then used to investigate screw designs, operating conditions, machine sizes and plastic properties. All of which is aimed at obtaining optimum processing techniques.

Predictions obtained from the mathematical model have checked out closely with experimental observations. So the resulting screw designs are now undergoing evaluation by engineers at our plants in Indianapolis and Shreveport.

Conclusion: For new designs and materials, the model can help reduce the development cost for new molded parts and materials. For manufacturing current products, operating costs can be reduced.

Perhaps most significant is that we're getting information about molding temperatures not available experimentally. And many other types of information can be obtained without the use of costly, time-consuming experimental work.

The end result will be more efficient plastic molding and therefore a better product for the lowest possible cost.

Western Electric

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Technology Assessment and Microwave Diodes

The advent of cheap solid-state devices for the generation of microwaves provides a rare opportunity for attempting to predict the impact of a technological development on society

by Raymond Bowers and Jeffrey Frey

The notion of technology assessment—the attempt to anticipate the effects, good or bad or both, of the introduction of new technology—has been widely discussed in recent years [see "The Assessment of Technology," by Harvey Brooks and Raymond Bowers; SCIENTIFIC AMERICAN, February, 1970]. Not much has been done, however, in the way of actually assessing a technology. In this article we attempt such an assessment, taking as a case in point the rapidly evolving technology of solid-state microwave devices. Our attempt cannot be comprehensive; it is beyond our competence, for example, to estimate the social consequences of microwave technology, just as it would have been difficult for anyone in 1950 to foresee the full social impact of television. We shall focus mainly on the problem of regulating microwave devices in order to ensure the efficient use of the electromagnetic spectrum. In addition we shall touch briefly on the potential hazards to health from the devices and on whether or not microwave technology might result in invasion of privacy. We hope these first steps will lead to an analysis of broader social implications.

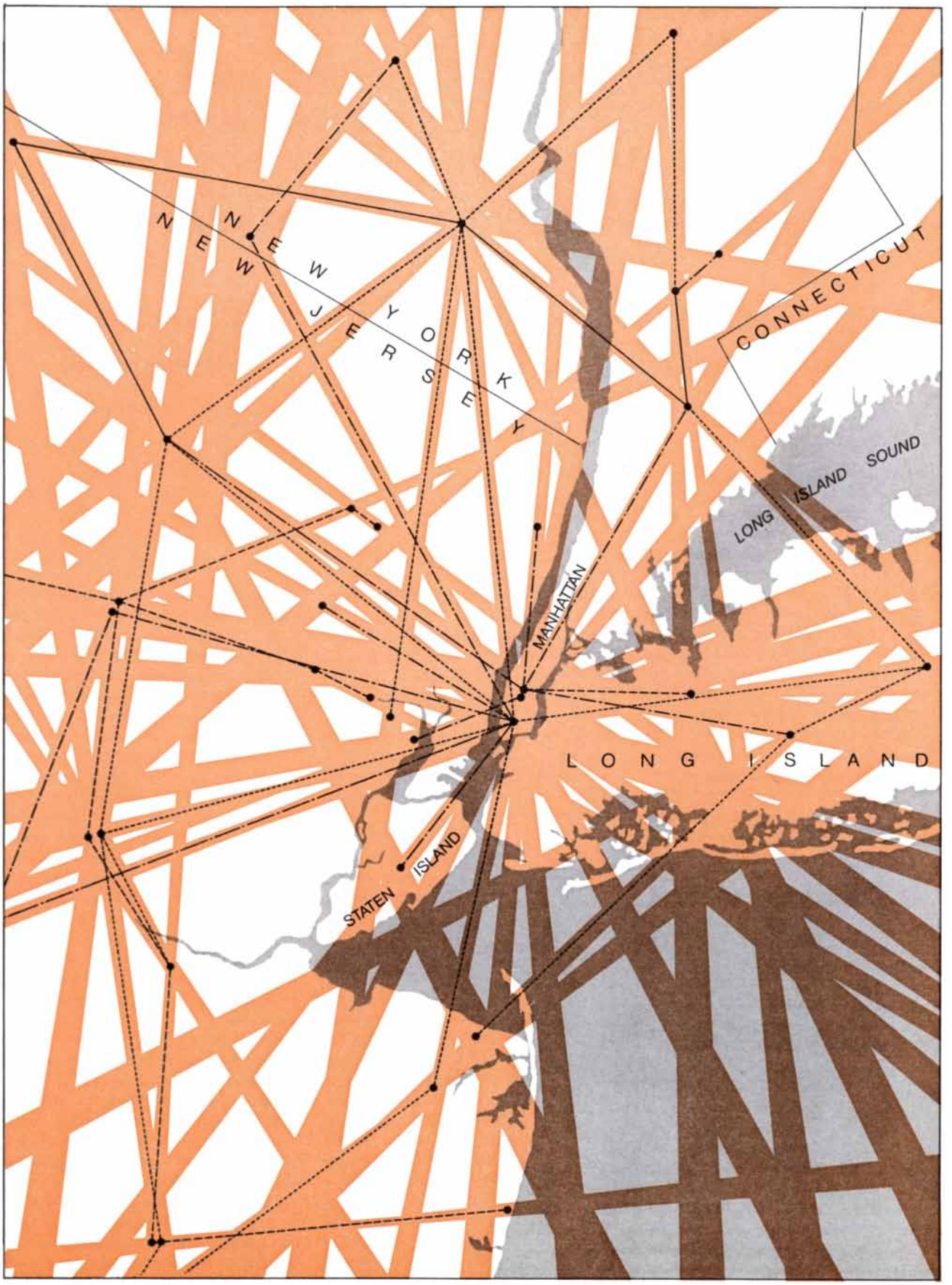
The term microwave refers to wavelength. Although the microwave region of the electromagnetic spectrum is not precisely defined, we use the term to describe radiation of wavelengths ranging from 30 centimeters to three millimeters. In terms of frequency the range is from one gigahertz (billion cycles per second) to 100 gigahertz [*see top illustration on pages 16 and 17*].

Devices that generate and receive microwaves have been developed for more than 30 years. They are now used widely for communications and navigation and in industrial electronics. Typical applications include television and telephone transmission, radar and machine control. In general, however, the microwave sources now in service are expensive. Such electron-tube sources as the klystron and the magnetron cost many hundreds or even thousands of dollars. As a result most microwave systems are operated by military and industrial organizations.

This situation is likely to change radically within the next decade. Reliable and cheap microwave sources, which in mass production can be expected to cost only a few dollars, are now being developed. They are solid-state devices that have resulted from the pioneering work of such investigators as W. Thornton Read, Jr., of the Bell Telephone Laboratories and J. B. Gunn of the International Business Machines Corporation, who showed that crystals such as gallium arsenide, silicon and germanium can, under certain conditions, generate or amplify electrical signals at microwave frequencies [see "A Solid-State Source of Microwaves," by Raymond Bowers; SCIENTIFIC AMERICAN, August, 1966].

Four devices in particular have been reasonably well developed and will be of major importance in the future. They are the Gunn oscillator; the L.S.A. (for limited space-charge accumulation) diode, which was invented by John Copeland of Bell Laboratories; the Read and IMPATT (for impact ionization avalanche transit time) diodes, which are basically similar to each other, and the TRAPATT (for trapped plasma avalanche triggered transit) diode. When these devices are used in the proper circuits, they act as negative conductances: a microwave voltage applied to their terminals causes a current to flow that is 180 degrees out of phase with the voltage. Unlike positive conductances, in which voltage and current flow are in phase so that the conductances absorb energy, negative conductances can transform direct-current energy supplied by a battery or some other source of power into microwave energy.

From the trend of development one can foresee that microwave devices will soon be on the market at prices that individuals can afford, with the likely result that microwave systems for use in homes, automobiles and boats will proliferate. (Microwave cooking ovens are already on the market, but our concern in this article is with microwave sources of considerably lower power.) One can also expect commercial organizations to use microwave sources on a large scale for transmitting information and controlling industrial processes. Indeed, microwave devices may proliferate as much as television sets have proliferated.



4 GIGAHERTZ ---------- 6 GIGAHERTZ —·—·—·—

4 AND 6 GIGAHERTZ ———— 6 AND 11 GIGAHERTZ —·—·—·—·—

11 GIGAHERTZ – – – – – – – – – –

The microwave part of the radio spectrum, particularly the range from one to 10 gigahertz, has been exploited for some time. One of the principal nonmilitary uses is for communication. Present long-distance communication links mostly occupy the bands from 3.7 to 4.2 gigahertz and 5.925 to 6.425 gigahertz. As these bands become saturated new links will be authorized in the band from 11.7 to 12.2 gigahertz.

Microwaves do not bend with the curvature of the earth, so that for long links it is necessary to use repeaters that receive, amplify and retransmit the signal. The spacing between repeaters in the lower two microwave bands is determined by the curvature of the earth, features of the terrain and acceptable antenna heights. A spacing of about 30 miles between repeaters is normal. The cost of the electronics (exclusive of antennas) in a typical repeater can be less than 10 percent of the total cost. In addition, expensive equipment must be installed at each terminal to switch incoming and outgoing calls to the proper circuits. When the cost of this equipment is included for a link operating below 10 gigahertz, the fraction of the total cost of the system that is attributable to microwave components is small. Therefore no major cost benefit is obtained by using solid-state devices below 10 gigahertz.

Above 10 gigahertz attenuation of the signal by the atmosphere becomes a major factor. Repeaters have to be more closely spaced; at 12 gigahertz the maximum practical spacing is about four miles, at 18 gigahertz it is 2.3 miles and at 30 gigahertz it is 1.3 miles. Microwave-equipment costs can become a significant part of total costs. The relatively inexpensive solid-state microwave devices therefore open the spectrum above 10 gigahertz to long-distance communication links and could have a considerable effect on activity across the spectrum.

Another field of application for solid-state microwave devices will certainly be in direct satellite-to-earth communication. The microwave devices will be important components in the home television sets that are equipped to receive directly from satellites. In reflecting on the potential social impact one might consider a satellite that the National Aeronautics and Space Administration plans to launch in 1973. The satellite could ultimately carry direct transmission to 600,000 village receivers in India. A recent World Administrative Radio Conference in Geneva set aside three new microwave bands (22.5 to 23, 41 to 43 and 84 to 86 gigahertz) for satellite-to-earth communication. It may well be that microwave systems will also be used for television broadcasting in local areas, providing another large area of application for solid-state microwave devices as oscillators in television receivers.

APPROACH TO SATURATION in microwave communication in part of the spectrum is indicated by the colored beams on this map of the New York metropolitan area. The routes, which do not produce as much mutual interference as the map suggests because several frequencies are involved, are radio channels that carry a variety of traffic. Map is based on data compiled by the Joint Technical Advisory Committee of the Institute of Electrical and Electronics Engineers and the Electronic Industries Association.

The new developments in solid-state microwave sources also have the potential for a major improvement of land-based, mobile communication systems. Automobile telephones, for example, could become common. Such telephones cannot be widely installed now because only a narrow band of the spectrum is assigned to this purpose, but if microwave or millimeter-wave bands were made available, the service could expand. Short-wave systems of this kind are directional and of short range, so that it would be necessary to have a large number of local terminals to receive and retransmit the signal from an automobile as the automobile moved along. A system for finding the automobile for incoming messages would also be required; it too probably would involve microwaves.

In the field of guidance and control, which includes radar, radio location and other operations, the availability of solid-state microwave devices is similarly expected to result more in the expansion of existing applications than in new applications. It will soon be possible for light aircraft to carry both altimeter radar and collision-avoidance radar at costs comparable to the cost of other electronic equipment for general aviation. Weather radar is also a possibility, but it will require higher peak power than is likely to be available within the next decade. Radar for small boats may well become practical.

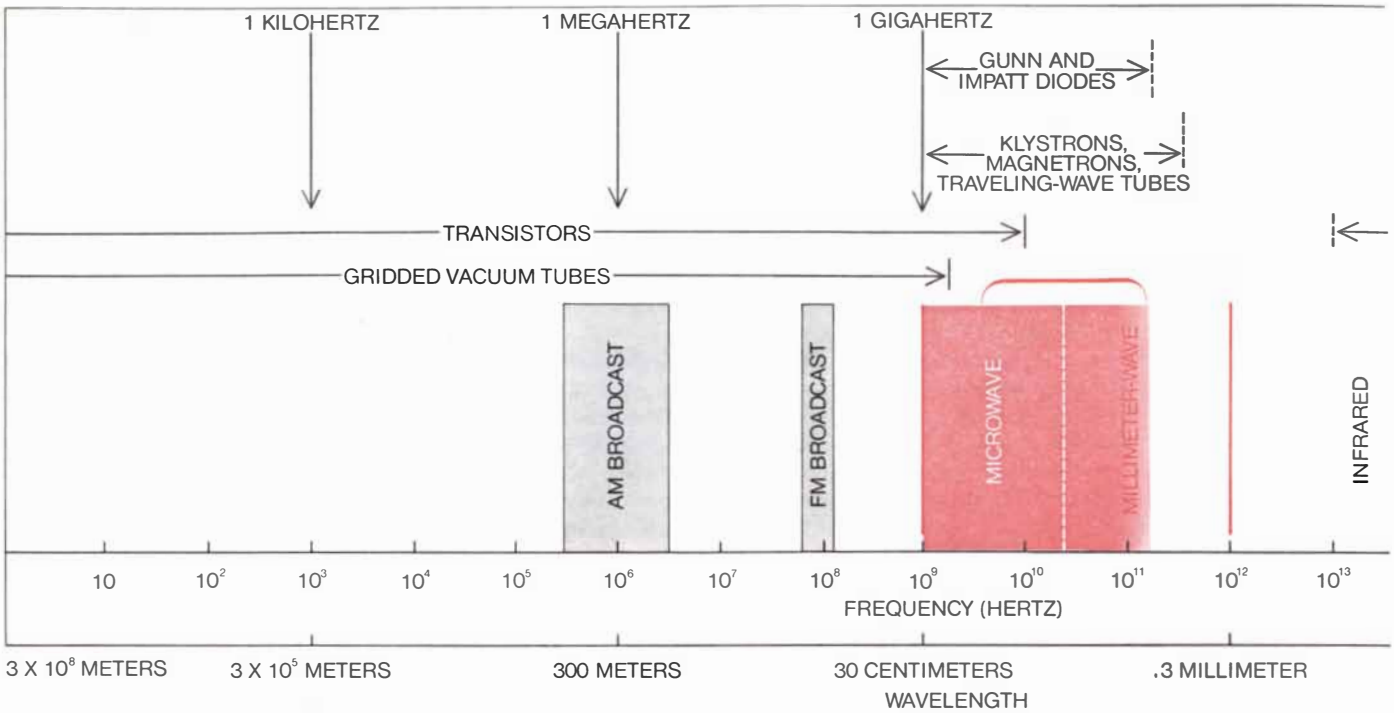
A new and large radar market could arise with the installation of radar in automobiles for such purposes as indicating clear lanes, warning of obstacles in backing up, providing automatic headway control and triggering passive-restraint devices such as the air bag. (The accelerometer devices that currently trigger air bags at the instant of impact must inflate the bag in such a short time that the accompanying noise is almost explosive. A simple radar trigger could yield the extra fraction of a second required to reduce this problem.)

Microwave systems are already in service as burglar alarms and have the potential for development as fire alarms. An electric company in Illinois is about to test an automatic meter-reading system in which a truck with a microwave transceiver will interrogate a small transponder on each house and obtain the meter reading, which will then be recorded on magnetic tape. Microwave systems could also be used to keep track of buses, service trucks, police cars and other vehicles whose location needs to be known. One can also foresee applications of microwaves in process control (counting, monitoring thickness and so on) and in medicine and biology for such purposes as detecting changes in the circulatory and respiratory systems.

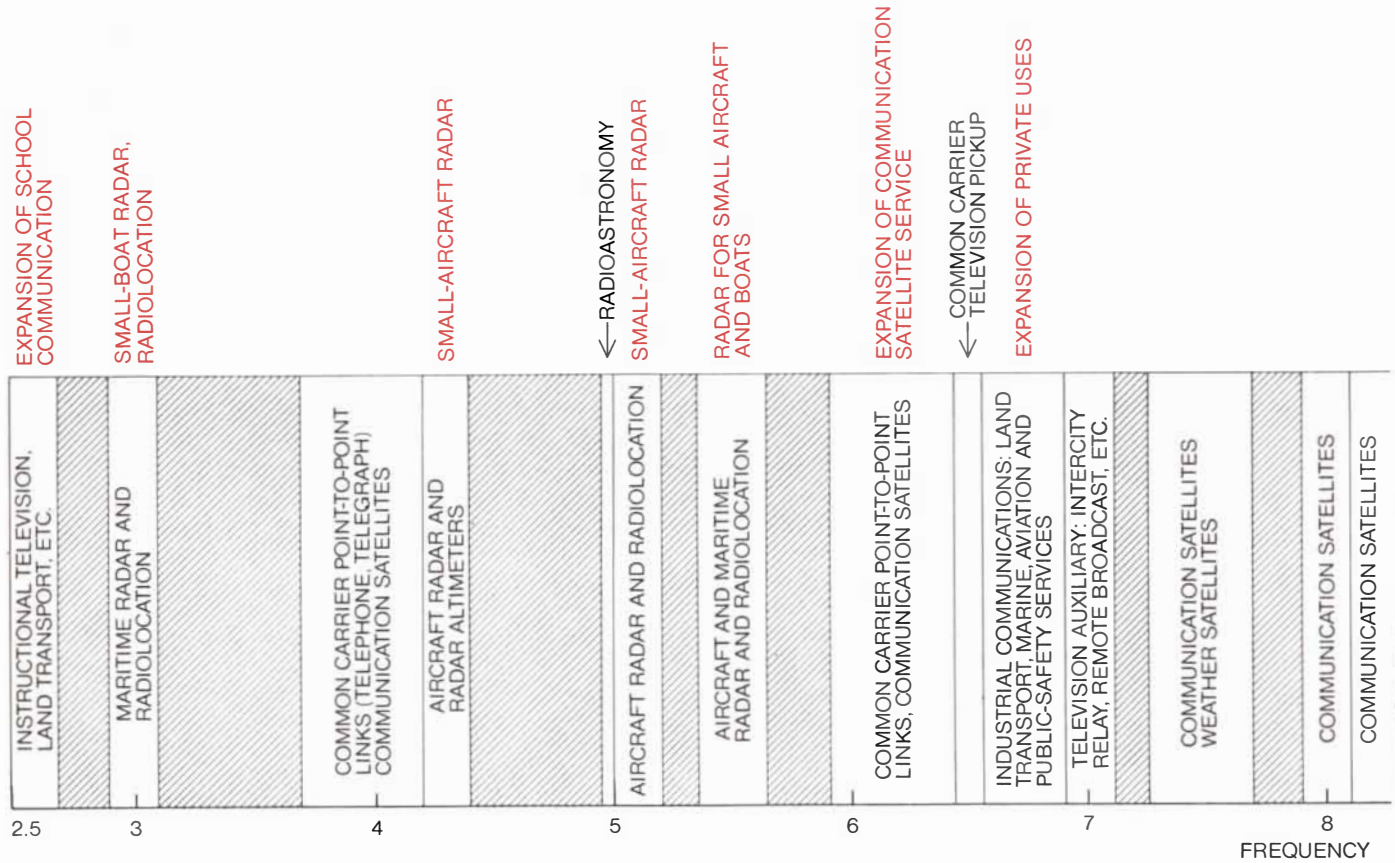
The benefits that could result from expanding microwave applications and developing new ones are considerable. The entire communication system could be improved by opening the frequency range above 10 gigahertz, thereby relieving the congestion at lower frequencies. The new sources also provide a potentially economical means of communication for places where wired systems are unavailable or impractical. As we have already implied, microwave systems have the potential to improve transportation, reduce damage by fire, aid crime detection and advance health care.

These benefits will be accompanied by a number of problems, which need attention soon if the benefits of microwave technology are to be maximized. Most of the problems are related to the fact that a large proliferation of microwave devices would make heavy demands on part of the electromagnetic spectrum and could result in a good deal of mutual interference not only among these devices but also with other electronic systems. Moreover, the possibility of a health hazard from widespread exposure to microwave radiation needs to be examined closely.

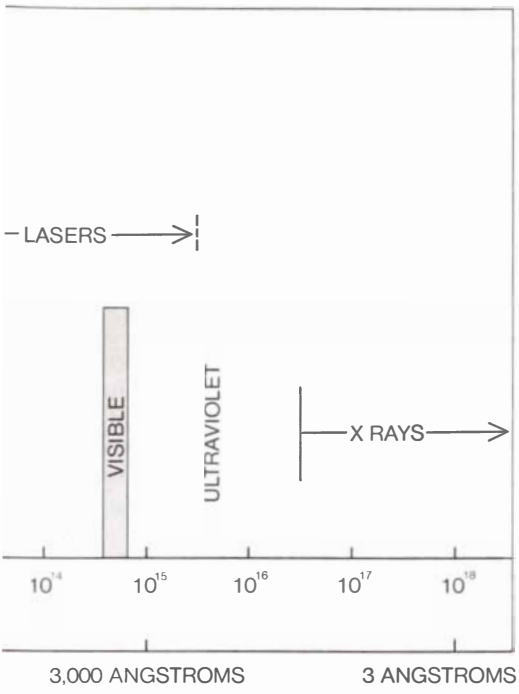
A fund of experience and a system of institutional arrangements are now in hand for controlling microwave systems (mostly military and industrial) that consist of no more than a few tens of thousands of units and that range in cost from $100,000 to $10 million per system. If unit prices fall to about $1,000 and microwave systems are installed extensively in light aircraft, large private boats



PORTION OF ELECTROMAGNETIC SPECTRUM that includes the microwave region (*color*) is portrayed. The microwave region is defined in various ways, which is why the color fades out toward the higher frequencies. Most of the current microwave applications occupy the range from one to 10 gigahertz. Most of them also use expensive klystron and magnetron tubes as microwave sources. The



MICROWAVE ACTIVITIES in the region of the spectrum from 2.5 to 14 gigahertz are shown according to present uses (*black*) and prospective uses (*color*) in the U.S. Allocations are made by the Federal Communications Commission. Hatched areas represent



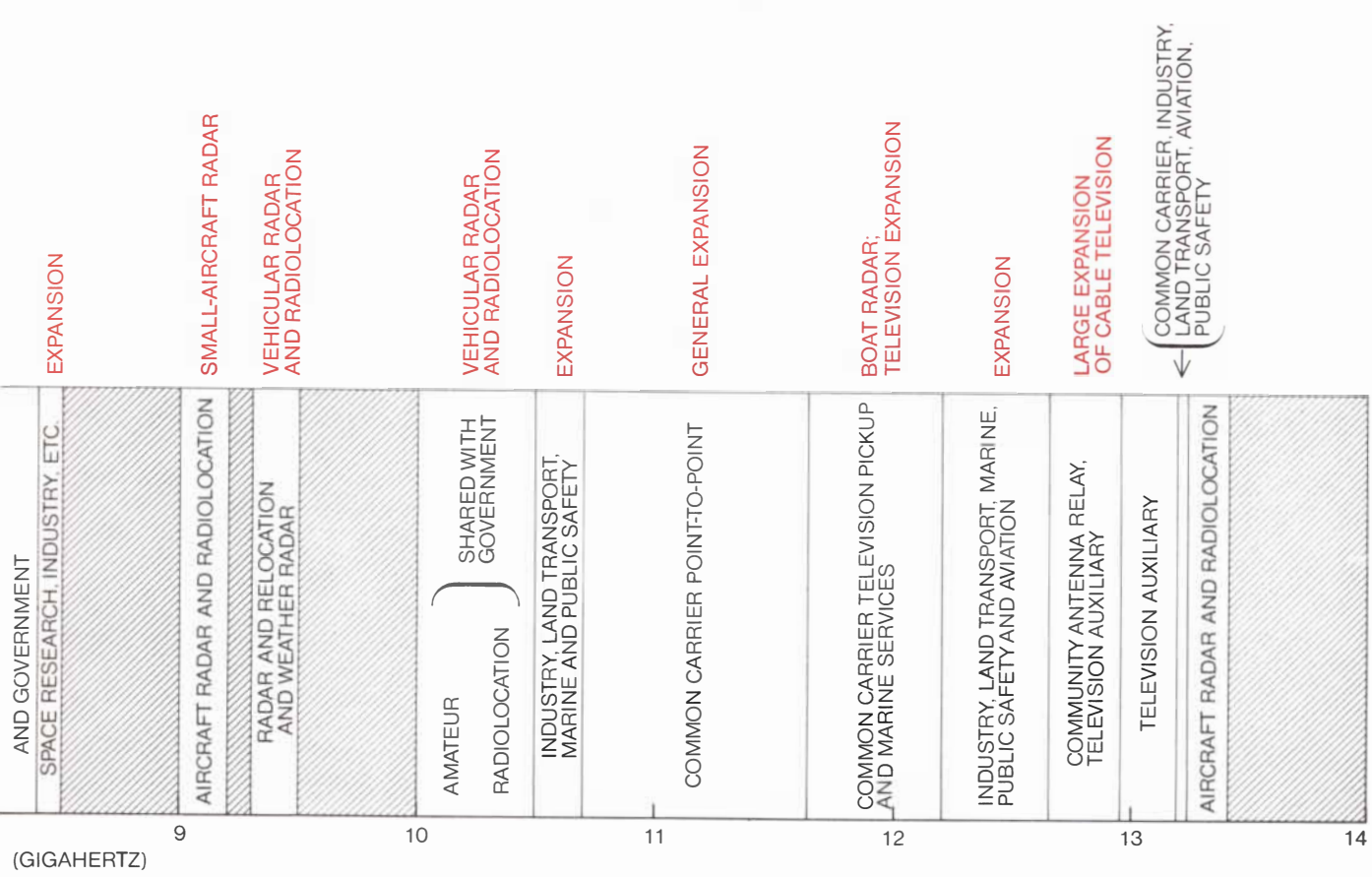
two diodes mentioned are among the inexpensive, solid-state sources that are expected to expand microwave applications.

and large trucks, the number of systems might rise to perhaps a million. Even with such numbers the problems would be manageable compared with what will happen if the unit price of microwave systems falls below $100 and the systems are widely installed in automobiles and trucks. Society is simply unprepared to deal with the number of systems (perhaps 100 million) that could result.

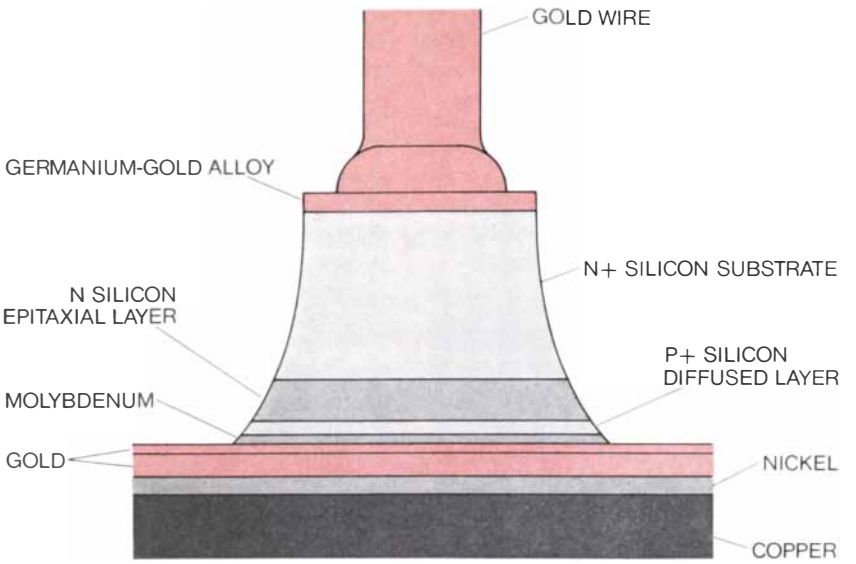
Let us examine the problems more closely, beginning with the problem of managing the electromagnetic spectrum. As recently as 1965 it was possible for the Joint Technical Advisory Committee of the Institute of Electrical and Electronics Engineers and the Electronic Industries Association to note that the spectrum space above 10 gigahertz "is unique at this point in history, in that there are relatively few services implanted in the band." Today, however, new common-carrier land transmitters are being assigned to the band from 10.7 to 11.7 gigahertz, cable-television relays are at 12.7 to 12.95 gigahertz and most satellite-to-earth links may well be above 12 gigahertz. These activities, which have a potential for substantial growth, are being forced above 10 gigahertz because of pressure on the spectrum from below rather than because of any technological advantage in having them there.

In the U.S. the spectrum is allotted in blocks for specific uses up to 90 gigahertz [*see illustration below*]. Recent proposals would extend block allocations to 300 gigahertz. Nonetheless, most of the spectrum above 10 gigahertz is currently unexploited. One of the difficulties in considering how the spectrum might be utilized is inadequate information on the number of present users. From the data that are available, however, one can conclude that the spectrum below 10 gigahertz is filling rapidly to the point where growth of microwave systems might be affected. Virtually all these systems employ the older, electron-tube sources of microwaves.

Congestion of the spectrum varies from place to place. In places as different as New York City and Venice, La., certain bands are saturated. The nature of the locality determines the type of congestion. New York, a center of commerce, communication and entertain-



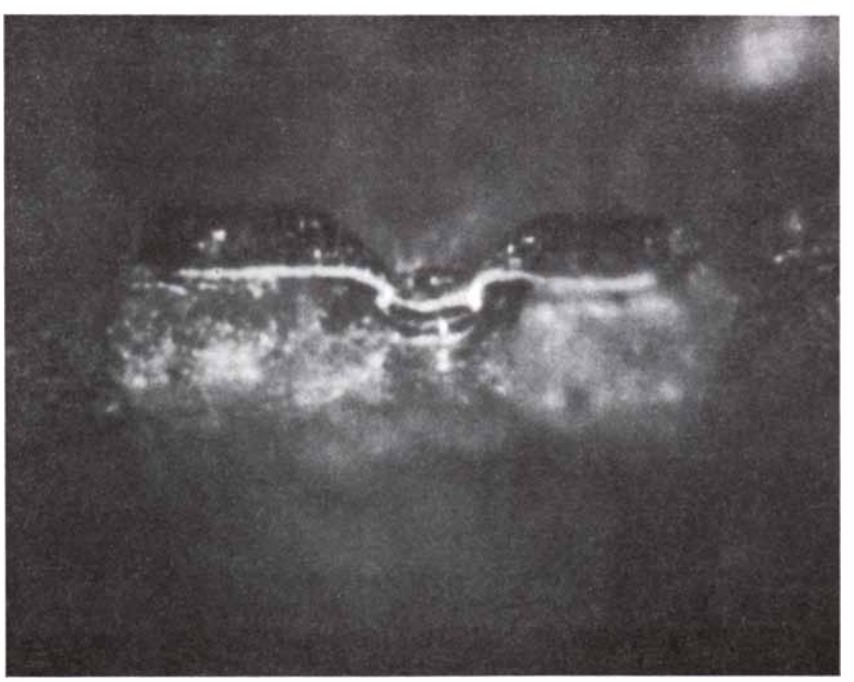
portions of the spectrum that are reserved for use by Government agencies. In addition, all bands allotted to radar and radiolocation are shared with Government agencies that carry on the same activities. Allocations up to 300 gigahertz have been proposed.



IMPATT DIODE is one of the solid-state microwave devices that promise to bring the cost of microwave systems within reach of individuals. The name is an acronym of impact ionization avalanche transit time. The letters *n* and *p* refer respectively to materials that have negatively charged carriers and those that contain positively charged "holes" created by the loss of electrons through impact. Such diodes generate and amplify microwave signals.

ment, is afflicted with saturation in the common-carrier band from 3.7 to 4.2 gigahertz and with severe congestion in the other two common-carrier bands below 12 gigahertz, and the petroleum area around Venice has safety and special-service bands that are nearly full. The block-allocation system followed by the Federal Communications Commission does not allow the transfer of the common-carrier spectrum to safety and special services or vice versa. As a result of this policy and the growth of commercial microwave systems the problem of the saturation of specific microwave bands in certain locations is growing.

One must therefore assume that there will be extensive exploitation of the spectrum above 10 gigahertz once economic and reliable systems are available. Indeed, if the large numbers of systems that are implicit in the potential application of microwave techniques are to be accommodated, the only place for them is above 10 gigahertz. Since solid-state microwave devices already span a range of frequencies up to 100 gigahertz, it is tempting to assume that a prospective increase by a factor of 10 in the microwave frequency range available should accommodate all expected applications. We think such an assumption may prove to be optimistic.



DIODE AND CONTACTS appear at center of a metal container three millimeters wide and four millimeters deep. A 50-gigahertz IMPATT diode is below center of contact ribbon.

A number of steps could be taken that might facilitate preparation for the proliferation of microwave systems. First, calculations should be made of the likely uses of the microwave spectrum. The calculations would take into account communities of varying population density having all the foreseeable microwave systems: fixed and mobile communication systems, automobile radar and so on. The aim would be to predict what degree of congestion might arise.

Second, an adequate base of data for making the calculations and for correlating them with the real situation should be established. One of the requirements for minimizing the congestion of the spectrum is complete information on how the spectrum is being used: a computerized data base containing information on the location, frequency, radiated power and power contour for every operating and proposed transmitter. Until recently the only organization that compiled much of this information, at least for the common-carrier bands, was the American Telephone and Telegraph Company. We think a more comprehensive system should be developed and maintained by an appropriate Government agency. Without an adequate data base it will be necessary to have excessively large margins on each side of every allocation of the spectrum in order to prevent overlap.

A third suggestion is that the principle of block allocation of frequencies in the microwave spectrum needs to be reconsidered. Simple block allocation is excessively rigid, as the cases of New York City and Venice show. Flexibility should be expressly built into the system. If account is taken of the directionality and polarization of each beam, multiple uses of the same frequency are possible, even in the same area. In addition, performance requirements should be established, differing for different services in different parts of the spectrum and applicable to both transmitters and receivers.

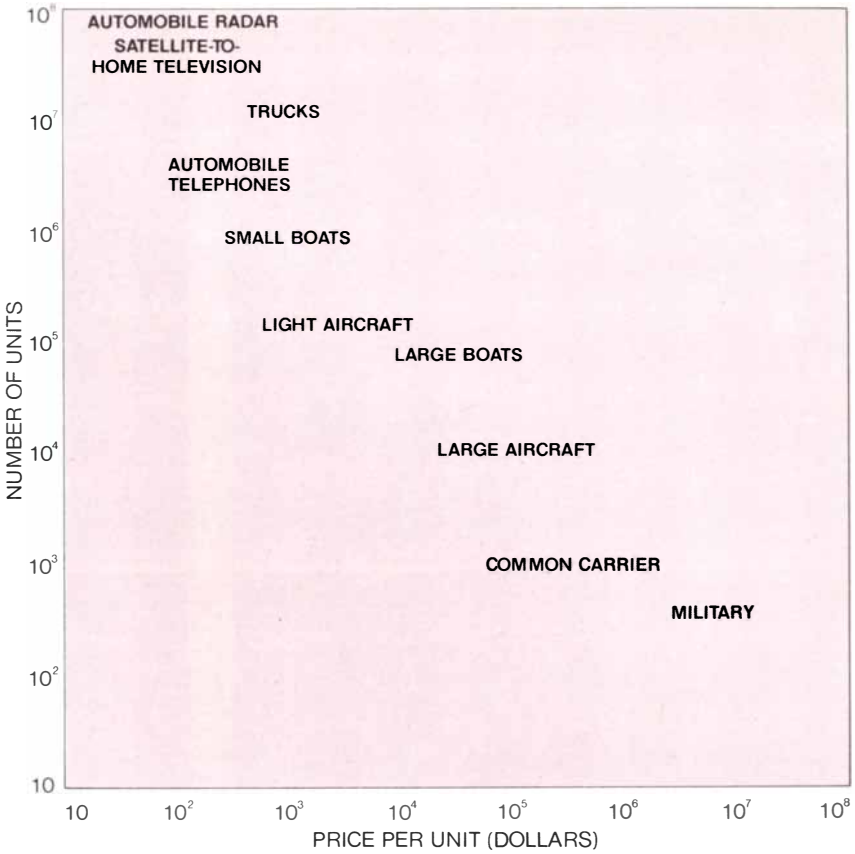
We should like to take note of a further problem that may arise if cheap sources of microwave power become available. The fact that the microwave

sources in service up to the present time have been expensive has led naturally to the development of expensive and high-quality components of microwave systems in order to obtain maximum benefit from the sources. The new sources, however, make "cheap and dirty" systems possible. It is conceivable that some manufacturers will sacrifice narrowness of beam and precision of frequency control in order to achieve lower costs. This development is particularly likely for devices with power below the level where licensing and strict regulation are normally required.

In this area a large responsibility rests on the engineering profession to ensure that these low-power devices are nonpolluting from the electromagnetic point of view. The question is whether the profession can establish standards that keep bandwidth, beam width and power at the minimum level to accomplish the objective of a given system. Standards of this kind involve a principle of conservation of a natural resource—the electromagnetic spectrum—that should be applied whether or not a problem of congestion is foreseen. If this much responsibility is not exercised by the profession, Government regulation and control will surely be necessary.

One area where engineering and manufacturing attention is needed in order to facilitate conservation of the spectrum is the area of antenna design. Techniques for the design of inexpensive, narrow-beam antennas (perhaps fiber-glass paraboloids or dielectric molded structures) do not seem to have kept pace with the improvements in microwave sources. One possibility is the development of active antennas, which provide a degree of amplification at the receiving end; they would allow the use of transmitters of lower power than would otherwise be required. In addition, frequencies for specific applications should be chosen (whenever it is possible) to take advantage of the natural attenuation of the signal in the atmosphere, so that a signal would not penetrate beyond the area that needs to receive it. If the engineering is done properly, many of the low-power microwave devices need be no more troublesome than a flashlight.

It seems to us that concern should be given to the prospect that microwave devices might be incorporated in toys (for both children and adults) and in systems where wired transmission could do the job equally well. Some people contend that since the broadcast spectrum is an exhaustible resource it should not be used for trivial purposes or in situations where the task can be accomplished by other means. We think it would be impracticable to prevent the development of such applications; indeed, to do so would involve a restraint on use of the spectrum that impinged on the rights of some developers. It seems much more realistic to assume that such systems will be developed and to assign them to frequency ranges that are well separated from systems serving more vital functions. The time may come when the spectrum is so congested that an embargo will have to be placed on all new broadcast microwave systems performing a function that could just as well be done with cables.

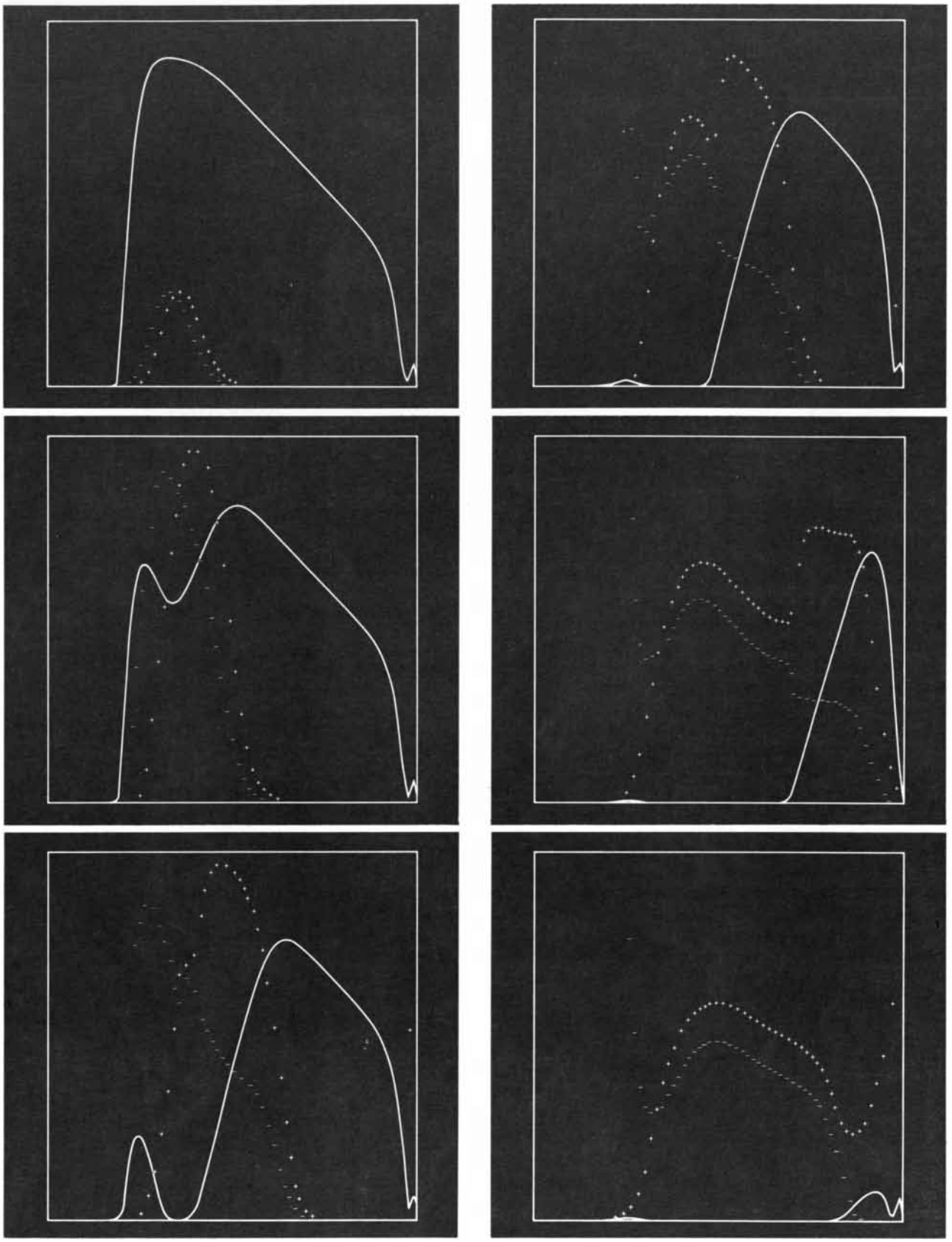


GROWTH IN USE of microwave systems is expected to follow declines in the price per unit. Here the relation between price per unit and number of units is plotted approximately.

Another type of interference, not connected with spectral overlap, has recently attracted attention. Microwave radiation can interfere with the operation of some nonmicrowave electronic systems even at low radiation levels, sometimes with unfortunate effects. For example, stray radiation from microwave ovens has been responsible for the malfunction of some heart pacemakers. The level of radiation needed to produce interference, according to the U.S. Public Health Service, is of the order of five microwatts per square centimeter. This level of power might well be present at reasonable distances from the kinds of system we have been discussing.

We turn now to microwaves as a possible health hazard. Since it is reasonable to expect that large numbers of microwave systems will be in the hands of private individuals and therefore will be relatively unsupervised, the need for exploring the biological effects of microwave radiation is urgent. Standards that were established at a time when microwave systems were fairly uncommon and when the average person was unlikely to be irradiated by a microwave beam may be inadequate when microwave beams are emitted from many automobiles, traffic signals and utility poles.

A measure of the magnitude of the problem can be obtained by considering automobiles with radar. A collision-avoidance radar on an automobile might have an average power output of 50 milliwatts; if the power were transmitted within a beam angle of two degrees, the power density at a distance of five meters from the vehicle would be more than 100 microwatts per square centimeter. It is unlikely that anyone would be irradiated by a single beam for any length of time, but he would be exposed to the



CHARGE PATTERN inside a TRAPATT diode at six intermittent moments (*top to bottom*) is depicted according to a computer simulation devised by D. L. Scharfetter of the Bell Telephone Laboratories. With the proper circuit conditions a large pulse of current flows in the diode's normally nonconducting direction, causing the electric field (*solid line*) to rise rapidly and achieve values that result in the generation of electrons (*minus signs*) and "holes" (*plus signs*) that are in excess of those normally attainable. Separation of these oppositely charged carriers results in space charge that reduces the electric field to low values. In effect the moving avalanche-generation zone sweeps through the diode, leaving behind a dense charge of plasma and a low-value electric field.

beams from many vehicles. The prospective levels of power from automobile radar units are inconsequential under safety standards current in the U.S., but they could be of consequence according to standards adopted in eastern Europe. We shall return to this point.

There is no doubt that microwave radiation can be harmful to living organisms, but there is considerable controversy over the levels of irradiation required to produce significant effects, over the permanence of the effects and over the physiological events that cause them. Cases are on record of cataracts and testicular damage in man and of death in animals exposed to microwave radiation experimentally. These effects were probably caused by heating due to absorption of microwave energy at power levels much higher than the ones we have been discussing. Subtler effects have been reported at low levels of power, however. They are called "athermal" effects because they do not seem to be directly attributable to heating. They include mutations in garlic root tips grown in a high-frequency field and a tendency for certain animals to respond to such fields in various ways.

The amount of microwave energy absorbed by an object depends on the electric properties of the object and the frequency (and hence the wavelength) of the radiation with respect to the size of the object. The human body begins to absorb radiation significantly when the frequency exceeds about 15 megahertz. The absorptivity of microwaves varies over parts of the body and also varies with time. Microwaves penetrate fat about 10 times more deeply than muscle, and the difference is presumably reflected in the absorption. Certain organs, notably the eye and the testes, are particularly sensitive to heating effects.

Athermal effects were not included when the current recommended U.S. radiation safety limit was set by the Department of Health, Education, and Welfare at an average of 10 milliwatts per square centimeter for long exposures. Athermal effects apparently were considered, however, when the U.S.S.R. established a maximum standard of 10 microwatts per square centimeter per working day—a factor 1,000 times smaller than the U.S. figure. A number of informed American workers are skeptical about many of the Russian results and consequently regard the Russian standards as being unnecessarily stringent, but skepticism is not a sufficient basis for setting standards.

The U.S. standard was set as a result of a program on the biomedical aspects of microwave radiation that was administered by the three military services from 1957 to 1961. Some workers see this research as being largely irrelevant to the subject of low-power microwave radiation because of the neglect of athermal effects and an apparent tendency of the investigators to reject data from eastern Europe on athermal effects. These data have included evidence of hypertension, disturbed heart rhythm and decreases in the sensitivity of various sense organs. The average power levels at which the effects were noted ranged upward from 30 microwatts per square centimeter, and frequencies were usually in the range from ultrahigh to low-microwave—a range where absorption by the skin and bone of the skull is small. Recent experiments in the U.S. are said to have demonstrated that the metabolic activity of the embryonic chick heart is disturbed by 24-gigahertz radiation and that the development of insect pupae can be adversely affected by irradiation with 10 gigahertz. Both of these experiments involved power levels too low to cause significant heating.

Another factor not included when the current U.S. standard was set is the duty cycle of the applied radiation, that is, the percentage of time during which the radiation is being emitted. In an experiment involving two groups of rabbits no members of a group that received 80 milliwatts per square centimeter of continuous-wave radiation for one hour developed cataracts, whereas cataracts did develop in all members of the second group, which received pulsed radiation of 400 milliwatts per square centimeter with a duty cycle of 20 percent (and hence the same average power as the first group received). Thus a radiation standard based solely on average power may not be adequate.

What emerges from this discussion is that the effects of microwave radiation on biological systems are poorly understood. Plainly it is necessary to do much more research in this area, emphasizing low-power effects, and to reexamine safety standards before microwave devices proliferate. The work should be concerned not only with human beings but also with other biological systems. If this research is not done, public controversy will surely develop once the devices proliferate, just as controversy has arisen over low-level radiation emitted from nuclear reactors. In the case of microwaves it is still possible to investigate the low-level effects before massive deployment of microwave devices. The Electromagnetic Radiation Advisory Council of the U.S. Office of Telecommunications Policy is said to be developing a national research program along these lines.

Our final point has to do with the concern that a number of people have expressed over the possibility that new developments in electronics may be used as a means of invading privacy. A related issue is that as more information is transmitted by way of microwave beams, banks, industrial organizations and other users of these links may become concerned over the possibility that transmissions will be intercepted.

We have examined the privacy question in a preliminary way and have come to the tentative conclusion that the new sources do not represent a special problem in the sense of adding a new dimension to the privacy issue. Indeed, in certain respects the new microwave systems seem to have certain advantages over telephone lines in maintaining privacy. To tap a microwave beam one must find it, and its position may not be physically apparent. Moreover, it appears likely that double-frequency transmission will be easier in the microwave range than it is over telephone lines. In such a system one frequency carries a coded message and the second one transmits the code. Anyone trying to intercept the information will have to find both frequencies; he will also be up against the fact that the signal transmitting the code can occupy an exceedingly narrow band.

If someone is really determined to intercept information, it is almost impossible to thwart him indefinitely. Our concern has been with making interception difficult enough to discourage it on a frequent or casual basis. It would seem prudent, when large amounts of information are to be transmitted by microwave systems, to encode it in at least a simple way.

We should like to emphasize that none of our conclusions about microwave technology is firm and that we have not dealt with certain important questions in our assessment of the technology. Our purpose has been mainly to initiate debate on these issues and to indicate areas where more detailed analysis is necessary. We hope particularly that the technical community, at its meetings and in its publications, will devote attention to these problems, inviting contributions from social scientists (who can add valuable perceptions to the assessment of broad social implications of microwave devices) as well as from physical scientists and experts in technology. To give attention to these problems is part of the public responsibility of the research and development community.

Brain Changes in Response to Experience

Rats kept in a lively environment for 30 days show distinct changes in brain anatomy and chemistry compared with animals kept in a dull environment. The implications of these effects for man are assessed

by Mark R. Rosenzweig, Edward L. Bennett and Marian Cleeves Diamond

Does experience produce any observable change in the brain? The hypothesis that changes occur in brain anatomy as a result of experience is an old one, but convincing evidence of such changes has been found only in the past decade. It has now been shown that placing an experimental animal in enriched or impoverished environments causes measurable changes in brain anatomy and chemistry. How these changes are related to learning and memory mechanisms is currently being studied by an interdisciplinary approach that involves neurochemical, neuroanatomical and behavioral techniques.

The earliest scientific account of brain changes as a result of experience that we have been able to find was written in the 1780's by an Italian anatomist, Michele Gaetano Malacarne. His experimental design is worth describing briefly, since it resembles the one we are using in our laboratory at the University of California at Berkeley. He worked with two dogs from the same litter and with two parrots, two goldfinches and two blackbirds, each pair of birds from the same clutch of eggs. He trained one member of each pair for a long period; the other member of the pair was left untrained. He then killed the animals and examined their brains. He reported that there were more folds in the cerebellum of the trained animals than in that of the untrained ones. Although his study was noted by some of his contemporaries, we have not found any evidence that others attempted to carry out similar experiments. Knowledge of Malacarne's experiment quickly faded away.

During the 19th century there was considerable interest in the relation between the size of the human head and intellectual ability and training. In the 1870's Paul Broca, a famous French physician and anthropologist, compared the head circumference of medical students and male nurses and found that the students had larger heads. Since he believed the two sets of young men were equal in ability, he concluded that the differences in head size must have been due to the differences in training. Clearly Broca's logic was not impeccable, and there are other possible explanations for the differences he found. His critics pointed to the lack of correspondence between skull size and brain volume, the important roles of age and body size in determining brain size and the relative stability of the size of the brain in comparison with the size of most other organs. By the beginning of the 20th century not only had experimenters failed to prove that training resulted in changes in the gross anatomy of the brain but also a consensus had developed that such changes could not be detected, and so the search was generally abandoned.

With the development of new biochemical tools and techniques in the 1950's, some investigators began to ask if chemical changes in the brain following training could be detected. They looked for changes at the synapses that transmit impulses from one nerve cell to another or for changes in the nucleic acids (RNA and DNA) of nerve cells. The techniques used to find chemical or anatomical changes in the brain following experience are not difficult in principle but they must be carried out with precision because many of the changes that occur are not large. Here is how a basic experiment is conducted with laboratory rats of a given strain. (In our experiments we have worked with several strains of rats and with laboratory mice and gerbils; we have observed similar effects in all these animals.) At a given age, often at weaning, sets of three males are taken from each litter. Usually a dozen sets of three males are used in an experiment. This yields stabler and more reliable results than working with a single set, as Malacarne did.

The use of rodents for these studies is convenient for several reasons. Brain dissection is simpler in rodents than it is in carnivores or primates because the cerebral cortex of rodents is smooth and not convoluted like the cortex of higher mammals. The gray cortex can be stripped away from the underlying white matter more readily in rodents than it can in higher mammals. Rodents are small, inexpensive and bear large litters, so that littermates with the same genetic background can be assigned to different conditions. In addition, geneticists have developed inbred lines of rats and mice, and working with these inbred lines gives us further control over the genetic background.

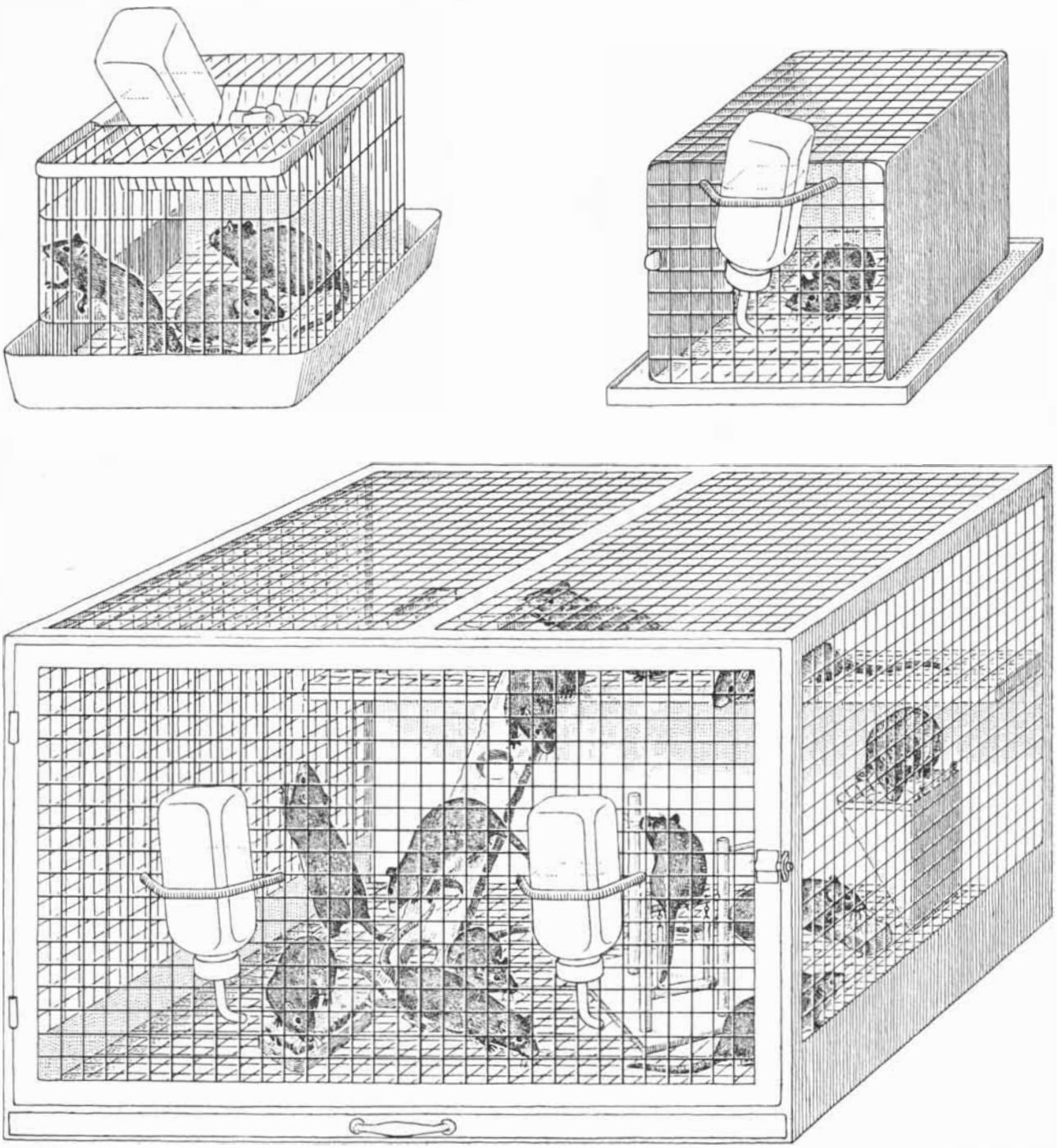
The three male rats from each litter are assigned at random so that one rat remains in the standard laboratory colony cage, one rat is placed in an enriched environment and the third is put in an impoverished environment. It should be noted that "enriched" and "impoverished" are not used in an absolute sense but only in relation to the standard laboratory colony environment that is the usual baseline for studies in anatomy, biochemistry, physiology, nutrition and behavior.

In the standard laboratory conditions a few rats live in a cage of adequate size with food and water always present [*see illustration on opposite page*]. In the enriched environment several rats live in a large cage furnished with a variety of objects they can play with. A new set of playthings, drawn out of a pool of 25 objects, is placed in the cage every day. In the impoverished environment each rat lives alone in a cage. Originally the

isolated rats were kept in a separate quiet room, but this turned out to be unnecessary.

At the end of a predetermined experimental period, which can be from a few days to several months, the rats are sacrificed and their brains are removed. The brain dissection and analysis of each set of three littermates are done in immediate succession but in a random order and identified only by code number so that the person doing the dissection does not know which cage the rat comes from. With practice a skillful worker can do dissections with considerable precision and reliability. To delineate the various cortical regions a small plastic calibrated T square is used [*see illustration on page 25*]. Samples removed from a cortical region are weighed to the nearest tenth of a milligram and then placed on dry ice. The samples are kept frozen until chemical analysis is performed to determine the activity of the neurotransmitter enzymes in them.

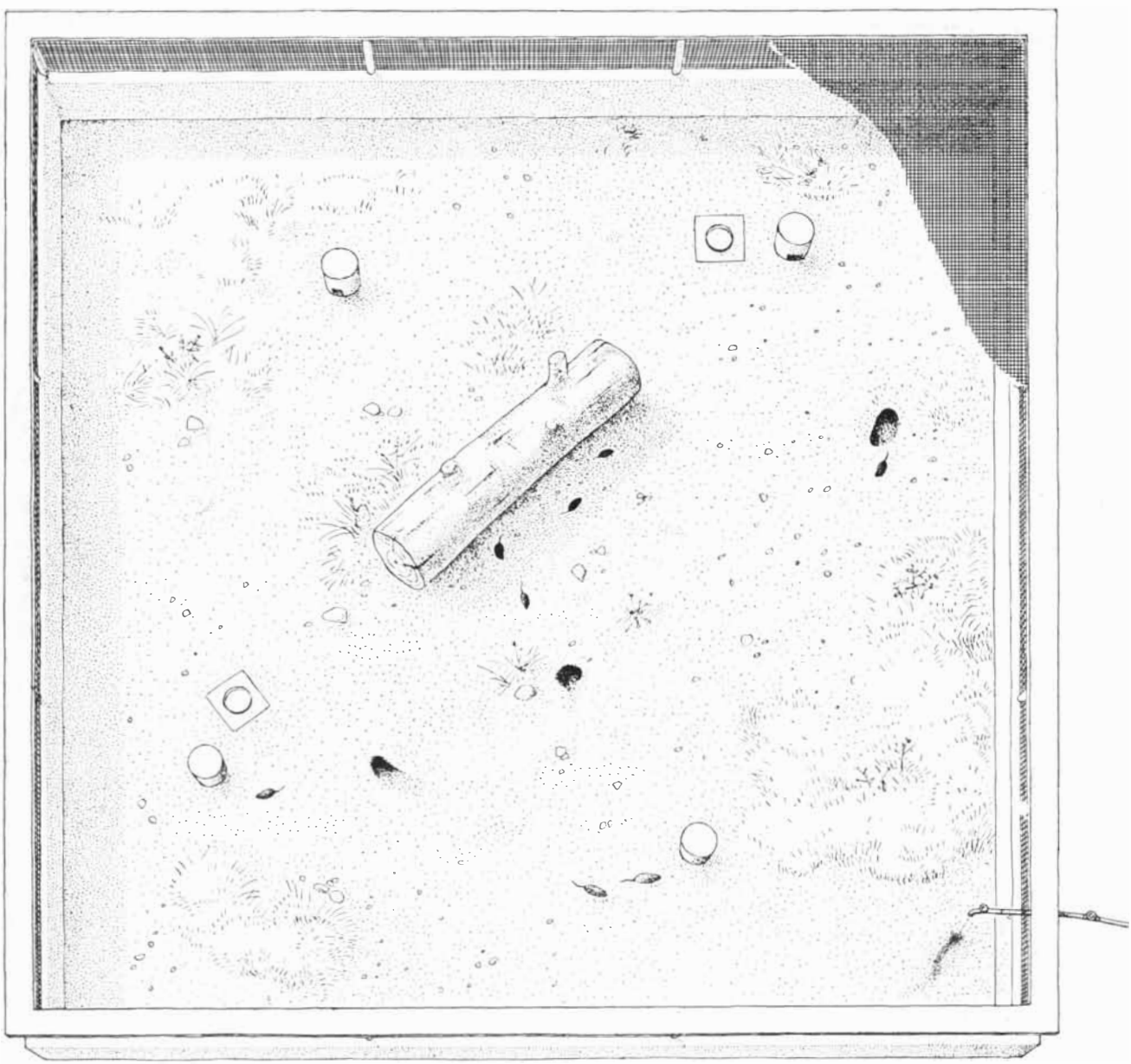
If the rat brains are to be used for anatomical studies, the animal is anesthetized and perfused with a fixative solution. Later sections of the brain are prepared for microscopy.



THREE LABORATORY ENVIRONMENTS that produce differences in brain anatomy of littermate rats are depicted. In the standard laboratory colony there are usually three rats in a cage (*upper left*). In the impoverished environment (*upper right*) a rat is kept alone in a cage. In the enriched environment 12 rats live together in a large cage furnished with playthings that are changed daily. Food and water are freely available in all three environments. The rats typically remain in the same environment for 30 days or more.

In the 1950's we had been attempting to relate individual differences in the problem-solving behavior of rats to individual differences in the amount of the enzyme acetylcholinesterase in the brain. (At the time and until 1966 the psychologist David Krech was a member of the research group.) The enzyme rapidly breaks down acetylcholine, a substance that acts as a transmitter between nerve cells. The excess transmitter must be neutralized quickly because nerve impulses can follow each other at a rate of hundreds per second. This enzymatic activity is often measured in terms of tissue weight, and so in our early experiments we recorded the weight of each sample of brain tissue we took for chemical analysis. We found indications that the level of brain acetylcholinesterase was altered by problem-solving tests, and this led us to look for effects of more extensive experience. To our surprise we found that different experiences not only affected the enzymatic activity but also altered the weight of the brain samples.

By 1964 we had found that rats that had spent from four to 10 weeks in the enriched or the impoverished environments differed in the following ways: rats with enriched experience had a greater weight of cerebral cortex, a greater thickness of cortex and a greater total activity of acetylcholinesterase but less activity of the enzyme per unit of tissue weight. Moreover, rats with enriched experience had considerably greater activity of another enzyme: cholinesterase, which is found in the glial cells and blood capillaries that surround the nerve cells. Glial cells (named from the Greek word for "glue") perform a variety of functions, including transportation of materials between capillaries and nerve cells, formation of the fatty insulating sheath around the neural axons and removal of dead neural tissue.

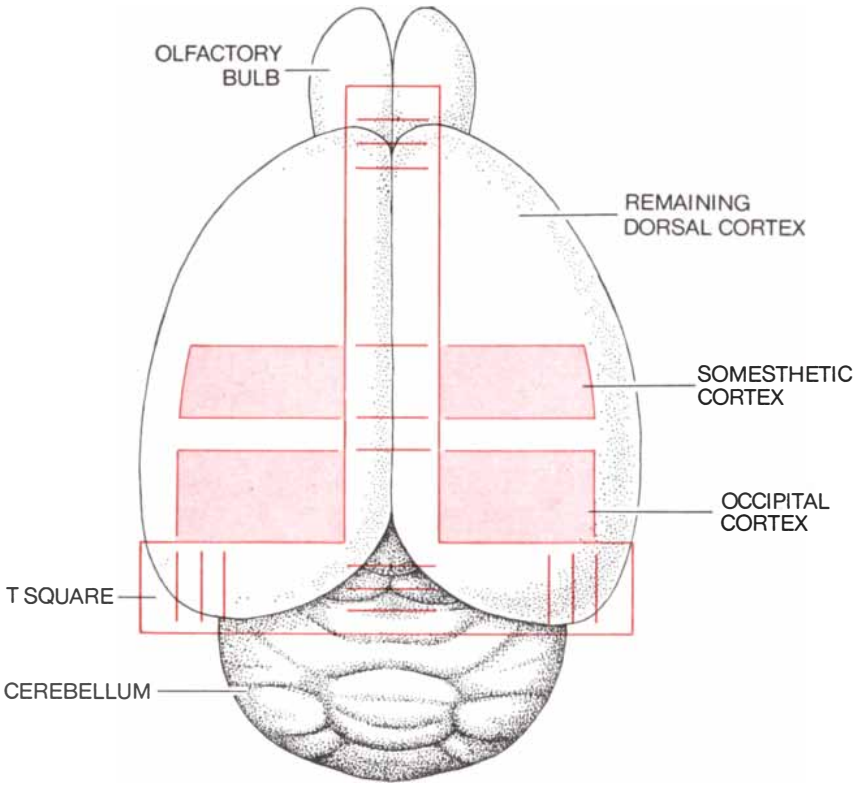


SEMINATURAL ENVIRONMENT for studying the effects of experience on the brain is provided by outdoor enclosures at the Field Station for Research in Animal Behavior at the University of California at Berkeley. The enclosures have a concrete base 30 feet by 30 feet with a screen over the top. Inbred laboratory rats thrive in the outdoor setting when food and water are provided. The rats revert to burrowing, something that their ancestors, which had lived in laboratory cages, had not done for more than 100 generations.

We later found that there were more glial cells in rats from the enriched environment than there were in rats from the impoverished one, and this may account for the increased activity of cholinesterase. Although differences in experience did not change the number of nerve cells per unit of tissue, the enriched environment produced larger cell bodies and nuclei. These larger cell bodies indicate higher metabolic activity. Further chemical measures involving RNA and DNA pointed in the same direction. The amount of DNA per milligram of tissue decreased, presumably because the bulk of the cortex increased as the number of neurons, whose nuclei contain a fixed amount of DNA, remained relatively constant. The amount of RNA per milligram remained virtually unchanged, yielding a significant increase in the ratio of RNA to DNA, and this suggests a higher metabolic activity. In most of the experiments the greatest differences between enriched and impoverished experience were found in the occipital cortex, which is roughly the rear third of the cortical surface.

We do not know why the occipital region of the cortex is affected by enriched experience more than other regions. At first we thought that differences in visual stimulation might be responsible, but when we used blinded rats, the occipital cortex still showed significant differences between littermates from the enriched and the impoverished environments. We found the same effects when normal rats were placed in the different environments and kept in darkness for the entire period. This is not to say that deprivation of vision did not have an effect on the anatomy and chemistry of the brain. The occipital cortex of rats that were blinded or kept totally in the dark gained less weight than the occipital cortex of littermates that were raised in standard colony conditions with a normal light-dark cycle, but this did not prevent the occurrence of the enrichment-impoverishment effect.

Although the brain differences induced by environment are not large, we are confident that they are genuine. When the experiments are replicated, the same pattern of differences is found repeatedly. For example, in 16 replications between 1960 and 1969 of the basic enriched-environment-v.-impoverished-environment experiment, using the same strain of rat exposed to the experimental conditions from the age of 25 to 105 days, each experiment resulted in a greater occipital-cortex weight for the rats in the enriched environment. Twelve of the 16 replications were statistically at better than the .05 level, that is, for each of the 12 experiments there was less than one chance in 20 that the difference was due simply to chance or biological variability. For weight of the total cortex, 13 of the 16 experiments showed significant differences [*see top illustration on next page*].

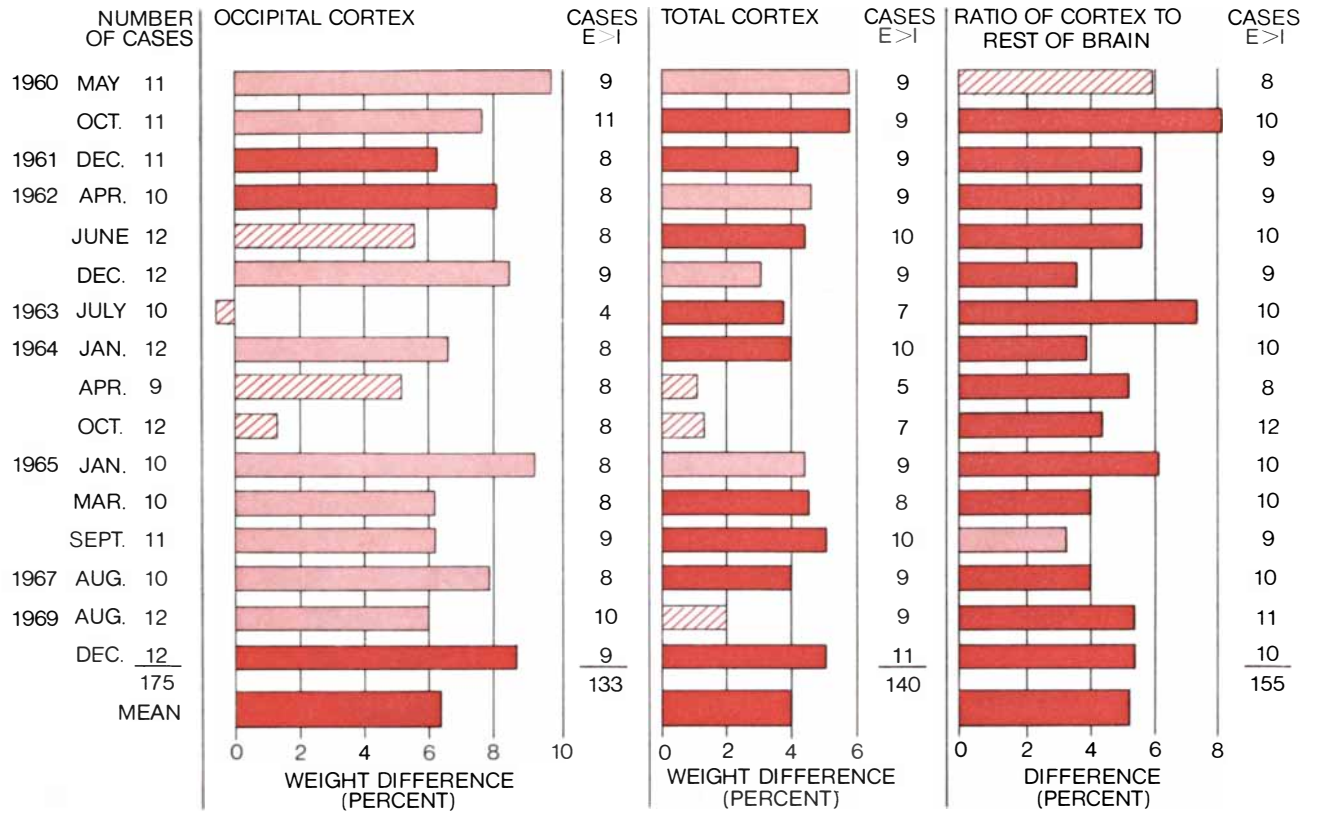


CORTICAL AREAS of a rat brain are located for dissection with the aid of a calibrated plastic T square to ensure uniform samples. The desired sections are removed, weighed and stored on dry ice. The remaining cortex and the subcortex also are weighed and frozen.

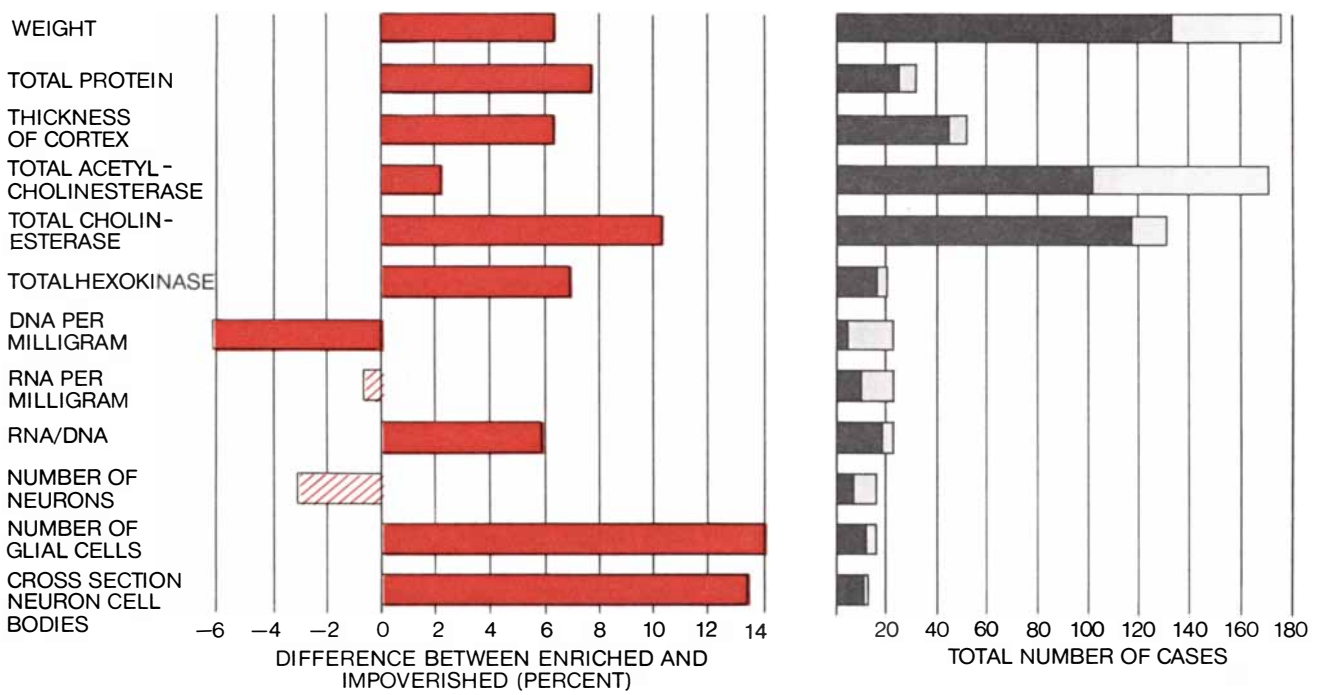
The most consistent effect of experience on the brain that we found was the ratio of the weight of the cortex to the weight of the rest of the brain: the subcortex. It appears that the cortex increases in weight quite readily in response to an enriched environment, whereas the weight of the rest of the brain changes little. Moreover, since rats with larger bodies tend to have both a heavier cortex and a heavier subcortex than smaller rats, the ratio of the cortex to the rest of the brain tends to cancel the influence of body weight. For animals of a given strain, sex, age and environment the cortex/subcortex ratio tends to be the same even if the animals differ in body weight. When the environment is such that the cortex grows, the cortex/subcortex ratio shows the change very clearly and reliably. On this measure 14 of the 16 experiments were significant at the .01 level.

One of the major problems for measuring the effects of experience on the brain is finding an appropriate baseline. Initially we took the standard laboratory colony condition as the baseline, as most other investigators have. The cortex/subcortex-weight ratio in rats from the enriched environment is greater than the ratio in rats from the standard colony environment, and this ratio in turn is greater than the ratio in rats from the impoverished environment. Where thickness of cortex is concerned, both environmental enrichment and impoverishment are effective but on different regions of the cortex.

Suppose that the natural environment in which the animals evolved were taken as the baseline. Compared with the laboratory environments, even the enriched one, a natural environment may be much richer in learning experiences. For inbred laboratory animals, however, it is no longer clear what the natural environment is. Laboratory rats and mice have been kept for more than 100 generations in protected environments, and inbreeding has made their gene pool different from the natural one. For this reason we have begun to study wild deer mice (*Peromyscus*). The mice are trapped in the San Francisco area and brought to our laboratory; some are kept in almost



BRAIN-WEIGHT DIFFERENCES between rats from enriched environments and their littermates from impoverished environments were replicated in 16 successive experiments between 1960 and 1969 involving an 80-day period and the same strain of rat. For the occipital cortex, weight differences in three of the replications were significant at the probability level of .01 or better (*dark colored bars*), nine were significant at the .05 level (*light colored bars*) and four were not significant (*hatched bars*). The ratio of the weight of the cortex to the rest of the brain proved to be the most reliable measure, with 14 of the 16 replications significant at the .01 level.



OCCIPITAL CORTEX of rats kept in enriched or impoverished environments from 25 to 105 days showed the effects of the different experiences. The occipital cortex of rats from the enriched environment, compared with that of rats from the impoverished one, was 6.4 percent heavier. This was significant at the .01 level or better, as were most other measures (*dark colored bars*). Only two measures were not significant (*hatched bars*). The dark gray bars on the right show the number of cases in which the rat from the enriched environment exceeded its littermate from the impoverished environment in each of the measures that are listed.

natural conditions at an outdoor station and others are put into laboratory cages. The work with deer mice is still in progress, but we have also placed laboratory rats in the outdoor setting. We found that when food is provided, laboratory rats can thrive in an outdoor enclosure even in a wet winter when the temperature drops to the freezing point. When the ground was not too wet, the rats dug burrows, something their ancestors had not done for more than 100 generations. In each of eight experiments the rats kept for one month in the outdoor setting showed a greater brain development than their littermates that had been kept in enriched laboratory cages. This indicates that even the enriched laboratory environment is indeed impoverished in comparison with a natural environment.

It is possible that the brain changes we found are not the result of learning and memory but are due to other aspects of the experimental situation, such as the amount of handling and stress, or perhaps an altered rate of maturation. For example, simply handling rats, particularly young ones, is known to increase the weight of their adrenal glands. Rats in the enriched environment are handled each day when they are removed from their cage while their playthings are being changed, whereas rats in the impoverished environment are handled only once a week for weighing. We tested the effects of handling on brain changes some years ago. Some rats were handled for several minutes a day for either 30 or 60 days; their littermates were never handled. There were no differences between the handled rats and the nonhandled ones in brain weight or brain-enzyme activity. More recently rats from both the enriched and the impoverished environments were handled once a day and the usual brain differences developed.

Stress was another possible cause of the cerebral effects. Rats from the impoverished environment might have suffered from "isolation stress" and rats from the enriched environment may have been stressed by "information overload." To test this notion Walter H. Riege subjected rats to a daily routine of stress. The rats were briefly tumbled in a revolving drum or given a mild electric shock. The stress produced a significant increase in the weight of the adrenal glands but did not give rise to changes in the brain measures that we use. It seems clear that stress is not responsible for the cerebral changes we have found.

It was also possible, since some of the brain changes we have found go in the same direction as changes that occur in normal maturation, that enriched experience simply accelerates maturation or that isolation retards it. Changes in the depth of the cerebral cortex and certain other changes resulting from an enriched environment go in the opposite direction to what is found in normal growth. The cortical thickness of standard colony rats reaches a maximum at 25 days after birth and then decreases slightly with age, whereas enriched experience causes cortical thickness to increase even in year-old rats. In fact, Riege has found that an enriched environment will produce as great an increase in brain weight in fully mature rats as it does in young rats, although the adult rats require a longer period of environmental stimulation to show the maximum effect.

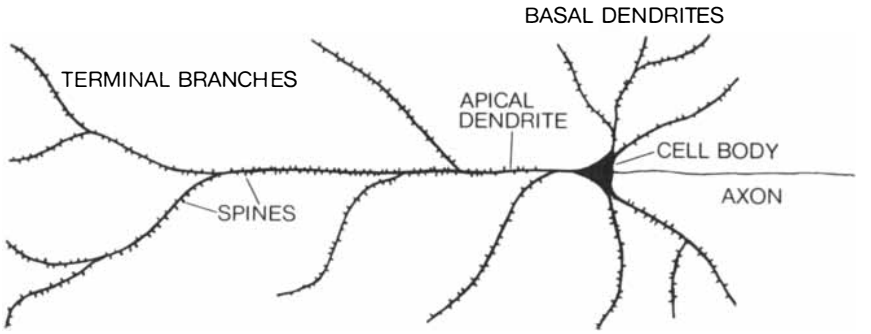
The effect of enriched environment on very young rats has been tested by Dennis Malkasian. He puts sets of three litters of six-day-old rat pups and their mother either into an unfurnished cage or into a cage containing play objects. Brains were taken for anatomical analysis at 14, 19 and 28 days of age. At each age pups from the enriched environment showed a greater thickness of cerebral cortex, and in some parts of the cortex the differences were larger than those found in experiments with rats examined after weaning.

When we first reported our results other investigators were understandably skeptical, since the effect of experience on the brain had not been previously demonstrated. After our findings had been replicated, some investigators began to think that the brain may be so plastic that almost any treatment can modify it, for example merely placing a rat for 15 minutes a day in any apparatus other than its home cage. This does not happen; although cerebral changes are easier to induce than we had supposed at first, a moderate amount of experience is still necessary. We recently demonstrated that two hours of daily enriched experience over a 30-day period is sufficient to produce the typical changes in brain weight. On the other hand, placing a group of 12 rats in a large unfurnished cage for two hours a day for 30 days did not bring about significant changes in our usual brain measures. Moreover, putting rats alone in large cages with play objects for two hours a day is not very effective, probably because a single rat does not play with the objects much and tends to rest or to groom itself. The enriched environment will produce cerebral changes in a single rat if the rat is stimulated to interact with the objects. This can be done by giving the rat a moderate dose of an excitant drug or by putting it into the enriched environment during the dark part of its daily cycle (rats are nocturnal animals). A recent experiment indicates that cerebral changes can also be achieved by putting the rat into the enriched environment after several hours of food deprivation and placing tiny pellets of food on and in the play objects.

There can now be no doubt that many aspects of brain anatomy and brain chemistry are changed by experience. Some of our most recent efforts have been directed toward determining the changes that occur at the synaptic level in the occipital cortex, a region of the brain that shows relatively large changes with experience in enriched environments. Over the past few years Albert Globus of the University of California at Irvine has been counting the number of dendritic spines in brain sections from rats that have been exposed to an enriched environment or an impoverished one in our laboratory. Most of the synaptic contacts between nerve cells in the cortex are made on the branchlike dendrites of the receiving cell or on the dendritic spines, which are small projections from the dendrites. Globus made his counts on the cortical neuron called a pyramidal cell [*see top illustration on next page*]. He found more spines, particularly on the basal dendrites, in rats exposed to an enriched environment than in littermates from the impoverished environment.

An even more detailed view of changes in the synaptic junctions has come out of a study we have done in collaboration with Kjeld Møllgaard of the University of Copenhagen, who spent a year in our laboratory. He prepared electron micrographs of brain sections from the third layer of the occipital cortex of rats. Measurement of the synaptic junctions revealed that rats from enriched environments had junctions that averaged approximately 50 percent larger in cross section than similar junctions in littermates from impoverished environments. The latter, however, had more synapses per unit area [*see illustration on page 29*].

William T. Greenough, Roger West and T. Blaise Fleischmann of the University of Illinois have also found that there is increased synaptic contact in enriched-experience rats. Some other workers have reported that increased size of synapse is associated with a decreased number of synapses, whereas decreased size of synapse is associated with an increased number. It seems that memory

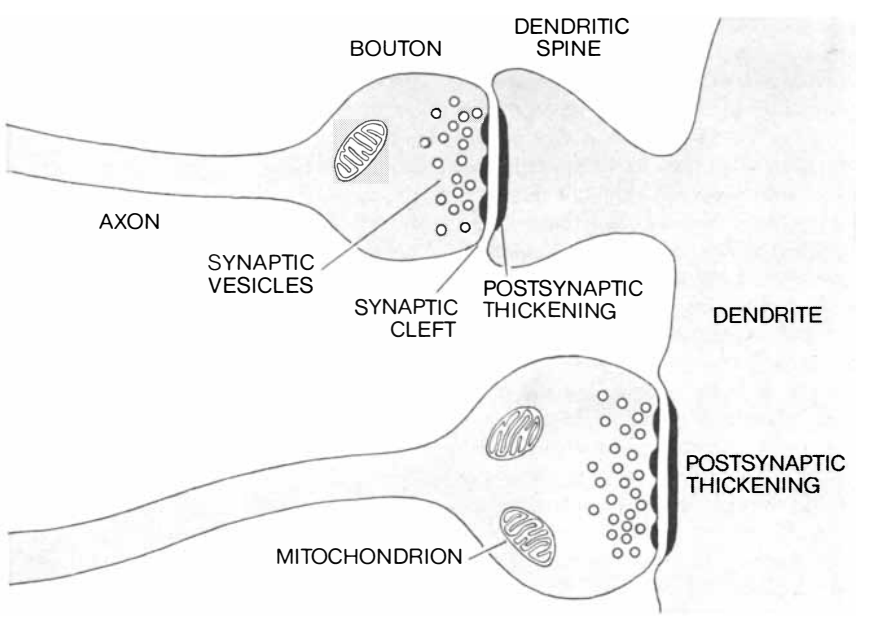


DENDRITIC SPINES, tiny "thorns," or projections from the dendrites of a nerve cell, serve as receivers in many of the synaptic contacts between neurons. The drawing is of a type of cortical neuron known as the pyramidal cell. Rats from an enriched environment have more spines on these cells than their littermates from an impoverished environment.

or learning may be encoded in the brain either by the selective addition of contacts between nerve cells or by the selective removal of contacts, and that both processes may go on at the same time.

Does an enriched environment or an impoverished environment alter learning ability? Although some studies suggest that experience in an enriched environment usually improves subsequent learning, the effects are often short-lived. The result depends on many factors, for example the measure of learning that is used, the age at which the enriched experience is provided and the type of task that is learned. Early enrichment may improve subsequent learning of one task, have no effect on another task and actually impair learning in a third. Perhaps we should not expect much transfer of capacity among entirely different kinds of behavior. Nor should we expect experience in an enriched environment to lead to an increase in "general ability"; every environment is specific and so are abilities. Harry F. Harlow of the University of Wisconsin has shown that early problem-solving in monkeys may have the deleterious effect of fixating infantile behavior patterns; such monkeys may never reach the efficient adult performance that they would have attained without the early training. Again, this result is specific and should be generalized only with caution.

Formal training of rats, such as teaching them to press a lever in response to a signal or to run a maze, produces changes in brain anatomy and chemistry, but the type of training seems to determine the kind of changes. Victor Fedorov and his associates at the Pavlov Institute of Physiology near Leningrad found changes in brain weight and in the activity of acetylcholinesterase and cholinesterase after prolonged training of rats, but the pattern of changes is different from what we found with enriched and impoverished environments. In our laboratory we have given rats daily formal training in either operant-conditioning devices or in a series of mazes for a month or more and have found changes in brain weight and brain enzymes. These changes, however, were rather small and also had a pattern different from the changes induced by environmental experience. This is clearly a problem that requires more research.



SYNAPTIC JUNCTIONS between nerve cells can be between axon and dendritic spine or between axon and the dendrite itself. The vesicles contain a chemical transmitter that is released when an electrical signal from the axon reaches the end bouton. The transmitter moves across the synaptic cleft and stimulates the postsynaptic receptor sites in the dendrite. The size of the postsynaptic membrane is thought to be an indicator of synaptic activity.

The effect of experimental environments on the brains of animals has sometimes been cited as bearing on problems of human education. We should like to sound a cautionary note in this regard. It is difficult to extrapolate from an experiment with rats under one set of conditions to the behavior of rats under another set of conditions, and it is much riskier to extrapolate from a rat to a mouse to a monkey to a human. We have found generally similar brain changes as a result of experience in several species of rodents, and this appears to have fostered the assumption that similar results may be found with carnivores and with primates, including man. Only further research will show whether or not this is so. Animal research raises questions and allows us to test concepts and techniques, some of which may later prove useful in research with human subjects.

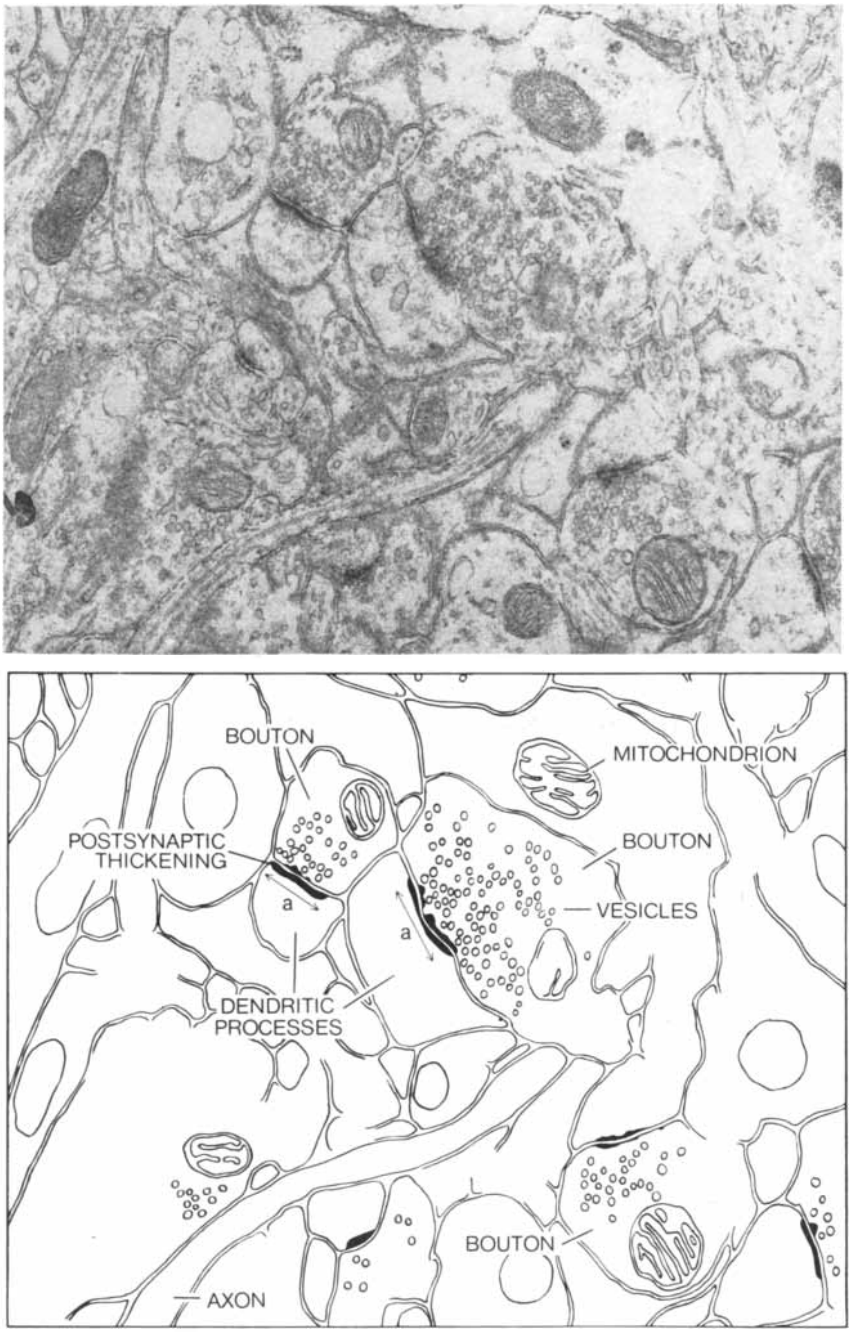
If this research leads to knowledge of how memories are stored in the brain, it will have obvious implications for the study of conditions that favor learning and memory and also of conditions that impair learning and the laying down of memories. Among the unfavorable conditions that are of great social concern are mental retardation and senile decline in ability to form new memories. Clues to the prevention or amelioration of these conditions could be of great social value. Let us also consider two other areas into which such research on brain plasticity may extend.

One of these areas concerns the effects of malnutrition on the development of the brain and of intelligence. Some investigators, such as R. H. Barnes and David A. Levitsky of the Cornell University Graduate School of Nutrition, have proposed that certain effects of malnutrition may actually be secondary effects of environmental impoverishment. That is,

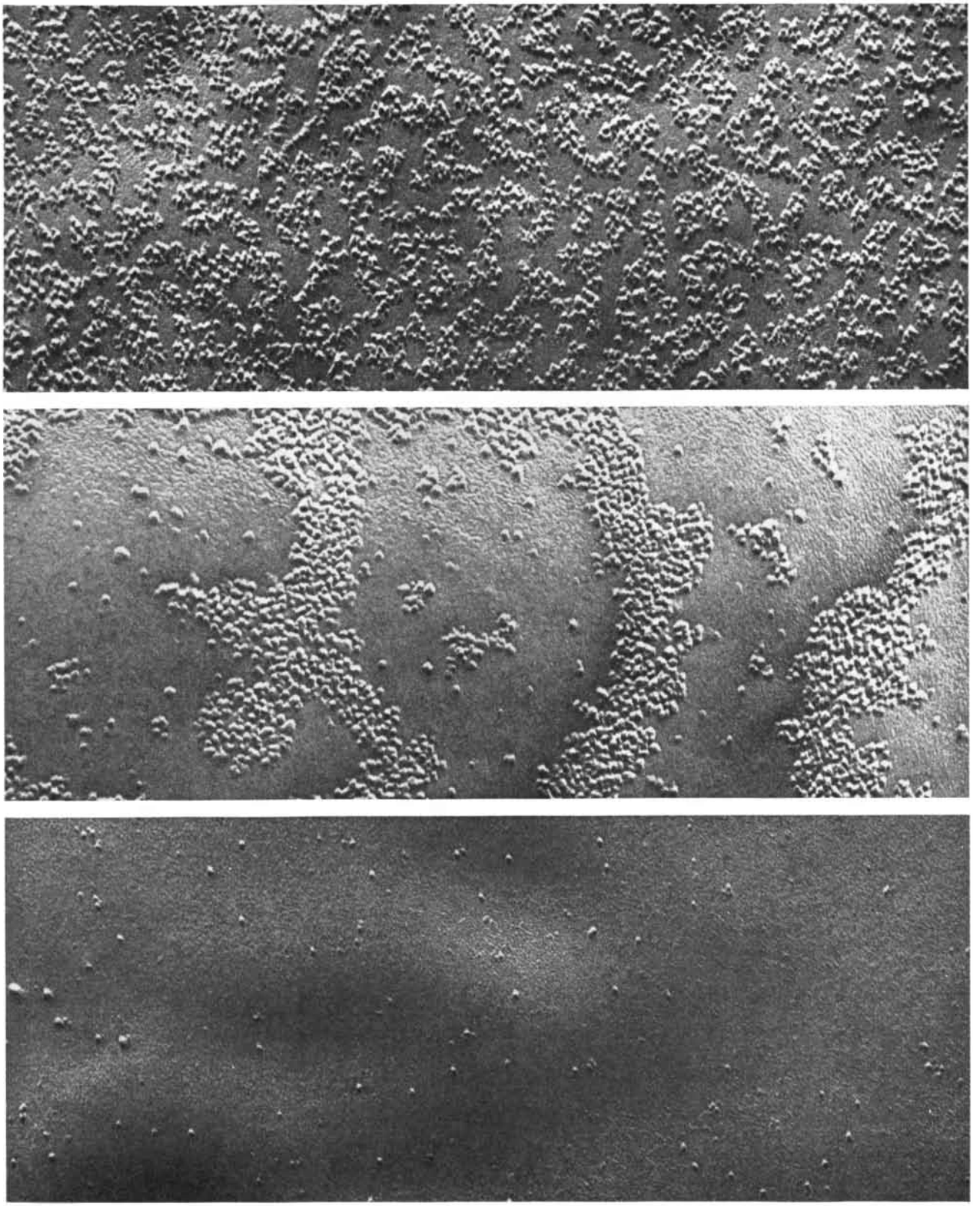
since a prominent effect of malnutrition is to make the person or animal apathetic and unresponsive to the environment, the individual then suffers from lack of stimulation, and this may be the direct cause of some of the symptoms usually associated with malnutrition. Current research suggests that some of the effects of malnutrition may be offset by programs of environmental stimulation or increased by environmental impoverishment.

Another possibly beneficial result of our research findings would be to stimulate a resurgence of attempts to determine relations between experience and brain anatomy in man. This was a topic of some interest late in the 19th century, and a number of reports were published. For example, in 1892 there was a publication on the postmortem examination of the brain of a blind deaf-mute, Laura Bridgman. It was found that the parts of her cortex that were involved in vision and hearing were thin and lacked the pattern of folding found in the normal human brain. In contrast, the region of her cortex devoted to touch had a normal appearance. It would be of interest to see if such results could be generalized by a large-scale modern postmortem study of brains of people who had been deprived of one or more senses. It would be even more interesting to find out if heightened employment of a sense leads to supranormal development of the associated brain region. Would musicians as a group, for example, show an enhanced development of the auditory cortex?

The human brain, because of the specialization of the two cerebral hemispheres, is more likely to provide answers to such questions than animal brains. Spoken words are analyzed in the auditory region of the left cerebral hemisphere, whereas music is analyzed in the auditory region of the right hemisphere. (These hemispheric functions are reversed in a few people.) The relative development of different regions in the same brain could be measured, so that the subjects would be their own control. In recent investigations Norman Geschwind and Walter Levitsky of the Harvard Medical School have found that 65 percent of the human brains they examined showed a greater anatomical development of the auditory area in the left hemisphere, 11 percent showed a greater auditory development in the right hemisphere and 24 percent showed equal development on the two sides. On the other hand, behavioral and physiological tests indicate that 96 percent of the people tested have left-hemisphere speech dominance and presumably have a greater development of the auditory area on that side. Is it possible that people with musical training account for most of the cases in which size of the right auditory area equals or exceeds the size of the left? In order to find out investigators will have to measure sufficient numbers of brains of individuals whose major abilities and disabilities are known. In fact, such a program was proposed 100 years ago by Broca, but the techniques available then were not adequate to carrying out the project. Today the results of our animal studies can serve as a guide, and investigators can look more penetratingly for the anatomical and chemical changes in the human brain that are correlated with experience and learning.



BRAIN SECTION from the occipital cortex of a rat is enlarged 37,000 times in this electron micrograph by Kjeld Møllgaard. The map identifies some of the components. Measurement of the postsynaptic thickening is shown in the map of the section by the arrow (*a*). The number of synaptic junctions was also counted. It was found that rats reared in an enriched environment had junctions approximately 50 percent larger than littermates from an impoverished environment, and the latter had more junctions, although smaller ones, per unit area.



EVIDENCE FOR PROTEINS within the bilayer structure of cell membranes is provided by freeze-etch electron microscopy. A suspension of membranes in water is frozen and then fractured with a sharp blade. The fracture will often split a membrane in the middle along a plane parallel to the surface. After platinum and carbon vapors are deposited along the fracture surface the specimen can be studied in the electron microscope. The micrograph at the top shows many particles 50 to 85 angstroms in diameter embedded in a fractured membrane from rabbit red blood cells. The other two views show how the number of particles is greatly reduced if the membrane is first treated with a proteolytic enzyme that digests 45 percent (*middle*) or 70 percent (*bottom*) of the original membrane protein. The missing particles have presumably been digested by the enzyme. The membrane preparations are enlarged some 95,000 diameters in these micrographs made by L. H. Engstrom in Daniel Branton's laboratory at the University of California at Berkeley.

The Structure of Cell Membranes

The thin, sturdy envelope of the living cell consists of lipid, phosphate and protein. The proteins act as both gatekeepers and active carriers, determining what passes through the membrane

by C. Fred Fox

Every living cell is enclosed by a membrane that serves not only as a sturdy envelope inside which the cell can function but also as a discriminating portal, enabling nutrients and other essential agents to enter and waste products to leave. Called the cytoplasmic membrane, it can also "pump" substances from one side to the other against a "head," that is, it can extract a substance that is in dilute solution on one side and transport it to the opposite side, where the concentration of the substance is many times higher. Thus the cytoplasmic membrane selectively regulates the flux of nutrients and ions between the cell and its external milieu.

The cells of higher organisms have in addition to a cytoplasmic membrane a number of internal membranes that isolate the structures termed organelles, which play various specialized roles. For example, the mitochondria oxidize foodstuffs and provide fuel for the other activities of the cell, and the chloroplasts conduct photosynthesis. Single-cell organisms such as bacteria have only a cytoplasmic membrane, but its structural diversity is sufficient for it to serve some or all of the functions carried out by the membranes of organelles in higher cells. It is clear that any model formulated to describe the structure of membranes must be able to account for an extraordinary range of functions.

Membranes are composed almost entirely of two classes of molecules: proteins and lipids. The proteins serve as enzymes, or biological catalysts, and provide the membrane with its distinctive functional properties. The lipids provide the gross structural properties of the membrane. The simplest lipids found in nature, such as fats and waxes, are insoluble in water. The lipids found in membranes are amphipathic, meaning that one end of the molecule is hydrophobic, or insoluble in water, and the other end hydrophilic, or water-soluble. The hydrophilic region is described as being polar because it is capable of carrying an ionic (electric) charge; the hydrophobic region is nonpolar.

In most membrane lipids the nonpolar region consists of the hydrocarbon chains of fatty acids: hydrocarbon molecules with a carboxyl group (COOH) at one end. In a typical membrane lipid two fatty-acid molecules are chemically bonded through their carboxyl ends to a backbone of glycerol. The glycerol backbone, in turn, is attached to a polar-head group consisting of phosphate and other groups, which often carry an ionic charge [*see illustration on next page*]. Phosphate-containing lipids of this type are called phospholipids.

When a suspension of phospholipids in water is subjected to high-energy sound under suitable conditions, the phospholipid molecules cluster together to form closed vesicles: small saclike structures called liposomes. The arrangement of phospholipids in the walls of both liposomes and biological membranes has recently been deduced with the help of X-ray diffraction, which can reveal the distance between repeating groups of atoms. An X-ray diffraction analysis by M. F. Wilkins and his associates at King's College in London indicates that two parallel arrays of the polar-head groups of lipids are separated by a distance of approximately 40 angstroms and that the fatty-acid tails are stacked parallel to one another in arrays of 50 or more phospholipid molecules.

The X-ray data suggest a structure for liposomes and membranes in which the phospholipids are arranged in two parallel layers [*see illustrations on page 33*]. The polar heads are arrayed externally on the bilayer surfaces, and the fatty-acid tails are pointed inward, perpendicular to the plane of the membrane surface. This model of phospholipid structure in membranes is identical with one proposed by James F. Danielli and Hugh Davson in the mid-1930's, when no precise structural data were available. It is also the minimum-energy configuration for a thin film composed of amphipathic molecules, because it maximizes the interaction of the polar groups with water.

Unlike lipids, proteins do not form orderly arrays in membranes, and thus their arrangement cannot be assessed by X-ray diffraction. The absence of order is not surprising. Each particular kind of membrane incorporates a variety of protein molecules that differ widely in molecular weight and in relative numbers; a membrane can incorporate from 10 to 100 times more molecules of one type of protein than of another.

Since little can be learned about the disposition of membrane proteins from a general structural analysis, investigators have chosen instead to study the orientation of one or a few species of the proteins in membranes. In the Danielli-Davson model the proteins are assumed to be entirely external to the lipid bilayer, being attached either to one side of the membrane or to the other. Although information obtained from X-ray diffraction and high-resolution electron microscopy indicates that this is probably true for the bulk of the membrane protein, biochemical studies show that the Danielli-Davson concept is an oversimplification. The evidence for alternative locations has been provided chiefly by Marc Bretscher of the Medical Research Council laboratories in Cambridge and by Theodore L. Steck, G. Franklin and Don-

ald F. H. Wallach of the Harvard Medical School. Their results suggest that certain proteins penetrate the lipid bilayer and that others extend all the way through it.

Bretscher has labeled a major protein of the cytoplasmic membrane of human red blood cells with a radioactive substance that forms chemical bonds with the protein but is unable to penetrate the membrane surface. The protein was labeled in two ways [*see illustration on pages 34 and 35*]. First, intact red blood cells were exposed to the label so that it became attached only to the portion of the protein that is exposed on the outer surface of the membrane. Second, red blood cells were broken up before the radioactive label was added. Under these conditions the label could attach itself to parts of the protein exposed on the internal surface of the membrane as well as to parts on the external surface.

The two batches of membrane, labeled under the two different conditions, were treated separately to isolate the protein. The purified protein from the two separate samples was degraded into definable fragments by treatment with a proteolytic enzyme: an enzyme that cleaves links in the chain of amino acid units that constitutes a protein. A sample from each batch of fragments was now placed on the corner of a square of filter paper for "fingerprinting" analysis. In this technique the fragments are separated by chromatography in one direction on the paper and by electrophoresis in a direction at right angles to the first. In the chromatographic step each type of fragment is separated from the others because it has a characteristic rate of travel across the paper with respect to the rate at which a solvent travels. In the electrophoretic step the fragments are further separated because they have characteristic rates of travel in an imposed electric field.

Once a separation had been achieved the filter paper was laid on a piece of X-ray film so that the radioactively labeled fragments could reveal themselves by exposing the film. When films from the two batches of fragments were developed, they clearly showed that more labeled fragments were present when both the internal and the external surface of the cell membrane had been exposed to the radioactive label than when the outer surface alone had been exposed. This provides strong evidence that the portion of the protein that gives rise to the additional labeled fragments is on the inner surface of the membrane.

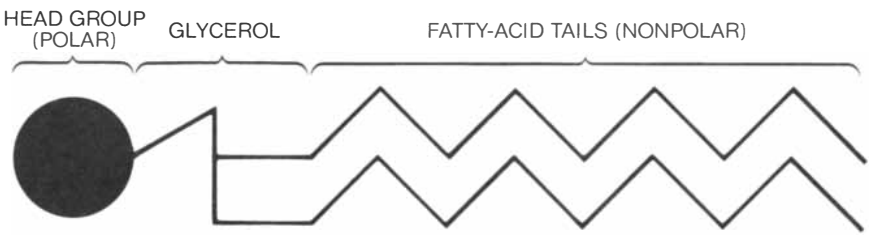
Steck and his colleagues obtained similar results with a procedure in which they prepared two types of closed-membrane vesicle, using as a starting material the membranes from red blood cells. In one type of vesicle preparation (right-side-out vesicles) the outer membrane surface is exposed to the external aqueous environment. In the other type of preparation (inside-out vesicles) the inner surface of the membrane is exposed to the external aqueous environment. When the two types of vesicle are treated with a proteolytic enzyme, only those proteins exposed to the external aqueous environment should be degraded. Steck found that some proteins are susceptible to digestion in both the right-side-out and inside-out vesicles, indicating that these proteins are exposed on both membrane surfaces. Other proteins are susceptible to proteolytic digestion in right-side-out vesicles but not in inside-out vesicles. Such proteins are evidently located exclusively on only one side of the membrane. This information lends credence to the concept of sidedness in membranes. Such sidedness had been suspected for many years because the inner and outer surfaces of cellular membranes are thought to have different biological functions. The development of a technique for preparing vesicles with right-side-out and inside-out configurations should be extremely useful in determining on which side of the membrane a given species of protein resides and thus functions.

Daniel Branton and his associates at the University of California at Berkeley have developed and exploited the technique of freeze-etch electron microscopy to study the internal anatomy of membranes. In freeze-etch microscopy a suspension of membranes in water is frozen rapidly and fractured with a sharp blade. Wherever the membrane surface runs parallel to the plane of fracture much of the membrane will be split along the middle of the lipid bilayer. A thin film of platinum and carbon is then evaporated onto the surface of the fracture. This makes it possible to examine the anatomy of structures in the fracture plane by electron microscopy.

The electron micrographs of the fractured membrane reveal many particles, approximately 50 to 85 angstroms in diameter, on the inner surface of the lipid bilayer. These particles are not observed if the membrane samples are first treated with proteolytic enzymes, indicating that the particles probably consist of protein [*see illustration on page 30*]. From quantitative estimates of the number of particles revealed by freeze-etching, Branton and his colleagues have suggested that between 10 and 20 percent of the internal volume of many biological membranes is protein.

Somewhere between a fifth and a quarter of all the protein in a cell is physically associated with membranes. Most of the other proteins are dissolved in the aqueous internal environment of the cell. In order to dissolve membrane proteins in aqueous solvents detergents must be added to promote their dispersion. One might therefore expect membrane proteins to differ considerably from soluble proteins in chemical composition. This, however, is not the case.

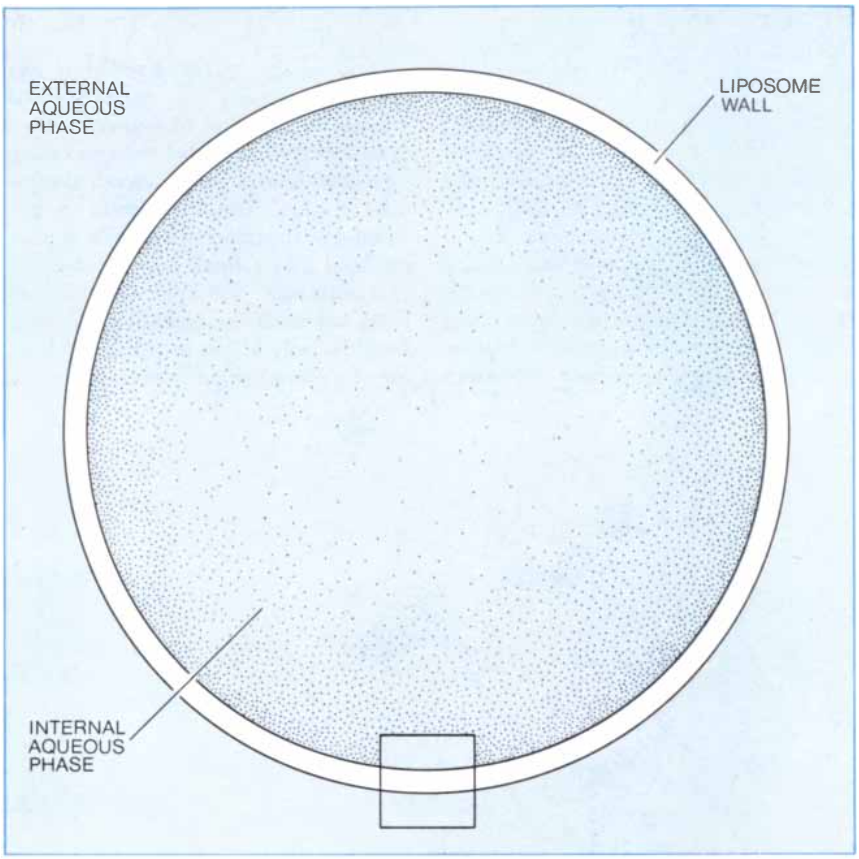
The amino acids of which proteins are composed can be classified into two groups: polar and nonpolar. S. A. Rosenberg and Guido Guidotti of Harvard University analyzed the amino acid composition of proteins from a number of membranes and found that they contain about the same percentage of polar and nonpolar amino acids as one finds in the soluble proteins of the common colon



TYPICAL MEMBRANE LIPID is a complex molecular structure, one end of which is hydrophilic, or water-soluble, and the other end hydrophobic. Such a substance is termed amphipathic. The hydrophilic, or polar, region consists of phosphate and other constituents attached to a unit of glycerol. The polar-head group, when in contact with water, often carries an electric charge. The glycerol component forms a bridge to the hydrocarbon tails of two fatty acids that constitute the nonpolar region of the lipid. In this highly schematic diagram the zigzag lines represent hydrocarbon chains; each angle is occupied by a carbon atom and two associated hydrogen atoms. The terminal carbon of each chain is bound to three hydrogen atoms. Phosphate-containing amphipathic lipids are called phospholipids.

bacterium *Escherichia coli*. Thus differences in amino acid composition cannot account for the water-insolubility of membrane proteins.

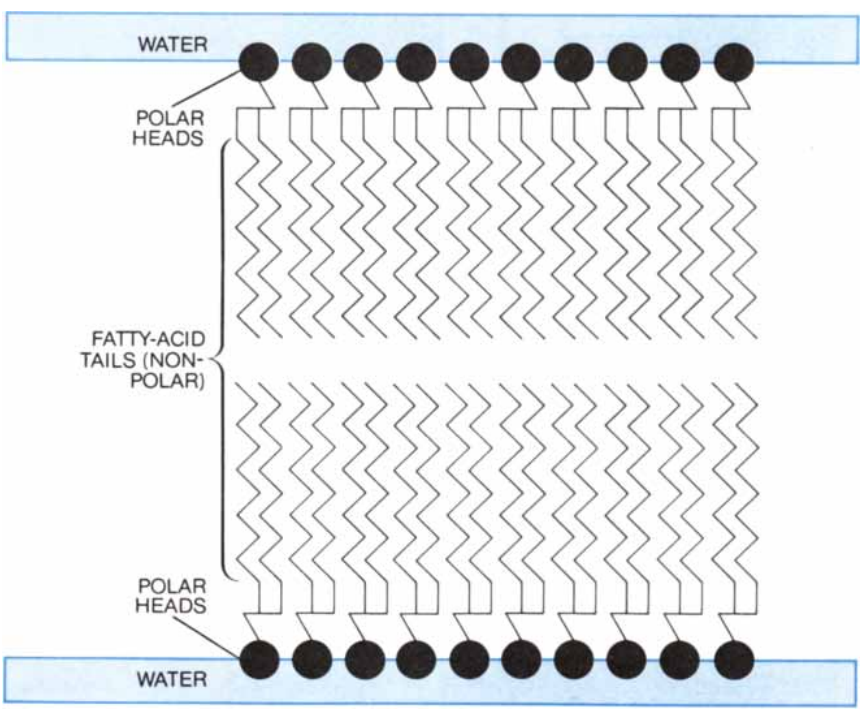
Studies conducted by L. Spatz and Philipp Strittmatter of the University of Connecticut indicate that the most likely explanation for the water-insolubility of membrane proteins is the arrangement of their amino acids. Spatz and Strittmatter subjected membranes of rabbit liver cells to a mild treatment with a proteolytic enzyme. The treatment released the biologically active portion of the membrane protein: cytochrome b_5. In a separate procedure they solubilized and purified the intact cytochrome b_5 and treated it with the proteolytic enzyme. This treatment also released the water-soluble, biologically active portion of the molecule, together with a number of small degradation products that were insoluble in aqueous solution. The biologically active portion of the molecule, whether obtained from the membrane or from the purified protein, was found to be rich in polar amino acids. The protein fragments that were insoluble in water, on the other hand, were rich in nonpolar amino acids. These observations suggest that many membrane proteins may be amphipathic, having a nonpolar region that is embedded in the part of the membrane containing the nonpolar fatty-acid tails of the phospholipids and a polar region that is exposed on the membrane surface.



ARTIFICIAL MEMBRANE-ENCLOSED SAC, known as a liposome, is created by subjecting an aqueous suspension of phospholipids to high-energy sound waves. X-ray diffraction shows that the phospholipids in the liposome assume an orderly arrangement resembling what is found in the membranes of actual cells. Area inside the square is enlarged below.

We are now ready to ask: How do substances pass through membranes? The nonpolar fatty-acid-tail region of a phospholipid bilayer is physically incompatible with small water-soluble substances, such as metal ions, sugars and amino acids, and thus acts as a barrier through which they cannot flow freely. If one measures the rate at which blood sugar (glucose) passes through the phospholipid-bilayer walls of liposomes, one finds that it is far too low to account for the rate at which glucose penetrates biological membranes. Information of this kind has given rise to the concept that entities termed carriers must be present in biological membranes to facilitate the passage of metal ions and small polar molecules through the barrier presented by the phospholipid bilayer.

Experiments with biological membranes indicate that the hypothetical carriers are highly selective. For example, a carrier that facilitates the transport of glucose through a membrane plays no role in the transport of amino acids or other sugars. An interesting experimental

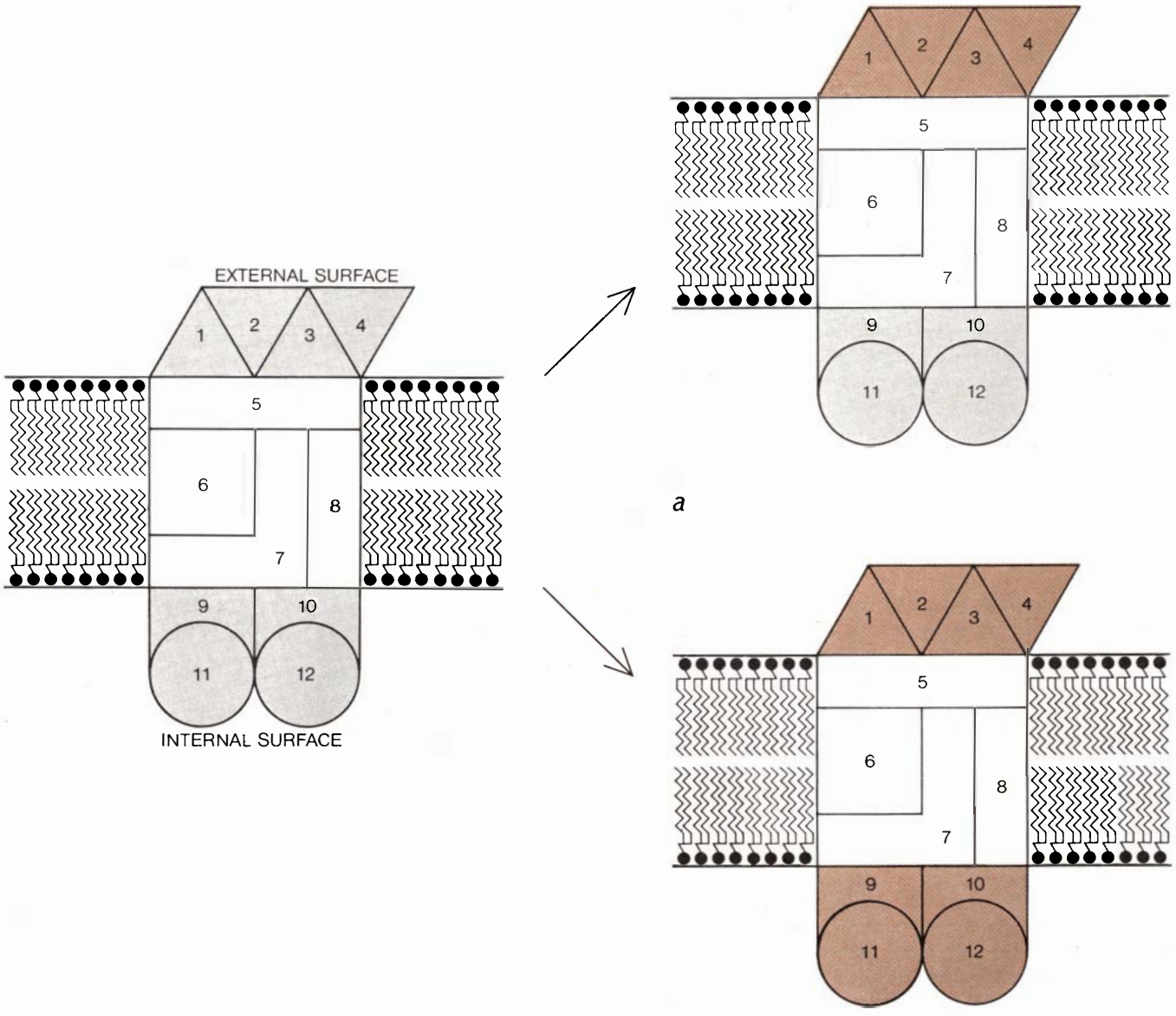


CROSS SECTION OF LIPOSOME WALL shows how the membrane is formed from two layers of lipid molecules. The polar heads of amphipathic lipids face toward the aqueous solution on each side while the nonpolar fatty-acid tails face inward toward one another.

system for measuring selective ion transport was developed by A. D. Bangham, M. M. Standish and J. C. Watkins of the Agricultural Research Council in Cambridge, England, and by J. B. Chappell and A. R. Crofts of the University of Cambridge. As a model carrier they used valinomycin, a nonpolar, fat-soluble antibiotic consisting of a short chain of amino acids (actually 12); such short chains are termed polypeptides to distinguish them from true proteins, which are much larger. Valinomycin combines with phospholipid-bilayer membranes and makes them permeable to potassium ions but not to sodium ions.

The change in permeability is conveniently studied by measuring the change in electrical resistance across a phospholipid bilayer between two chambers containing a potassium salt in aqueous solution. The experiment is performed by introducing a sample of phospholipid into a small hole between the two chambers. The lipid spontaneously thins out until the chambers are separated by only a thin membrane consisting of a phospholipid bilayer. Electrodes are then placed in the two chambers to measure the resistance across the membrane.

The resistance across a phospholipid bilayer in the absence of valinomycin is several orders of magnitude higher than the resistance across a typical biological membrane: 10 million ohms centimeter squared compared with between 10 and 10,000. This indicates that phospholipid-bilayer membranes are essentially impermeable to small hydrophilic ions. If a small amount of valinomycin (10^{-7} gram per milliliter of salt solution) is intro-



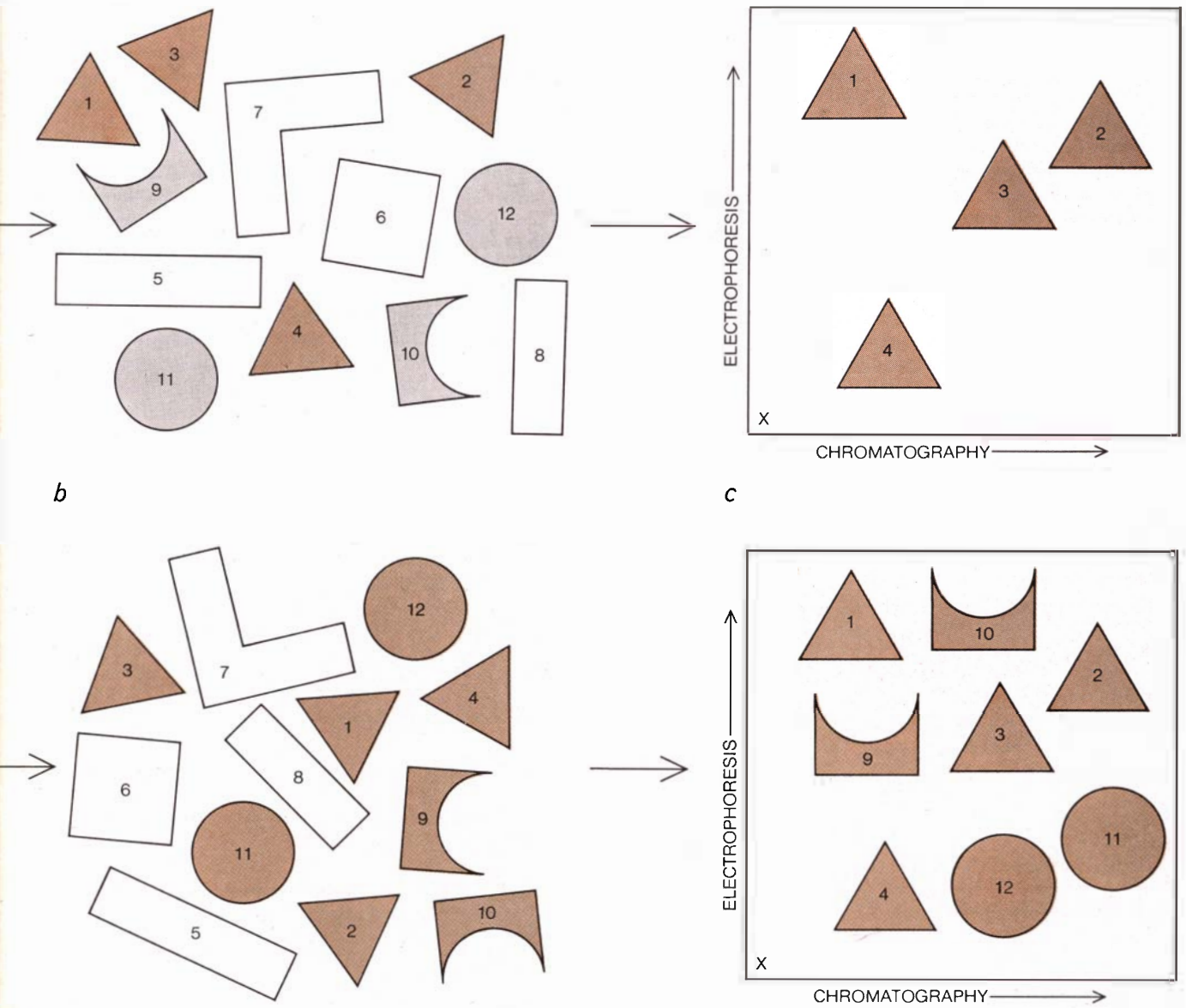
LOCATION OF PROTEINS IN MEMBRANES can be inferred by attaching radioactive labels to the proteins. These diagrams depict an experiment in which a major protein in the membrane of red blood cells was labeled (*a*). When intact cells (*top sequence*) are exposed to the radioactive substance, only the portion of the protein on the outside wall picks up the label (*color*). When the cells are broken before labeling (*bottom sequence*), the radioactive label is able to reach portions of the protein that are exposed to the internal as well as to the external surfaces of the membrane. This can be demonstrated by isolating and purifying the protein labeled under the two conditions. The protein is then broken up into defined fragments (*numbered shapes*) by treating it with a proteolytic enzyme (*b*). Portions of the two batches of fragments are spotted on the corners of filter paper for "fingerprinting" (*c*). This is a

duced into the chambers containing the potassium solution, the resistance falls by five orders of magnitude and the permeability of the phospholipid bilayer to potassium ions rises by a like amount. The permeability of the experimental membrane now essentially duplicates the permeability of biological membranes.

If the experiment is repeated with a sodium chloride solution in the chambers, one finds that the addition of valinomycin causes only a slight change in resistance. Hence valinomycin meets two of the most important criteria for a biological carrier: it enhances permeability and it is highly selective for the transported substance. The question that now arises is: How does valinomycin work?

First of all, valinomycin is nonpolar. Thus it is physically compatible with and can dissolve in the portion of the bilayer that contains the nonpolar fatty-acid tails. Second, valinomycin can evidently diffuse between the two surfaces of the bilayer. S. Krasne, George Eisenman and G. Szabo of the University of California at Los Angeles have shown that the enhancement of potassium-ion transport by valinomycin is interrupted when the bilayer is "frozen" by lowering the temperature. Third, valinomycin must bind potassium ions in such a way that the ionic charge is shielded from the nonpolar region of the membrane. Finally, valinomycin itself must have a selective binding capacity for potassium ions in preference to sodium or other ions.

With valinomycin as a model for carrier-mediated transport, one can postulate three essential steps: recognition of the ion, diffusion of the ion through the membrane, and its release on the other



technique that combines chromatography with electrophoresis. By chromatography alone protein fragments would migrate at different rates depending primarily on their solubility in the solvent system. Electrophoresis involves establishing an electric-potential gradient along one axis of the filter paper. Since various fragments have different densities of electric charge they are further separated. A piece of X-ray film is then placed over each sheet of filter paper. Radiation from the labeled fragments exposes the film and reveals where the various fragments have come to rest. A comparison of the X-ray films produced in the parallel experiments shows that more protein fragments are labeled when the red blood cells are broken before labeling and that the additional fragments (*9, 10, 11, 12*) must represent portions of the original protein that extend through the membrane and penetrate the inner surface.

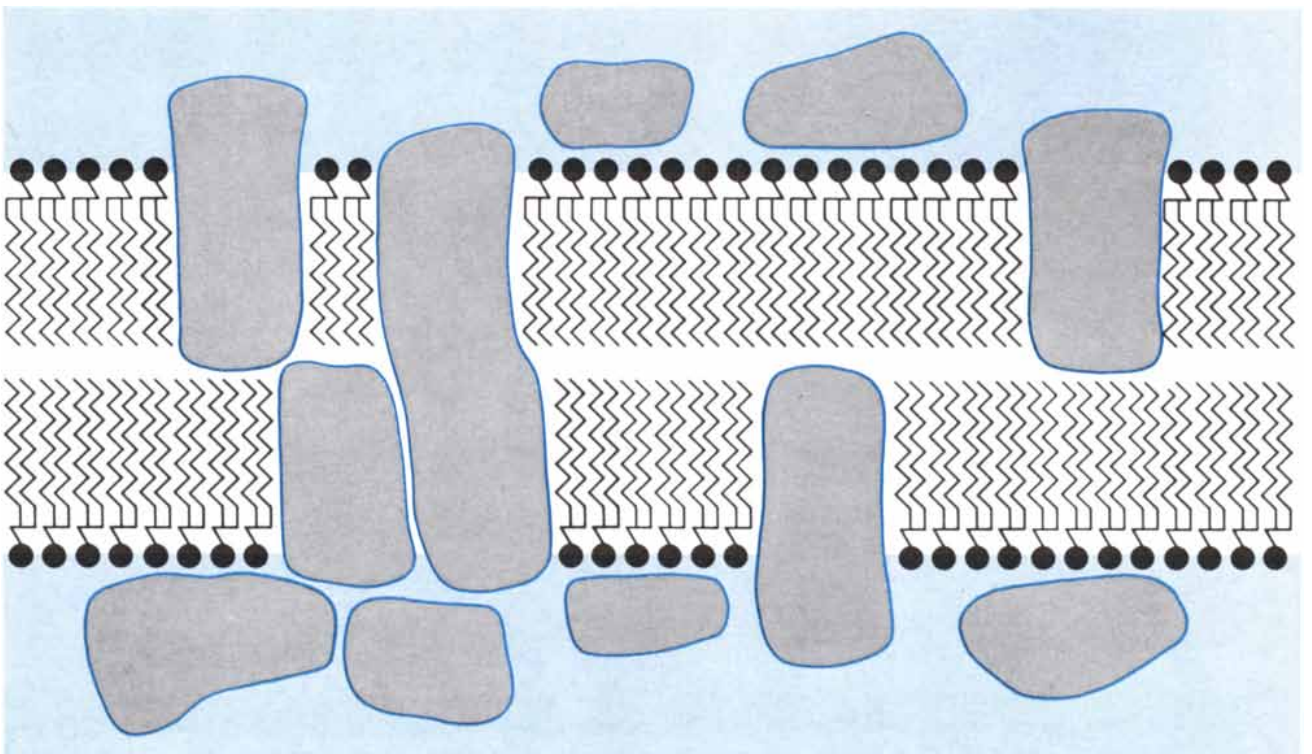
side. In the first step some part of the valinomycin molecule, embedded in the membrane, "recognizes" the potassium ion as it approaches the surface of the membrane and captures it. In the second step the complex consisting of valinomycin and the potassium ion diffuses through the membrane. Finally, on reaching the opposite surface of the membrane the potassium ion is dissociated from the complex and is released.

The argument to this point can be summarized in a few words. The fundamental structure of biological membranes is a phospholipid bilayer, the phospholipid bilayer is a permeability barrier and carriers are needed to breach it. In addition, the membrane barrier must often be breached in a directional way. In a normally functioning cell hundreds of kinds of small molecule must be present at a higher concentration inside the cell than outside, and many other small molecules must be present at a lower concentration inside the cell than outside. For example, the concentration of potassium ions in human cells is more than 100 times greater than it is in the blood that bathes them. For sodium ions the concentrations are almost exactly reversed. The maintenance of these differences in concentration is absolutely essential; even slight changes can result in death.

Although the model system based on valinomycin provides considerable insight into the function and selectivity of carriers, it sheds no light on the transport mechanism that can pump a substance from a low concentration on one side of the membrane to a higher concentration on the other. Our understanding of concentrative transport (or, as it is usually termed, active transport) owes much to the pioneering effort of Georges Cohen, Howard Rickenberg, Jacques Monod and their associates at the Pasteur Institute in Paris. The Pasteur group studied the transport of milk sugar (lactose) through the cell membrane of the bacterium *Escherichia coli*. Genetic experiments suggested that the carrier for lactose transport was a protein. Studies of the rate of transport revealed that the transport process behaves like a reaction catalyzed by an enzyme, giving further support to the idea that the carrier is a protein. The Pasteur group also found that the lactose-transport system is capable of active transport, producing a lactose concentration 500 times greater inside the cell than outside. The active-transport process depends on the expenditure of metabolic energy; poisons that block energy metabolism destroy the ability of the cell to concentrate lactose.

A model that accounts for many (but not all) of the properties of the active-transport system that are typified by the lactose system postulates the existence of a carrier protein that can change its shape. The protein is visualized as resembling a revolving door in the membrane wall [*see illustration on opposite page*]. The "door" contains a slot that fits the target substance to be transported. The slot normally faces the cell's external environment. When the target substance enters the slot, the protein changes shape and is thereby enabled to rotate so that the slot faces into the cell. When the target substance has been discharged into the cell, the protein remains with its slot facing inward until the cell expends energy to rotate the protein so that the slot again faces outward.

Working with Eugene P. Kennedy at the Harvard Medical School in 1965, I succeeded in identifying the lactose-transport carrier. We found, as we had expected, that it is a protein with an enzyme-like ability to bind lactose. Since then a number of other transport carriers have been identified, and all turn out to be proteins. The lactose carrier resides in the membrane and is hydrophobic; thus it is physically compatible



ANATOMY OF BIOLOGICAL MEMBRANE is suggested in this schematic diagram. Phospholipid molecules stacked side by side and back to back provide the basic structure. The gray shapes represent protein molecules. In some cases several proteins (for example the five at the left) are bound into a single functional complex. Proteins can occupy all possible positions with respect to the phospholipid bilayer: they can be entirely outside or inside, they can penetrate either surface or they can extend through the membrane.

with the nonpolar-lipid phase of the membrane.

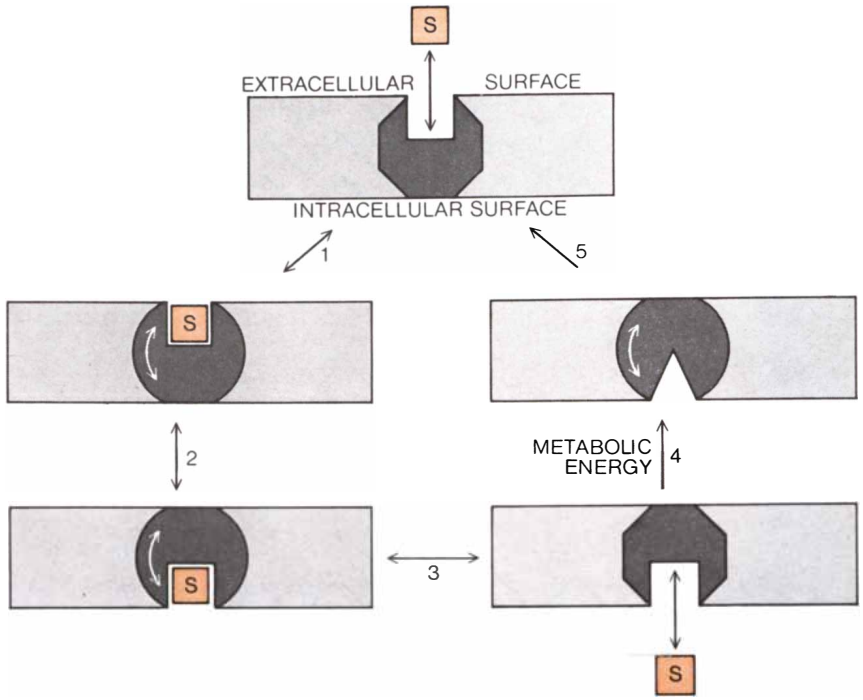
In 1970 Ron Kaback and his associates at the Roche Institute of Molecular Biology observed that the energy that drives the active transport of lactose and dozens of other low-molecular-weight substances in *E. coli* is directly coupled to the biological oxidation of metabolic intermediates such as D-lactic acid and succinic acid. How energy derived from the oxidation of D-lactic acid can be used to drive active transport is one of the more interesting unsolved problems in membrane biology.

Since transport carriers must be mobile within the membrane in order to move substances from one surface to the other, one might guess that the region of the membrane containing the fatty-acid tails should not have a rigid crystalline structure. X-ray diffraction studies indicate that the fatty acids of membranes in fact do have a "liquid crystalline" structure at physiological temperature, that is, around 37 degrees Celsius. In other words, the fatty acids are not aligned in a rigid crystalline lattice. The techniques of electron paramagnetic resonance and nuclear magnetic resonance can be used to study the flexibility of the fatty-acid side chains in membranes. Several investigators, notably Harden M. McConnell and his associates at Stanford University, have concluded that the fatty acids of membranes are quasi-fluid in character.

Membranes incorporate two classes of fatty acids: saturated molecules, in which all the available carbon bonds carry hydrogen atoms, and unsaturated molecules, in which two or more pairs of hydrogen atoms are absent (with the result that two or more pairs of carbon atoms have double bonds). The fluid character of membranes is largely determined by the structure and relative proportion of the unsaturated fatty acids. In phospholipids consisting only of saturated fatty acids the fatty-acid tails are aligned in a rigidly stacked crystalline array at physiological temperatures. In phospholipids consisting of both saturated and unsaturated fatty acids the fatty acids are packed in a less orderly fashion and thus are more fluid. The double bonds of unsaturated fatty acids give rise to a structural deformation that interrupts the ordered stacking necessary for the formation of a rigid crystalline structure [*see illustration on next page*].

My colleagues and I at the University of Chicago (and later at the University of California at Los Angeles) and Peter Overath and his associates at the University of Cologne have varied the fatty-acid composition of biological membranes to study the effects of fatty-acid structure on transport. When the membrane lipids are rich in unsaturated fatty acids, transport can proceed at rates up to 20 times faster than it does when the membrane lipids are low in unsaturated fatty acids. These experiments show that normal membrane function depends on the fluidity of the fatty acids.

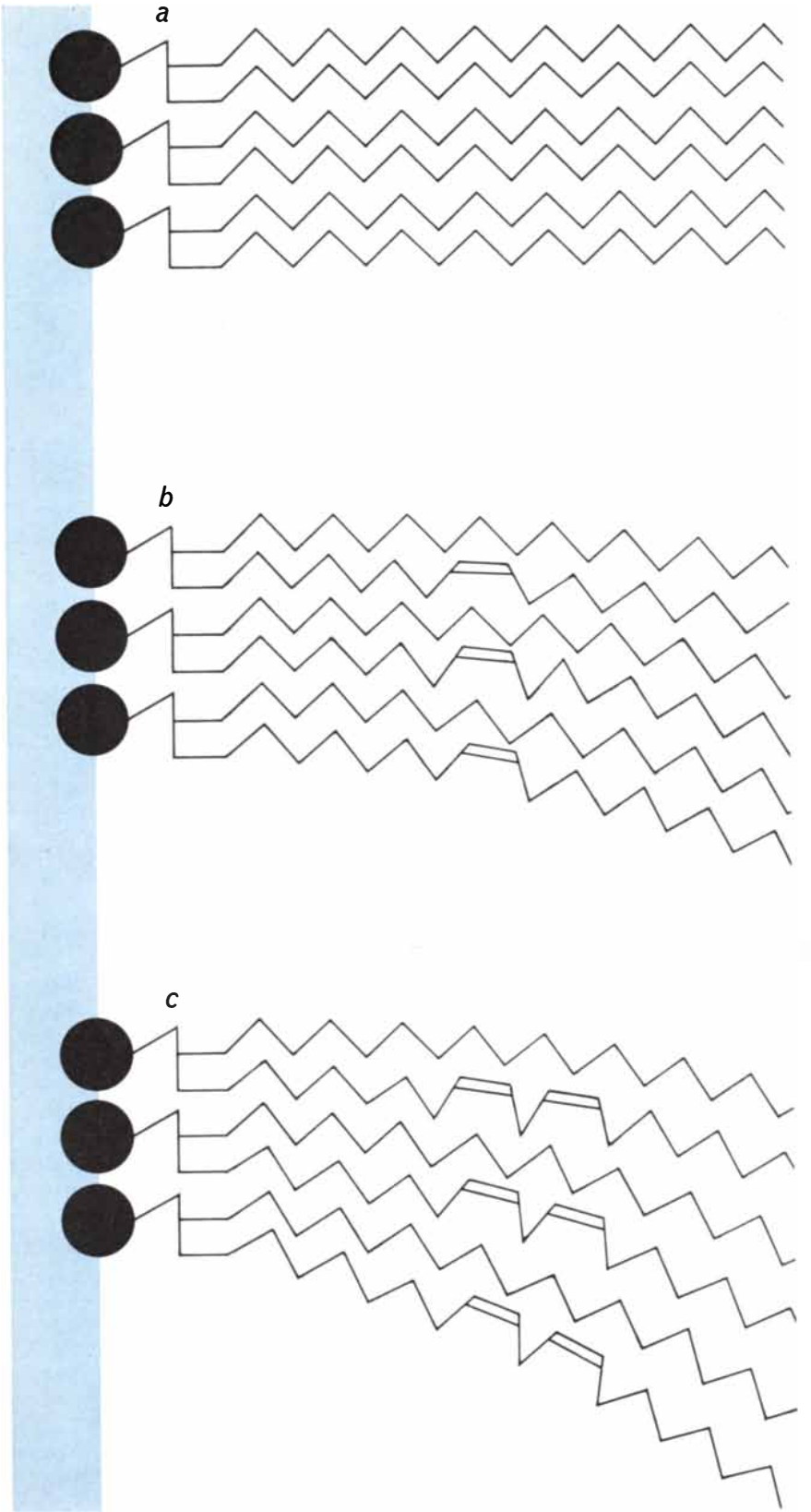
The temperature at which cells live and grow can have a pronounced effect on the amount of unsaturated fatty acid in their membranes. Bacteria grown at a low temperature have membranes with a greater proportion of unsaturated fatty acid than those grown at a higher temperature. This adjustment in fatty-acid composition is necessary if the membranes are to function normally at low temperature. A similar adjustment can take place in higher organisms. For example, there is a temperature gradient in the legs of the reindeer; the highest temperature is near the body, the lowest is near the hooves. To compensate for this temperature gradient the cells near the hooves have membranes whose lipids are enriched in unsaturated fatty acids.



MECHANISM OF "ACTIVE" TRANSPORT may involve a carrier protein (*dark gray*) with the properties of a revolving door. A carrier protein can capture a substance, *S*, that exists outside the membrane in dilute solution and transport it to the inside of the cell, where the concentration of *S* is greater than it is outside. When *S* is bound to the protein, the protein changes shape (*1*), thus enabling it to rotate (*2*). When *S* becomes detached and enters the cell (*3*), the protein returns to its immobile form. Metabolic energy must be expended (*4*) to alter the protein's shape so that it can rotate and again present its binding site to the cell exterior (*5*). Other protein carriers have the capacity to transport substances from low concentration inside the cell to solutions of higher concentration outside the cell.

Although, as we have seen, phospholipids can spontaneously form bilayer films in water, this process only provides a physical rationale as to why the predominant structure in membranes is a phospholipid bilayer. The events leading to the assembly of a biological membrane are far more complex. The cells of higher organisms contain a number of unique membrane structures. They differ widely in lipid composition, and each type of membrane has its own unique complement of proteins. The diversity in protein composition and in the location of proteins within membranes explains the functional diversity of different types of membrane. Rarely does a single species of protein exist in more than one type of membrane.

Since all membrane proteins are synthesized at approximately the same cellular location, what is it that determines that one type of protein will be incorporated only into the cytoplasmic membrane and that another type will turn up only in a mitochondrial membrane? At present this question can be answered only by conjecture tinctured with a few facts. Two general hypotheses for membrane assembly can be offered. One pos-



VARIATION IN FATTY-ACID COMPOSITION can disrupt the orderly stacking of phospholipids in a biological membrane. In a lipid layer composed entirely of saturated fatty acids (*a*) the fatty-acid chains contain only single bonds between carbon atoms and thus nest together to form rigid structures. In a lipid layer containing unsaturated fatty acids with one double bond (*b*) the double bonds introduce a deformation that interferes with orderly stacking and makes the fatty-acid region somewhat fluid. When fatty acids with two double bonds are present (*c*), the deformation and the consequent fluidity are greater still.

sibility is that new pieces of membrane are made from scratch by a self-assembly mechanism in which all the components of a new piece of membrane come together spontaneously. This new piece could then be inserted into an existing membrane. A second possibility is that newly made proteins are simply inserted at random into a preexisting membrane.

Recent studies in my laboratory at the University of California at Los Angeles and in the laboratories of Philip Siekevitz and George E. Palade at Rockefeller University support the second hypothesis. That is all well and good, but what determines why a given protein is incorporated only into a given kind of membrane? Although this must be answered by conjecture, it is known that many proteins are specifically bound to other proteins in the same membrane. Such protein-protein interactions are not uncommon; many of the functional entities in membranes are complexes of several proteins. Thus the proteins in a membrane may provide a template that is recognized by a newly synthesized protein and that helps to insert the newly synthesized protein into the membrane. In this way old membrane could act as a template for the assembly of new membrane. This might explain why different membranes incorporate different proteins.

Why, then, do different membranes have different lipid compositions? The answers to this question are even more obscure. In general lipids are synthesized within the membrane; the enzymes that catalyze the synthesis are part of the membrane. Some lipids, however, are made in one membrane and then shuttled to another membrane that has no inherent capacity to synthesize them. Since there is an interchange of lipids between various membranes, it seems unlikely that the variations in lipid composition in different membranes can be explained by dissimilarities in the synthetic capacity of a given membrane for a given type of lipid. There are at least two possible ways of accounting for differences in lipid composition. One possibility is that different membranes may destroy different lipids at different rates; another is that the proteins of one species of membrane may selectively bind one type of lipid, whereas the proteins of another species of membrane may bind a different type of lipid. It is obvious from this discussion that concrete evidence on the subject of membrane assembly is scant but that the problems are well defined.

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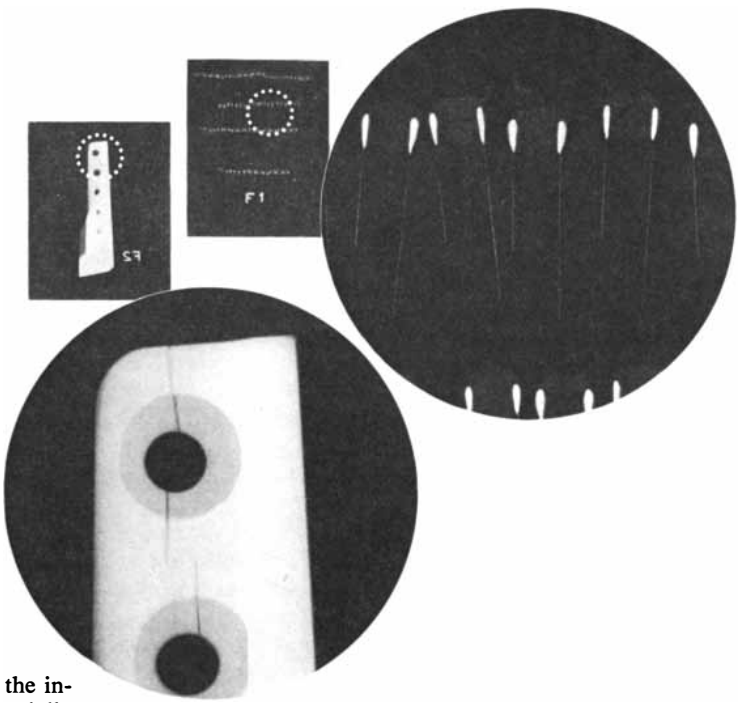

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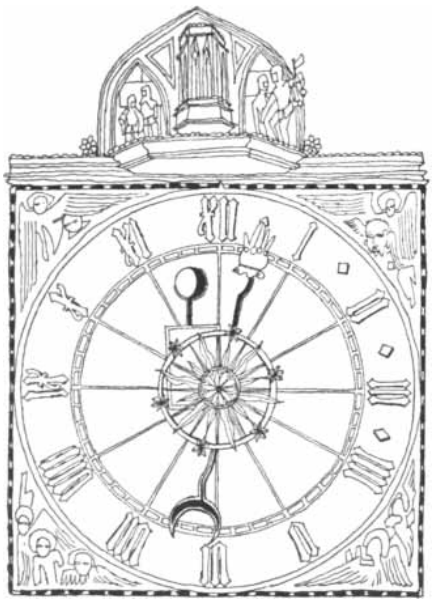

Science off Its Pedestal

The British government has just published two reports on science policy, one prepared by a committee under Sir Frederick Dainton, the other by Lord Rothschild, head of the Central Policy Review Staff. The first report contains little that is new or controversial but the second is sufficiently heretical to guarantee the "wide public debate" invited by the British government. Rothschild, a biologist and chairman of Shell Research Ltd., fires a broadside at "the anachronism [that] can be summed up by the phrase Pedestalization of Science, particularly in respect of applied research by virtue of the admiration, indeed reverence, we have for pure science."

Over the past half-century British science policy has operated under the "Haldane principle," enunciated by a committee headed by J. B. S. Haldane. The principle, in brief, is that science flourishes best when the agency responsible for research is completely insulated from the government department that stands to benefit most. In spite of the blank wall set up between the laboratory and the government, the Haldane committee exhorted scientists "to promote an increase of material production; to promote the health of the entire community; to apply science to industry."

"It is hard to put the clock back," said Rothschild recently in a talk before the Royal Society of Arts, "and visualize a society in which such diffuse precepts could have had much meaning or achieved any useful results. This is not to say that they had no effect, some of them good. On the contrary, the effects are still with us; one of those is the polarization of society into scientists, and to a lesser extent technologists—and the rest. Not only has this adversely affected government research and development department by department; but it also catalyzed the emergence of autonomous bodies, the Research Councils, accountable to Parliament as all government agencies directly or indirectly must be, but not accountable to anyone else, in spite of their names, which include such bizarre words as 'agricultural,' 'medical' and 'natural environment.' Is it not strange that though the taxpayer pays for these bodies, he has no say in what they do? 'Not a bit,' the scientist replies."

Rothschild's radical proposal is that in the area of applied research, which accounts for some 85 percent of the British government's expenditure on science, the relationship between the laboratory and the government should resemble the relationship between a contractor and his customer. Rothschild argues that there are only two kinds of research, basic and applied, and that the two are indistinguishable as to *how* they are done. "The distinction lies in *why* [research] is done and *who* wants it done." Although Rothschild thinks some basic research has become excessively expensive (notably high-energy physics), he concedes that it cannot be directed. If, however, the British government is to continue supporting a Medical Research Council, an Agricultural Research Council and a Natural Environment Research Council, it must become directly involved, on behalf of the taxpayer, in setting goals and evaluating results. As it is now the various research councils have virtual autonomy, guided by their directors, with the help of a variety of advisory committees, which themselves constitute a kind of interlocking directorate.

"Applied research," Rothschild observes, "is one of the human activities which may be necessary to achieve a practical objective. The research worker should *not* formulate the objective, though he can and should help. The research worker should *not* decide that the objective requires research for its achievement. He should *not* decide that the research should be done, assuming it is necessary. He should *not* decide when to stop. Nor should he decide to change the objective in midstream, however desirable it may seem to him to do so. What then remains for the research worker to do? The answer is an enjoyable one for him and quite simple, even if the execution is difficult: Do the research and help that other man, who has the onerous task of doing all those things you are not to do, as much as you can. He will need all the help he can get, if only because his responsibilities may be both new and strange to him—that is the worrying thing. Even the formulation of an objective is a complex and difficult undertaking, one of the hardest parts of which is to avoid the inclusion, in the formulation, of hidden assumptions."

In concluding his talk to the Royal Society of Arts, Rothschild said: "I do not believe there is such a thing as a policy for science as a whole, popular as the concept is. We must have a policy about pollution, ocean resources, food supply, population, water, natural resources and the many other headaches and benefits we can all enumerate. And science, engineering and mathematics—and the research associated with them—will and should contribute to the formulation and implementation of these policies. But that is all: science as a whole is not an activity to be carried on in isolation. It must be part of society's integrated effort to make the world a better place."

The Family Clinic

Hospital outpatient clinics, once primarily concerned with providing medical care for the poor, have emerged as a major source of health care for the American public as a whole. In 1970, 21 percent of all visits to physicians took place in hospital clinics and emergency rooms. In 1954 only 10 percent of visits to physicians were in hospital clinics. The total number of outpatient visits to hospitals reached 181 million in 1970, nearly triple the number of such visits in 1954. The number of people seeking medical aid at hospital clinics has grown much faster than the U.S. population and also faster than the total number of visits to physicians.

The trend toward the increasing use of

hospital clinics is described in a report prepared for the Association for the Aid of Crippled Children in New York by Nora Piore, Deborah Lewis and Jeannie Seeliger. To a great many people, they write, the hospital clinic has become "their usual physician, sometimes their only doctor."

The extraordinary rise in outpatient services has not been matched by a similar rise in hospital inpatient volume. In 1954 the nation's hospitals averaged 2.7 outpatient visits per admitted patient; by 1970 there were 4.6 outpatient visits for each inpatient. Emergency rooms account for a third of all the hospital outpatient visits.

People in large cities tend to use outpatient clinics more than the average for the nation: in the 50 largest cities the per capita average for outpatient visits was 1.1 in 1969 compared with .6 for the nation. Wealthier states—California, New York, Pennsylvania, Illinois, Ohio and Michigan—have the highest rate of utilization of outpatient services. States with low utilization tend to be poor and not highly urbanized.

According to the authors of the report, the unexpected role of hospital outpatient clinics in providing health care to a substantial portion of the American public has important implications for future systems of health care delivery, in particular the national health insurance schemes now under consideration. They believe it is reasonable to assume that in America, as in Britain, public health programs will be geared to existing medical care institutions and arrangements rather than attempting to bring about a radical transformation in the delivery of medical services.

"From past experience," they write, "it seems unlikely that any program dependent on special grants, such as the Office of Economic Opportunity [neighborhood health] centers, will provide the volume of ambulatory care resources necessary to replace existing outpatient departments." The authors suggest that the nation could be provided with several thousand comprehensive care centers in very short order if hospitals were assisted and induced to reshape presently fragmented utilization of clinic resources into a more systematic and orderly pattern.

"This could be accomplished," they continue, "by a simple formula: Any community hospital with a substantial outpatient service, in order to qualify for [Federal construction] funds or as a provider under Medicare, Medicaid or any proposed national health insurance scheme, could be required and assisted to develop and offer a prepaid comprehensive health care option to persons in the catchment area who elect to enroll in such a program."

Coming of Age

In 1936 Edwin P. Hubble, with the help of Milton L. Humason, finished an extensive survey in which he estimated the distance and the spectral red shift of a large sample of galaxies within range of the 100-inch telescope on Mount Wilson. The result was the "Hubble constant," which expresses the ratio between the red shift, indicative of the rate at which galaxies appear to be receding from one another, and distance. Hubble's value was 536 kilometers per second per megaparsec (a distance equal to 3.26 million light-years). The value was immediately questioned because it implied that the universe was created, presumably in a "big bang," only 1.8 billion years ago, thus making the universe younger than the earth (as inferred from its geology).

With the completion in 1949 of the 200-inch telescope on Palomar Mountain a long-range project was initiated to recalculate the Hubble constant. By the mid-1950's it was apparent from new measurements that the rate of expansion of the universe was considerably lower than the original value calculated by Hubble, with the result that the big bang was moved back to about 10 billion years. This still left an uncomfortably small margin between the age of the universe and the age of the oldest stars, calculated in various ways. In fact, many stars in the "halo" of our galaxy seem to be between 10 billion and 13 billion years old.

The latest revision of the Hubble constant, made by Allan Sandage of the Hale Observatories, is given in the annual report of the president of the Carnegie Institution of Washington. Sandage, assisted by Gustav A. Tammann, extensively revised the distance indicators used to estimate distance. "A critical step in the procedure," says the Carnegie report, "was the calibration of linear sizes of H II (ionized hydrogen) regions in nearby galaxies and the application of that calibration to remote galaxies in which H II regions have also been measured." As a result the distance to the most remote galaxies can now be estimated in eight steps, beginning with the direct trigonometric measurement of the parallax of nearby stars.

The new value of the Hubble constant is 53 ± 5 kilometers per second per megaparsec, or almost exactly one-tenth of Hubble's original value. The new rate of expansion pushes the age of the universe up to 18 billion years.

Dust to Dust

A speculative but intriguing scheme for disposing of man-made solid wastes by dumping them into "tectonic sinks" has been put forward by two investigators at the University of Washington. The plan, outlined recently by Robert C. Bostrom and Mehmet A. Sherif in *Proceedings of the Royal Society of London,* would take advantage of two features of the earth's surface: regions called subduction sinks, where sedimentary material is being drawn downward into the earth's mantle as a consequence of sea-floor spreading, and regions such as river deltas where sedimentary fans capable of burying waste material are deposited at a rapid rate.

In support of their scheme Bostrom (a geologist) and Sherif (a civil engineer) point out that the production of industrial and domestic waste increases continuously, "but no means is in sight as to its disposal. As more nations become industrialized, the problem will increase without limit." In their view the most intractable form of waste is highly fabricated solid-state refuse; the waste-disposal techniques that have been proposed so far to deal with this aspect of the dilemma "are not answers to the problems faced. For instance, any form of incineration does no more than redistribute the elements forming waste, in the form of atmospheric pollution and solid residue. Distribution of waste in 'land-fill' or other form (apart from difficulty in finding room for this activity near the major sources of waste, our cities) results in a particularly long-lasting form of contamination"—ultimately the contamination of the world ocean.

In analyzing the feasibility of their approach Bostrom and Sherif cite the abundant geophysical evidence pointing to the conclusion that the phenomenon of sea-floor spreading is "the earth's primary tectonic mechanism." According to this hypothesis, new crust is formed along the crest of the sea-floor ridge system and an equivalent volume of material is being drawn into the mantle in the system of trenches, or subduction zones, that marks the opposite boundaries of the vast, shifting tectonic plates. The incorporation in such sedimentary sinks of unwanted artifacts, Bostrom and Sherif state, "would be the most ready way of ridding our planet of their presence at surface, if the processes concerned are sufficiently swift." In this connection they note that the waste pro-

duced by man, although it amounts to more than a half-billion tons per year, "does not yet compete in tonnage with that produced as sediments. The production of solid waste is less than 1 25 the mass of sediments, and both together form much less than 1 10 part of the igneous crust being drawn into the mantle each year."

Questions to be answered by further research, according to Bostrom and Sherif, include: "(1) Within the system of tectonic trenches, where are located the zones of most intense deposition; and what is the rate? (2) What burial rate is required to sequester compressed refuse in such a fashion that the expulsion of connate fluids is below an acceptable minimum? (3) What would be the long-term effect of the efflux into the world ocean of fluids expressed from sediments containing waste? (4) In respect to tectonic sinks not located in zones of subduction, are there localities close to waste sources in which deposited material would be rapidly buried and not subject to reworking?"

A hypothetical disposal system outlined by Bostrom and Sherif would consist of three stages: collection, compaction of waste into blocks and its sea transportation to tectonic sinks. "No claim is made that the system outlined is final or viable, but merely that cost analyses and trade-off studies (allotment of priorities) are justified. If the geologic problems can be solved, it is obvious that large scope exists for technical innovation." They conclude that "if ideally it is found possible to entomb waste in areas of subduction, the one-way system involved would take care of quantities larger than we can produce. As we do not await its completion the slowness of the ingestion process is of no account. Disposal in these regions would ensure the early return to the mantle, from which momentarily their matter is separate, of the redwood sawdust, the cognitive data files and the products of our kind yet to be devised."

Hot Plants

Recent investigations in plant physiology have suggested that the efficiency of photosynthesis can in some instances be increased by as much as 40 percent. The possibility exists because in most plants the uptake of the basic raw material carbon dioxide is controlled by two factors. The first concerns the primary metabolic pathway for the fixation of carbon. In most plants a central role is played by phosphoglyceric acid, the three-carbon compound that is the first stable product of carbon dioxide fixation. The second factor is the inhibitory effect of atmospheric oxygen. Since air is 21 percent oxygen, the maximum carbon dioxide uptake of most plants is only 60 percent of the maximum that would be possible in an oxygen-poor environment.

Some plants (among them such economically important members of the grass family as sorghum, millet, sugarcane and maize) do not depend exclusively on the three-carbon pathway for carbon fixation. They possess an additional pathway characterized by a four-carbon compound, oxaloacetic acid. Olle Björkman of the Carnegie Institution of Washington's Department of Plant Biology has now shown that atmospheric oxygen does not inhibit these plants' carbon dioxide uptake. The reason is that the four-carbon pathway works in series with the three-carbon pathway in a leaf mechanism that is highly efficient in the uptake of carbon dioxide. The plants are particularly well adapted to hot, arid conditions. This discovery and certain hybridization experiments Björkman and his colleagues have undertaken lend substance to the possibility that the extra four-carbon pathway can be bred into economically important plants that now utilize the three-carbon mode of photosynthesis.

Studies at the Department of Plant Biology imply that the number of genes determining inheritance of the four-carbon pathway components is small. So far, however, optimum recombination of the genes in hybrid individuals appears to be infrequent. Björkman and his colleagues are using for their experiments certain species of saltbush (*Atriplex*); some of these species depend on the three-carbon pathway and others utilize both pathways. Among economically important plants one prime target for hybridization might be the sugar beet; more remote possibilities include wheat, barley and soybeans.

Through a Glass Handily

The use of a laser beam as a high-capacity channel for carrying voice, video, digital and other signals has seemed an attractive possibility, and a challenge to communications engineers, ever since the laser was first demonstrated in 1960. A single coherent beam of light can in principle carry the equivalent of several thousand television channels. Until recently it seemed that if a laser beam was to be useful in communications, it would have to travel in a carefully designed pipe complete with lenses and other features enabling the light to bend around corners. A much more attractive possibility, recently described in *Bell Laboratories Record* by Tingye Li and Enrique A. J. Marcatili, is to use thin glass fibers to carry the laser beam.

Within the past 15 years optical fibers have been widely used to carry light over short distances, particularly where the light path must be flexible, for example in such medical instruments as endoscopes. The glass fibers consist of a core and a jacket of slightly different refractive indexes, so that the light is confined to the core by total internal reflection. No one had considered the fibers as a long-distance medium for optical communication, however, because transmission losses in commercially available fibers amounted to about one decibel per meter, or 1,000 decibels per kilometer (equal to attenuation by a factor of 10^{100}).

A few years ago British workers pointed out that within the visible and near-infrared parts of the spectrum the fundamental losses in glass fibers should be no more than a few decibels per kilometer. This stimulated efforts to produce low-loss fibers. At the Bell Telephone Laboratories experimental fibers have been made from ultrapure soda-lime-silicate glasses that exhibit an absorption loss of about 60 decibels per kilometer, and fibers with a loss as low as 18 decibels per kilometer have been made by the Corning Glass Works.

Fibers with losses in the range of these experimental samples would be suitable for communication over distances from one kilometer to several kilometers without requiring repeaters. With repeaters spaced every mile or two, glass-fiber systems could, according to Li and Marcatili, "be a strong contender for future long-haul transmission applications."

Ecology of the Tooth

It is widely believed that the two major dental diseases—periodontitis, or inflammation of the supporting tissues of the teeth, and caries, or tooth decay—are caused by the presence of microorganisms. D. F. G. Poole and H. N. Newman of the Dental Unit of the British Medical Research Council advance a somewhat different hypothesis: Both diseases result from disturbances in the ecology of the various organisms that make up dental plaque, the feltlike layer of closely packed microorganisms occupying the surface of the teeth. Setting forth their viewpoint in *Nature*, Poole and Newman caution against "haphazardly and maybe dangerously interfering

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with the balance of the oral microbiota."

Poole and Newman suggest that the standard view of plaque has "failed to consider it as forming just one part of the body flora," which "does not normally produce disease but, on the contrary, maintains a commensal or symbiotic relationship with the human host." Since plaque is present in both periodontitis and caries, it would seem that the diseases result when something upsets the normal symbiotic relationship. For example, many of the organisms in plaque metabolize oxygen but are capable of switching to anaerobic metabolism when oxygen is minimal. This switchover may occur when oxygen becomes deficient in stagnant areas between the teeth, where periodontitis and caries often start. The deficiency of oxygen, in turn, may result from the fact that these areas are not readily accessible to cleaning and plaque builds up. In such circumstances some organisms might produce an excess of acid, which is a factor in tooth decay, or of the protein-digesting substances involved in periodontitis.

Poole and Newman regard it as essential to recognize that plaque is "a complex ecological phenomenon." Such a view, they say, should influence the approach to the treatment of caries and periodontitis, directing it away from haphazard interference with the community of organisms and toward "modifying the diet or the plaque without the use of antiseptics, antibiotics or other agents which are likely to produce cures worse than the diseases."

Deadly Daylight

An unusual agent for controlling insect pests without harming other organisms (including man) is being investigated by three workers with the Agricultural Research Service of the U.S. Department of Agriculture. The agent is light. The basic idea is that, when the days begin to get shorter in the fall, the larvae of many insects go into diapause, a state resembling hibernation. Then, when the days begin to get longer in the spring, the larvae resume their life cycle and metamorphose into adults. Since diapause is triggered by the length of the day, why not prolong the days with artificial light, so that the larvae do not go into diapause but metamorphose in the fall, when the adult insects will be exposed to harsher climatic conditions? The work, involving codling moths, which infest apples, and European corn borers, which infest corn, is described in *Agricultural Research*.

Many insects enter diapause when daylight lasts no longer than about 12 hours. The three experimenters—Dora K. Hayes, a biochemist, William N. Sullivan, an entomologist, and Milton S. Schechter, a chemist—interfered with the natural signal by using artificial light to maintain 17 hours of illumination daily between June and December, when the duration of natural light ranged from 14 to 9½ hours. Small plots of corn were artificially infested with corn borers and clear plastic boxes containing apples were artificially infested with codling moths. Artificial light was supplied by 40-watt fluorescent lamps. In these circumstances more than 70 percent of the insects failed to go into diapause, continuing instead to develop into adult moths that emerged in the fall rather than in the spring. Nearly all insects in control plots with no artificial light developed normally. The investigators point out that their procedure cannot be tried on a large scale until more research is done to determine costs and optimum lighting conditions.

Young Man with a Horn

Insect songs range in intensity from the intimate whisper of the courting fruit fly to the loud stridulations of the cicada, the locust and the cricket. The prince of singers is the mole cricket (*Gryllotalpa vineae*). This insect excavates a burrow in the shape of a double-belled horn: a single tunnel that branches into two tunnels opening on the surface. The insect takes up a position below the junction of the tunnels, and its wing vibrations drive a tiny rasp across a resonating bar. The burrow acts as a pressure transducer that delivers a signal with a sound level of 90 decibels one meter away from the paired surface openings.

The mole cricket's performance is one of a number of insect singing feats discussed recently in *Nature* by H. C. Bennet-Clark of the University of Edinburgh. He notes one writer's comment that "if moonlight could be heard," it would surely resemble the low-pitched 50-decibel signal of the tree cricket (*Oecanthus*). The field cricket (*Gryllus*) is many times louder than the tree cricket, but still quiet compared with the mole cricket in its burrow. Bennet-Clark suggests that the adaptive advantage responsible for the evolution of the mole cricket's song stems from the fact that the fan-shaped beam of sound emerging from the cricket's horn is half again as likely to be detected by a cricket on the wing as the equivalent hemispheric sound pattern produced by an insect stridulating on a flat surface.

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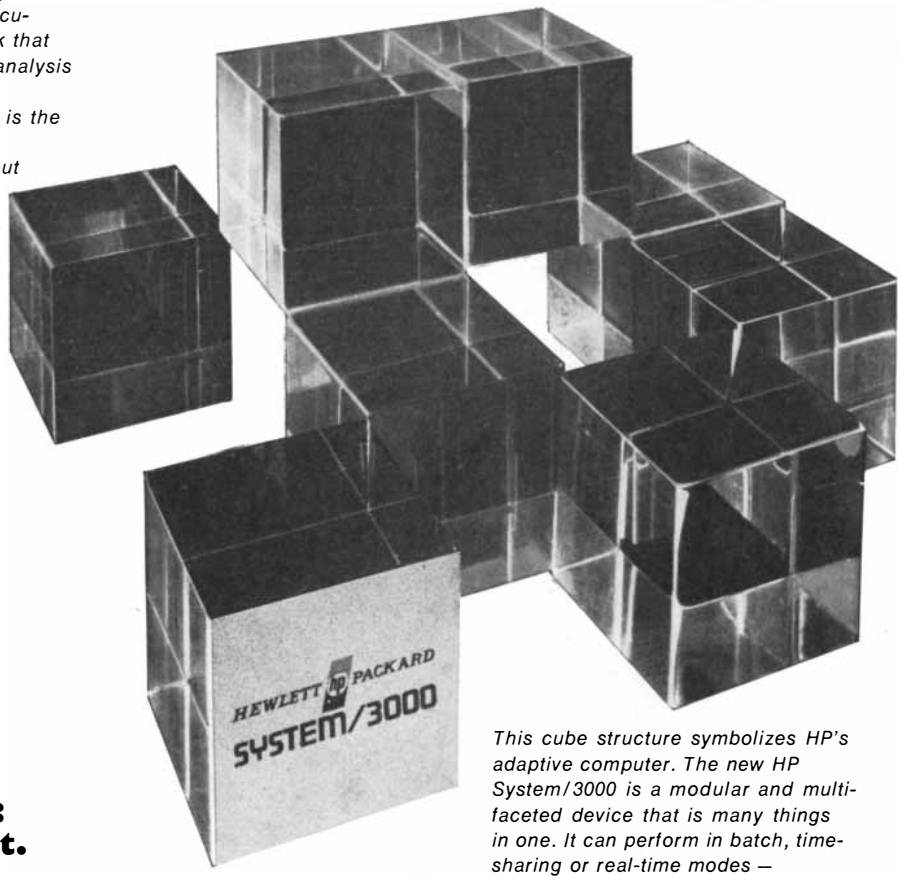

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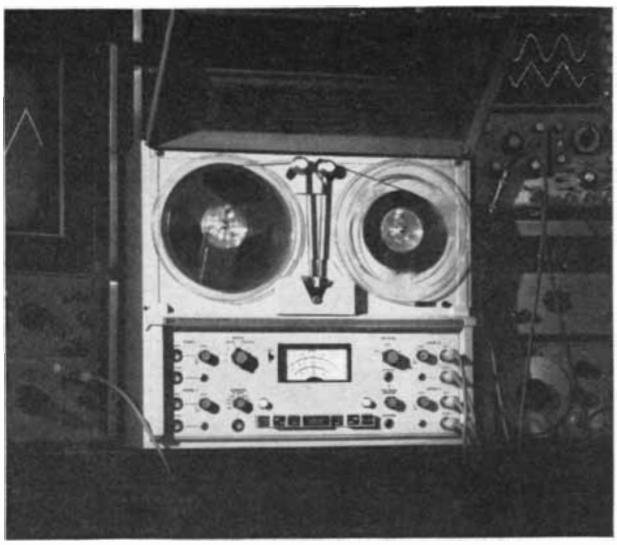

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THE SYNTHESIS OF SPEECH

Electronic speaking machines capable of synthesizing output speech with no recourse to any vestige of human speech are in the process of development. They may provide articulate voices for computers

by James L. Flanagan

If computers could speak, they could be given many useful new tasks. The telephone on one's desk might then serve as a computer terminal, providing automatic access to such things as airline and hotel reservations, selective stock market quotations, inventory reports, medical data and the balance in one's checking account. In principle such information could be provided by recordings of an actual voice, just as telephone companies already provide weather reports and other repetitive messages. Prerecording is not practical, however, if the information desired is only a small extract from a voluminous file, if the information changes rapidly (as stock market prices do) and particularly if the information must be gathered to order. Although one might assemble verbal messages of any complexity from a prerecorded vocabulary of speech fragments, the result would be highly unsatisfactory. Thus if a computer is to speak with a large, sophisticated vocabulary, and if it is expected to frame messages in many contexts, the simple technique of prerecording actual speech is ruled out. The alternative is to develop a mechanism, basically electrical, that is capable not only of synthesizing speech but also of introducing the various inflections characteristic of natural spoken language. There are other important motivations for attempting to synthesize speech. One is learning how speech is produced in the human vocal tract. Another is applying such knowledge to the reduction of the amount of information needed to transmit speech signals.

Human speech is remarkable in many ways, not the least of which is that it employs a physiological apparatus designed for other purposes: breathing and eating. The specialized acoustic code we call speech must have developed slowly over aeons. At least one speculation holds that early man's first means of communication were hand signals. Speech perhaps evolved when man discovered he could supplement his hand signals by grunts and other distinctive "gestures" of his vocal tract. "What drove man to the invention of speech," Sir Richard Paget has suggested, "was ... not so much the need of expressing his thoughts as the difficulty of 'talking with his hands full.' It was the continual use of man's hands for craftsmanship, the chase, and the beginnings of art and agriculture, that drove him to find other methods of expressing his ideas—namely, by a specialized pantomime of the tongue and lips."

The Origin of Speech Sounds

The fundamental principles of sound generation in the vocal tract and the acoustic filtering that takes place in the tract are now understood in considerable detail. The main gaps in knowledge have to do largely with nonlinearities in the generation of sound in the vocal tract and with certain interactions, still obscure, between the sound sources and the soft-walled pipe of the vocal tract. Apart from such details, however, enough is known about human speech production to allow the design of successful speech synthesizers. On the other hand, comparatively little is known so far about the linguistic rules that dictate the ordered activities of the vocal system. Much fundamental study is currently being devoted to speech prosody: the way the speaker unconsciously introduces stresses and pauses and alters the pitch of his voice. These factors are closely related to the dynamical properties of vocal-tract motion, another aspect of current study.

The human vocal tract is an acoustic tube of variable cross section about 17 centimeters long, extending from the vocal cords to the lips [*see illustration on page 50*]. The cross-sectional area of the vocal tract can be varied from zero (complete closure) to about 20 square centimeters by the placement of the lips, the jaw, the tongue and the velum: the flexible tissue—the soft palate—attached to the back of the roof of the mouth. The trapdoor action of the velum couples the vocal tract proper to a secondary cavity involved in speech production: the nasal tract. The nasal cavity is about 12 centimeters long and has a volume of about 60 cubic centimeters.

The vocal system can produce three basic kinds of sounds: voiced sounds, fricative sounds and plosive sounds. Voiced sounds, exemplified by the vowels, are produced by raising the air pressure in the lungs and forcing air to flow through the glottis (the orifice between the vocal cords), causing the vocal cords to vibrate. The vibrations interrupt the airflow and generate quasi-periodic broad-spectrum pulses that excite the vocal tract. The vibrating ligaments of the vocal cords are some 18 millimeters long and the glottal opening typically varies in area from zero to about 20 square millimeters.

Fricative sounds, exemplified by the consonants *s*, *sh*, *f* and *th*, are generated when the vocal tract is partly closed at some point and air is forced through the constriction at high enough velocity to produce turbulence. Plosive sounds, typified by the consonants *p*, *t* and *k*, are produced when the vocal tract is closed completely (usually with the lips or tongue), allowing air pressure to build up behind the closure, and is then abruptly opened. The sharp sound produced when the air is released is often

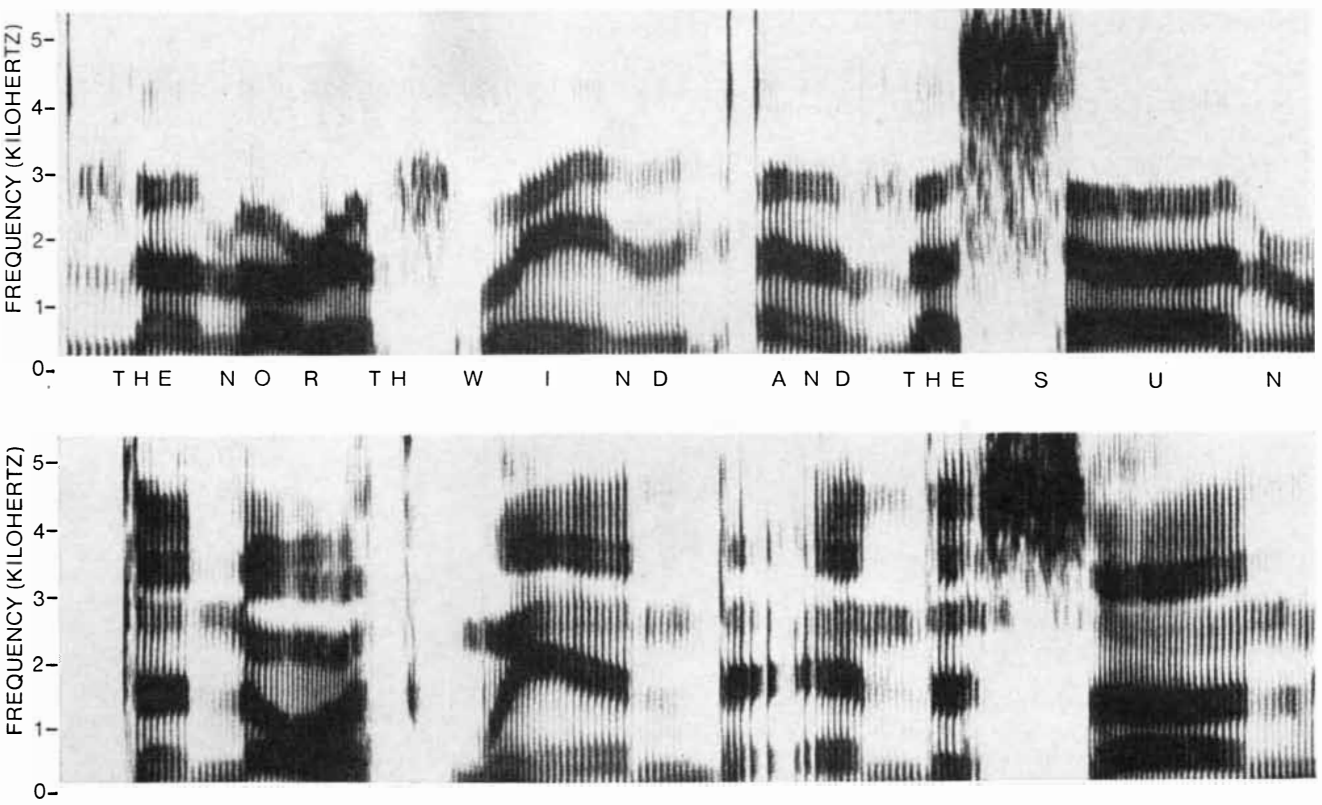
followed by a fricative sound or aspiration. All these vocal sources, whether for periodic voiced sounds or for aperiodic voiceless (fricative or plosive) sounds, have a fairly broad spectrum of frequencies extending over the voice-frequency range from about 100 cycles per second to more than 3,000. The vocal system acts as a time-varying filter to impose its resonant characteristics on the sound waves generated by the broad-spectrum sources. Operation of the voiced and voiceless sources is not mutually exclusive. For some sounds, such as the voiced fricative consonants *v* and *z*, two sound sources act in combination.

Because the interaction between the sound sources and the vocal system is fairly loose, the two can be represented diagrammatically as being linearly separable [*see top illustration on page 51*]. The sound radiated from the mouth has a frequency spectrum that, to a first approximation, can be considered the mathematical product of the source spectrum and the transmission characteristics of the vocal system (the combination of the vocal and nasal tracts).

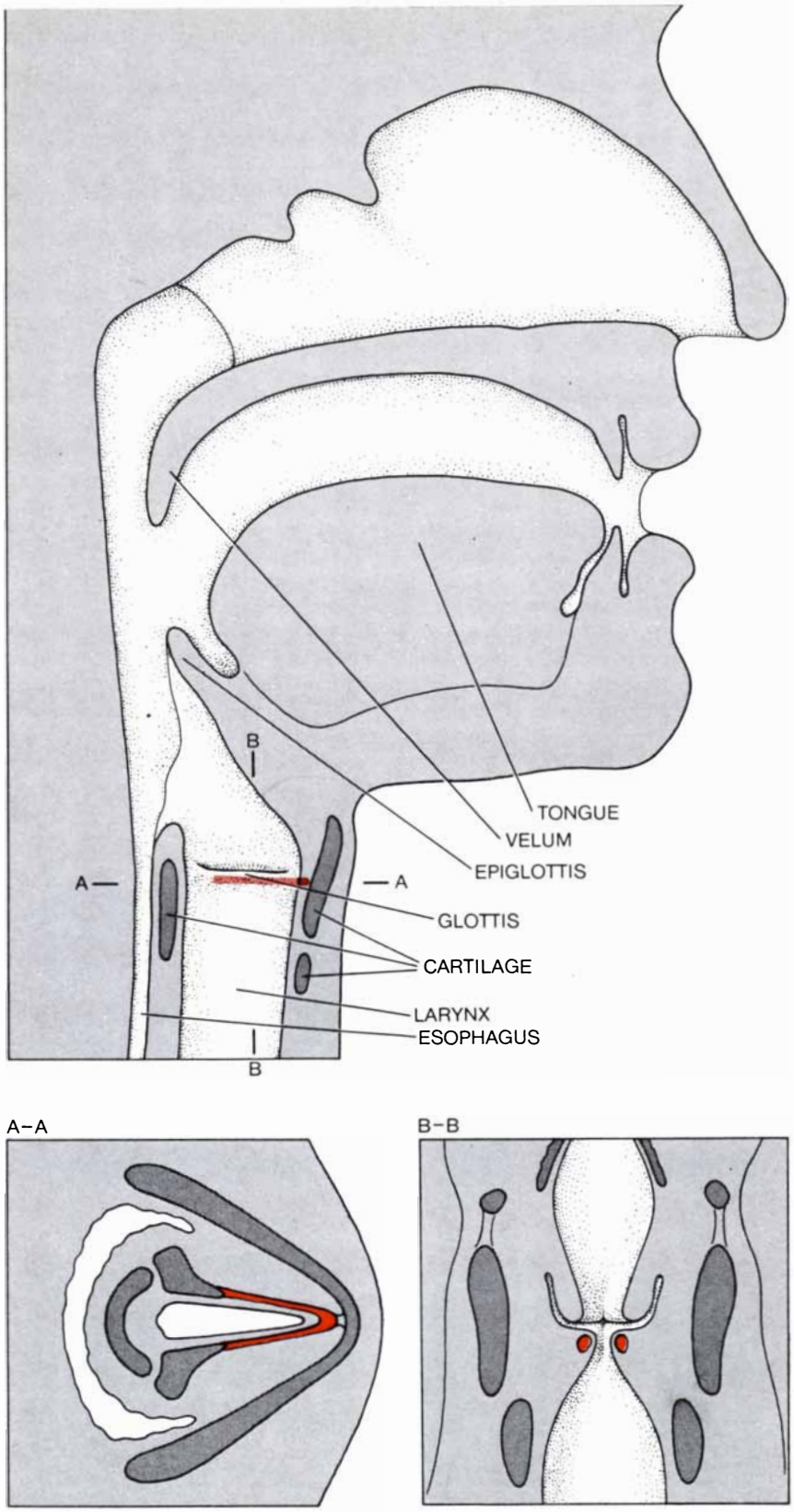
For voiced sounds the excitation source is the volume velocity of air passing the vocal cords. The flow is typically pulsive and periodic, with a spectrum whose harmonics diminish in amplitude approximately as 1 over the frequency squared. The vocal tract acts on this source as a filter with transmission "poles," or favored frequencies, corresponding to the acoustic resonances of the vocal tract. These resonances are often referred to as formants. It happens that, at the usual frequencies of speech, sound has a wavelength comparable to the length of the vocal tract. The tract is open at the mouth end and essentially closed at the glottal end. Therefore its resonant frequencies correspond roughly to the odd quarter-wave resonances of a pipe 17 centimeters long. For a straight pipe of this length the first three resonant frequencies are 500, 1,500 and 2,500 cycles per second.

For vowel sounds, in which the nasal tract is closed off, there are no additional resonances in this frequency range and thus the transmission filter operates to emphasize just these three frequencies. When the nasal tract is made part of the transmission system, another resonant pole is typically introduced at about 1,000 cycles per second adjacent to an antiresonance, or "zero," also near 1,000 cycles. The voiced sound that issues from the mouth is therefore a line spectrum that has imposed on it an envelope that reflects the resonances produced by passage through the vocal transmission system. The various voiced sounds of speech are produced by changing the shape of the vocal tract, thereby changing its resonances. In a similar manner the unvoiced sounds are excited from a noise source that has a fairly broad, uniform spectrum. Because the source is typically positioned at some point along the tract it alters the length of pipe acting as a resonance system so that the resonances and antiresonances now fall at different frequencies. Again the radiated sound reflects the frequencies that are favored or suppressed by the resonant system.

In continuous speech the formant resonances move around as the vocal tract changes shape. Because the tongue, the jaws, the lips and the velum have significant mass their accelerations are limited by the forces that the articulatory muscles can generate. Thus the vocal tract changes shape rather slowly compared with the rate of pressure fluctuations in the speech wave. When the speech wave is recorded in a sound spectrogram, which shows the changes



SOUND SPECTROGRAM of a spoken sentence synthesized from printed text by a computer-controlled electronic speaking machine designed and built at the Bell Telephone Laboratories is shown at top. A comparable spectrogram for a human utterance of the same sentence is shown at bottom. At the present stage of development the machine's intelligibility is just beginning to be acceptable.



HUMAN VOCAL SYSTEM consists of two main parts: the vocal tract proper, an acoustic tube of variable cross section extending from the vocal cords to the lips, and the nasal tract, a secondary cavity coupled to the vocal tract proper by means of the trapdoor action of the velum. View at top is a median sagittal section of the entire system; views at bottom are a transverse section (*A–A*) and a vertical section (*B–B*) of the vocal-cord region. The vocal system can produce three basic kinds of sounds: voiced sounds (such as vowels), fricative sounds (such as the consonants *s, sh, f* and *th*) and plosive sounds (such as *p, t* and *k*).

in sound frequency and intensity with time, one can see the relatively slow rates at which formants change their frequency [*see bottom illustration on opposite page*].

Mechanical Speaking Machines

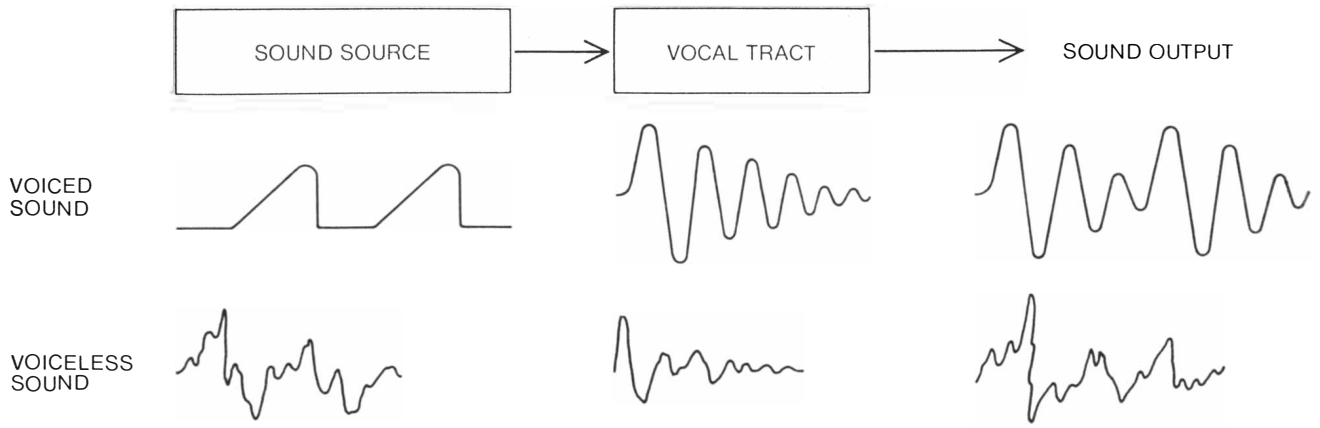
Just as some early inventors attempted to build flying machines with wings that flapped like a bird's, others tried to build speaking machines by crudely duplicating the physiology of the human vocal tract. On the whole the second group of inventors had somewhat greater success than the first.

One of the earliest efforts at speech simulation was made by Christian Gottlieb Kratzenstein, who won a prize offered in 1779 by the Imperial Academy of St. Petersburg. For its scientific competition that year the academy posed the following two questions: "(1) What is the nature and character of the sounds of the vowels *a, e, i, o, u* [that make them] so different from one another? (2) Can an instrument be constructed like the *vox humana* pipes of an organ, which shall accurately express the sounds of the vowels?"

Kratzenstein's winning solution consisted of a set of acoustic resonators somewhat similar in form and dimension to the human mouth [*see top illustration on page 52*]. He activated the resonators with a vibrating reed that mimicked the human vocal cords by interrupting an airstream. (Apparently Kratzenstein invented this particular type of reed, subsequently used in the harmonica.) It is reported that Kratzenstein's mechanism imitated the five vowels "with tolerable accuracy."

A machine that not only more successfully imitated the vowel sounds and several consonants but also connected speech utterances was built a dozen years later by Wolfgang von Kempelen of Vienna. His device was not taken seriously by his scientific colleagues, however, because he had earlier exhibited a fake chess-playing machine. The "machine," which won many games, concealed a legless Polish army officer named Worouski who was a master chess player.

Von Kempelen's speaking machine was nevertheless a completely legitimate device. It had a bellows to supply air to a reed that in turn excited a single, hand-controlled resonator that imitated voiced sounds. Consonants, including nasals, were simulated by four separate constricted passages, which the operator controlled with the fingers of his other



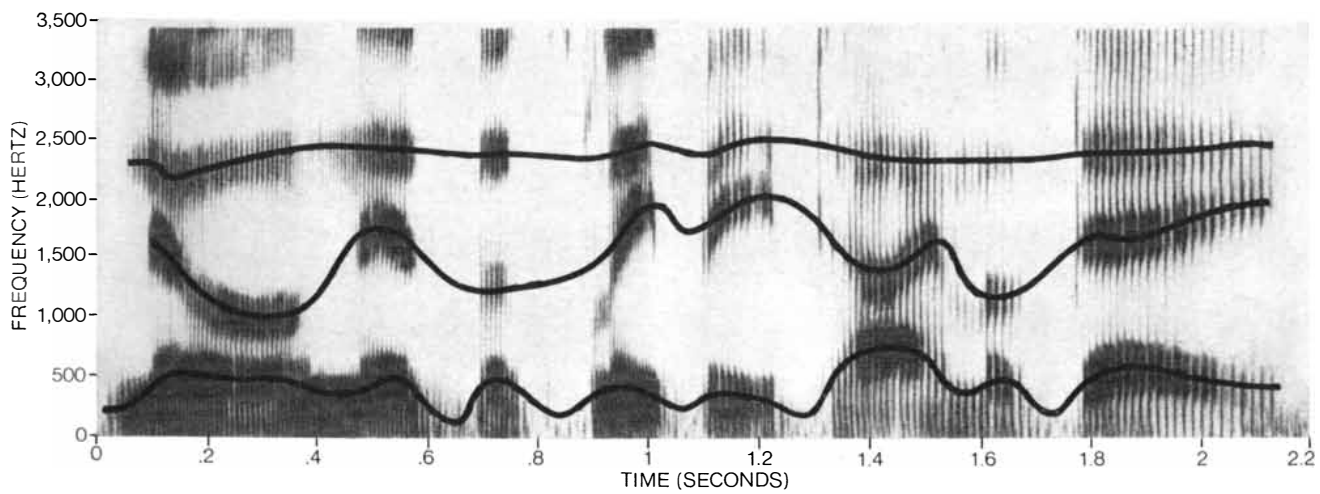
MODEL OF HUMAN SPEECH PRODUCTION represents the sound sources for periodic voiced sounds and for aperiodic voiceless sounds as being linearly separable from the vocal system, which acts as a time-varying filter to impose its resonant characteristics on the sound waves generated by the broad-spectrum sources. According to this model, the frequency spectrum of the sound radiated from the mouth is the mathematical product of the source spectrum and the transmission characteristics of the vocal system. Equivalently, the output sound wave is the convolution of the source wave form with the impulse response of the vocal system.

hand [*see bottom illustration on next page*].

Von Kempelen's ingenious device had a more far-reaching influence than he could have suspected. When Alexander Graham Bell was a boy in Edinburgh in the 1850's, he was greatly impressed by a reproduction of von Kempelen's machine that had been built by Sir Charles Wheatstone, a maker of musical instruments who later contributed to the development of electric telegraphy. Young Alexander was encouraged by his father, who was an elocutionist, to construct a speaking automaton of his own.

Assisted by his brother Melville, Alexander attempted to copy the vocal organs by making a cast of a human skull. The boys used gutta-percha and other simple materials to represent the lips, tongue, palate, teeth, pharynx and velum. The lips were a framework of wire covered with rubber that had been stuffed with cotton batting. The cheeks were made of rubber; the tongue was simulated by wooden sections surrounded by batting and covered with rubber skin. There was a sheet-metal box for a larynx and a flexible tube for a windpipe. A vocal-cord structure consisted of a slotted rubber sheet stretched over metal supports. The various parts were activated by levers controlled from a keyboard. Bell recalled that the device produced both vowels and nasals and could even be manipulated to emit a few simple utterances.

More than 100 years later, even with the great progress in electronics and computational methods, there are still a number of speech and acoustic questions that are best approached through mechanical models of the vocal tract. These questions relate particularly to nonlinear properties of turbulent flow, and mechanical analogues can provide data about the location, intensity, spectrum and internal impedance of the sound sources for unvoiced sounds. All these factors are difficult to measure in the human vocal tract.



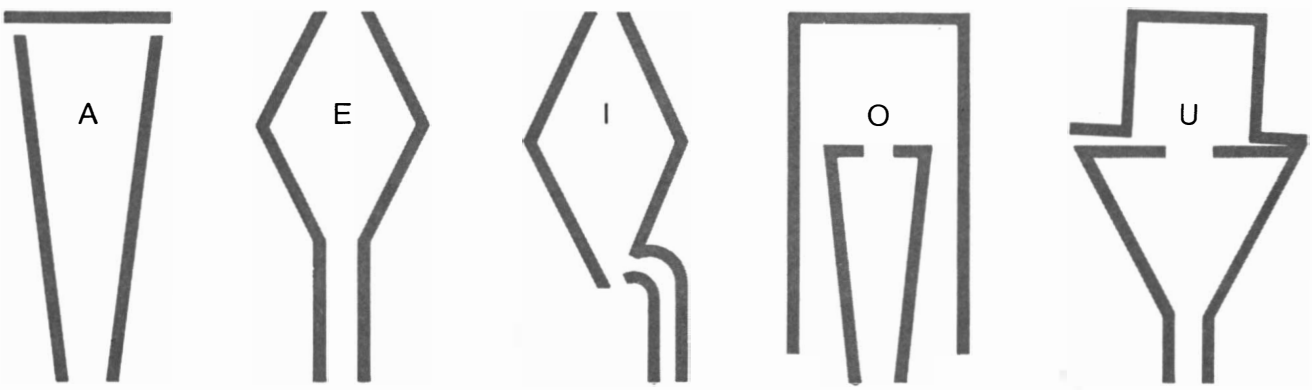
FIRST THREE FORMANTS, or natural acoustic resonances of the human vocal tract, occur at frequencies of approximately 500, 1,500 and 2,500 hertz (cycles per second). In this sound spectrogram of a short sentence ("Noon is the sleepy time of day") the relatively slow rates at which these formants change their frequency with time (*solid black curves*) are evident. The vocal tract changes rather slowly compared with the rate of pressure fluctuations in the speech wave, because the tongue, the jaws, the lips and the velum have significant mass and their accelerations are accordingly limited by the forces that the articulatory muscles can generate.

The ability to send spoken words over wires, dating from Bell's invention of the telephone in 1876, has provided a continuing motivation to learn how words are generated, how they can be electrically transmitted with economy and how they can be synthesized with fidelity. Modern developments in electronic technology have therefore shifted the emphasis in speech synthesis from mechanical and semimechanical methods to all-electrical systems.

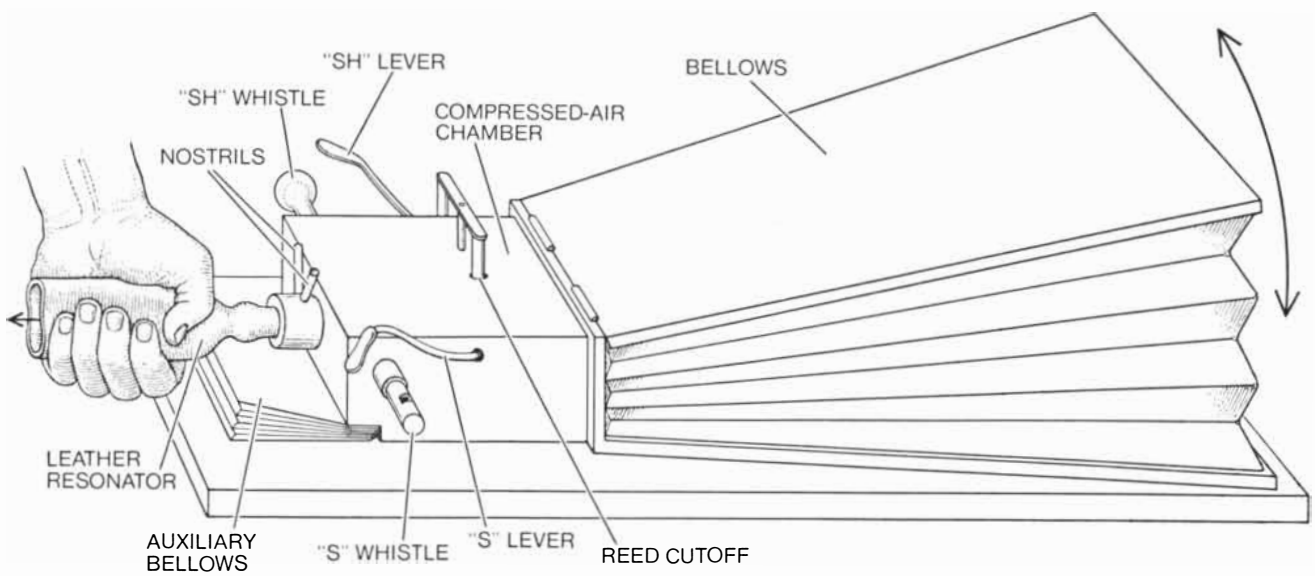
Electrical Speech Synthesis

One of the first electrical synthesizers that attempted to produce connected speech was the Voder ("voice-operation demonstrator"), which was exhibited at the New York world's fair in 1939 and a year later at the San Francisco world's fair. The Voder employed two sound sources: a wide-band noise source and a periodic buzz oscillator [*see illustration on opposite page*]. These sounds were modified by passing them through a "resonance control" box (the "vocal tract") containing 10 contiguous band-pass filters that spanned the frequency range of normal speech. The outputs of the band-pass filters were modulated by gain controls individually operated by 10 finger keys. Three additional keys provided a transient excitation of selected filters to simulate three types of plosive sound: *t-d*, *p-b* and *k-g*. The operator had a wrist bar for selecting either the noise or buzz source and a foot pedal for controlling the pitch of the buzz oscillator. The operators who demonstrated the Voder at the two world fairs required a year or more of training, but eventually they learned to "play" the Voder much as if it were an organ or a piano, and they were able to produce intelligible speech with considerable facility.

The Voder and related developments led to other analogue electronic synthesizers of speech. The devices ranged from analogue circuitry that duplicated the vocal resonances to electrical simulation of the vocal tract as a bilateral transmission line. The efforts had the two motivations of gaining fundamental knowledge of speech production and of finding new ways to transmit the voice with high efficiency. The technological



ACOUSTIC RESONATORS somewhat similar in form and dimension to the human mouth were devised by Christian Gottlieb Kratzenstein in 1779 for the synthesis of vowel sounds. The resonators were activated with a vibrating reed that mimicked the human vocal cords by interrupting an air stream. Kratzenstein's novel mechanism reportedly imitated the five vowels "with tolerable accuracy."



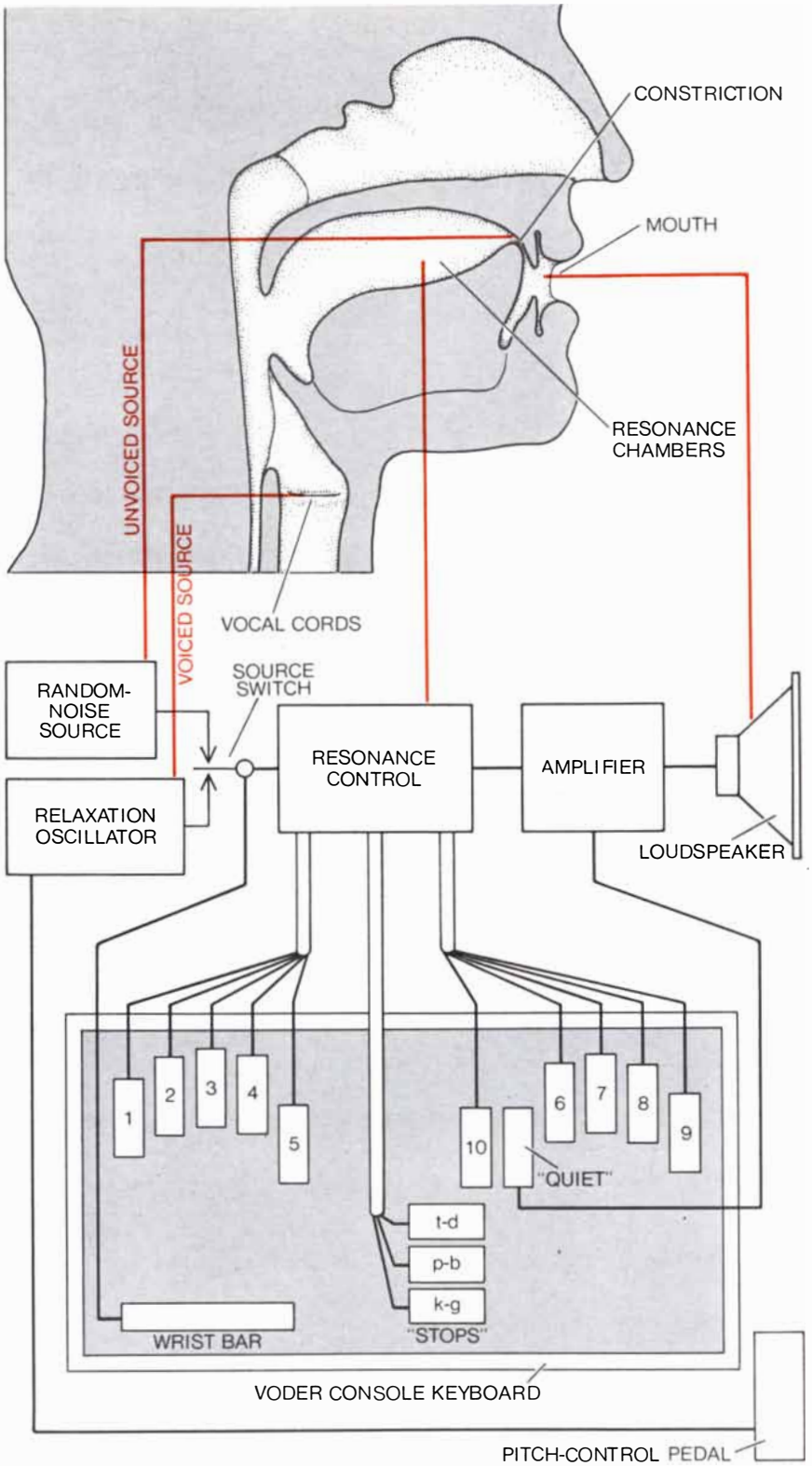
MORE SUCCESSFUL SPEAKING MACHINE was designed in 1791 by Wolfgang von Kempelen. The device had a bellows to supply air to a reed that in turn excited a single, hand-controlled resonator that imitated voiced sounds. Consonants, including nasals, were simulated by four separate constricted passages, which the operator controlled with the fingers of his right hand. The illustration shows a reconstruction of von Kempelen's original speaking machine described by Sir Charles Wheatstone in 1837.

goal, drawing on techniques of both speech analysis and speech synthesis, was to effect a significant reduction in the bandwidth needed to transmit speech signals.

On the fundamental side good progress continued to be made in the understanding of speech production. On the technological side complete band-compression systems were devised and tested. The most notable early system was the Vocoder, invented by Homer Dudley at about the same time that the Voder was being demonstrated. It is fair to say that the Vocoder spawned an entire new subfield of communication study, one having as its principal aim the efficient coding and transmission of speech signals. The Vocoder samples the amplitude spectrum of a speaker's voice at a number of different frequencies and derives electrical voltages that describe the relatively slow fluctuations of these samples. It also derives a voltage that represents the voice pitch and whether a sound is voiced or unvoiced. Since only these slowly changing quantities are transmitted over the communication channel, they require less bandwidth than a normal voice channel. At the receiving end the transmitted quantities are used to resynthesize the original frequency range of the speaker's voice.

Although the Vocoder and its many relatives cannot reproduce all the subtle qualities of the human voice, they can usually indicate such things as whether the speaker is male or female and whether he or she has a distinctive accent. The Vocoder and similar systems have been used for a number of years in special applications where bandwidth is at a premium, but no such system has yet been introduced into civil telephony. In its transoceanic telephone facilities the Bell system has achieved useful savings in bandwidth in a different way, by a time-division switching method.

This system, called TASI (for Time Assignment Speech Interpolation), exploits the fact that in ordinary two-way telephone conversations each speaker is silent roughly half the time. In addition, normal speech has many pauses and silent intervals. A given talker therefore transmits a signal only 35 or 40 percent of the total time. In long-distance communication, where amplification of the signal is necessary, the two-way communication channels are normally four-wire circuits—or two unilateral transmission paths. Each party has a transmit circuit and a receive circuit. Because of the relative inactivity of each talker, a single one-way channel is not used 60



VODER ("voice-operation demonstrator"), an all-electrical speech synthesizer exhibited at the New York world's fair in 1939, was one of the first electrical synthesizers to produce connected speech. The Voder employed two sound sources: a wide-band random-noise source and a periodic buzz oscillator. These sounds were modified by passing them through a "resonance control" box containing 10 contiguous band-pass filters that spanned the frequency range of normal speech. The outputs of the band-pass filters were modulated by gain controls individually operated by 10 finger keys. Three additional keys provided a transient excitation of selected filters to simulate three kinds of plosive sounds: *t-d*, *p-b* and *k-g*. A wrist bar was used to select either noise or buzz and a foot pedal to control the pitch of the buzz oscillator. Analogies to human speech-production components are in color.

or 65 percent of the time. When a large group of such connections is accessible from single transmit and receive locations, as is the case for an undersea cable, the statistical properties of the conversation ensemble make a significant amount of time and bandwidth available for signal transmission, and the system can serve a number of talkers greater than the number of unilateral circuits. The incoming transmit circuit of each talker is equipped with a fast-acting speech detector, or voice switch. When the detector indicates the presence of speech on its line, an automatic electronic switch connects the line to an available transmit path of the TASI group.

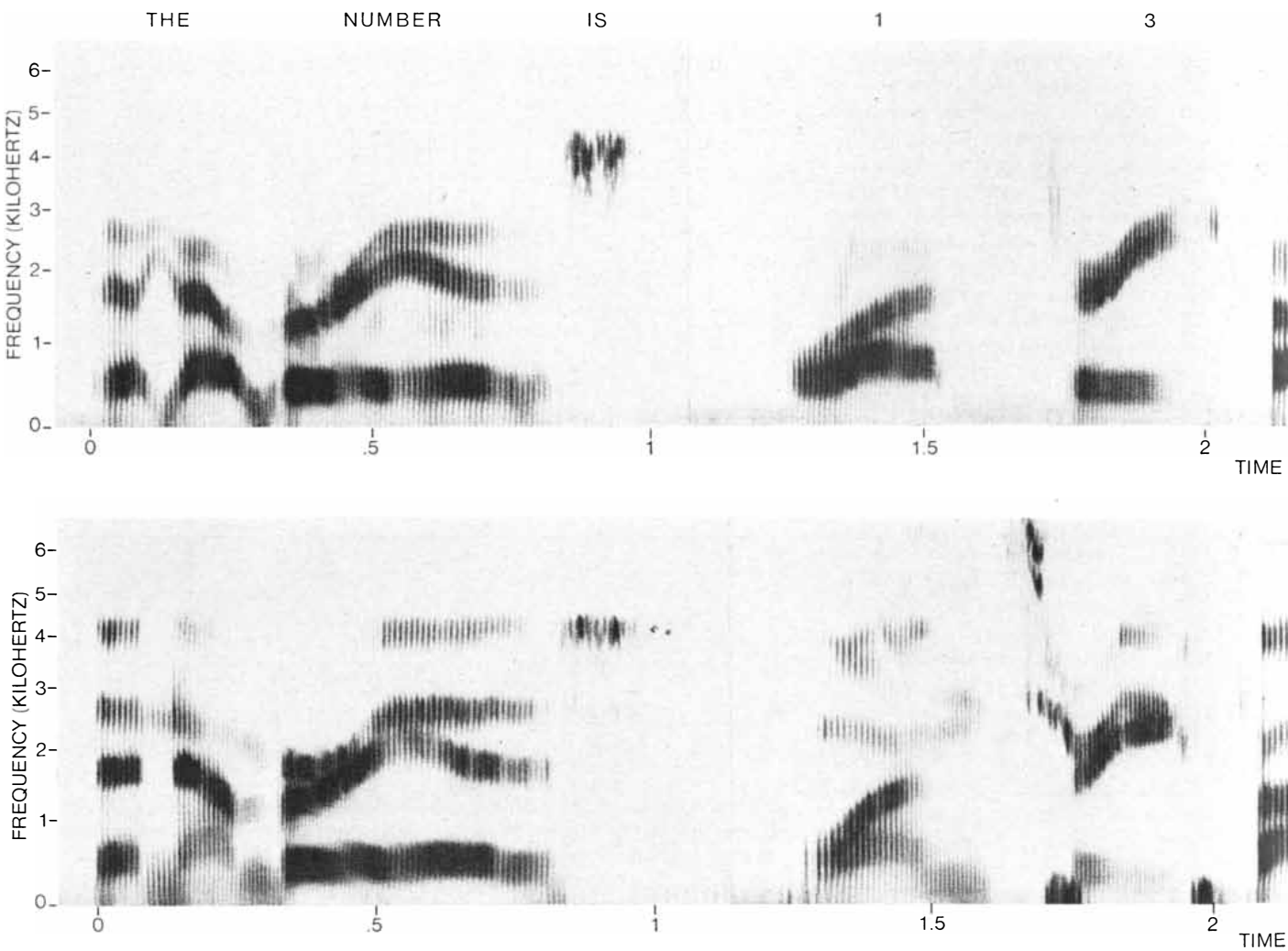
During pauses and silent intervals a given talker loses his priority on the transmit link. He is reassigned a channel—often a different one—when he again becomes active. The TASI switch must consequently keep track of who is talking to whom, and it must identify the recipient of each signal presented for transmission. This "message-addressing" information can be transmitted in the form of a very short identification signal, either before each talk spurt or over an auxiliary channel that serves the entire system.

A limit obviously exists to the number of incoming signals that can be transmitted by a given group of transmit paths before some "freeze-out," or loss of speech signals, occurs. Among other things, this limit is a function of the size of the cable group, the circuit signal-to-noise ratio and the sensitivity of the speech detectors. Several TASI systems have been put into practical operation on undersea cables. On a 36-channel cable, for example, the effective increase in transmission bandwidth is roughly two or three times the bandwidth of the physical circuit.

With the advent of digital computers, low-cost integrated circuits and sophisticated understanding of sampled-data theory, the techniques of speech analysis and synthesis have acquired new attractiveness. Sampled-data theory tells one how to represent the behavior of continuous physical systems (for example the vocal tract) in terms of discrete numerical operations. Computers are able to perform the arithmetic of these operations quickly and accurately; associated memory devices are able to store large quantities of numbers that can represent speech signals. Advances in integrated circuitry enable one to build small, inexpensive, complex electrical components, including the digital circuits needed in computers.

Talking Computers

Along with these developments, and with the still growing understanding of speech acoustics, the foci of fundamental



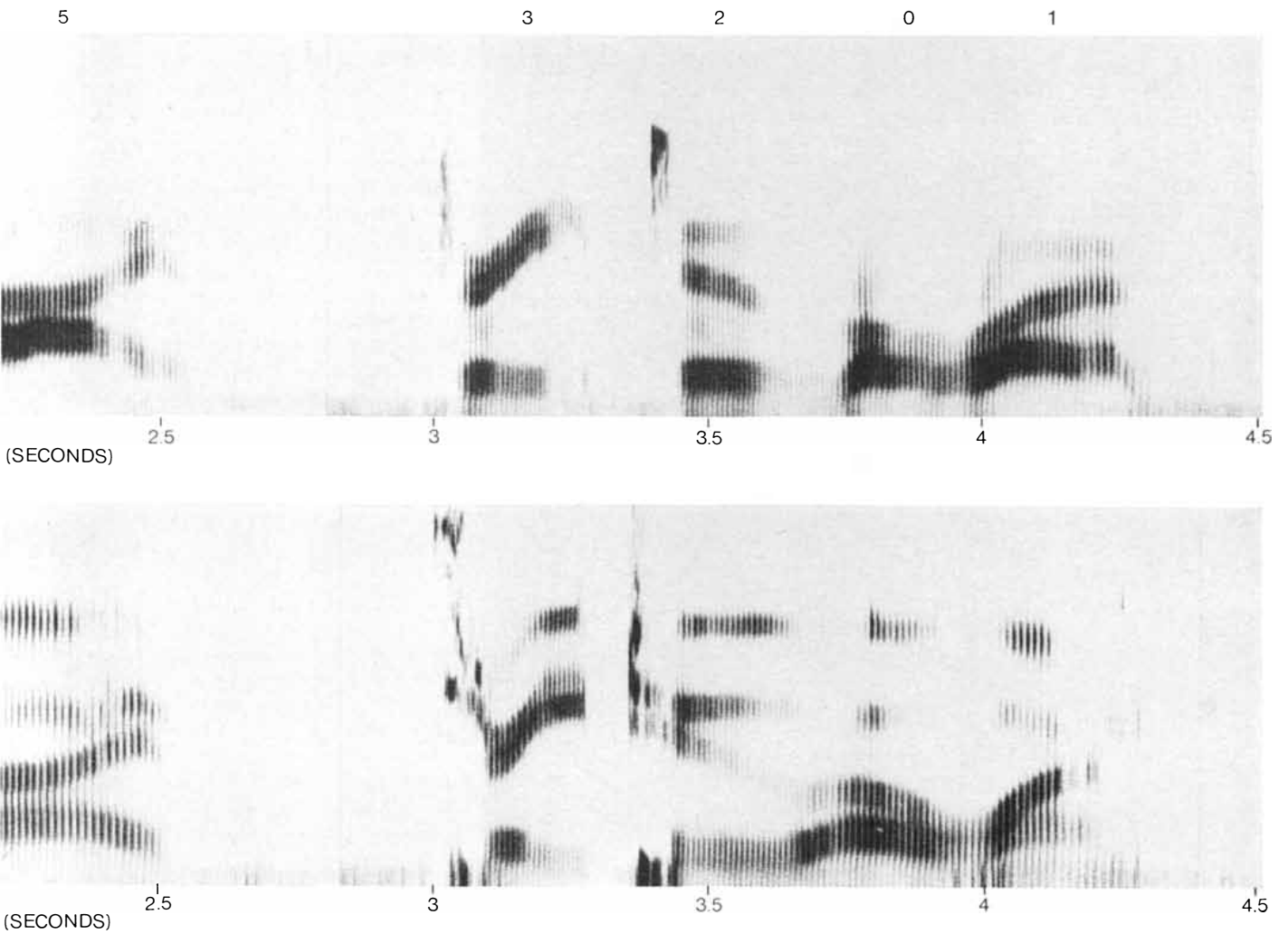
SEVEN-DIGIT TELEPHONE NUMBER synthesized by a computer-controlled formant-synthesis system at Bell Laboratories is represented by a sound spectrogram (*top*) that closely resembles a spectrogram of the same message spoken by a human (*bottom*).

and applied research have shifted somewhat. On the fundamental side linguistic and semantic problems of speech are coming under scrutiny through the power of digital computers. On the applied side two notable goals have emerged. One is to raise the quality of Vocoder-like systems by exploiting the complex digital processing made possible by low-cost integrated circuitry. Bandwidth savings achieved in this way would be highly desirable in satellite communication, deep-space exploration and mobile radiotelephony. A second, and perhaps more compelling, goal is to provide voices for computers, thus opening up new possibilities in automatic information services, computer-based instruction and the design of simple, inexpensive terminals. If computers could voice their answers, as well as print them on a typewriter or display them on a cathode ray tube, their capabilities could be applied in many new ways.

Let us consider what is required to give a computer a voice. Synthesis of a meaningful speech signal requires a description, in some form, of the vocal-tract resonances corresponding to that signal and suitable sound sources for exciting these resonances. A digital synthesis system may therefore operate as follows. A random-number generator simulates the source for voiceless sounds; its variance is controlled as a function of time by a noise-amplitude signal. A digital counter simulates the vocal-cord source for voiced sounds and produces pulses at the required pitch frequency. The amplitude of the voiced source is altered as required by an input designated the voicing-intensity parameter. The two sources—one for voiced sounds, the other for voiceless sounds—are then applied to a recursive filter whose coefficients are determined by the speech resonances and antiresonances as they change with time. Three variable resonances are typically used for voiced sounds and a combination of resonances and antiresonances for voiceless sounds. The digital output of the system is converted to analogue form to give the synthetic signal an audible form.

The recursive filter generates quantized samples, expressed in binary numbers, of the synthetic speech signal. The filter can be organized to operate digitally in a number of ways. A particularly convenient approach is to represent the resonances and antiresonances individually by second-order difference equations. The recursion relations can be programmed directly in the computer that is doing the "talking" or they can be accomplished by special digital circuitry—in effect a hardware digital filter that is controlled by the computer.

The control functions that specify the resonances, the antiresonances and the excitation of the filter must be supplied by the computer. Two computer tech-



The formant-synthesis method employs a computer program that analyzes natural speech to obtain the variation of three formants and the voice pitch. The particular system used to make the top spectrogram is implemented on a Honeywell DDP-516 computer.

niques for providing the control functions are available. In one technique, called formant synthesis, the control values are measured directly from human speech and are stored in the machine. In another, called text synthesis, the control values are calculated solely from programmed knowledge of the speech process.

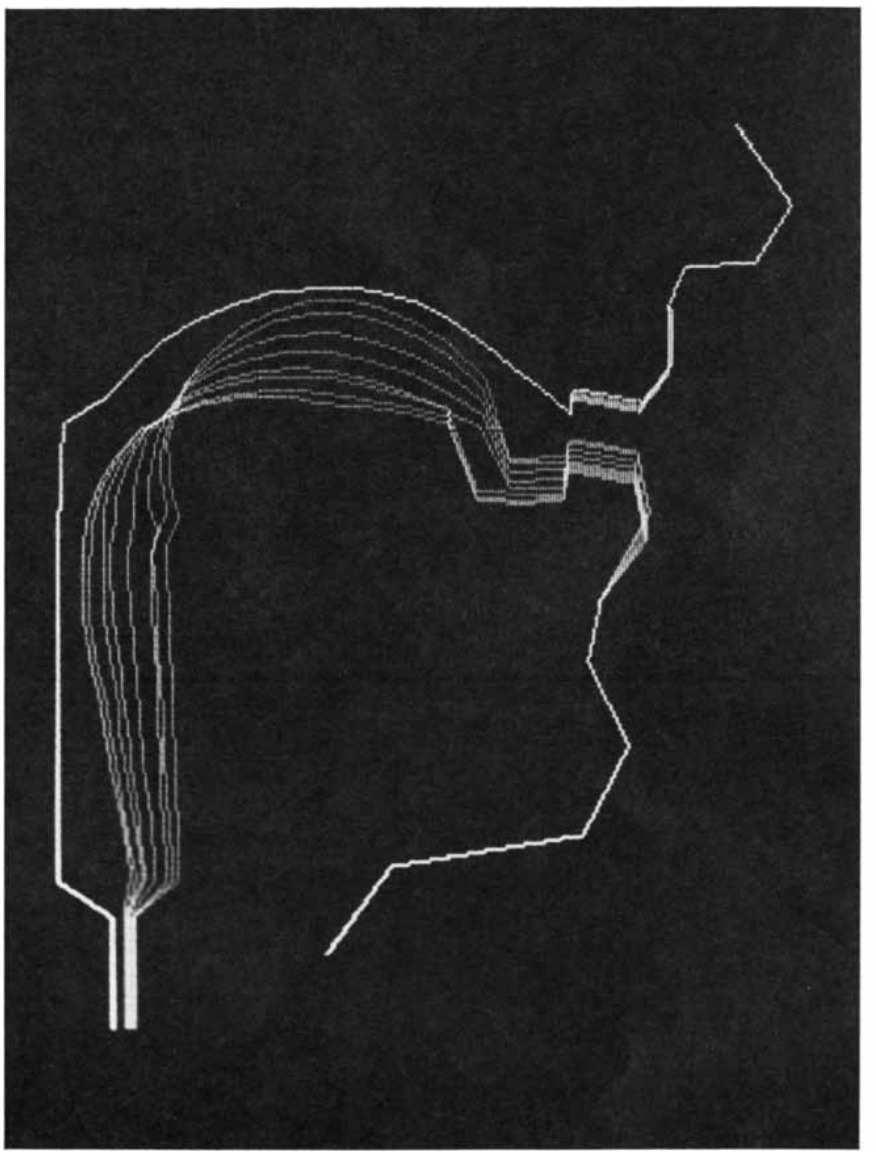
Formant Synthesis

The formant-synthesis method employs a computer program that analyzes natural speech to obtain the variation of three formants and the voice pitch. When data so derived are provided to a synthesizer, they produce speech that closely resembles the original utterance.

Economical storage and flexibility of vocabulary are achieved by storing a library of formant-coded words. Individual, naturally spoken words are analyzed for formants and the formant functions so obtained are stored. Only 530 bits (binary digits) per second are needed to record the formant-coded data, whereas about 50,000 bits per second would be needed to record and store the complete wave form of natural speech. When the computer is instructed to articulate a particular word sequence, or message, by the "answer back" program, it turns to its library of formant functions and looks up the required functions in the prescribed sequence. By means of a stored program it calculates the duration and the pitch inflection for each word to fit the prescribed context. It then calculates smooth transitions of the formant functions at the word boundaries to produce a realistic concatenation of the words in the message. Finally, the computer issues the resulting control functions to a digital speech synthesizer.

The system described has been implemented at the Bell Telephone Laboratories on a Honeywell DDP-516 computer. In this case the speech synthesizer is a hardware digital filter, external to the computer. The program that creates the control functions for the hardware synthesizer runs about 10 times faster than is necessary to generate speech at the normal word rate, thus making it possible for one computer to serve up to 10 external synthesizers. The system has been applied experimentally to the automatic generation of seven-digit telephone numbers and to the synthesis of spoken instructions for the production-line wiring of telephone circuits. A spectrogram of a typical message synthesized by the computer system ("The number is 135–3201") closely resembles a spectrogram of the same message spoken by a human [*see illustration on preceding two pages*].

Formant synthesis offers sufficient economy of storage and flexibility of vocabulary to make it attractive for "middle-sized" vocabularies such as inventory reporting, flight information and computer instruction. If, however, a computer is expected to compose messages from encyclopedic amounts of information, a more economical storage system is required. This can be provided by the text-synthesis technique.



OSCILLOSCOPE DISPLAY of a model of the human vocal tract changes shape with each sound uttered by the associated printed-text speech synthesizer at Bell Laboratories. An expanded set of phonemes, with their individual pitch and duration calculated to satisfy the context of the message, constitutes "commands" that are given to the computer-programmed model of the vocal tract, which simulates the shape of the actual human vocal tract. The photograph shown here is a multiple exposure of the actual oscilloscope display.

Mimicking the Vocal Tract

In text synthesis the computer stores a pronouncing dictionary that contains essentially what one finds in an ordinary desk dictionary: a phonemic transcription of each word, an indication of syllable stress, some rudimentary grammatical information (whether the word is a noun, a verb, an adjective and so on) and information about endings and derived forms. The message to be converted into speech is supplied as the printed English text. Each word is looked up in the dictionary, and the resulting information is passed on to a

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program that incorporates linguistic and syntactic rules for English. In this program a strategy is formed for the stress and phrasing of each sentence, pauses are inserted where necessary, and the duration and pitch of individual phonemes are assigned. The result is an output of discrete symbols representing the sequence of phonemes, with their individual pitch and duration calculated to satisfy the context of the message. This string of symbols represents an expansion of two or three times over the input of discrete alphabetic symbols. (Thus, for example, the English-text message "the north wind and the sun" becomes "4dh 4a 6n $4aw 2er 6th 6w *qq5i 4n-4d 4aa -n -d -dh 4a 6s *qq5uh 6n.")

The expanded set of symbols constitutes "commands" that are given to a programmed dynamic model of the vocal tract that simulates the shape of the human vocal tract. The DDP-516 computer programmed for text synthesis at Bell Laboratories also provides an oscilloscope display of the vocal tract showing how it changes shape with each sound uttered by the associated speech synthesizer [*see illustration on page 56*]. The shape of the vocal tract is defined by seven articulatory parameters. They assume values dictated by the expanded set of phonetic symbols but in responding to these discrete commands they impose their own time constants, governed by physiological constraints. About 100 times per second the formants of the model vocal tract are computed as the tract deforms; the results, along with calculated excitation information, are issued to an external speech synthesizer similar to the one described above.

In this scheme the machine synthesizes the output speech with no recourse to any vestige of human speech. The storage economy in text synthesis approaches 1,000 to one when compared with a facsimile recording of the speech wave form. Comparison spectrograms of synthesized speech and natural speech give an idea of what can be achieved with text synthesis [*see illustration on page 49*]. As might be expected, the machine displays its own distinctive accent and the accent can be varied by changing the linguistic rules. At the present stage of development the machine's intelligibility is beginning to be acceptable. It is "learning" the rules of speech generation as fast as investigators can formulate, quantify and interpret them for the digital computer. Ultimately both the text-synthesis technique and the formant-synthesis method may provide articulate voices for computers.

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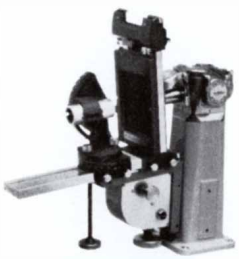
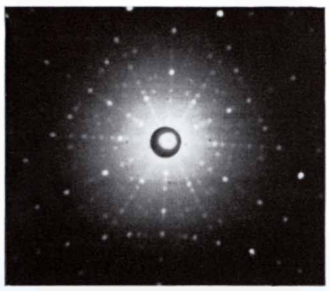
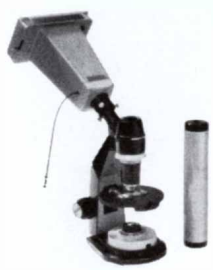


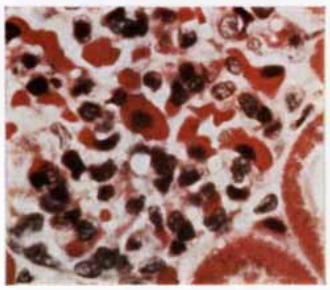
XR-7 FOR X-RAY CRYSTALLOGRAPHY



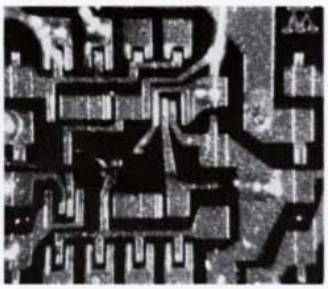
Diffraction pattern, sapphire



ED-10 FOR PHOTOMICROSCOPY

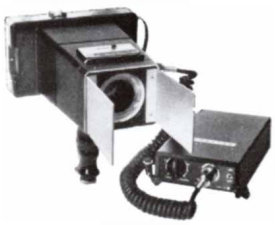


Section, mouse kidney, 1000x



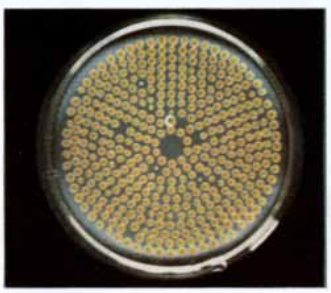
Integrated circuit, 80x

Pinus leaf section, 100x

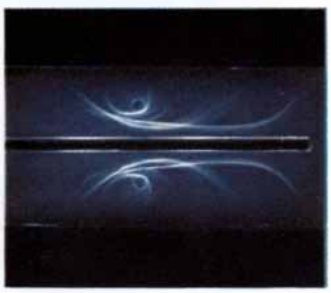


CU-5 FOR CLOSE-UPS

Clinical dental record



Macrophotograph, bacteria colonies



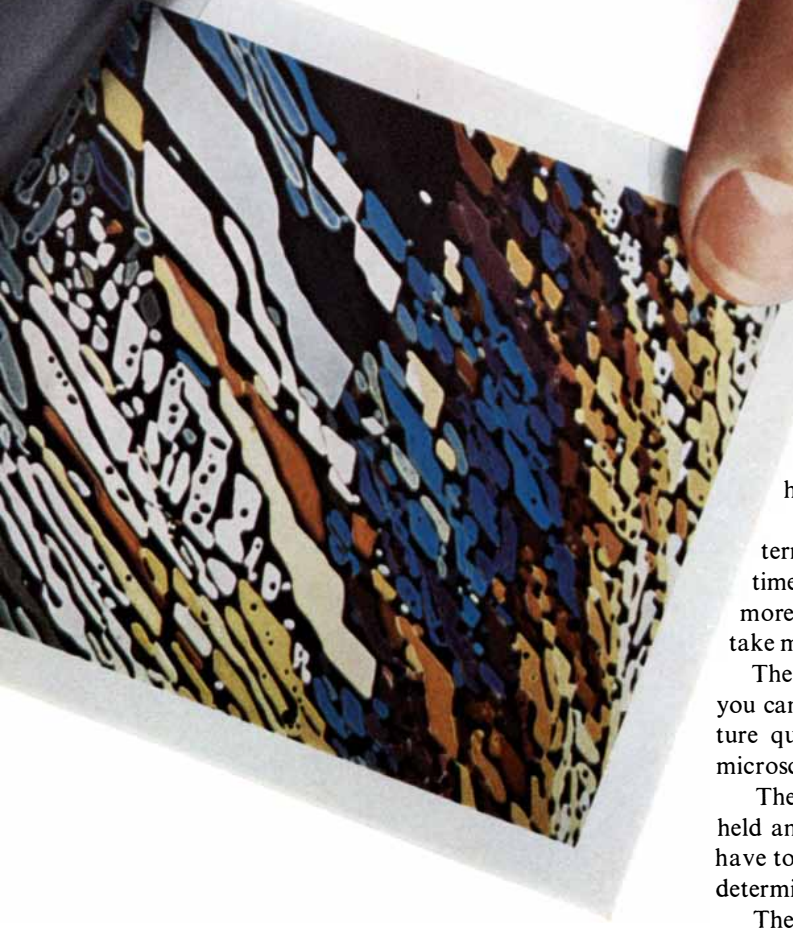
Immunoelectrophoresis

MP-3 MULTIPURPOSE

High contrast copy, continuous-tone art

Macrophotograph, diode fractures

Fingerprint record, negative



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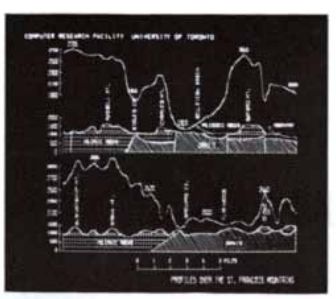
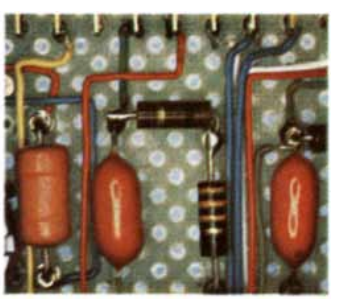
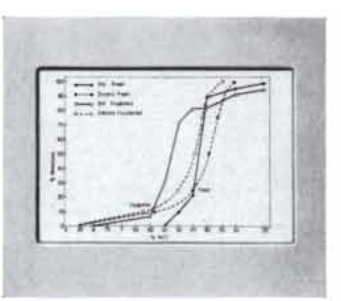


Hard copy, computer terminal display

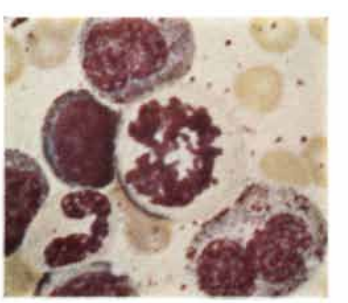


Electronic components

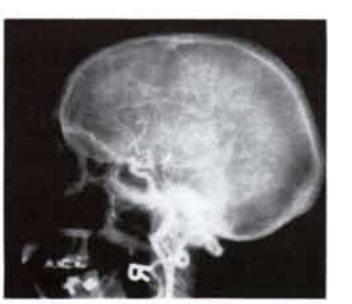
Gross specimen, intestinal fibroma



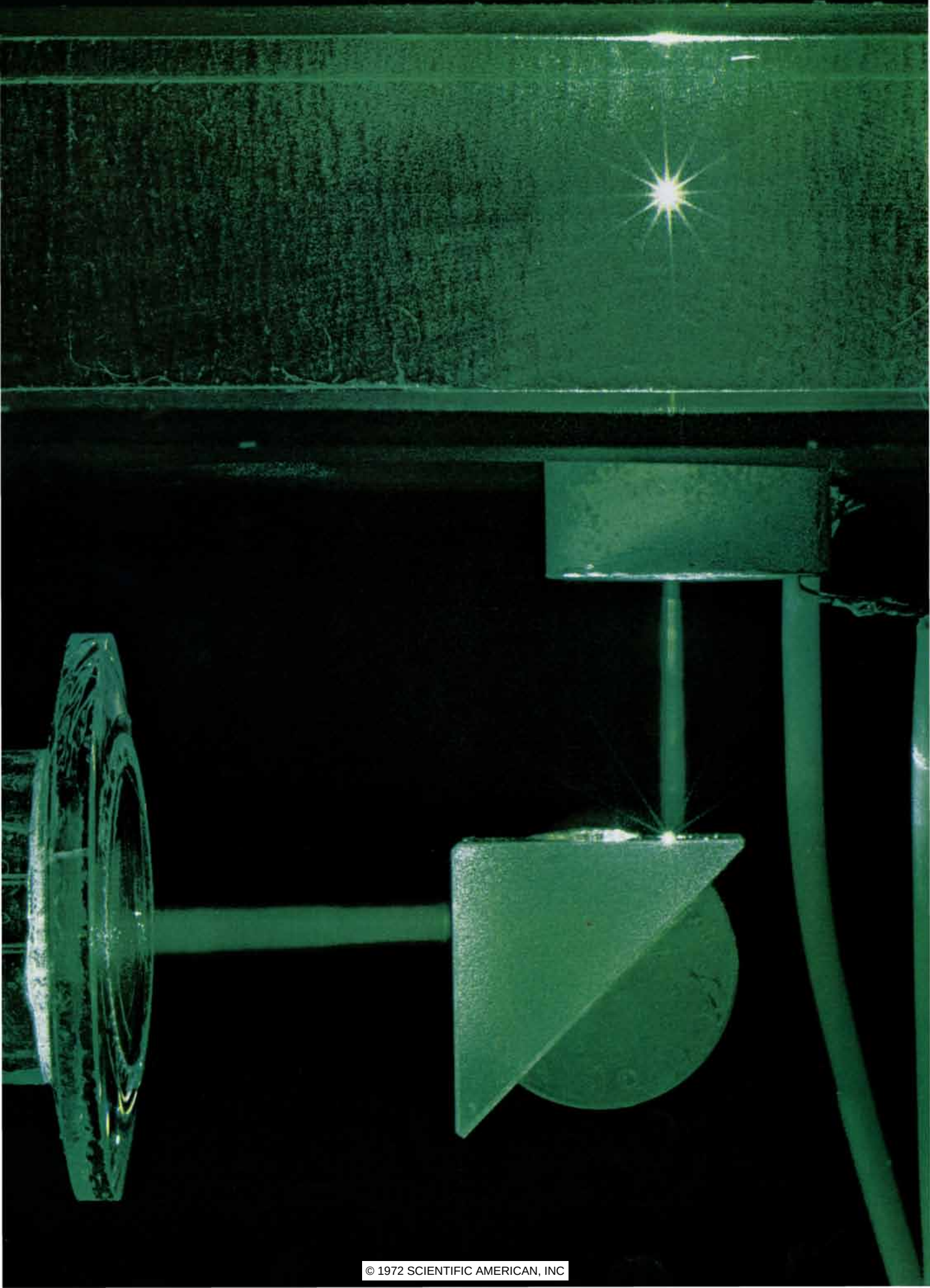
Graph for presentation, 35mm



Human leukemia, 1600x



X-ray copy



THE PRESSURE OF LASER LIGHT

The forces exerted by a focused beam of laser light are strong enough to push tiny particles around freely in various mediums. Several applications based on this recent finding are proposed

by Arthur Ashkin

It is common knowledge that light carries energy. Less obvious is the fact that light also carries momentum. When we sit in sunlight, we are quite conscious of the heat from the light but not of any push. Nonetheless, it is true that whenever ordinary light strikes an object, the collision gives rise to a small force on the object. This force is called radiation pressure.

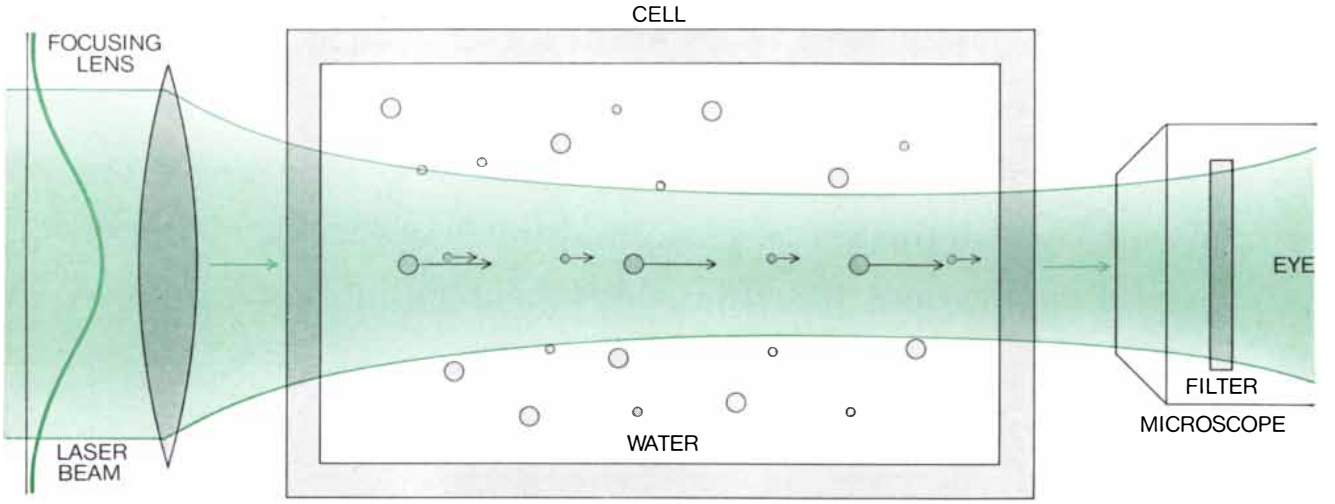
The possibility that light could exert pressure goes back to Johannes Kepler, who in 1619 postulated that the pressure of light is what causes comets' tails to always point away from the sun. The corpuscular theory of light introduced by Isaac Newton made the idea of radiation pressure more plausible and stimulated many experimental attempts to measure it. During the 18th and 19th centuries all such attempts to detect the postulated pressure failed to reveal any force that could not be attributed to convection in the air caused by heat. In 1873 Sir William Crookes thought he had discovered radiation pressure in a partly evacuated chamber, only to find that he had invented the radiometer. (The little rotating-vane toy seen in many opticians' windows is a radiometer. It responds to the forces of molecular bombardment on surfaces heated by light rather than to radiation pressure. These thermal forces are called radiometric forces.) It was also in 1873 that James Clerk Maxwell predicted the magnitude of radiation pressure based on his new theory of electromagnetic waves. The predicted pressure was extremely small for ordinary light sources. In Crookes's experiment, for example, it was four or five orders of magnitude smaller than the observed radiometric forces.

The existence of radiation pressure, free of disturbing thermal effects, was finally demonstrated experimentally around the turn of the century by Ernest F. Nichols and G. F. Hull in the U.S. and by P. N. Lebedev in Russia. In both experiments the radiation pressure exerted by a light source was detected by a twisting motion of a vane suspended by a fine fiber in a high vacuum. The magnitude of the force measured in this way confirmed Maxwell's prediction. Commenting on the subject of radiation pressure in his presidential address to the British Physical Society in 1905, John H. Poynting said: "A very short experience in attempting to measure these light forces is sufficient to make one realize their extreme minuteness—a minuteness which appears to put them beyond consideration in terrestrial affairs." Poynting's view of the situation held true until just recently. The experiments described here, which show that the phenomenon of radiation pressure does indeed merit "consideration in terrestrial affairs," could not have been conducted before the invention of the laser in 1960.

The laser has opened up new fields of optical research and rejuvenated old ones. The special features of laser light that have brought about these changes are its high degree of spectral purity and its spatial coherence. These properties make it possible, among other things, to focus a laser beam to a spot with a radius close to the theoretical limit of one wavelength. Thus even with a power of a few watts one can obtain a light intensity at one wavelength that is some 10,000 times greater than the intensity available from the entire visible spectrum at the surface of the sun! Moreover, a laser beam operates with a simple, mathematically perfect, well-controlled intensity profile called a transverse mode. The most useful mode has a cross section with a simple Gaussian, or bell-shaped, energy distribution. Another important achievement has been the development of tunable lasers, with which one can select the wavelength of the light at will.

Radiation pressure has recently been reexamined in the light of these new laser sources and has been found to be a strong effect. Indeed, the forces exerted by laser sources have been shown to be large enough to move small particles around freely in various mediums. Accelerations as large as a million g (a million times the acceleration of gravity) are attainable on a continuous basis for tiny macroscopic particles as well as for individual atoms and molecules. These findings have given rise to new applications based on the physical motion of small particles driven by radiation pressure. This rather exotic force has also been found to have a number of unique

OPTICAL LEVITATION of a very small particle by means of a vertically directed beam of green laser light is demonstrated in the photograph on the opposite page. The particle, a transparent glass sphere 20 microns in diameter, is shown levitated in air about a centimeter above a glass plate by the 250-milliwatt beam. Although the particle is barely visible to the unaided eye, it scatters enough laser light to sparkle brilliantly in this experiment; the bright spikes radiating from its image in the photograph are caused by diffraction around the blades of the diaphragm inside the camera. Smoke was blown in the path of the laser beam to make it visible after it left the focusing lens (*lower left*) and was reflected upward by a prism (*lower right*) before entering the glass enclosure. The structure with the two wires attached is a piezoelectric ceramic cylinder used to vibrate the particle momentarily in order to break the weak van der Waals forces holding it to the surface of the glass plate. The interference pattern visible against the back wall of the enclosure is caused by light scattered at an angle of about 90 degrees by the particle.



HORIZONTALLY FOCUSED LASER BEAM is used to push transparent plastic spheres of two sizes, 2.5 microns and .5 micron in diameter, through a water-filled cell. The larger spheres are observed to move faster than the smaller ones (*left*). The motions of the particles are viewed from beyond the far end of the cell with a microscope and a filter that absorbs the laser light. It is possible in this way to observe the trapping of a particle at the far face of the cell (*right*). A sphere originally trapped at the center of the beam will wander off randomly when the beam is turned off and will return directly to the beam center when the beam is turned on

features, some not realized before and some resulting from the nature of laser light itself. A few of the possible applications are the separation of particles in liquids, the optical levitation of particles in air and vacuum, the high-velocity acceleration of electrically neutral particles, the separation of isotopes and the analysis of atomic beams.

The starting point of all this work was simply a hunch on the part of the author that the radiation pressure of laser light could be a large effect even with the modest power available from continuously operating lasers. The following simple order-of-magnitude calculation was made. Suppose a watt of continuous green laser light (with a wavelength of about .5 micron) is focused to a spot with a radius equal to the wavelength of the light. What is the force exerted on a small spherical particle of the same size placed at the focus? Assuming that the particle acts as a perfect mirror, one computes a force of approximately 10^{-3} dyne. If the particle has unit density, its mass is about 10^{-12} gram. By Newton's law this result implies an acceleration of a million times the acceleration of gravity—obviously a large acceleration!

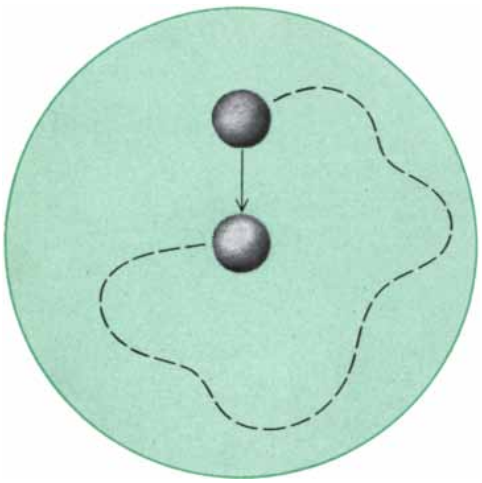
Such calculations strongly suggested trying an experiment to move small particles with light pressure. Highly reflecting metal particles were considered, but even with a reflectivity of 98 percent the residual absorption of 2 percent would surely cause severe heating, possibly even melting. Here again one is up against the thermal problems that were the bane of early experimenters. One of the prices of increased light intensity is increased heating. The solution seemed clear: to use transparent dielectric (nonconducting) particles. Although the reflectivity of bare dielectric surfaces such as glass or plastic is relatively low, the forces are still considerable.

In the following experiment, carried out in my laboratory at the Bell Telephone Laboratories, small, precisely spherical, transparent plastic particles made by the Dow Chemical Company were used. These spheres are customarily supplied in water and therefore it seemed natural to try the first experiments in water. Besides, the high optical transparency and high thermal conductivity of water would further help to keep the particles cool. A few drops of water containing some particles were accordingly placed in a glass cell under a microscope and a green argon-ion laser beam was focused through the cell from below. By wearing special eyeglasses that absorb only the laser light it was possible to protect one's eyes and still observe the particles by ordinary light. The laser beam was visible anyway by virtue of a mild yellow fluorescence that it induces in almost anything it hits. Hence it turned out to be a simple matter to see the beam, focus it and manipulate it by moving the focusing lens. Since the plastic spheres had the same density as the water, they remained essentially stationary as fixed targets. When a vertically directed Gaussian-mode laser beam with a power of about 10 milliwatts and a diameter of 15 microns was directed at a particle a few microns across, the particle began to rise at a constant velocity of some 10 microns per second until it reached the top surface of the cell. (One expects a particle moving in a viscous medium under the influence of a constant force to travel at a constant velocity, in accordance with Stokes's law.)

So the particles moved. Several questions remained. For example, is the motion really due to radiation pressure or is it due to some residual thermal effects such as convection or photophoresis? In the case of convection the entire liquid would move, carrying the particles along. In the case of photophoresis single particles would be heated asymmetrically by the light and would as a result move through the surrounding medium.

To answer these questions a second experiment was performed with two modifications. Particles of two sizes, 2.5 microns and .5 micron in diameter, were used simultaneously and the beam was passed through the cell horizontally. Thus if the liquid through which the beam passes were heated, the liquid would tend to rise rather than flow along the axis of the light beam. Again the particles moved in the direction of the light beam, only now the larger particles moved rapidly past the slower-moving small particles [*see illustration above*]. This observation in itself ruled out convection as a cause of the motion.

In addition it was observed that when a particle hit the far face of the cell, it remained there, seemingly trapped in the center of the beam. If the beam was interrupted, the particle began to wander off center. If the light was turned on again when the particle was in the fringes of the light, it was immediately drawn



again. The laser beam in these experiments operates with an intensity profile (called a transverse mode) that has a cross section with a simple Gaussian energy distribution (*colored bell-shaped curve at extreme left*).

back to the center of the beam. Similarly, if a particle in the bulk of the liquid was illuminated off center near the fringes of the beam, it was observed not only to move in the direction of the beam but also to be drawn into the center of the beam where the light intensity was a maximum [*see bottom illustration on this page*]. There seemed no escaping the conclusion that there was not only a force along the beam but also a transverse force drawing particles into the center of the light beam.

This observation helped to rule out photophoresis as the cause of the observed motion of the particles. In photophoresis the force on the hot side of a particle is larger than it is on the cool side and an off-center particle would be pushed out of the beam, contrary to what was observed. Also in photophoresis a partially transparent particle heated by the beam would tend to move backward with respect to the direction of the light, again contrary to the observation. (This backward motion, called negative photophoresis, can be readily seen if one shines laser light on partially transparent smoke particles floating in air. Its explanation is based on the converging effect of light passing through the particle, which makes the downstream side of the particle the hot side.)

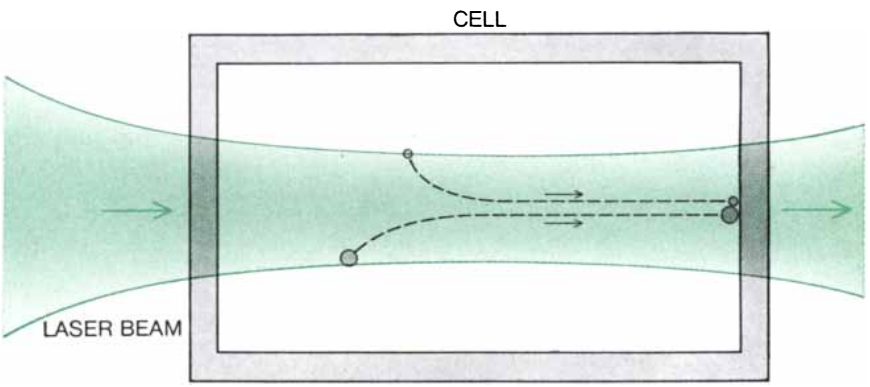
It now remains to show how radiation pressure accounts for the observations. The magnitude of the force on the plastic sphere can be calculated by adding the effects of all the light rays hitting it. Each ray, as it is partially reflected and refracted at the surfaces of the sphere, carries off some of the light in different directions and gives rise to a contribution to the net force. From the value of the force when the particle is on the beam axis and from Stokes's law one can compute the expected velocity of the sphere through the water. The computed velocity agrees with the measured velocities within experimental error. This agreement alone indicates that no other large forces are operative.

Similarly one can show how the transverse components of the force act on a sphere located off axis in a Gaussian beam. Imagine a beam of light striking a plastic sphere that has a higher index of refraction than the surrounding water [*see top illustration on next page*]. Consider a typical pair of light rays, a and b, situated symmetrically with respect to the center of the sphere. Disregard surface reflections and consider only the transmitted part of each ray, since this usually is the strongest part and makes the principal contribution to the force. The rays are bent in such a way as to give rise to two forces, F_a and F_b, located along the direction of the momentum changes for the rays. Since ray a is stronger than ray b, force F_a is greater than force F_b, and one would expect a net transverse force pulling the high-refractive-index sphere in toward the center of the beam, where the intensity is a maximum. That is what happens.

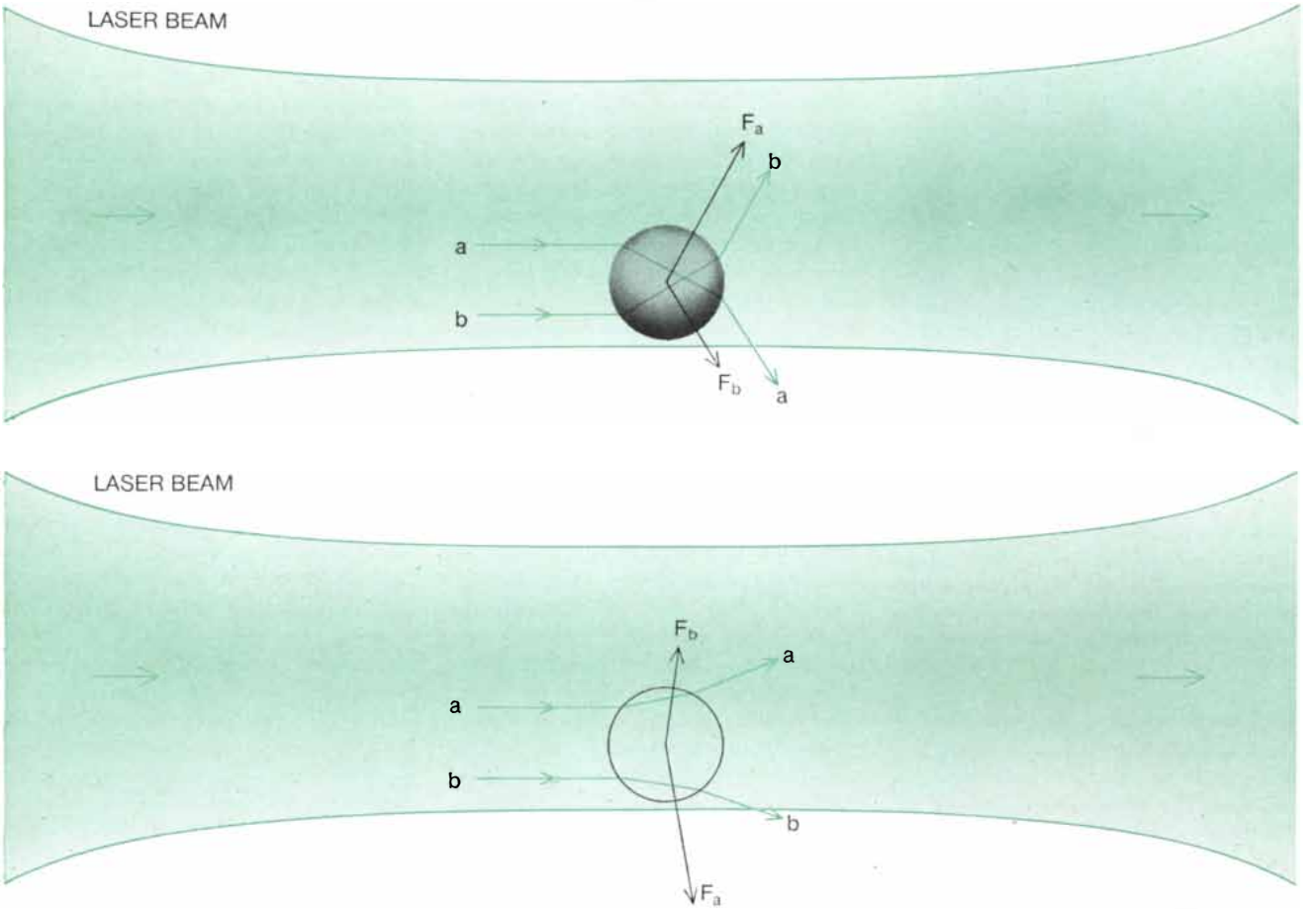
There is an obvious extension of this argument. If the sphere has a lower index of refraction than its surrounding medium, forces F_a and F_b would reverse, and such a sphere should be pushed out of the beam, away from the maximum light intensity. This also happens. After a frustrating search for low-refractive-index particles in a high-refractive-index liquid it occurred to me to use tiny air bubbles in a viscous liquid such as glycerin. After all, bubbles behave like particles, and there is a discontinuity in refractive index at the surface of a bubble, so that light should exert a force on it. Furthermore, a bubble represents the ultimate in a nonabsorbing particle, and it has the lowest possible index of refraction. Small bubbles of the desired size can be generated by using a blender to agitate glycerin diluted with water. When the bubbles are hit with a laser beam, they move as expected, forward and out of the light beam. They avoid the light, in contrast to the behavior of high-refractive-index particles.

The picture of how the transverse forces arise is now complete. An important consequence of this picture is that it implies one can shape light beams that will trap particles by radiation pressure alone, forming what might be called an "optical bottle." A high-index particle placed at a certain point in such a nonmaterial container should be in stable equilibrium, since any displacement would result in an optical restoring force. When an actual light configuration of this type was set up in a water cell, the particles drifting into the fringe fields were sucked into the trap, where they remained stationary [*see bottom illustration on next page*]. The fact that a particle was really trapped was demonstrated by intercepting one beam for a moment. The particle pushed by the second beam rapidly began to escape, whereupon the first beam was turned on again. The particle then returned to the equilibrium point, only more slowly, since it was operated on by the differential restoring force. The procedure could be repeated many times with either beam being interrupted.

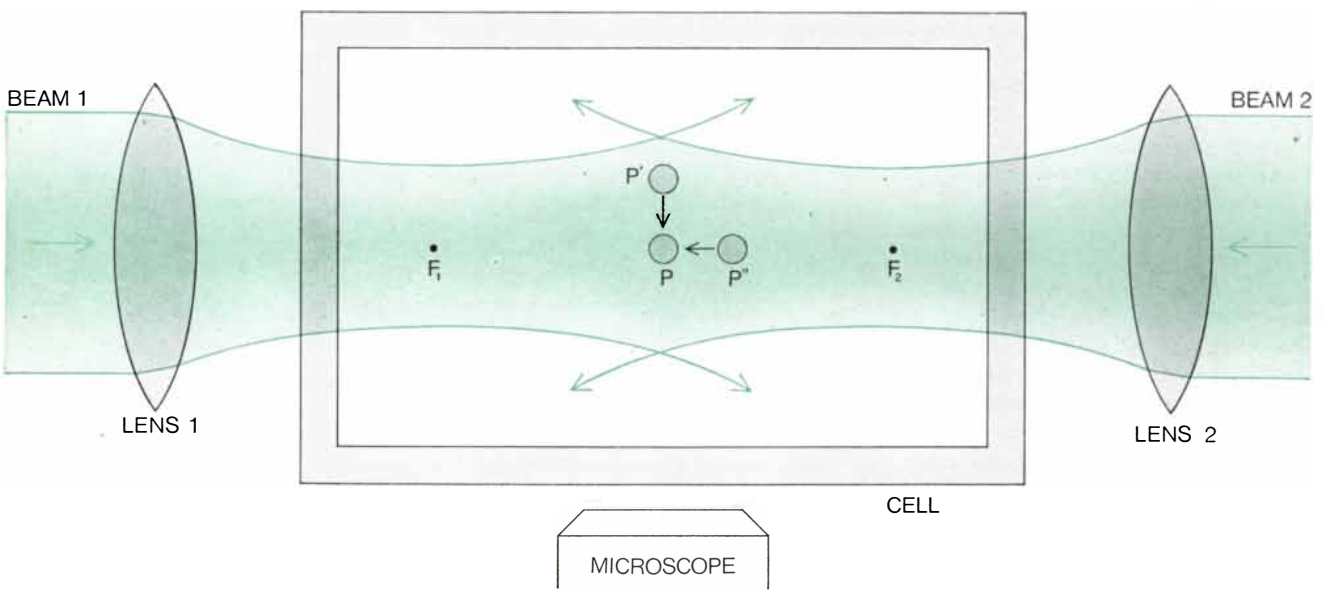
Liquid has clearly proved to be a useful experimental medium for studying radiation pressure. Liquid may also be the preferred medium for many applications of radiation pressure, such as schemes for particle separation. Differ-



PARTICLES ILLUMINATED NEAR THE EDGE of a Gaussian-mode laser beam are not only pushed in the direction of the light but also drawn toward the center of the beam.



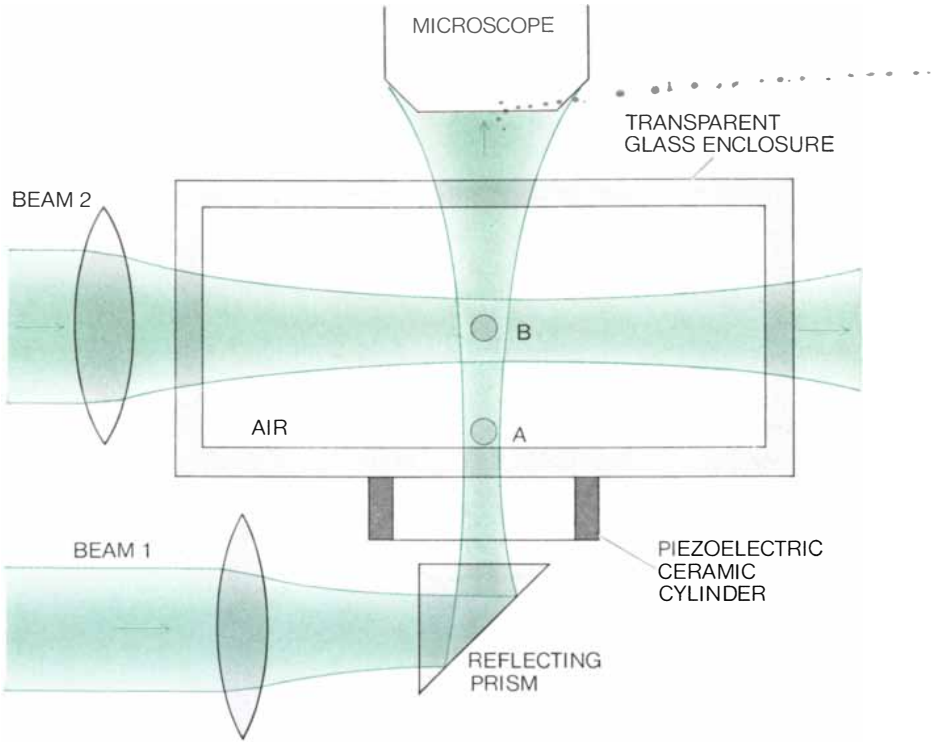
INDEX OF REFRACTION of a particle with respect to its surroundings determines whether the laser beam will push it toward or away from the center of the beam. The top diagram shows the forces associated with the refraction of a pair of typical light rays (*a*, *b*) as they pass through an off-center sphere that has a higher index of refraction than its surroundings. Force F_a is greater than force F_b; therefore there is a net transverse component of force toward the beam center. The bottom diagram shows the corresponding forces for an off-center sphere with a lower index of refraction than its surroundings. The refraction of the light rays is reversed; since F_a is still greater than F_b but is now pointed away from the center, there is a net transverse force pushing the particle away from the center. In both cases F_a and F_b have components pushing the sphere in the direction of the light as well.



"OPTICAL BOTTLE" shown in this diagram is made up of two opposing Gaussian-mode laser beams. Points F_1 and F_2 represent the foci of beams *1* and *2*, that is, the points where the beam diameters are a minimum. Beyond the foci the beams spread by diffraction. A sphere placed at the symmetry point *P* is in stable equilibrium since any displacement results in an optical restoring force. At *P'* the transverse forces of each of the two beams push the particles back to *P*. At *P''* the force of beam *1* decreases because of the spreading of that beam; beam *2* is more concentrated, however, and hence its force increases, pushing the particle back to *P*.

ent particles will travel at different velocities in the light beam and thus can be separated. I have already described an instance of the separation of .5-micron plastic spheres from 2.5-micron spheres based only on their difference in size. If one wishes to separate biological specimens such as viruses, macromolecules or cells in liquid, the separation would depend not only on their size but also on factors such as the index of refraction and the shape and orientation of the objects. Thus this approach to particle separation could conceivably be more suitable for particular particles than existing separation techniques based on the use of the ultracentrifuge. In any such application care would of course have to be taken to avoid excessive heating.

The preceding observations apply to a range of particle sizes extending from .1 micron to 100 microns. Accelerations as large as 1,000 or 10,000 *g* are possible over part of this range. Interestingly enough, there is no problem in observing particles that are small compared with a wavelength of light. Although they cannot be resolved in an optical microscope, one can still detect the presence of even a single particle by observing the light scattered out to the side of the main beam by the particle.



LEVITATION SCHEME employs a single-beam optical bottle. The vertical beam (*1*) lifts the particle off its resting place at point *A* and levitates it to point *B*, where radiation pressure balances gravity. In a later experiment a variable probe beam (*2*) was used to measure the strength of the optical restoring forces by pushing horizontally on the particle.

Let us now consider particles in more dilute mediums such as air or even vacuum. In these circumstances particles move more freely and gravity plays a more important role than it does in liquids. In particular a demonstration of an optical bottle in air would in essence be a demonstration of optical levitation, where optical forces physically support a particle. In a sense it would be a fulfillment of a search proposed in 1909 by Peter J. W. Debye for a situation in which radiation pressure was strong enough to neutralize gravity. The proposal was part of Debye's Ph.D. thesis on radiation pressure. As an example of such a neutralization of gravity, Debye imagined the case of very small particles close to the sun. Levitation in this instance would give only neutral equilibrium. As our experiments show, however, levitation with truly stable equilibrium is possible here on the earth with a simple optical bottle consisting only of a single light beam.

Using the laser-levitation approach, a fraction of a watt of laser light was found to be sufficient to support particles about 20 microns in diameter. The transparent glass sphere was placed on a glass plate located inside a glass enclosure, which served to reduce air currents. A vertically directed beam with a power of about 250 milliwatts was focused on the sphere. The beam exerted a vertical force of several *g* on the particle. The object was to lift the sphere off the baseplate.

Unfortunately the scheme as described did not work. The trouble was that small particles stick tenaciously to any surface by the forces of molecular attraction known as van der Waals forces. For a 20-micron particle the attractive force is roughly 10,000 *g*. It was possible, however, to shake the particle loose with a sharp blow to the plate. This suggested a more controlled technique of breaking the van der Waals bond, namely acoustic vibrations. A short burst of acoustic energy coupled into the plate from a piezoelectric ceramic cylinder was enough to momentarily shake the particle loose. Once it was free light pressure took over and the particle began to rise in the diverging vertical beam, coming to rest at the equilibrium point above the plate where radiation pressure and gravity were equal. The particle was levitated!

Since this experiment involved a particle with a high refractive index it was easy to give the particle transverse stability around the equilibrium point. Hence it is possible to achieve levitation with the particle at rest in a position of stable equilibrium. Apart from a technique based on superconducting particles, all other levitation schemes based on electromagnetic forces involve some motion of the levitated particle. In such schemes either the equilibrium is dynamic or some kind of negative feedback is required to correct the particle's position when it moves.

Once a particle is trapped it remains aloft as long as the light is focused on it. By moving the position of the lens one can move the focus of the beam and therefore the position of the particle very precisely. A particle levitated in this way can be photographed by its own scattered light [*see illustration on page 62*].

The levitated particle can also be observed precisely with a microscope focused directly on it. This capability was utilized in an interesting experiment to measure the strength of the optical restoring forces in the optical bottle. By hitting the particle from the side with a second beam it was determined how much power was needed to eventually push the particle out of the bottle [*see illustration above*]. It was found in this way that the transverse restoring force can be as high as .5 *g* for an off-axis particle when the vertical levitating force is *g*.

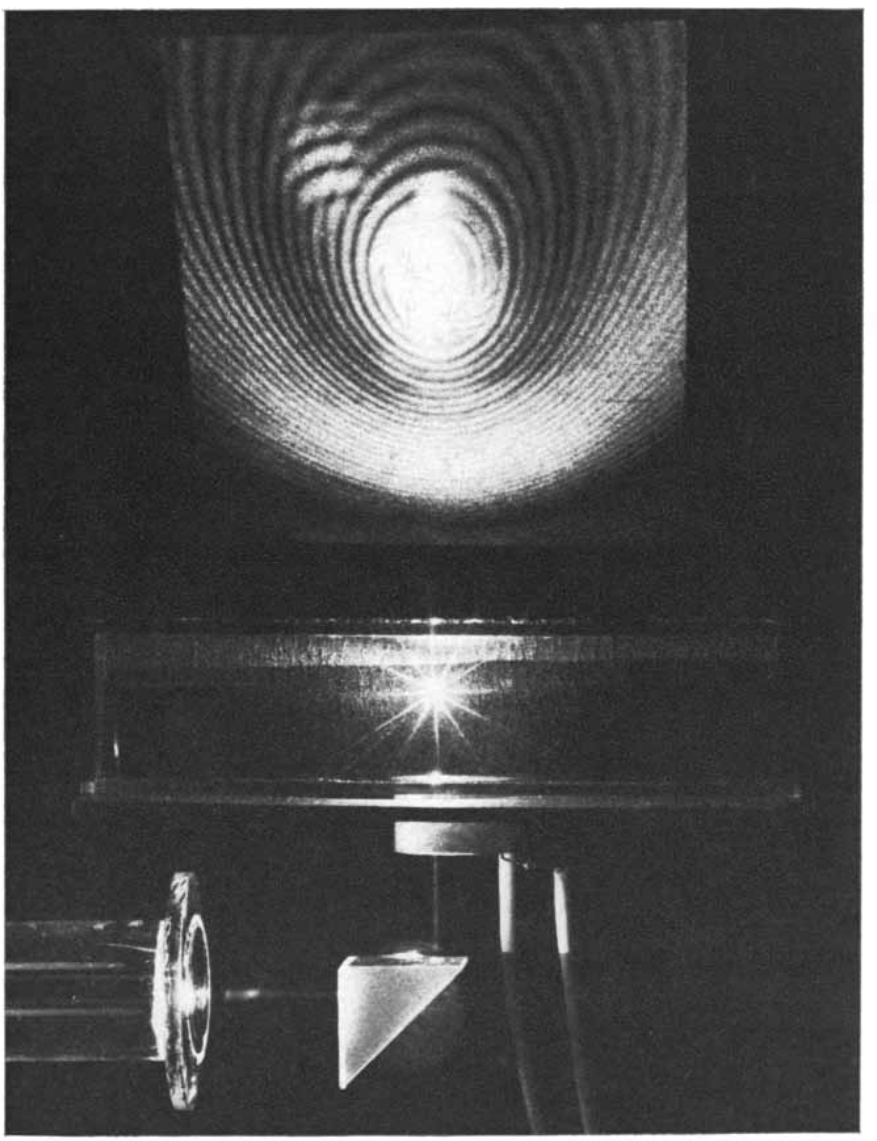
The levitation technique thus permits

the precise micromanipulation of small particles, a capability that is useful in itself. For instance, just being able to introduce a small particle and hold it still as a target for a high-power pulsed laser is important in obtaining laser-generated plasmas for thermonuclear research. By the same token the levitation technique is ideally suited for studying light-scattering from small dielectric spheres, a phenomenon known as Mie scattering. The theory of this type of scattering, developed by Gustav Mie in 1908, bears on the explanation of many phenomena, from rainbows to the angular distribution of light scattered by refractive inhomogeneities in passing through optical transmission mediums. By levitating a single particle of known size and shape one can measure Mie scattering free of any disturbance.

In one demonstration of forward Mie scattering from the supporting laser beam itself it is possible to generate a complicated series of interference rings [*see illustration below*]. These rings, which arise from the basic wave nature of light, are seen with unusual clarity in this case. It is also possible to use the spacing of the 90-degree Mie-scattering rings to obtain a precise measurement of the diameter of a particle. The reason is that at 90 degrees the rings essentially arise from the interference of two bright sources of known spacing [*see illustration on opposite page*].

Clearly more possibilities would be opened up if levitation were possible in high vacuum. High vacuum eliminates the viscous forces that in air damp out all motions. The optical forces, apart from a minute radiation damping, are frictionless, and a particle set in oscillation or set spinning would continue in this motion indefinitely. Interesting inertial experiments are possible in such instances, perhaps even experiments utilizing the angular, or rotational, momentum of the light. The main problem is how to prevent fluctuations in the laser light from perturbing the particle. So far levitation down to pressures of the order of one torr has been achieved before the particles were lost. At a pressure of one torr the viscous damping is already reduced and oscillations due to perturbations build up and lead to the eventual escape of the particle. Stabilization of the laser power and stronger optical bottles involving several beams are possible and would allow levitation at still lower pressure. A simple optical feedback system based on particle position or velocity, however, might have to be introduced eventually. This would be a way of simultaneously stabilizing laser power and particle position that could be made very sensitive.

Another potential application of radiation pressure involving high vacuum is the acceleration of small neutral particles to high velocity. If a high-power laser beam is applied to a particle, the particle will be accelerated rapidly along the axis of the beam while being trapped transversely by the beam. What, one wonders, limits the ultimate velocity attainable? The answer is probably only the eventual melting and vaporization of the particle. Setting melting as the limit, if one knows the optical absorption coefficient of the particle, one knows how much light one can apply to the particle and one can calculate the final velocity. The best optical glass available has an absorption coefficient of roughly 3×10^{-5} per centimeter. (This number is important for optical communication through glass fibers and much work is currently being done to decrease it.) Using this value, one gets a final velocity of about 3×10^{8} centimeters per second for a .5-micron particle. That is an incredible velocity for a macroscopic particle. If such a particle were to strike a target or another particle of the same size and velocity, one would obtain a pulse with a power of some 10^{11} watts for about 10^{-13} second. The particle would vaporize and form a plasma whose temperature would be some 50 times higher than the temperature needed for thermonuclear reactions in deuterium. This approach might therefore be



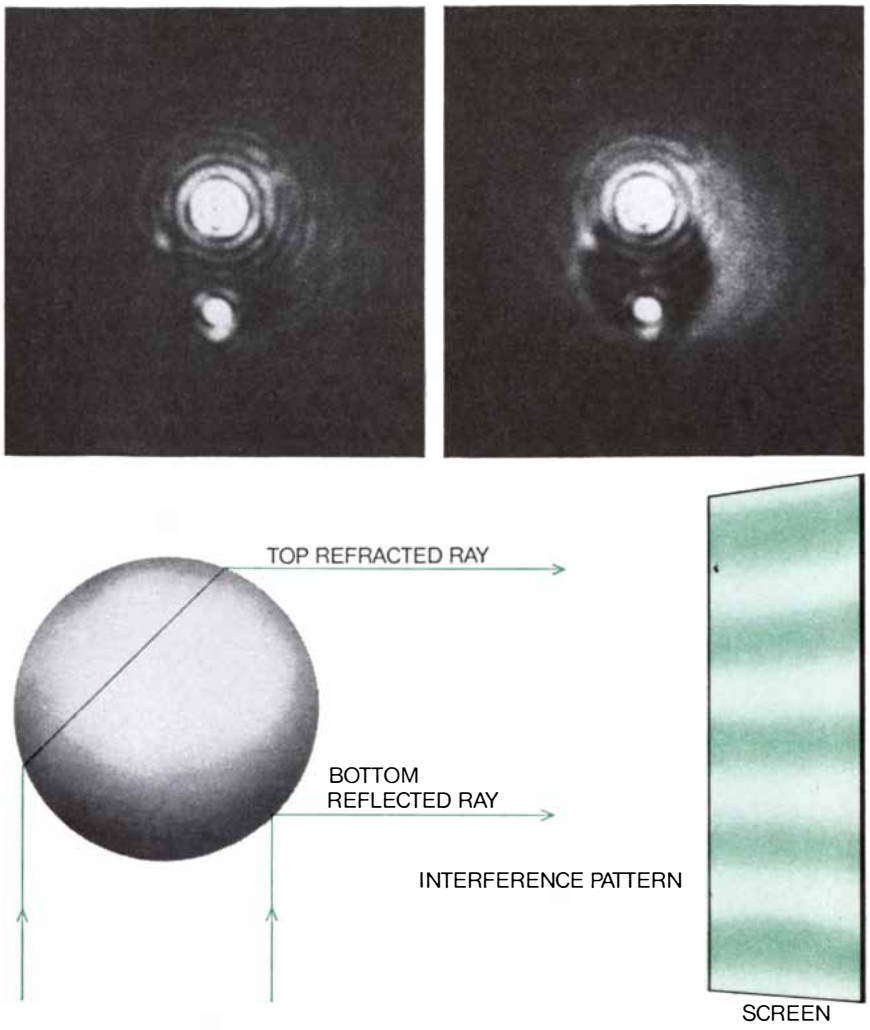
FORWARD MIE SCATTERING of the light from a vertically directed supporting laser beam by means of a levitated dielectric (nonconducting) glass sphere produces a complicated series of interference rings on a screen held at an angle above the levitated particle. The characteristic ring structure associated with this type of light-scattering, originally described by Gustav Mie in 1908, can be seen with unusual clarity in this demonstration.

of interest in thermonuclear research and other areas where short high-power pulses are important. The apparatus for such a particle accelerator is well within present technology. Unfortunately it might end up almost as long as the two-mile Stanford linear particle accelerator because of the need to keep the intensity low enough to avoid nonlinear absorption. Such an experiment would be no small undertaking.

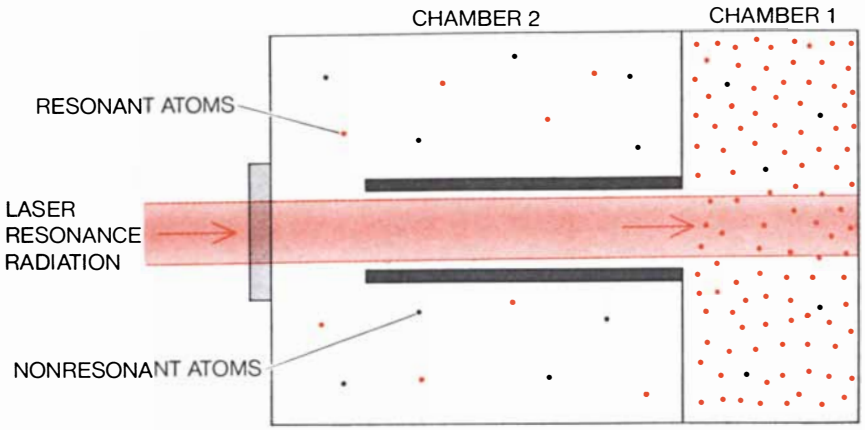
Thus far I have described the effects of concentrating laser light on small nonabsorbing particles with a diameter in the range between .1 and more than 100 times the wavelength of the light. If we consider really small particles such as atoms, which are a few thousandths of a wavelength in diameter, we might expect negligible pressure effects, since waves tend to diffract around such small objects without much deviation. Although light does generally pass through gases with little interaction, there are important exceptions. To appreciate these special cases one must resort to quantum theory, which is the basis of our present understanding of light and matter. Light, in addition to being a wave phenomenon, is known to have a particulate nature. A light beam is revealed as the sum of the irreducible units of energy known as photons, each with a definite energy and momentum. Likewise the atom is shown to be a resonant structure that can exist only in particular energy states. Atoms interact strongly with light when the energy of the photon is just enough to change the atom from one distinct energy state to another. This is a resonance phenomenon. A measure of the strength of the resonant interaction is a quantity called the absorption cross section. The idea of an absorption cross section is based on the concept that any photon striking this area is absorbed. For atoms "on resonance" the absorption cross section is roughly equal to the wavelength squared. Since one can focus laser light to a spot having a theoretical area almost equal to the wavelength squared, this finding implies that a single atom properly placed at the focus of such a beam will absorb almost all the light in the beam. This turns out to be essentially true for low intensities where saturation effects are absent. In any case resonant atoms are the most absorbent material known for light. This fact implies large radiation-pressure effects.

In the absorption process both the energy and the momentum of the photon are delivered to the atom. Consider, for example, a sodium atom originally in its ground, or lowest-energy, state, which absorbs a photon of yellow "*D* line" resonance radiation. The atom not only is raised to an excited state but also receives an increment in velocity of about two centimeters per second in the direction of the incident light. The atom remains in the excited state for an average time, called the excited-state lifetime, before it returns to the ground, or absorbing, state. It does so spontaneously with the emission of a photon of the same frequency in a random direction. This gives another randomly directed impulse of two centimeters per second to the atom. Subsequent absorptions and spontaneous emissions give additional directed impulses along the beam followed by random impulses. The result is a net force directed along the light beam. The effect is similar to the force a water hose exerts on a ball that scatters the stream in all directions.

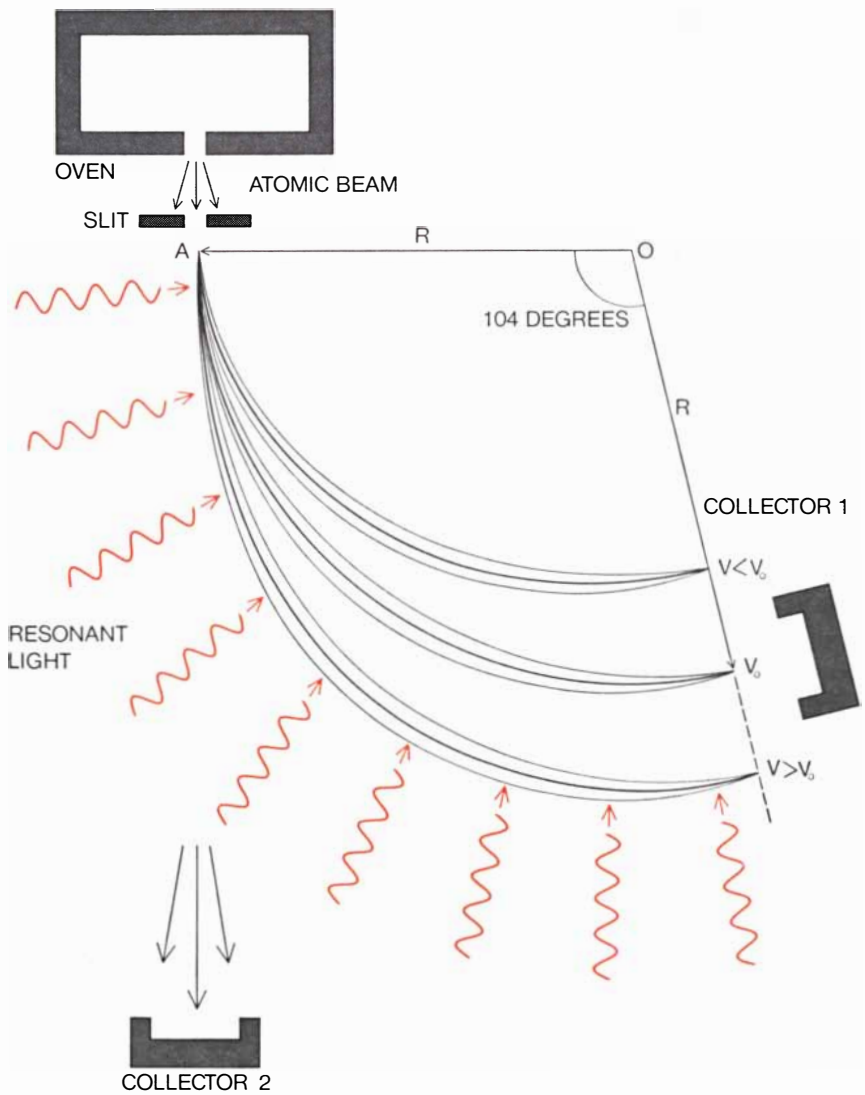
This optical force, called resonance radiation pressure, has some unique features. First, it does not keep on increasing with increasing optical power but rather becomes saturated at a fixed maximum value that is related to the finite lifetime of the excited state for spontaneous emission. If the average lifetime is about 10^{-8} second, as it is for sodium, one might expect the atom to be capable of scattering at most 10^8 photons per second. Actually it can scatter only half that amount, for reasons associated with stimulated emission from the excited state back down to the ground state. In this process, which occurs at high light intensities, the atom is stimulated to give a photon back to the beam. That by it-



TWO SEPARATE BRIGHT SOURCES appear when a levitated particle is viewed at an angle of 90 degrees by its own scattered light with a microscope focused on the particle (*top left*). With a light background added behind the particle (*top right*) one can more readily see the outline of the particle and the location of the sources with respect to it. The diagram at bottom explains the origin of the two sources at 90 degrees. One refracted ray emerges close to the top of the particle, while a weaker reflected ray bounces off the particle somewhat above its bottom edge. These two sources interfere to give the horizontally striped far-field interference pattern observed on a screen located a long distance away.



GASES CAN BE SEPARATED by the resonance radiation pressure of laser light. In this proposed scheme the laser light acts as a pump, pushing most of the resonant gas atoms (*colored dots*) into chamber *1* without affecting the nonresonant gas atoms (*black dots*).



ATOMIC-BEAM VELOCITY ANALYZER employing resonant laser light would make it possible to select atoms of a particular velocity from a multivelocity beam. The resonance light directed radially inward toward point *O* is perpendicular to a circular orbit of radius *R*. Collector *1* detects refocused atoms of different velocity at different radii after they are deflected through an angle of 104 degrees. Unaffected nonresonant atoms go to collector *2*.

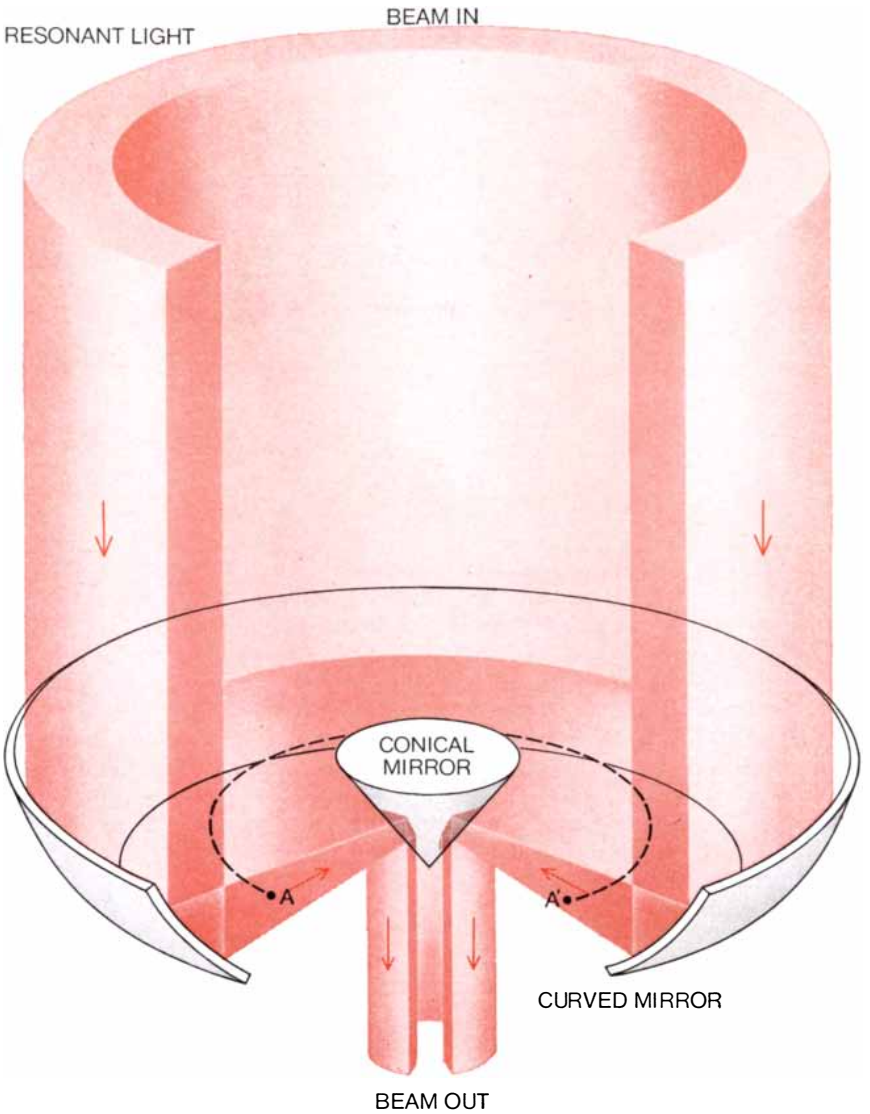
self contributes negligibly to the force but results in an atom's spending only half as much time in the excited state, from which it can decay randomly by spontaneous emission. The net result, however, is a saturated resonance-radiation-pressure force of some 100,000 *g* on the atom.

The other unique feature of this effect is the need for exact resonance. Consider a laser beam tuned to resonance for an atom at rest. If the atom begins to move in the direction of the light because of resonance radiation pressure, then as a result of the Doppler shift it will no longer be in strict resonance and the force will decrease.

One possible use of this force is the separation of gases, with light as an actual pump that operates selectively on resonant atoms [*see top illustration at left*]. Suppose one fills a double-chambered vessel with two gases and shines light that is resonant with only one of the gases down the open pipe connecting the chambers. The constant saturated force on the resonant atoms causes an exponential pressure distribution along the pipe starting at some high value in the far chamber and falling to a low value in the near chamber when the system finally comes to equilibrium with the light force. The nonresonant gas remains unaffected by the light. The gases could thus be separated in this way, which is analogous to the way the constant force of gravity separates gases of varying weights into different exponential pressure distributions in the earth's atmosphere. With resonance radiation pressure even different isotopes of the same atom could presumably be separated by virtue of the isotope shift in the frequency of the resonance. Separation of isotopes is often difficult because of the similarity in chemical properties of isotopes of the same atom.

Other possible applications of radiation-pressure techniques involve atomic and molecular beams. Much fundamental knowledge has been obtained from such beams by studying their deflection in static fields and their interaction with electromagnetic waves and other particles. It should now be possible using the large forces of radiation pressure to optically deflect atomic beams through large angles and thus study them by a new means. One possible velocity-analyzer scheme selects atoms of a particular velocity from a multivelocity beam, with resonance radiation focused to a point to establish a uniform centralized optical force field [*see bot-*

tom illustration on opposite page]. Such a constant radial force is possible even though the light intensity varies with position owing to the saturation property of the force. This field has the interesting property that all resonant atoms injected at a certain point with a particular velocity refocus themselves to a point after being deflected by 104 degrees, but at a radius that depends on the velocity. Such large deflections free of Doppler shifts are possible because all the atoms move in orbits close to a circle passing through the input point. Along the circle the constant force of radiation pressure and centrifugal force exactly balance and no motion occurs in the direction of the light. The situation is analogous to the familiar motion of a particle rotating at the end of a string with constant tension. Thus if a collector is placed at an angle of 104 degrees, it can collect atoms of different velocity at different radii. Any nonresonant species present in the original beam are undeflected and pass to another collector. To make a velocity selector of this type in which a beam of sodium atoms emerging from a heated oven is bent around a radius of five centimeters would require about a watt of resonant light. If one were to extend the converging light beam completely around the circle and add some convergence to the light along the axis of the field, one can conceive of trapping resonant atoms stably in a closed circular orbit [*see illustration at right*]. Such an arrangement would then be, for atoms, the closest analogue to the optical bottle for macroscopic particles. The implementation of these applications of radiation pressure to atoms calls for laser sources of sufficient power and tunability. The rapid strides being made in tunable dye lasers and tunable parametric oscillators will, one hopes, make such experiments possible.



HYPOTHETICAL APPARATUS for optically trapping resonant atoms in a stable circular orbit (*AA'*) would be analogous to the optical bottle for macroscopic particles. The concept is a variation of the velocity-analyzer scheme, with the converging light beam extended around the circle and with some convergence added to the light along axis of field.

Many aspects of this work have clear historical precedents. The recoil of the electron in a single high-energy photon-electron collision, known as the Compton effect, is an example of radiation pressure (although it is not a resonant interaction). In more closely related work the minute recoil of neutral sodium atoms after absorbing and emitting a single photon from a weak resonance lamp was observed by Otto R. Frisch in an extremely sensitive atomic-beam experiment in 1939. The idea evidently extends back to Einstein, since Frisch called his achievement the observation of the "Einstein recoil." More recently evidence of resonance radiation pressure on a cosmic scale has been discovered in astronomy. From observations made on far-ultraviolet resonance lines with rockets shot above the atmosphere, Donald C. Morton of Princeton University has concluded that large quantities of gas are being ejected from very hot stars at velocities as high as 2×10^8 centimeters per second. Leon B. Lucy and Philip M. Solomon of Columbia University attribute this phenomenon to the fact that the resonance radiation pressure of the star's intense ultraviolet thermal radiation can greatly exceed gravity for various ionized atoms. Owing to the continuous nature of the thermal radiation, Doppler effects do not reduce the driving force as the velocity of the ejected atoms increases. The forces involved are still much less than the saturated forces one can hope to obtain with lasers.

In another area G. S. Kutter and Malcolm P. Savedoff of the University of Rochester suggest an explanation of the origin of planetary nebulas in terms of radiation pressure. In their view planetary nebulas (the gas clouds observed around many white-dwarf stars) are thought to result from flare-ups of the star's surface temperature.

Clearly the history of the study of radiation pressure has been closely related to the history of science itself. This association, however, is merely an example of how the entire structure of science is inextricably bound together. New knowledge and techniques discovered in one area are inevitably related to new knowledge and techniques in other areas.

INTERCONTINENTAL RADIO ASTRONOMY

The structure of quasars and of other radio sources is being examined with interferometers consisting of radio telescopes separated by distances approaching the diameter of the earth

by K. I. Kellermann

Until recently the images of celestial objects formed by radio telescopes lacked the detail of those formed by optical telescopes. The reason is that the resolution of a telescope increases with the ratio of its aperture to the wavelength of the received signal. Since radio waves are roughly a million times longer than light waves, it has been generally accepted that radio telescopes are fundamentally limited to a poor angular resolution compared with optical telescopes.

Actually this is not the case, for two reasons. First, the resolution of large optical telescopes is limited not by their size but by irregularities in the earth's atmosphere. The limit is about one second of arc—only about 100 times better than the unaided human eye. At radio frequencies the fluctuations in the length of the path of the incoming signal through the atmosphere are small compared with the length of radio waves, so that the effect of atmospheric irregularities is much less important. Second, the radio signal or the optical signal must be coherent, or in phase, over the entire dimensions of the telescope. Coherent radio waves are much easier to manipulate than coherent light signals, so that radio telescopes can operate much closer to the theoretical limit of resolution than optical telescopes.

The commonest form of radio telescope is the steerable paraboloid, which typically has an aperture, or diameter, between 10 and 100 meters. Although the resolution of a given aperture increases as the wavelength decreases, the performance begins to deteriorate significantly when the wavelength approaches the dimensions of the structural imperfections in the antenna. Since for obvious reasons the largest antennas have the least precise surfaces, the best resolution that has been obtained with paraboloidal antennas does not depend strongly on wavelength and is about one minute of arc. Although it is possible to build more precise large antennas, it does not seem feasible to achieve a resolution much better than .1 minute of arc in this way. For that reason radio astronomers have turned to interferometry, where in effect two relatively small antennas act as opposite edges of a single huge radio telescope.

Interferometers working with light waves were employed for astronomical purposes as early as 1920. At that time A. A. Michelson and F. G. Pease used an instrument with two mirrors separated by as much as 20 feet to measure the diameter of a few bright stars. In the Michelson type of interferometer a light wave is intercepted by two separated mirrors that reflect two beams to a common point, where the beams are combined [*see illustration on page 74*]. If the path of one beam is made slightly longer or shorter than the other, the light waves in one beam will be out of phase with the waves in the other. When the beams are combined, the two trains of waves will interfere both constructively and destructively, and if one looks at the combined beam, one will see a pattern of alternating light and dark "fringes." In a radio interferometer the advancing wave front from a celestial object simply falls on two separate radio telescopes, and the signals are carried to a common point and compared electrically.

Attempts to extend the optical interferometer to longer baselines in order to obtain higher resolution have been unsuccessful, primarily because it is difficult to keep the light waves in the system coherent and to maintain the alignment of the mirrors within a fraction of a wavelength. With a radio instrument the problems of transmitting the signals from each interferometer element to a common point are much simpler. Thus two or more radio antennas can be employed to synthesize large apertures and achieve high angular resolution. With such an instrument one can determine not only the size and shape of discrete radio sources but also their precise position in the sky.

As the spacing of radio interferometers has increased and as advances in technology have made it possible to work with shorter wavelengths, the resolution obtained by radio instruments has steadily improved. Although many radio sources are well resolved by an interferometer that has a baseline about a kilometer long and a resolution of the order of one minute of arc, it was realized by the late 1950's that further increases in resolution would be required to study the structure of these sources in more detail and to resolve the smaller sources.

It is now generally accepted that the radio emission of discrete sources such as radio galaxies and quasars is "synchrotron" radiation from electrons moving in weak cosmic magnetic fields at relativistic speeds, that is, speeds close to the velocity of light. The energy required to account for the observed radiated power is exceedingly large, and the problem of the origin of this energy and its conversion to relativistic particles has been one of the most challenging in modern astrophysics [see "The Astrophysics of Cosmic Rays," by V. L. Ginzburg; SCIENTIFIC AMERICAN, February, 1969].

Soon after the discovery of galactic and extragalactic synchrotron emission it was thought that the relativistic particles might be accelerated by what is called the Fermi process, in which the electrons repeatedly bounce off moving

magnetic clouds that act as magnetic mirrors. Because head-on collisions are more frequent than overtaking collisions (as driving on the wrong side of the road will quickly demonstrate) the electrons can be accelerated up to relativistic velocities.

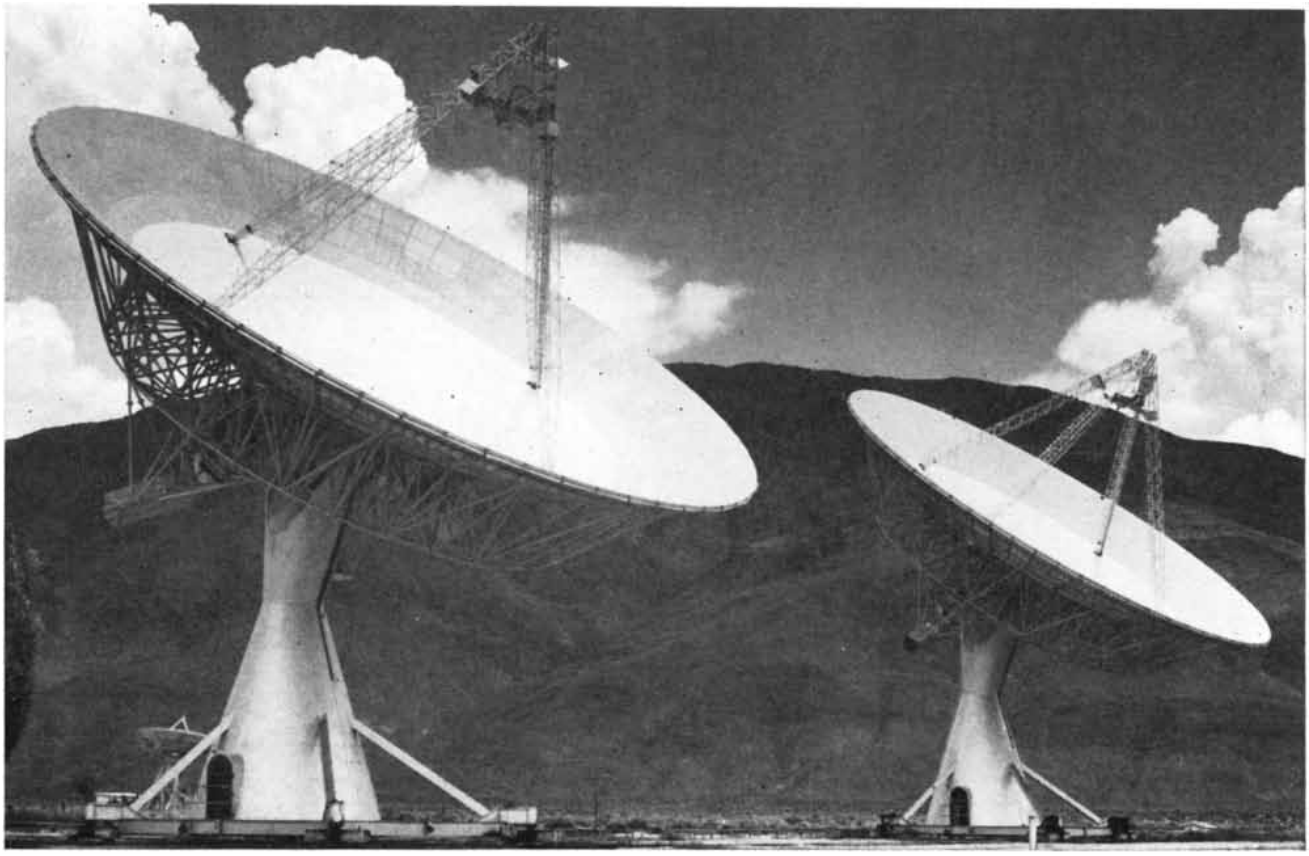
Estimates of the characteristic time scale for the electrons to reach sufficient energy in this way to radiate at radio frequencies range from a million to 100 million years. The recent discovery of rapid variations in the intensity of some radio galaxies and quasars, however, implies that the time scale of acceleration is measured in months rather than in millions of years. That precludes the possibility of any acceleration of the type described by Fermi.

Initially the observations of radio galaxies and quasars were concentrated at relatively long wavelengths (near one meter), but as techniques at the shorter wavelengths have improved there has been increasing emphasis on the centimeter and millimeter wavelengths, particularly in the U.S. and the U.S.S.R. Today two essentially different types of radio source are distinguished. One has a large angular extent and is strongest at the longer wavelengths. The other is relatively compact and is strongest at the shorter wavelengths. Somewhat surprisingly there is no simple relation between the angular extent of the radio emission and the optical emission from galaxies and quasars. Compact radio sources are not restricted to quasars; many are identified with the nuclei of galaxies. Moreover, many quasars are large extended radio sources.

The large radio sources have a complex distribution of radio emission that typically extends over several hundred thousand light-years of space, corresponding to angular dimensions between a few arc seconds and a few arc minutes. Many of these "extended sources" consist of two or more spatially separated components whose dimensions are of the order of half of the distance between them. Where the radio source is identified with an optical object the identified galaxy or quasar may either lie near the center of radio emission or be coincident with one of the radio components. In many instances there are bright knots of radio emission either at the center of the source or within one or both of the separated components. In at least one case—the double radio galaxy Cygnus A—each of the two major components apparently contains within itself a tiny double source.

Although it is generally agreed that the relativistic particles are ejected from an explosion at some common origin, it is difficult to understand how the smaller components can remain intact after being ejected so far from the point of origin. Some astrophysicists have speculated that what is being ejected instead are massive objects, which then produce the high-energy particles *in situ* either as the result of single or repetitive explosions or by some continuous acceleration process.

The compact radio sources are so small and their particle density is so great that, because relativistic particles absorb radiation as well as emit it, the source becomes opaque to its own radiation at long wavelengths and little energy escapes. The self-absorption cutoff frequency depends only on the flux density, on the angular size and (weakly) on the magnetic-field strength. The smaller the source, the shorter the wavelength at which it becomes opaque.



TWO RADIO TELESCOPES at the California Institute of Technology's Owens Valley Radio Observatory can be linked together and used as an interferometer to investigate the emission from celestial radio sources. The 90-foot dishes are mounted on heavy rails and can be moved as much as 1,600 feet apart. Moreover, this pair of antennas has been used with another pair at the National Radio Astronomy Observatory in Green Bank, W.Va., to form an interferometer for the simultaneous observation of two radio sources.

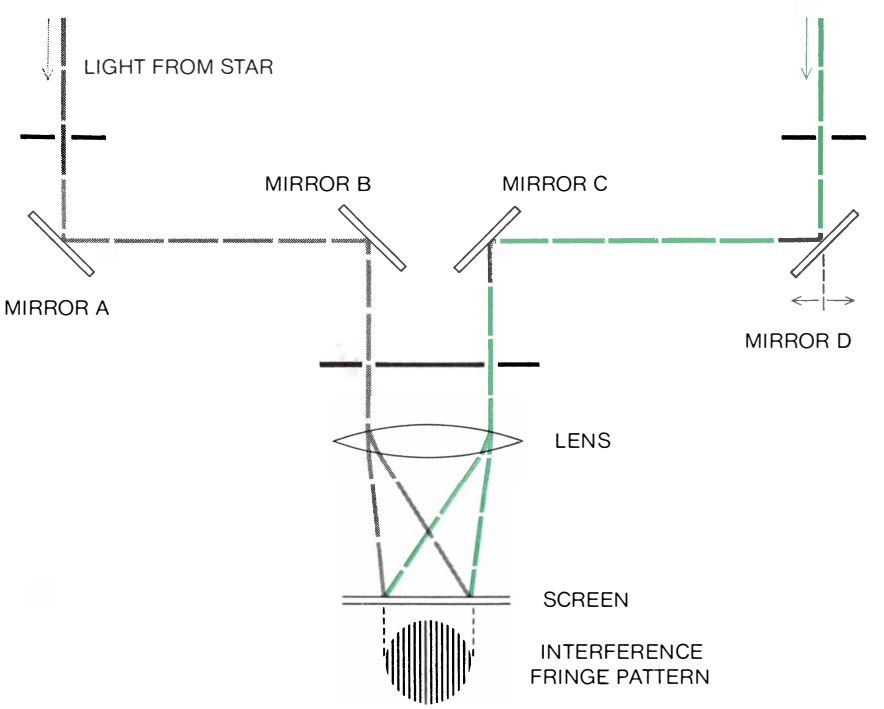
Since the compact sources are relatively weak at the long wavelengths where most of the early observations of extragalactic radio sources were made, they remained essentially unnoticed for many years until sensitive receivers for short wavelengths became available. At that time, as a result of the discovery of radio sources that are opaque at decimeter and even centimeter wavelengths, it was realized that for "reasonable" values of the magnetic-field strength (near 10^{-4} gauss) the angular size of the opaque sources must be very small indeed, perhaps as small as a hundredth or a thousandth of a second of arc and orders of magnitude beyond the resolution of any existing radio telescope.

Further indirect evidence for such small dimensions for the opaque radio sources comes from the dramatic discovery by William A. Dent in 1965 that the radio emission from the quasar 3C 273 is variable. It was widely assumed that the radiation from any object could not vary on a time scale significantly less than the time it would take light to travel across the source. Otherwise the apparent variations would be smoothed out by the differences among the travel times for signals coming from different parts of the source. Since 3C 273 showed a significant change on a time scale of about a year, the dimensions of the variable component were estimated to be of the order of a light-year or less. The measured red shift of 3C 273 corresponds to a recessional velocity of about a sixth the velocity of light. The Hubble expansion law that relates red shift and distance gives the object a distance of about 1.5 billion light-years and thus an angular size of less than .001 second of arc.

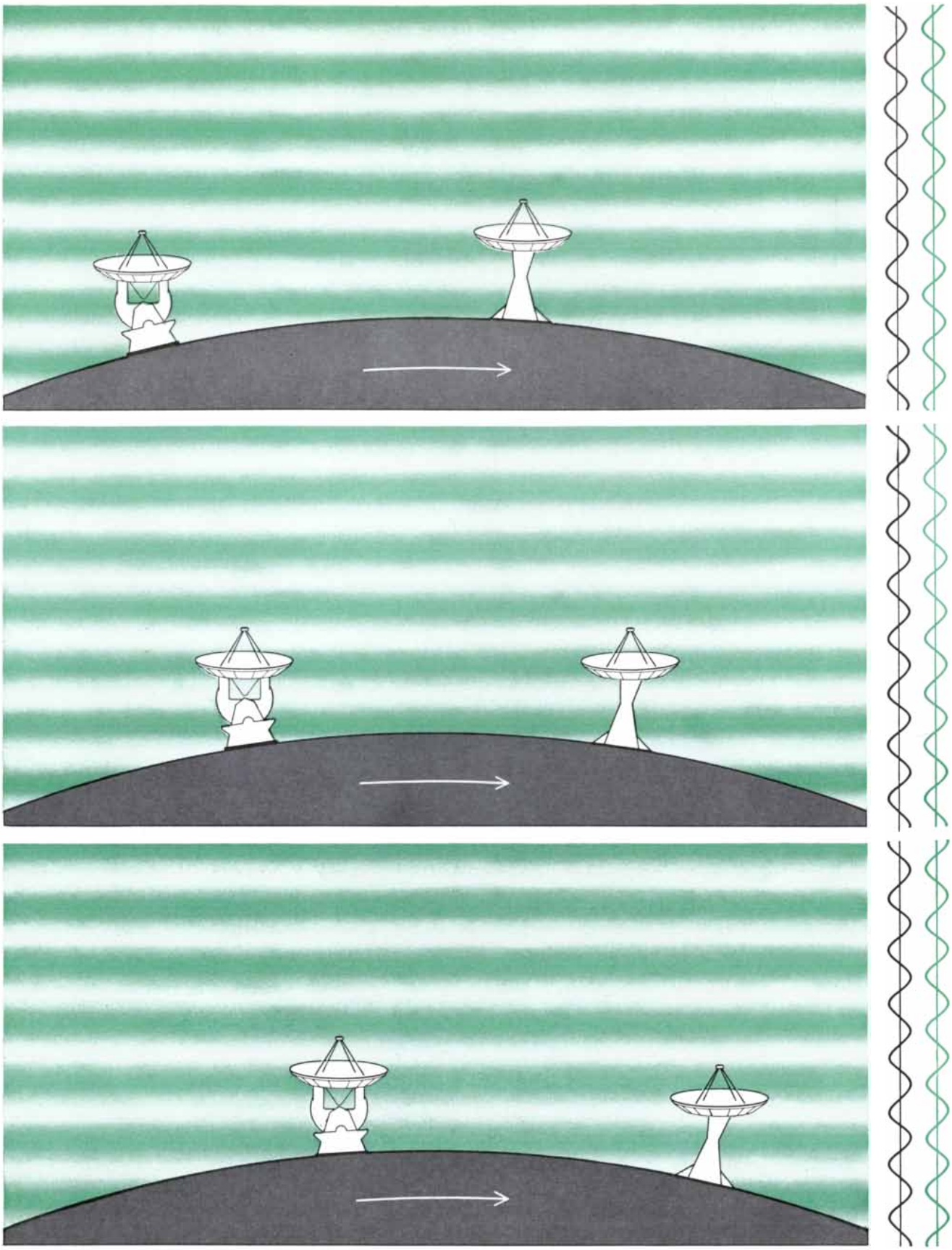
Further studies of variable radio emission have shown that the phenomenon is not confined to quasars but occurs in the nuclei of some galaxies as well. The observed variations do not show any periodicity such as is found in many ordinary variable stars. Rather the variations appear to be generally in the form of large outbursts that may appear first at short wavelengths and then propagate with reduced amplitude toward longer wavelengths. The typical time scale for an individual outburst ranges from a few weeks to a few years, and in some sources the interval between outbursts is shorter than the duration of a single outburst. It has been concluded from the observed variations that there are repeated explosions in the nuclei of galaxies and in quasars that produce an expanding cloud of relativistic particles radiating by the synchrotron process. Each cloud appears to be produced on a time scale of only a few months and in a volume of space less than a few light-months across. Initially the cloud is opaque at the longer radio wavelengths. As it expands the amount of energy escaping increases as the radiating surface becomes larger; at the same time the strength of the magnetic field decreases and the electrons lose energy as a result of the expansion. When the cloud becomes so tenuous that it is transparent, the intensity then decreases with time, first at the shorter wavelengths and then at the longer ones. At the time of each outburst the magnetic-field strength in the cloud appears to be of the order of one gauss, about equal to the field on the surface of the earth. The expansion of the cloud causes the field strength to decrease rapidly until it reaches about 10^{-4} gauss, after which the relativistic particles appear to diffuse through a fixed magnetic field. It is believed the continued production and diffusion of the relativistic particles from the compact centers of activity then lead to the establishment of the familiar extended radio sources.

The basic question, however, of the source of energy and how this energy is converted to relativistic particles remains unanswered. Some astronomers believe that here we have reached the limit of conventional physics and that only fundamentally new theories will explain the seemingly fantastic energy output of galactic nuclei and quasars. Clearly the solution to the problem lies in being able to study these incredibly tiny objects in sufficient detail to unravel the complex phenomenon that produces the intense radio emission. Until recently, however, obtaining the required angular resolution was beyond the most optimistic dreams of radio astronomers, since it called for interferometer baselines that appeared to be unreasonably long.

Longer baselines for conventional interferometers were not feasible partly because of the increased cost of the cable between the interferometer elements, and partly because of the greater difficulty of getting right-of-way across roads and private property, not to mention the natural limits imposed by rivers, mountains and ultimately oceans. A significant improvement in resolution was obtained by replacing the connecting cables with microwave radio relay links. This technique was used first by Australian and British radio astronomers to get baselines more than 100 kilometers long and a resolution of better than one second of arc. In order to resolve the compact variable sources with expected



LIGHT INTERFEROMETER illustrates the principle of the radio interferometer. Light from a distant source is reflected from the outer mirrors (*A and D*) to the inner mirrors (*B and C*) and then combined at the projection screen. Moving one of the mirrors (*D*) makes one light path slightly longer than the other, shifting its light waves out of phase with respect to the waves that travel the other path. The two beams, when they are combined at the screen, will interfere with each other, creating a pattern of "fringes" (*bottom*).



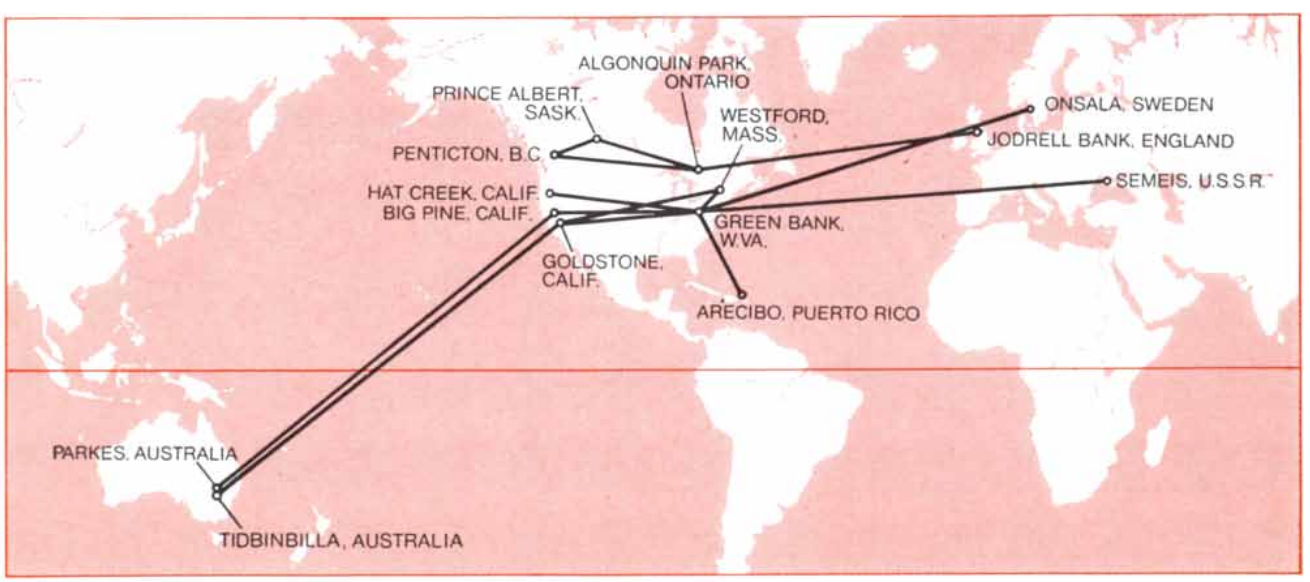
RADIO INTERFEROMETER allows the rotation of the earth to change the distance that celestial radio emission must travel to each radio telescope. At a given moment a crest of the radio wave front may be received at one telescope and a trough at the other (*top*). The waves will be out of phase with each other and will interfere destructively. At a later moment rotation of the earth will have moved the telescopes into a position such that both will simultaneously receive crests and troughs (*middle*). At a still later moment the waves will be out of phase again. Here the amount of rotation needed to change the phase relations is greatly exaggerated.

dimensions of about .001 second, however, baselines comparable to the dimensions of the earth were needed. Further large improvements in the resolution of radio-link interferometers were not practical; microwave radio links are limited to line-of-sight operation, and the installation of large numbers of repeater stations is costly and technically complex.

For many years radio astronomers had discussed the possibility of completely eliminating the direct electrical connection between interferometer elements by separately recording the signals at each end on magnetic tape and later comparing the two recordings. If this is to be done successfully, two requirements must be met. The first is that the recordings on the two tapes must be synchronized so that the time when a given wave front is received at each station is precisely known. The required precision of the time synchronization is approximately the reciprocal of the bandwidth of the recorded signal, or about one microsecond (one millionth of a second) for a typical bandwidth of one megahertz (one million cycles per second). The other requirement has to do with the fact that radio telescopes receive signals that are at too high a frequency to be recorded directly on magnetic tape. Independent local oscillators must therefore be used to "heterodyne" the radio-frequency signal, which is typically several gigahertz (billion cycles), to a much lower intermediate frequency (near one megahertz) so that it can then be recorded. If the intermediate frequency signals are to be correlated, the oscillators must remain coherent over the observing time. This means that the relative phase change of the two oscillators must remain small over the observing period, so that the change in frequency is less than the reciprocal of the recording time. For example, at a frequency of one gigahertz a 100-second integration time calls for a frequency stability better than one part in 100 billion.

The possibility of independent-local-oscillator tape-recording interferometers was considered in the U.S.S.R. as early as 1961. At that time, however, the stable frequency standards and wide-band tape recorders needed for high sensitivity were not generally available. A tape-recording interferometer was first actually used in radio astronomy by a University of Florida group to study the dimensions of the radio storms on the planet Jupiter at a frequency of 18 megahertz. The Jupiter bursts are so intense that an integration time considerably less than a second and a bandwidth of about one kilohertz give adequate sensitivity. Thus a frequency stability of only one part in 100 million and a time synchronization of about one millisecond were sufficient to maintain coherence at the two ends of the interferometer, and the necessary frequency stability and time synchronization were easily provided by the time signals from the National Bureau of Standards station WWV. In this way it has been possible to determine that the dimensions of the radio-emitting regions are less than .1 second of arc, or 200 miles on the surface of Jupiter. This resolution is considerably better than the highest resolution in photographs made of Jupiter at optical wavelengths.

The use of tape-recording interferometers to study the much weaker radio emission of radio galaxies and quasars had to wait until stable atomic frequency standards and high-speed tape recorders were commercially available. At that time two systems for tape-recording interferometry were developed independently in the U.S. and in Canada. A system developed by a joint Canadian team from the National Research Council and the University of Toronto employed television tape recorders to record data in a four-megahertz bandwidth. (The recorders were of the same type that is used to show an "instant replay" during a televised sports event.) A system developed by a U.S. group from the National Radio Astronomy Observatory and Cornell University used a standard computer tape-drive to record digital data in a 300-kilohertz band. Although the Canadian system had the advantage of greater bandwidth and thus greater sensitivity, it required more complex special equipment to synchronize the tapes on playback. In the American system the digital data were simply fed to a large computer, which stored and correlated the two data streams. A new system has recently been developed at the National Radio Astronomy Observatory by Barry G. Clark and others that employs television tape recorders to record digital data and a special-purpose digital processor to correlate the tapes. In this way both large bandwidth and the convenience of modern digital data-processing techniques are preserved.



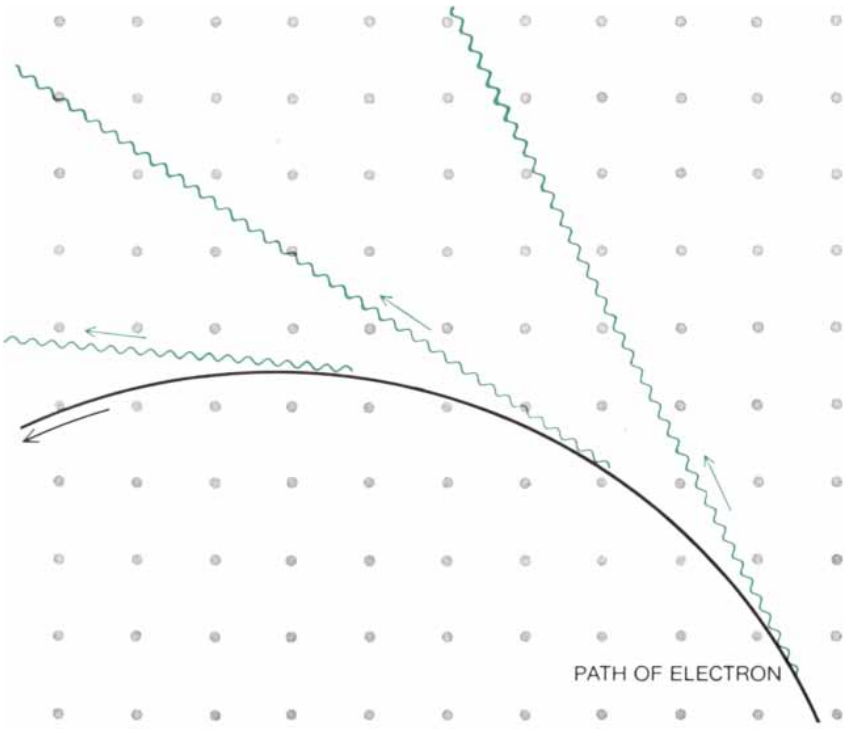
WORLD MAP shows some of the interferometer baselines used for high-resolution studies of radio galaxies and quasars. The longest baseline employed so far is the one stretching across the 6,600 miles separating Goldstone, Calif., and Tidbinbilla in Australia.

In these systems atomic frequency standards are used to provide accurate time synchronization throughout the recordings and to maintain the frequency of the local oscillator. Although the atomic clocks keep sufficiently accurate time in the course of an individual recording lasting up to many hours, it is first necessary to synchronize the clocks at the different locations. This can be done by directly comparing the two clocks at the same location and then transporting one to the distant site, which is often inconvenient, or by reference to one of the continuously running atomic clocks kept at time bureaus in many countries or to the Loran C navigational signals that are available in many parts of the world.

Synchronization of the order of one microsecond is required, but the initial synchronization need not be so precise, because the data can be played back repeatedly with different time delays until the interference fringes are found. In this way relative time delays up to 100 microseconds can be readily searched; when the fringes are found, the clocks are synchronized after the fact to better than one microsecond. With larger bandwidths, or with observations made at several frequencies to synthesize a large effective bandwidth, it is possible in principle to synchronize remote clocks in this way to an accuracy of a few nanoseconds (billionths of a second).

The atomic frequency standards used in the earlier experiments were commercially available rubidium-vapor standards with a relative frequency stability of about one part in 100 billion. Hydrogen masers have a stability of about 100 to 1,000 times better, corresponding to a clock error of less than one microsecond per year. These masers, however, are expensive, complex to operate and not easy to transport. Although the rubidium standards are sufficiently stable to provide an interference pattern and a measurement of its amplitude, they do not in general have sufficient stability to allow the phase of the interference pattern to be measured. Some experiments have already been made with hydrogen masers as frequency standards to provide improved phase stability, and it is expected that as masers become more readily available they will be routinely employed for the purpose of controlling time and frequency in tape-recording interferometers.

The first long-baseline measurements with tape-recording interferometers were made in 1967 at radio wavelengths of 75, 50 and 18 centimeters on baselines across Canada and the U.S. They quickly confirmed the expected small size of many radio galaxies and quasars. Although some of the objects studied were found to be resolved at dimensions of the order of a hundredth of a second of arc, many were still unresolved. Higher resolution was obviously needed.



SYNCHROTRON RADIATION, which is believed to be the source of the radio emission of radio galaxies and quasars, is generated by electrons spiraling at relativistic speeds (that is, near the speed of light) in a magnetic field. Here the lines of magnetic force are perpendicular to the page (*gray dots*). The electron is traveling counterclockwise and emitting radiation (*wavy lines*) in the plane of the page. The predominant wavelength of the synchrotron radiation depends on energy of electron and strength of the magnetic field.

The baselines were rapidly extended in a series of cooperative intercontinental experiments conducted in 1968 and 1969 by American, Swedish and Australian radio astronomers. With a wavelength of six centimeters resolutions of about .001 second of arc were obtained on the longest baselines. Still, many sources had components that appeared to be unresolved even at this extraordinary resolution. The California-to-Australia baseline was already 6,600 miles long, more than 80 percent of the earth's diameter, so that a further significant increase in the physical baseline was not feasible without the expensive procedure of setting up stations in space or on the moon.

A cheaper and simpler alternative was to observe at shorter wavelengths. Outside North America, however, only two radio telescopes were suitable for operation at short wavelengths and also large enough to provide adequate sensitivity for long-baseline interferometry. Both of these instruments are in the U.S.S.R.

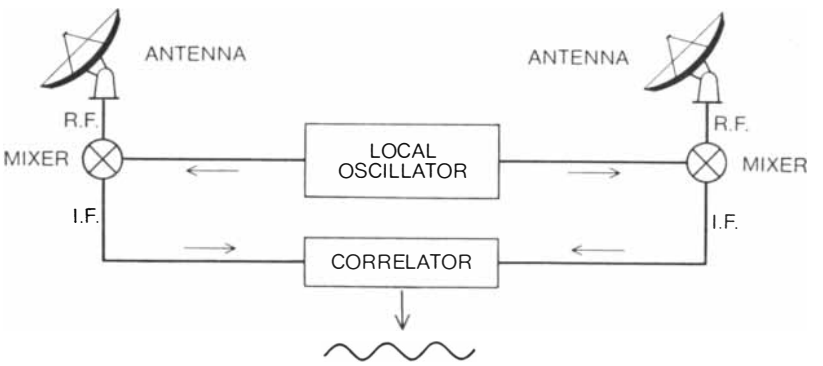
Even in the joint experiment within the Western countries logistical problems such as transporting magnetic tapes and fragile equipment and negotiating with U.S. and foreign customs authorities had proved to be as much of a challenge as technical considerations. These problems were particularly formidable for experiments between the U.S. and the U.S.S.R., since there is relatively little exchange of advanced scientific or technical equipment between the two countries.

The first joint interferometer experiment between the U.S. and the U.S.S.R. was completed late in 1969. The instruments at the two ends of the baseline were the 140-foot antenna at the National Radio Astronomy Observatory in Green Bank, W.Va., and a new 72-foot precision radio telescope located on the shores of the Black Sea in the Crimea. Last spring a second experiment was conducted involving in addition to the Green Bank and Crimea telescopes the ultrasensitive 210-foot radio telescope at Goldstone, Calif., and the "Haystack" telescope in northern Massachusetts. (The Goldstone instrument is operated by the National Aeronautics and Space Administration; the Haystack one, by the Massachusetts Institute of Technology.)

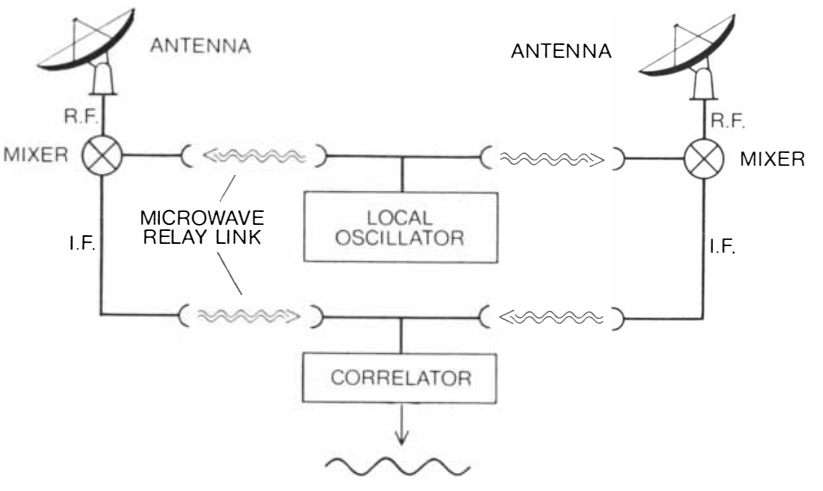
More than 20 investigators from eight institutions in both countries participated in the second experiment, which included observations of interstellar clouds of water vapor as well as of radio galaxies and quasars.

The data from the Goldstone-Crimea baseline obtained at a wavelength of 3.5 centimeters give the highest resolution obtained so far in the study of radio galaxies and quasars: approximately .0003 second of arc. This is a very small angle indeed: it is equivalent to the angle subtended by the height of these letters at a distance of about 1,500 miles. In contrast, an optical telescope operating under ideal conditions can just distinguish an object the size of a man at the same distance. The measurements of the water-vapor clouds, which were made at shorter wavelengths, give even higher resolution.

The smallest physical dimension that has been directly measured in an extragalactic radio source is in the nucleus of the nearby radio galaxy Messier 87; it has an angular size of about .001 second of arc, corresponding to a linear extent of only a quarter of a light-year. It is believed the relativistic particles that now fill an extensive radio "halo" more than 100,000 light-years in diameter have been produced or accelerated in this compact nucleus by continuing or repeated activity over a million years or more. Similar radio nuclei are found in other spiral and elliptical galaxies as well as in strong radio galaxies.



CONVENTIONAL RADIO INTERFEROMETER employs a cable to link the two telescopes, which are separated by distances of up to a few kilometers. For purposes of analysis the high-frequency radio signal received from the celestial radio source must be converted to a lower frequency. This is done by mixing a signal from a local oscillator with the radio-frequency signal (*denoted R.F.*) to create an intermediate-frequency "beat" signal (*I.F.*).



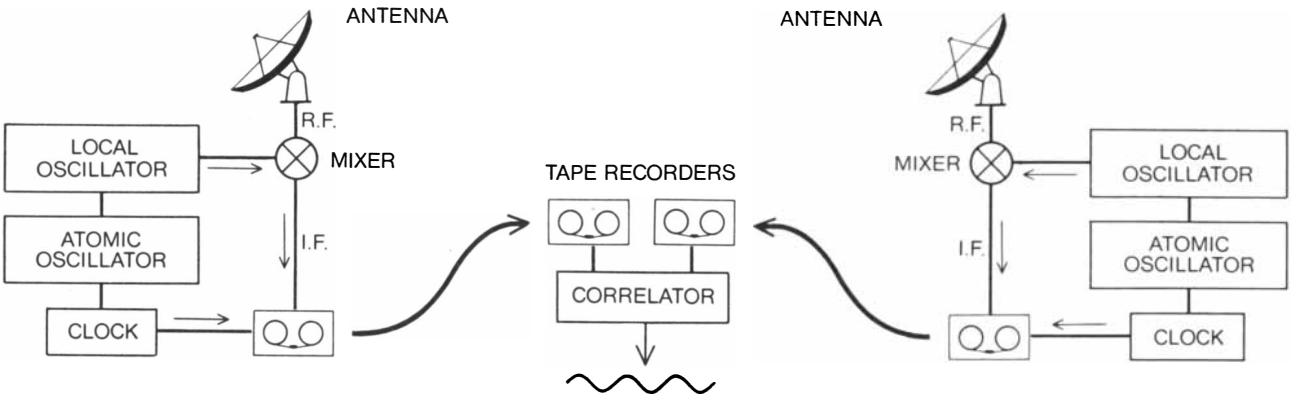
RADIO-LINK INTERFEROMETER joins the radio telescopes by a microwave-relay link similar to those used for long-distance telephone transmission. The local-oscillator signal is transmitted to the mixers, and the I.F. signals are returned for correlation. If the I.F. signals from each antenna are to be coherent (in phase), the local-oscillator signal at each end must also be coherent and so is derived from a common source and carried to the mixers.

By combining data from the various long-baseline experiments we have begun to obtain crude pictures of the structure of the radio nuclei and the compact quasars with resolutions exceeding .001 second of arc. This resolution is about 1,000 times better than is possible at optical wavelengths, where quasars and the nuclei of galaxies appear as only fuzzy points of light, and it presents unprecedented opportunities for studying the violent events in these objects in considerable detail.

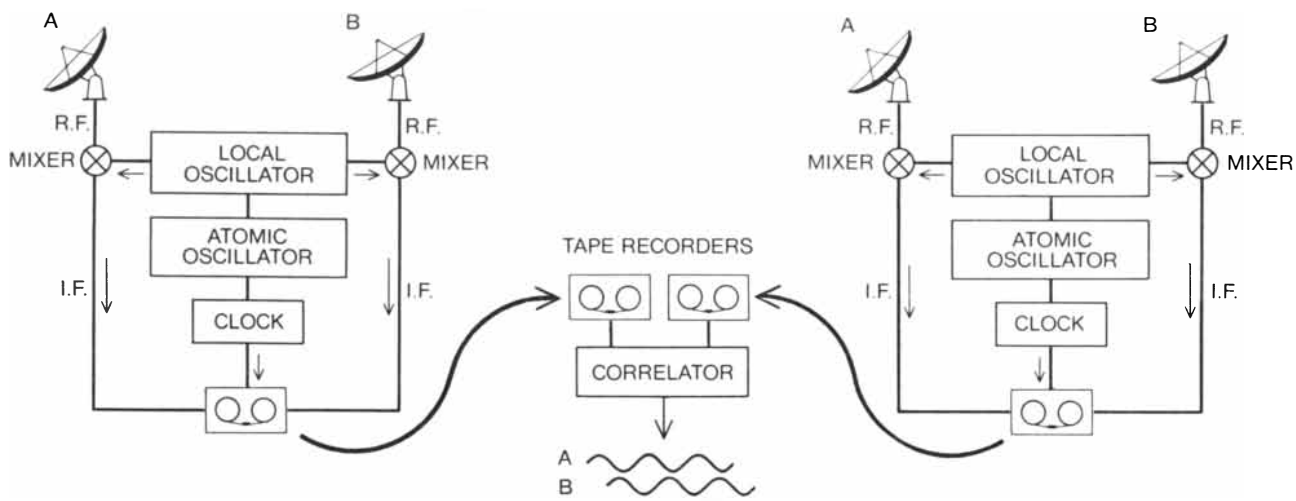
In conventional radio interferometers one or more antennas can be moved over distances of up to a few miles in order to obtain the number of interferometer spacings needed to reconstruct an image of the source. For very-high-resolution interferometry, where the baselines span oceans and continents, it is clearly impractical to move large antennas around. The observations have therefore been made with already existing radio telescopes at fixed locations throughout the world, restricting the range of available baselines. This gives rise to considerable ambiguity in the detailed interpretation of the data, and so only crude pictures are obtained.

For those sources that have been studied in some detail the structure has been found to be complex and generally lacking circular symmetry. Often there is a hierarchy of component sizes ranging from less than .001 second of arc to .1 second or more in a single radio galaxy or quasar. In general the smallest components are strongest at the shorter wavelengths, a result that can be predicted from the synchrotron theory. In those cases where the angular size, spectral cutoff frequency and peak flux density are observed, the magnetic-field strength can be estimated from the synchrotron theory and is typically of the order of 10^{-4} gauss.

Many of the compact components appear to be spatially dissected, with a region of relatively low brightness near the middle. Although generally it has not been possible to decide unambiguously between an elliptical ring structure and a double structure, in most cases the data appear to favor the double structure. It is a remarkable fact that this characteristic double structure of radio galaxies and quasars is apparent on angular scales between .001 second of arc and several minutes of arc. This is a range of about one to 100,000 in size,



TAPE-RECORDING INTERFEROMETER makes it possible to do interferometry with radio telescopes as far apart as opposite sides of the earth. (The microwave-relay link is practical only for antennas that are on a line of sight with respect to each other.) The intermediate-frequency signals from each antenna are separately recorded at each end of the interferometer system, and later the magnetic tapes are transported to a common location where recorded data are correlated in a large digital computer or a special correlator.



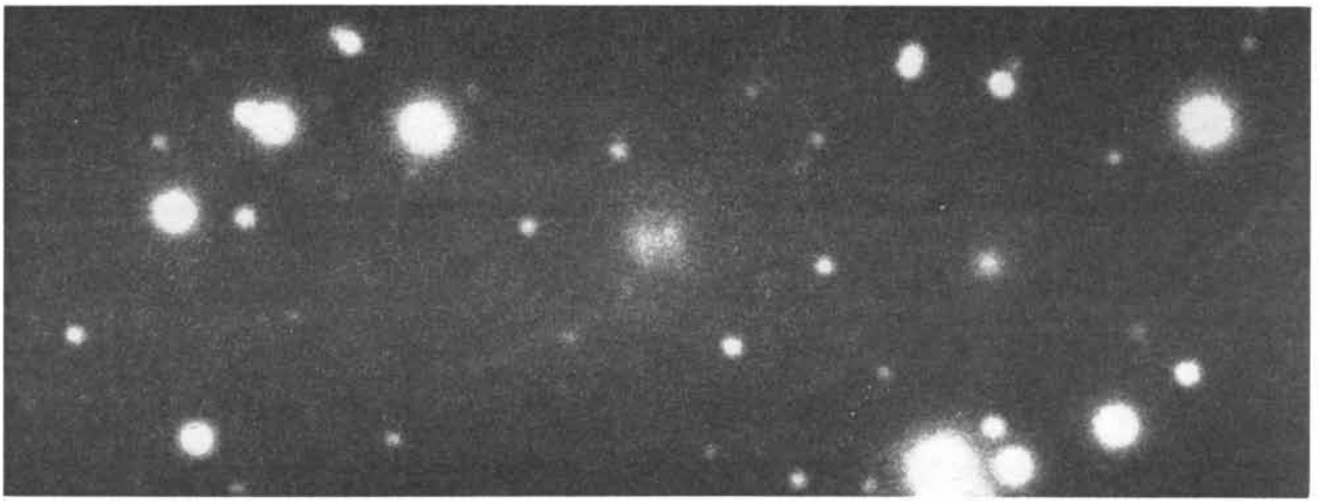
MORE SOPHISTICATED tape-recording system employs two radio telescopes at each end of the interferometer to observe two sources simultaneously. One source serves as a point-source reference to determine the phase of the other source. The phase difference of the two interference patterns can be measured directly, independent of any phase changes in either of the local oscillators or in the atmospheric path to the two antennas. In this way it is possible to make precise measurements of the positions of radio sources and to completely reconstruct the intensity distribution by combining observations that have been made on many baselines.

which corresponds to linear dimensions measuring between less than one light-year and several hundred thousand light-years.

Although the measured angular dimensions of the individual components and those predicted from the self-absorption cutoff frequency are in good agreement with the synchrotron model, the rapid variations in intensity, and the large energies required to explain the powerful radiation observed from some quasars, are difficult to explain. For some time it was hoped that a more definitive test of the synchrotron theory would come from measuring the change of size of the variable sources, since the theory predicts a close relation between the rate of change of size and the rate of change of intensity. Now that data of this kind are available, however, the results are perplexing and raise more questions than they answer.

It has been suggested that the individual outbursts observed can be explained as being the result of a violent explosion that releases a dense cloud of relativistic electrons, which then radiate by the synchrotron process. The rapid variations in intensity that are observed in some of the radio sources require that the particles be accelerated to relativistic energies on time scales between a few months or less and a few years. If it is assumed that the dimensions of the variable source cannot exceed the distance traveled by light during the characteristic time scale of the variations, one can set an upper limit to the size of the variable source. Typically this size is of the order of a light-year. If the distance is known, one can calculate an upper limit to the angular size and the magnetic field and a lower limit to the electron energy.

For relatively nearby radio galaxies this minimum required energy is of the order of 10^{52} ergs of relativistic particles per outburst. This is of the same order as the energy released in a powerful supernova explosion. In the case of the quasars (assuming that their red shifts are associated with the expansion of the uni-



RADIO GALAXY CYGNUS A, the strongest radio source in the sky, appears as a fuzzy spot in the center of the photograph at left, which was made with the 200-inch telescope on Palomar Mountain. Interferometer studies of the radio emission of the source indicate that it comes from two regions on each side of the visible object. The apparent structure of these regions is shown at the same scale

verse and that they are at cosmological distances) the energy apparently required in each outburst is as much as a million times greater, and it is very difficult to understand how so much energy can be released in such a small volume of space and in such a short time. Moreover, it has been pointed out that the intense synchrotron-radiation fields from the dense collection of relativistic electrons would in turn cause the electrons to immediately lose their energy by inverse Compton scattering rather than by synchrotron emission. Such scattering results when an energetic electron encounters a photon of lower energy. The photon gains energy and the electron loses it; the net result is that the electron energy is radiated away at shorter wavelengths such as infrared radiation or X rays rather than by synchrotron radiation at radio wavelengths.

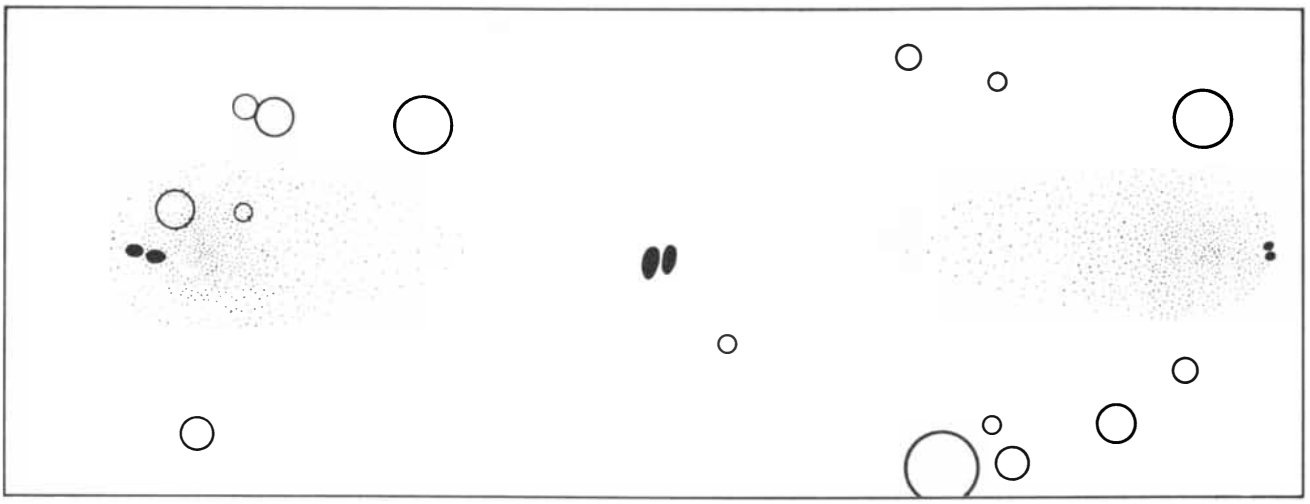
This apparent paradox was interpreted by some investigators as evidence that either the quasars must be at closer distances than is indicated by their red shift, and hence their radiation field must be much weaker, or the radiation mechanism is more efficient than the synchrotron process. Martin J. Rees of the University of Cambridge has suggested a possible alternative: the "superlight-velocity" theory. If the radio source expands at a velocity close to the velocity of light, then since it takes a finite time for radio signals to reach an observer, the signal arriving from the receding part of the source will have originated at an earlier time, when it was closer to the point of origin, than the signals from the approaching parts. Under these conditions the *apparent* velocity of expansion may indeed exceed the velocity of light. Thus the true dimensions of the source may be greater than what is given by the restriction that the apparent expansion velocity is less than the velocity of light, and the energy requirements, which are inversely proportional to the 10th power of the size, are much reduced.

Evidence that this effect might be important in the quasar 3C 279 was first obtained in a series of transpacific observations made between 1968 and 1970 by a joint team from Australia and the California Institute of Technology. Working with NASA tracking antennas at Goldstone in California and Tidbinbilla in Australia as two elements of a long-baseline interferometer, this group found that a component of the source that had first appeared in 1966 had reached a diameter of about .001 second of arc by the end of 1969. The corresponding linear diameter is about 12 light-years, assuming that the source's red shift of .54 is of cosmological origin.

Hence, as predicted by Rees, the apparent expansion velocity was about twice the velocity of light. More detailed measurements were made of 3C 279 in October, 1970, by a group from M.I.T., NASA and the University of Maryland using a transcontinental baseline. These observations were originally designed to measure the gravitational bending of the radio signals from 3C 279 as it approached the sun on October 8, but they showed clearly that the compact source in 3C 279 was complex and appeared to have at least two components separated by .00155 second of arc, or about 20 light-years. In February, 1971, this source was reobserved by the same group and also by workers from the National Radio Astronomy Observatory, Cal Tech and Cornell group using the same baseline and techniques. There had been a distinct change in 3C 279 in only four months. Again the source appeared double, but the separation was greater by two light-years: 10 percent more than previously. Thus the two components appear to be receding from a common point of origin with an apparent velocity about three times the velocity of light.

Although this would seem to confirm the predictions made by Rees, a serious problem remains. The difference in the Doppler shift of the two components should cause the approaching component to appear much more intense than the receding component. Yet the observed intensities of two components are equal to within a few percent, so that the effect of the Doppler shift must be exactly canceled by the difference in the intrinsic luminosity of the two components. This would seem to be a somewhat remarkable coincidence.

On the other hand, the apparent motions may be a "searchlight" effect caused by the excitation of stationary material by a moving shock front. The point of contact between the shock front and the material may appear to move with almost unlimited velocity, like the beam of a rotating searchlight seen at a great distance. It is also possible that the apparent change in size observed in the structure of 3C 279 may not be the result of component motions at all; it may merely reflect a change in the relative intensity of one or more stationary components. For example, a ring with a point source at the center or a triple source would appear to expand if



in the drawing at right. Each of the two major components contains within itself a tiny double source. The radio picture is based on observations made with a one-mile radio interferometer at the University of Cambridge, a 2.7-kilometer interferometer at the National Radio Astronomy Observatory and a 35-kilometer microwave-link interferometer also at the National Radio Astronomy Observatory.

the intensity of the inner component decreased or the intensity of the outer parts increased. Although this is the most straightforward and least spectacular interpretation of the data, it still leaves unexplained the problem of the huge energy requirement, unless the distance of 3C 279 is very much less than is deduced from its red shift.

The present measurements do not distinguish between these various models, although it may be expected that future detailed observations will demonstrate whether or not there is actual motion of the individual components. Even if the large apparent velocities are confirmed, however, there will still be more questions than answers. Those who believe that the quasar red shifts are cosmological can cite the super-light-velocity theory to reduce the enormous energy requirements, which have been one of the main arguments against the cosmological interpretation of the quasar red shifts [see "The Evolution of Quasars," by Maarten Schmidt and Francis Bello; SCIENTIFIC AMERICAN, May, 1971]. Those who believe the quasars are local emphasize that the apparent super-light-velocity may be only an artifact of the assumption that the quasars are at great distances. They point out that the apparent angular expansion rate, the observed flux densities and the rates of variation are similar for the nearby galaxies and the supposedly more distant quasars, and that the apparent large differences in the corresponding intrinsic properties are merely the result of the assumption that the quasar red shifts are cosmological.

Although measurements of the apparent change in the structure of compact radio sources may not help to clarify this problem, they will determine (1) whether the successive outbursts that are observed occur in exactly the same volume of space or whether they are spatially separated, (2) the kinematics, or mechanics, of the expansion and (3) how the magnetic field and total energy vary with time. With this information we may hope to reach a better understanding of the process by which violent events lead to the creation of intense radio sources, in particular a better understanding of the source of energy and how this energy is converted into relativistic particles.

Although the sensitive long-baseline interferometer systems were initially developed to study the compact extragalactic radio sources, the technique has also been used to study the radio emission from interstellar clouds of hydroxyl radicals (OH) and water vapor. These clouds, which radiate like giant interstellar masers, emit such powerful radio signals that high-resolution interferometer measurements of their size can easily be made with standard high-fidelity audio-frequency tape recorders. All the observations made so far of these interstellar masers, however, have been made with the more sophisticated wide-band techniques that allow the simultaneous measurement of several clouds (which, because of their high velocities in various directions, are Doppler-shifted and radiate over a wide range of frequencies). Typically the clouds are dispersed over a volume of the order of several light-years across, although the individual components are as small as one astronomical unit (the distance between the sun and the earth).

One of the main restrictions of tape-recording interferometry so far has been the lack of sufficient oscillator stability to determine the phase of the interference pattern. We have noted the improvement to be expected from the use of hydrogen masers as frequency standards. Even with infinitely stable oscillators, however, there are still problems created by fluctuations in the path length through the atmosphere at the two widely separated observing sites. Experiments are now being conducted with a total of four antennas to overcome this problem and to eliminate the effect of local-oscillator instabilities. In these double-interferometer experiments two antennas located at Green Bank, W.Va. (at the National Radio Astronomy Observatory), and two at the Cal Tech Owens Valley Observatory in California are used to observe two sources simultaneously and to determine their relative positions.

If phase-stable interferometry could be done on baselines comparable to dimensions of the earth, angular positions could in principle be established with an accuracy approaching .0001 second of arc. Such precision would make it possible to measure the actual motion of nearby galactic objects such as pulsars, interstellar molecular masers and those stars that show strong radio emission. The possibility of applying this technique to determining small departures from the uniform motion of stars that might be caused by the gravitational attraction of planets is an exciting one; it may offer the only direct way of detecting other planetary systems in our galaxy. In addition, the detection of small apparent motions in pulsars or interstellar molecular masers caused by the

motion of the earth around the sun (parallax) would allow for the first time a direct determination of their distance.

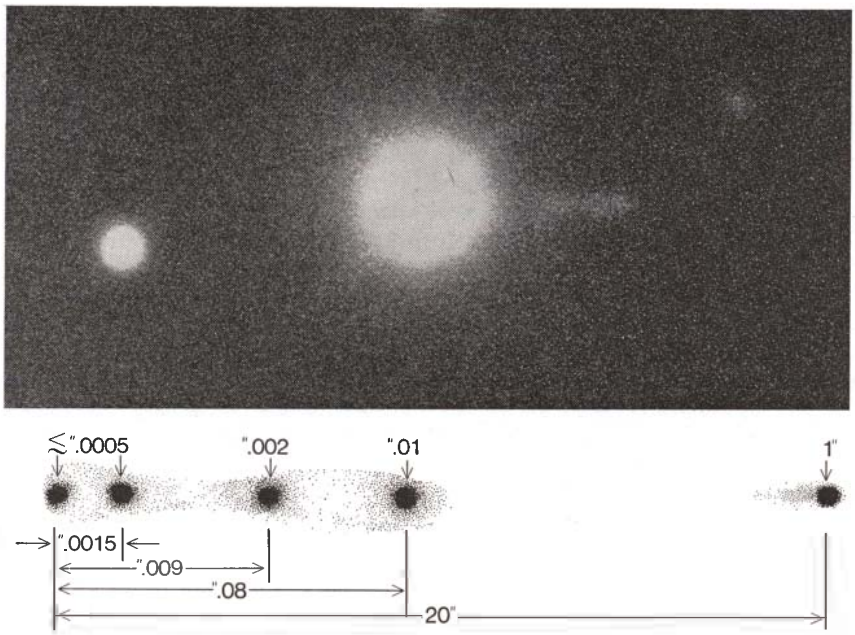
Another particularly interesting application of tape-recorder interferometry is the testing of the prediction of Einstein's general theory of relativity that an electromagnetic wave such as a radio or light wave that passes close to a massive body is deflected by the gravitational field of the body. The expected deflection for rays from a distant celestial source that pass close to the edge of the sun is 1.76 seconds of arc, and many optical measurements have been made of the apparent positions of stars near the sun at the time of a solar eclipse. Although these measurements have shown a displacement of about the magnitude predicted by the general theory, the accuracy of the measurements is at best of the order of 10 percent of the deflection. This is not good enough to distinguish between the predictions made by the general theory and competing gravitational theories.

The ability to determine relative angular positions of celestial objects with an accuracy of .001 second of arc by radio interferometry offers a potential accuracy considerably better than 1 percent. The circumstances for such an experiment are favorable each October, when the compact quasar 3C 279 is eclipsed by the sun. A second strong compact quasar, 3C 273, is located only 10 degrees away in the sky and provides a convenient position reference for measuring the daily deflection of 3C 279 as it passes closer and closer to the sun.

Richard Sramek has conducted an experiment of this type with a conventional interferometer at the National Radio Astronomy Observatory that has a baseline of 2.7 kilometers. His results show a slight discrepancy from the result predicted by the general theory of relativity and agree better with an alternative theory: the Brans-Dicke theory of gravity. The accuracy, however, is not sufficient to definitely exclude the general theory. Nevertheless, this is one of only a few experimental results in the more than 60 years since Einstein's theory was published that even suggest a possible discrepancy, and the current opportunity to improve the accuracy by one or two orders of magnitude is an exciting prospect for fundamental physics.

An M.I.T.-NASA group has conducted extensive studies of the October eclipse of 3C 279 with transcontinental tape-recording interferometers, but so far no conclusive results have been obtained. The joint program of the National Radio Astronomy Observatory and Cal Tech utilizing two antennas at Green Bank and two at Owens Valley to measure the simultaneous difference in the positions of 3C 279 and 3C 273 is expected to overcome many of the experimental difficulties and may well yield a very precise test of the general theory of relativity.

Even when the instrumental problems of controlling local-oscillator stability and eliminating the effect of the atmosphere are overcome, the measurement of angular positions to an accuracy of better than .001 second of arc will not be simple. At that level of precision significant errors are introduced by uncertainties in the rate of rotation of the earth itself, in the direction of the earth's axis of rotation at any one moment and in the relative coordinates of the antennas on the earth's surface. The errors in phase produced by uncertainties in these quantities are all related, and repeated observations of a suitably selected grid of sources can sort out these effects with techniques commonly applied to optical astrometric measurements. When this is done, it will be possible to determine (a) positions in the sky to within .001 second of arc, (b) the length of the day to within .0001 second of time, (c) transcontinental and intercontinental baseline distances to within a few centimeters and (d) global clock synchronization to within a few nanoseconds. Such precise data will open up to radio astronomers an entire class of geophysical experiments, including the direct measurement of tides in the solid earth, of continental drift, of variations in the rate of rotation of the earth and of the wobble of the earth's axis.



QUASAR 3C 273 is seen in the photograph at top, made with the 200-inch telescope. Extending to the right of the central image is a peculiar "jet." The drawing at bottom, which is not to the same scale as the photograph, shows the radio structure of the object. The numbers below the drawing give the distance in seconds of arc from the center of the object on a logarithmic scale. The numbers above the drawing give the size of the components in seconds. Wavelength of the radio emission is progressively longer with distance from center.

Is there a limit to the resolution of long-baseline interferometers, or will the baselines continue to extend into space, to the moon and beyond? Just as turbulence in the atmosphere affects optical astronomy, so at short wavelengths will it affect radio astronomy. Even more important is the effect of the scattering of radio waves by electrons in the solar "wind" and in the interstellar medium, which become important for measurements made at long radio wavelengths. The present evidence indicates that only for wavelengths less than about 10 centimeters can baselines much greater than the diameter of the earth be effectively used. Thus hydroxyl emission regions, which radiate at 18 centimeters, and pulsars, which radiate most strongly at meter wavelengths, are not likely to be targets for a space interferometer.

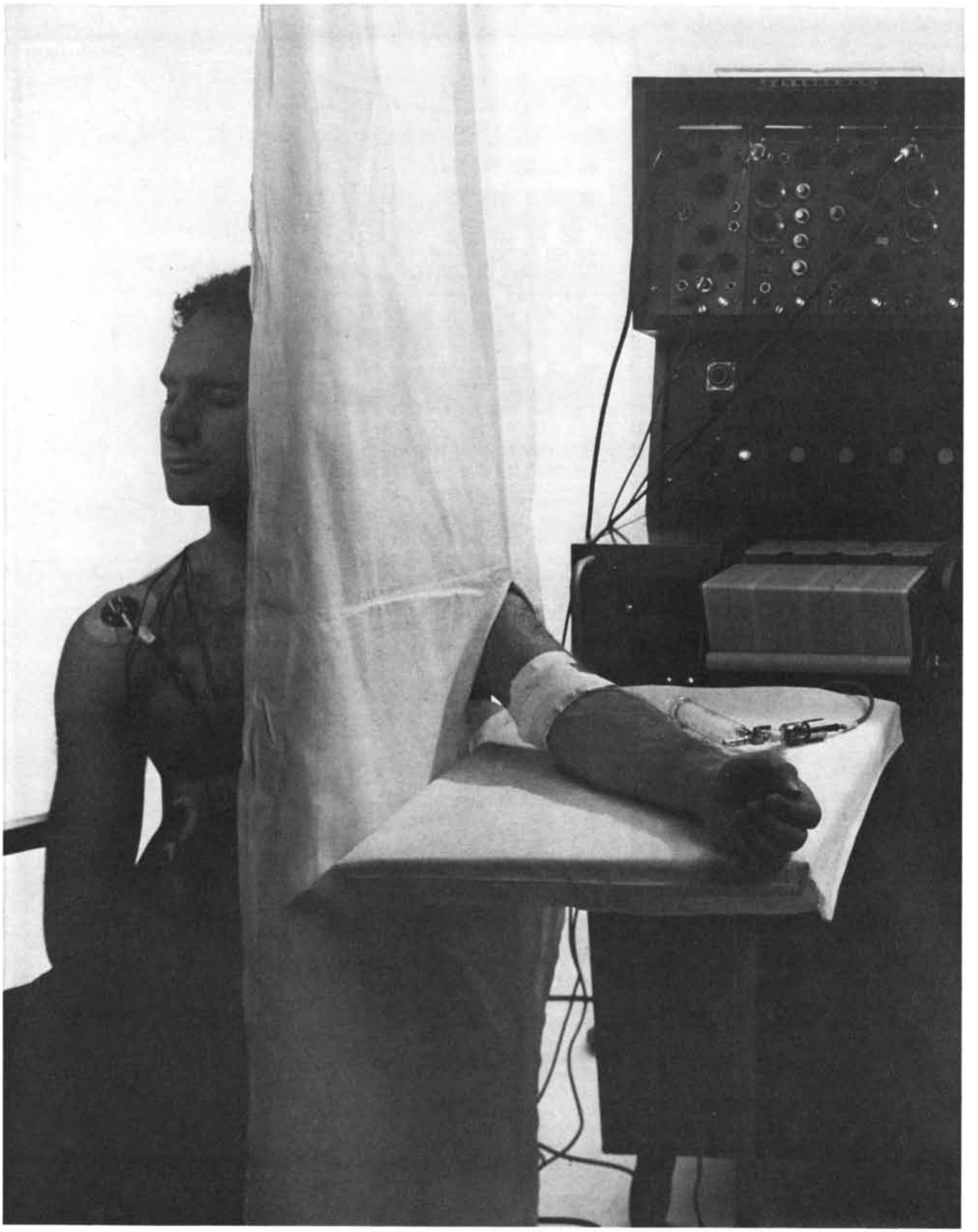
Where the synchrotron sources are concerned there is a more fundamental limit to the maximum baseline. As we have noted, if the dimensions of the synchrotron system are below a critical size, the relativistic particles quickly lose

all their energy by inverse Compton scattering and so do not have time to radiate radio energy. This critical angular size is proportional to the wavelength at which the flux density is the highest. Since the resolution of a fixed-length interferometer is inversely proportional to the wavelength of observation, the two effects cancel each other if the observations are made near the wavelength of maximum intensity (as they usually are to obtain the highest sensitivity). The maximum baseline needed to resolve synchrotron sources is hence nearly independent of the wavelength of operation; in fact, it is comparable to the diameter of the earth for the stronger radio galaxies and quasars. Baselines in space or on the moon will therefore probably not be necessary to study even the smallest radio nuclei and quasars.

The simple extension of interferometer baselines is only part of the story, however. Many baselines of intermediate length are also required to give a complete picture of the complex radio structure observed for the radio galaxies, quasars and interstellar molecular masers. Today the simple two-element radio interferometer of the 1950's has grown into multielement synthesis arrays. Radio astronomers look forward to the time when many radio telescopes throughout the world can be linked together to form an ultra-high-resolution array.

Although radio telescopes currently exist that are suitable for this purpose, they are not at optimum locations. Moreover, in view of the great variety of other important problems being studied by radio astronomers throughout the world and the wide range of instrumentation being employed at different observatories, it is virtually impossible to schedule a large number of radio telescopes for observing the same object at a common wavelength. In order to obtain a sufficient range of interferometer spacings, it may be necessary to construct a special global long-baseline interferometer network.

The task of collecting all the tape recordings at a common location and correlating all possible pairs of telescopes will be a formidable one. An attractive solution will be to dispense with the tape recordings entirely and telemeter the data from each antenna to a common center by means of synchronously orbiting satellites. Such a very-long-baseline array would require a truly international effort, but the opportunities it would provide for both astrophysics and geophysics are enormous.



ISOLATED SUBJECT is connected with an instrument array that continuously records such physiological variables as heart rate and blood pressure. A catheter in the subject's left arm draws samples of arterial blood at 10-minute intervals; these samples are analyzed for oxygen and carbon dioxide content and for blood acidity and blood-lactate level. The subject's arm is screened from his view to minimize the psychological effects of blood withdrawal. Each subject first sat quietly for an interval and then was invited to meditate for a 30-minute period. At the end of the period the subject was asked to stop meditating but to continue sitting quietly during a further recording interval. Thirty-six qualified "transcendental" meditators from 17 to 41 years old volunteered as subjects for the study, which was conducted both at the Harvard Medical Unit of the Boston City Hospital and at the University of California at Irvine.

THE PHYSIOLOGY OF MEDITATION

Is the meditative state that is achieved by yogis and other Far Eastern mystics accompanied by distinct physiological changes? A study of volunteer subjects in the U.S. indicates that it is

by Robert Keith Wallace and Herbert Benson

How capable is the human organism of adjusting to psychologically disturbing changes in the environment? Our technological age is probably testing this capacity more severely than it was ever tested in the past. The impact of the rapid changes—unprecedented in scale, complexity and novelty—that technology is bringing about in our world seems to be having a deleterious effect on the mental and physical health of modern man. Some of the common disorders of our age, notably "nervous stomach" and high blood pressure, may well be attributable in part to the uncertainties that are burgeoning in our environment and daily lives. Since the environment is not likely to grow less complex or more predictable, it seems only prudent to devote some investigative attention to the human body's resources for coping with the vicissitudes of the environment.

There are in fact several ways in which an individual can control his physiological reactions to psychological events. Among the claims for such control the most notable have come from practitioners of meditation systems of the East: yoga and Zen Buddhism. This article will review and discuss recent studies of the effects of meditation that have been made by ourselves and by other investigators.

Yogis in India have long been reputed to perform phenomenal feats such as voluntarily stopping the heartbeat or surviving for extended periods in an "airtight" pit or in extreme cold without food or in a distorted physical posture. One of the first investigators to look into these claims in an objective way was a French cardiologist, Thérèse Brosse, who went to India in 1935 equipped with a portable electrocardiograph so that she could monitor the activity of the heart. Brosse concluded from her tests that one of her subjects actually was able to stop his heart. In 1957 two American physiologists, M. A. Wenger of the University of California at Los Angeles and B. K. Bagchi of the University of Michigan Medical School, conducted a more extensive investigation in collaboration with B. K. Anand of the All-India Institute of Medical Sciences in New Delhi. None of the yogis they studied, with more elaborate equipment than Brosse had used, showed a capability for stopping the heart. Wenger and Bagchi concluded that the disappearance of the signal of heart activity in Brosse's electrocardiogram was probably an artifact, since the heart impulse is sometimes obscured by electrical signals from contracting muscles of the thorax. (In attempting to stop the heart the yogis usually performed what is called the Valsalva maneuver, which increases the pressure within the chest; it can be done by holding one's breath and straining downward.) Wenger, Bagchi and Anand did find, however, that some of the yogis could slow both heartbeat and respiration rate.

Reports of a number of other investigations by researchers in the 1950's and 1960's indicated that meditation as practiced by yoga or Zen meditators could produce a variety of physiological effects. One of the demonstrated effects was reduction of the rate of metabolism. Examining Zen monks in Japan who had had many years of experience in the practice of deep meditation, Y. Sugi and K. Akutsu found that during meditation the subjects decreased their consumption of oxygen by about 20 percent and reduced their output of carbon dioxide. These signs of course constitute evidence of a slowing of metabolism. In New Delhi, Anand and two collaborators, G. S. Chhina and Baldeu Singh, made a similar finding in examination of a yoga practitioner; confined in a sealed metal box, the meditating yogi markedly reduced his oxygen consumption and carbon dioxide elimination.

These tests strongly indicated that meditation produced the effects through control of an "involuntary" mechanism in the body, presumably the autonomic nervous system. The reduction of carbon dioxide elimination might have been accounted for by a recognizably voluntary action of the subject—slowing the breathing—but such action should not markedly affect the uptake of oxygen by the body tissues. Consequently it was a reasonable supposition that the drop in oxygen consumption, reflecting a decrease in the need for inhaled oxygen, must be due to modification of a process not subject to manipulation in the usual sense.

Explorations with the electroencephalograph showed further that meditation produced changes in the electrical activity of the brain. In studies of Zen monks A. Kasamatsu and T. Hirai of the University of Tokyo found that during meditation with their eyes half-open the monks developed a predominance of alpha waves—the waves that ordinarily become prominent when a person is thoroughly relaxed with his eyes closed. In the meditating monks the alpha waves increased in amplitude and regularity, particularly in the frontal and central regions of the brain. Subjects with a great deal of experience in meditation showed other changes: the alpha waves slowed from the usual frequency of nine to 12 cycles per second to seven or eight cycles per second, and rhythmical theta waves at six to seven cycles per second appeared. Anand and other investigators in India found that yogis, like the Zen monks, also showed a heightening of alpha activity during meditation. N. N. Das and H. Gastaut, in an electroencephalographic examination of seven yogis,

observed that as the meditation progressed the alpha waves gave way to fast-wave activity at the rate of 40 to 45 cycles per second and these waves in turn subsided with a return of the slow alpha and theta waves.

Another physiological response tested by the early investigators was the resistance of the skin to an electric current. This measure is thought by some to reflect the level of "anxiety": a decrease in skin resistance representing greater anxiety; a rise in resistance, greater relaxation. It turns out that meditation increases the skin resistance in yogis and somewhat stabilizes the resistance in Zen meditators.

We decided to undertake a systematic study of the physiological "effects," or, as we prefer to say, the physiological correlates, of meditation. In our review of the literature we had found a bewildering range of variation in the cases and the results of the different studies. The subjects varied greatly in their meditation techniques, their expertise and their performance. This was not so true of the Zen practitioners, all of whom employ the same technique, but it was quite characteristic of the practice of yoga, which has many more adherents. The state called yoga (meaning "union") has a generally agreed definition: a "higher" consciousness achieved through a fully rested and relaxed body and a fully awake and relaxed mind. In the endeavor to arrive at this state, however, the practitioners in India use a variety of approaches. Some seek the goal through strenuous physical exercise; others concentrate on controlling a particular overt function, such as the respiratory rate; others focus on purely mental processes, based on some device for concentration or contemplation. The difference in technique may produce a dichotomy of physiological effects; for instance, whereas those who use contemplation show a decrease in oxygen consumption, those who use physical exercise to achieve yoga show an oxygen-consumption increase. Moreover, since most of the techniques require rigorous discipline and long training, the range in abilities is wide, and it is difficult to know who is an "expert" or how expert he may be. Obviously all these complications made the problem of selecting suitable subjects for our systematic study a formidable one.

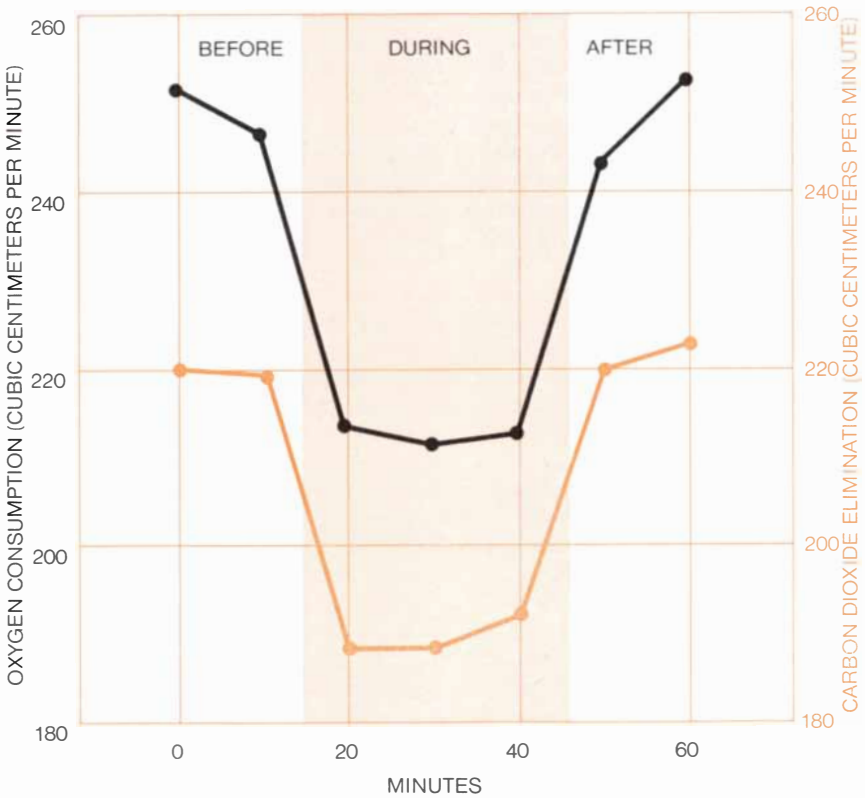
Fortunately one widely practiced yoga technique is so well standardized that it enabled us to carry out large-scale studies under reasonably uniform conditions. This technique, called "transcendental meditation," was developed by Maharishi Mahesh Yogi and is taught by an organization of instructors whom he personally qualifies. The technique does not require intense concentration or any form of rigorous mental or physical control, and it is easily learned, so that all subjects who have been through a relatively short period of training are "experts." The training does not involve devotion to any specific beliefs or life-style. It consists simply in two daily sessions of practice, each for 15 to 20 minutes.

The practitioner sits in a comfortable position with eyes closed. By a systematic method that he has been taught, he perceives a "suitable" sound or thought. Without attempting to concentrate specifically on this cue, he allows his mind to experience it freely, and his thinking, as the practitioners themselves report, rises to a "finer and more creative level in an easy and natural manner." More than 90,000 men and women in the U.S. are said to have received instruction in transcendental meditation by the organization teaching it. Hence large numbers of uniformly trained subjects were available for our studies.

What follows is a report of the detailed measurements made on a group of 36 subjects. Some were observed at the Thorndike Memorial Laboratory, a part of the Harvard Medical Unit at the Boston City Hospital. The others were observed at the University of California at Irvine. Twenty-eight were males and eight were females; they ranged in age from 17 to 41. Their experience in meditation ranged from less than a month to nine years, with the majority having had two to three years of experience.

During each test the subject served as his own control, spending part of the session in meditation and part in a normal, nonmeditative state. Devices for continuous measurement of blood pressure, heart rate, rectal temperature, skin resistance and electroencephalographic events were attached to the subject, and during the period of measurement samples were taken at 10-minute intervals for analysis of oxygen consumption, carbon dioxide elimination and other parameters. The subject sat in a chair. After a 30-minute period of habituation, measurements were started and continued for three periods: 20 to 30 minutes of a quiet, premeditative state, then 20 to 30 minutes of meditation, and finally 20 to 30 minutes after the subject was asked to stop meditating.

The measurements of oxygen consumption and carbon dioxide elimination confirmed in precise detail what had



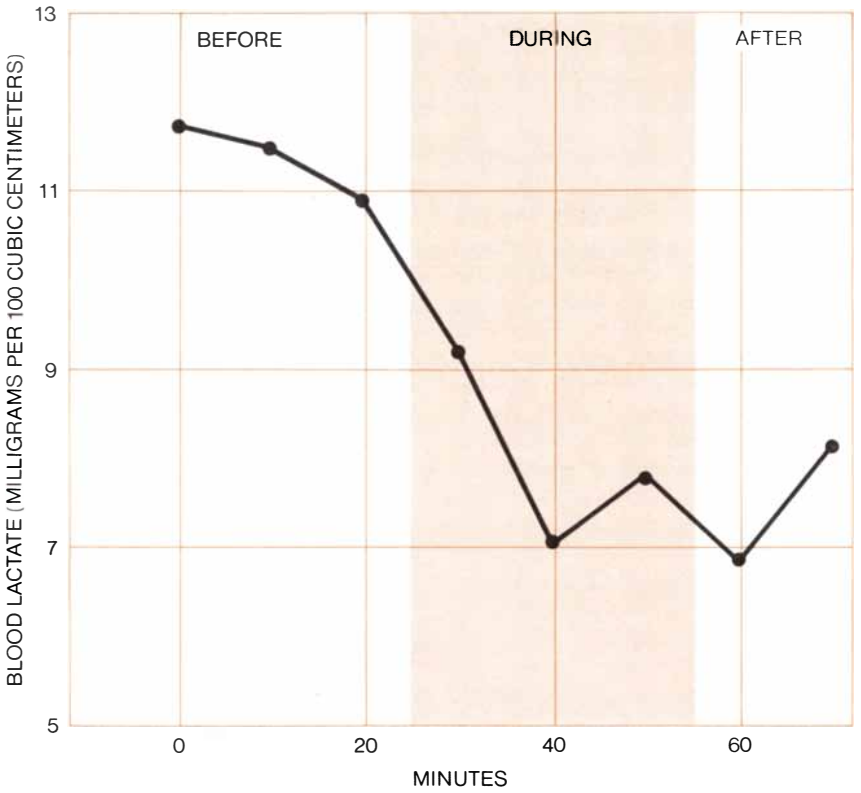
EFFECT OF MEDITATION on the subjects' oxygen consumption (*black*) and carbon dioxide elimination (*color*) was recorded in 20 and 15 cases respectively. After the subjects were invited to meditate both rates decreased markedly (*colored area*). Consumption and elimination returned to the premeditation level soon after the subjects stopped meditating.

been reported earlier. Oxygen consumption fell sharply from 251 cubic centimeters per minute in the premeditation period to 211 cubic centimeters during meditation, and in the postmeditation period it rose gradually to 242 cubic centimeters. Similarly, carbon dioxide elimination decreased, from 219 centimeters per minute beforehand to 187 cubic centimeters during meditation, and then returned to about the premeditation level afterward. The ratio of carbon dioxide elimination to oxygen consumption (in volume) remained essentially unchanged throughout the three periods, which indicates that the controlling factor for both was the rate of metabolism. The reduction in metabolic rate (and hence in the need for oxygen) during meditation was reflected in a decrease, essentially involuntary, in the rate of respiration (off two breaths per minute) and in the volume of air breathed (one liter less per minute).

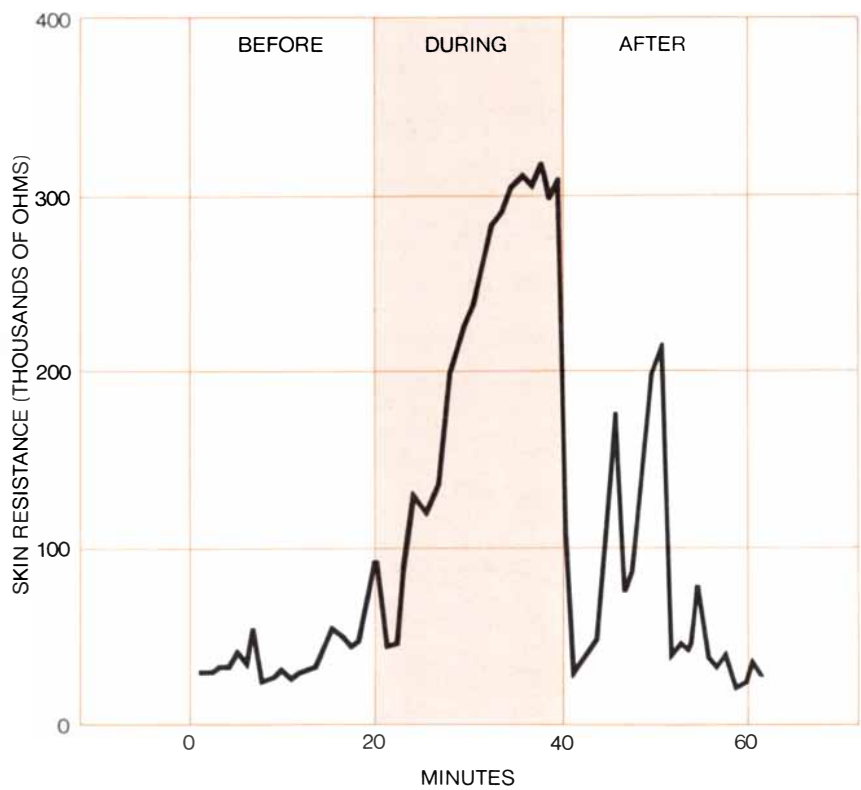
For the measurement of arterial blood pressure and the taking of blood samples we used a catheter, which was inserted in the brachial artery and hidden with a curtain so that the subject would not be exposed to possible psychological trauma from witnessing the drawing of blood. Since local anesthesia was used at the site of the catheter insertion in the forearm, the subject felt no sensation when blood samples were taken. The blood pressure was measured continuously by means of a measuring device connected to the catheter.

We found that the subjects' arterial blood pressure remained at a rather low level throughout the examination; it fell to this level during the quiet premeditation period and did not change significantly during meditation or afterward. On the average the systolic pressure was equal to 106 millimeters of mercury, the diastolic pressure to 57 and the mean pressure to 75. The partial pressures of carbon dioxide and oxygen in the arterial blood also remained essentially unchanged during meditation. There was a slight increase in the acidity of the blood, indicating a slight metabolic acidosis, during meditation, but the acidity was within the normal range of variation.

Measurements of the lactate concentration in the blood (an indication of anaerobic metabolism, or metabolism in the absence of free oxygen) showed that during meditation the subjects' lactate level declined precipitously. During the first 10 minutes of meditation the lactate level in the subjects' arterial blood decreased at the rate of 10.26 milligrams per 100 cubic centimeters per hour, nearly four times faster than the rate of



RAPID DECLINE in the concentration of blood lactate is apparent following the invitation to start meditating (*colored area*). Lactate is produced by anaerobic metabolism, mainly in muscle tissue. Its concentration normally falls in a subject at rest, but the rate of decline during meditation proved to be more than three times faster than the normal rate.



RAPID RISE in the electrical resistance of the skin accompanied meditation (*colored area*) in a representative subject. The 15 subjects tested showed a rise of about 140,000 ohms in 20 minutes. In sleep skin resistance normally rises but not so much or at such a rate.

decrease in people normally resting in a supine position or in the subjects themselves during their premeditation period. After the subjects ceased meditating the lactate level continued to fall for a few minutes and then began to rise, but at the end of the postmeditation period it was still considerably below the premeditation level. The mean level during the premeditation period was 11.4 milligrams per 100 cubic centimeters, during meditation 8.0 milligrams and during postmeditation 7.3 milligrams.

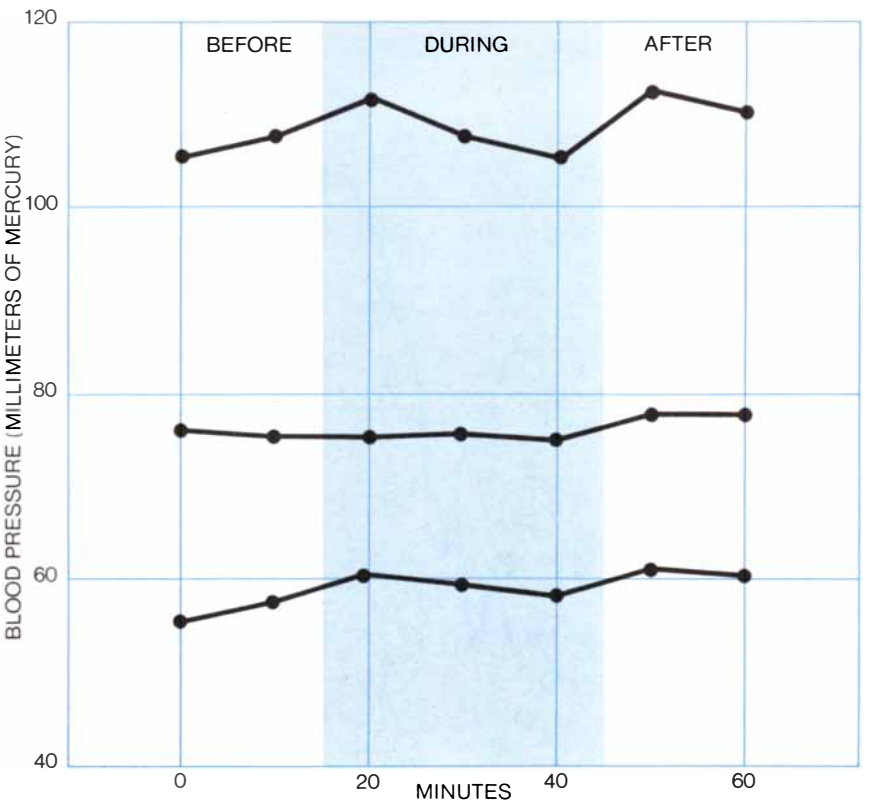
How could one account for the fact that lactate production, which reflects anaerobic metabolism, was reduced so much during meditation? New experiments furnished a possible answer. These had to do with the rate of blood flow in meditating subjects; the explanation they suggest appears significant with respect to the psychological benefits that can be obtained from meditation.

In studies H. Rieckert conducted at the University of Tübingen, he reported that during transcendental meditation his subjects showed a 300 percent increase in the flow of blood in the forearm. In similar measurements on our subjects we found the increase in forearm blood flow to be much less: 32 percent. Still, this increase was interesting, and it offered an explanation of the relatively large decrease in blood-lactate concentration. The main site of lactate production in the body is the skeletal muscle tissue. Presumably the observed acceleration of blood flow to the forearm muscles during meditation speeds up the delivery of oxygen to the muscles. The resulting gain in oxidative metabolism may substitute for anaerobic metabolism, and this would explain the sharp drop in the production of lactate that accompanies meditation.

The intriguing consequence of this view is that it brings the autonomic nervous system further into the picture. In a situation of constant blood pressure (which is the case during meditation) the rate of blood flow is controlled basically by dilation or constriction of the blood vessels. The autonomic nervous system, in turn, controls this blood-vessel behavior. One element in this system, a part of the sympathetic nerve network, sometimes gives rise to the secretion of acetylcholine through special fibers and thereby stimulates the blood vessels to dilate. Conversely, the major part of the sympathetic nerve network stimulates the secretion of norepinephrine and thus causes constriction of the blood vessels. Rieckert's finding of a large increase in blood flow during meditation suggested that meditation increased the activity of the sympathetic nerve network that secretes the dilating substance. Our own finding of a much more modest enhancement of blood flow indicated a different view: that meditation reduces the activity of the major part of the sympathetic nerve network, so that its constriction of the blood vessels is absent. This interpretation also helps to account for the great decrease in the production of lactate during meditation; norepinephrine is known to stimulate lactate production, and a reduction in the secretion of norepinephrine, through inhibition of the major sympathetic network, should be expected to diminish the output of lactate.

Whatever the explanation of the fall in the blood-lactate level, it is clear that this could have a beneficial psychological effect. Patients with anxiety neurosis show a large rise in blood lactate when they are placed under stress [see "The Biochemistry of Anxiety," by Ferris N. Pitts, Jr.; SCIENTIFIC AMERICAN, February, 1969]. Indeed, Pitts and J. N. McClure, Jr., a co-worker of Pitts's at the Washington University School of Medicine, showed experimentally that an infusion of lactate could bring on attacks of anxiety in such patients and could even produce anxiety symptoms in normal subjects. Furthermore, it is significant that patients with hypertension (essential and renal) show higher blood-lactate levels in a resting state than patients without hypertension, whereas in contrast the low lactate level in transcendental meditators is associated with low blood pressure. All in all, it is reasonable to hypothesize that the low level of lactate found in subjects during and after transcendental meditation may be responsible in part for the meditators' thoroughly relaxed state.

Other measurements on the meditators confirmed the picture of a highly relaxed, although wakeful, condition. During meditation their skin resistance to an electric current increased markedly, in some cases more than fourfold. Their heart rate slowed by about three beats per minute on the average. Electroencephalographic recordings disclosed a marked intensification of alpha waves in all the subjects. We recorded the waves from seven main areas of the brain on magnetic tape and then analyzed the patterns with a computer. Typically there was an increase in intensity of slow alpha waves at eight or nine cycles per second in the frontal and central regions of the brain during meditation. In several subjects this change was also accompanied by prominent theta waves in the frontal area.

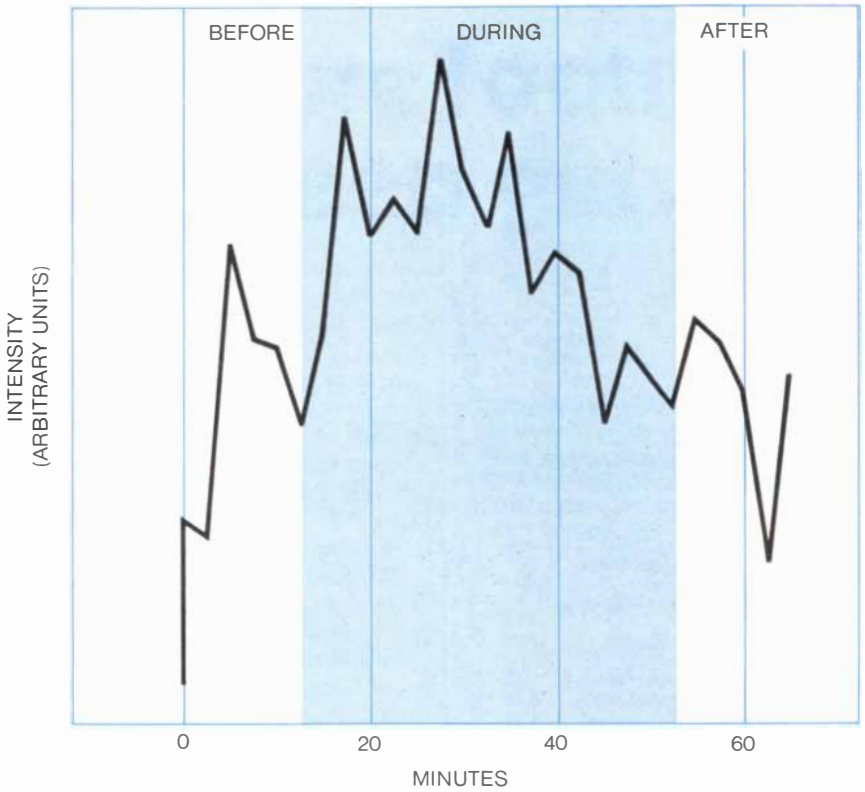


NO SIGNIFICANT CHANGE was observed in nine subjects whose arterial blood pressure was recorded before, during and after meditation. Systolic pressure (*top*), mean pressure (*middle*) and diastolic pressure (*bottom*), however, stayed relatively low throughout.

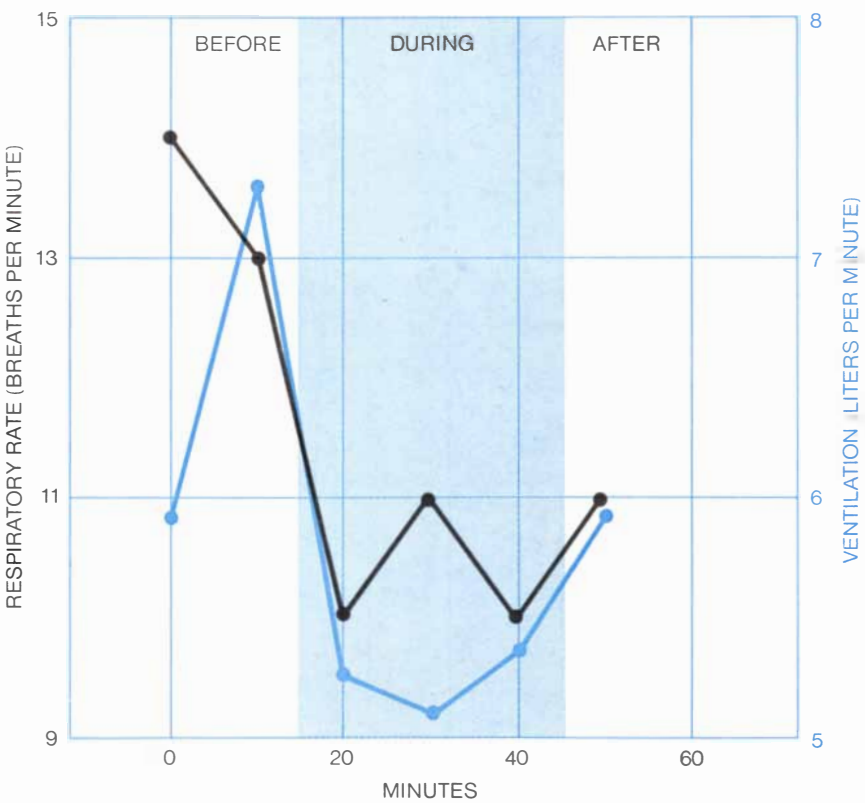
To sum up, our subjects during the practice of transcendental meditation manifested the physiological signs of what we describe as a "wakeful, hypometabolic" state: reductions in oxygen consumption, carbon dioxide elimination and the rate and volume of respiration; a slight increase in the acidity of the arterial blood; a marked decrease in the blood-lactate level; a slowing of the heartbeat; a considerable increase in skin resistance, and an electroencephalogram pattern of intensification of slow alpha waves with occasional theta-wave activity. These physiological modifications, in people who were practicing the easily learned technique of transcendental meditation, were very similar to those that have been observed in highly trained experts in yoga and in Zen monks who have had 15 to 20 years of experience in meditation.

How do the physiological changes during meditation compare with those in other relaxed states, such as sleep and hypnosis? There is little resemblance. Whereas oxygen consumption drops rapidly within the first five or 10 minutes of transcendental meditation, hypnosis produces no noticeable change in this metabolic index, and during sleep the consumption of oxygen decreases appreciably only after several hours. During sleep the concentration of carbon dioxide in the blood increases significantly, indicating a reduction in respiration. There is a slight increase in the acidity of the blood; this is clearly due to the decrease in ventilation and not to a change in metabolism such as occurs during meditation. Skin resistance commonly increases during sleep, but the rate and amount of this increase are on a much smaller scale than they are in transcendental meditation. The electroencephalogram patterns characteristic of sleep are different; they consist predominantly of high-voltage (strong) activity of slow waves at 12 to 14 cycles per second and a mixture of weaker waves at various frequencies—a pattern that does not occur during transcendental meditation. The patterns during hypnosis have no relation to those of the meditative state; in a hypnotized subject the brain-wave activity takes the form characteristic of the mental state that has been suggested to the subject. The same is true of changes in heart rate, blood pressure, skin resistance and respiration; all these visceral adjustments in a hypnotized person merely reflect the suggested state.

It is interesting to compare the effects obtained through meditation with those that can be established by means of operant conditioning. By such conditioning



INCREASE IN INTENSITY of "slow" alpha waves, at eight to nine cycles per second, was evident during meditation (*colored area*) in electroencephalograph readings of the subjects' frontal and central brain regions. This is a representative subject's frontal reading. Before meditation most subjects' frontal readings showed alpha waves of lower intensity.



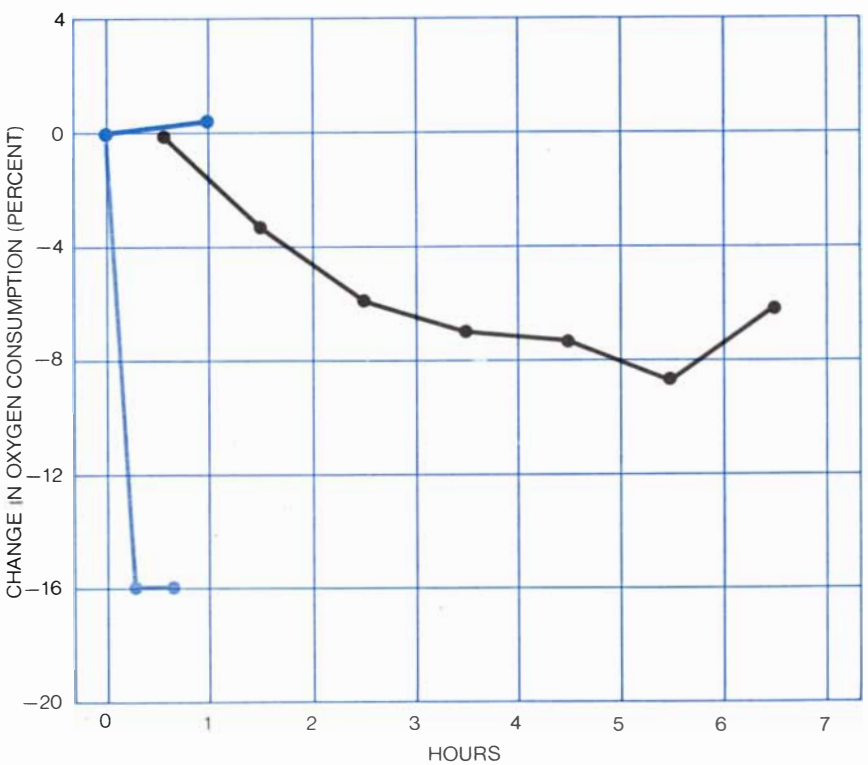
DECREASES OCCURRED in respiratory rate (*black*) and in volume of air breathed (*color*) during meditation. The ratio between carbon dioxide expired and oxygen consumed, however, continued unchanged and in the normal range during the entire test period.

animals and people have been trained to increase or decrease their heart rate, blood pressure, urine formation and certain other autonomic functions [see "Learning in the Autonomic Nervous System," by Leo V. DiCara; SCIENTIFIC AMERICAN, January, 1970]. Through the use of rewards that act as reinforcers a subject is taught to make a specific visceral response to a given stimulus. This procedure and the result are quite different, however, from what occurs in transcendental meditation. Whereas operant conditioning is limited to producing specific responses and depends on a stimulus and feedback of a reinforcer, meditation is independent of such assistance and produces not a single specific response but a complex of responses that marks a highly relaxed state.

The pattern of changes suggests that meditation generates an integrated response, or reflex, that is mediated by the central nervous system. A well-known reflex of such a nature was described many years ago by the noted Harvard physiologist Walter B. Cannon; it is called the "fight or flight" or "defense alarm" reaction. The aroused sympathetic nervous system mobilizes a set of physiological responses marked by increases in the blood pressure, heart rate, blood flow to the muscles and oxygen consumption. The hypometabolic state produced by meditation is of course opposite to this in almost all respects. It looks very much like a counterpart of the fight-or-flight reaction.

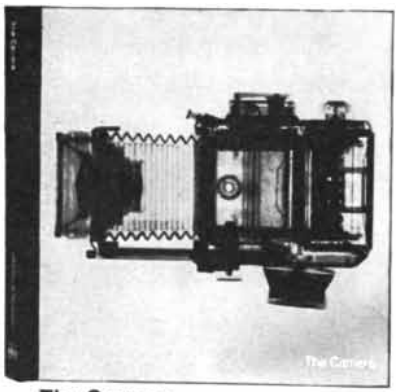
During man's early history the defense-alarm reaction may well have had high survival value and thus have become strongly established in his genetic makeup. It continues to be aroused in all its visceral aspects when the individual feels threatened. Yet in the environment of our time the reaction is often an anachronism. Although the defense-alarm reaction is generally no longer appropriate, the visceral response is evoked with considerable frequency by the rapid and unsettling changes that are buffeting modern society. There is good reason to believe the changing environment's incessant stimulations of the sympathetic nervous system are largely responsible for the high incidence of hypertension and similar serious diseases that are prevalent in our society.

In these circumstances the hypometabolic state, representing quiescence rather than hyperactivation of the sympathetic nervous system, may indicate a guidepost to better health. It should be well worthwhile to investigate the possibilities for clinical application of this state of wakeful rest and relaxation.

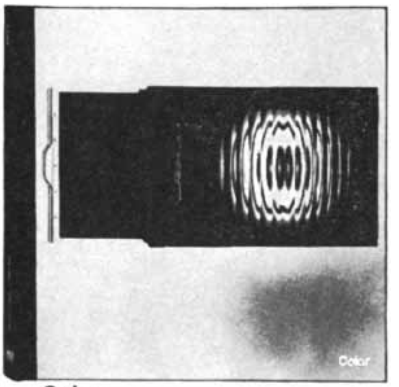


CONSUMPTION OF OXYGEN is compared in three different circumstances: during hypnosis (*color*), sleep (*black*) and meditation (*light color*). No significant change occurs under hypnosis. One study shows that oxygen consumption is reduced by about 8 percent after five hours' sleep. Meditation brings twice the reduction in a fraction of the time.

There is a paradox about photography...



The Camera



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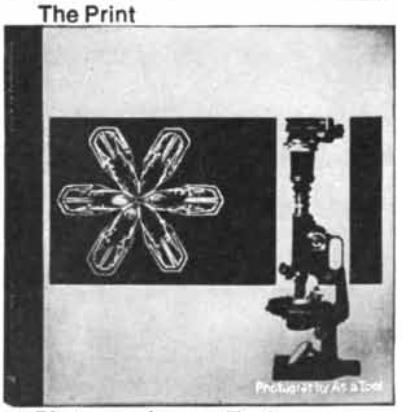

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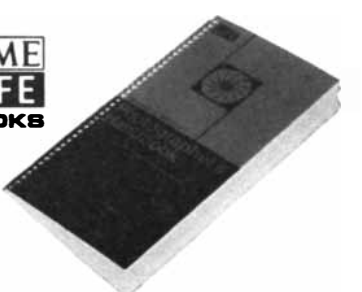

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INFANTICIDE, involuntary or otherwise, is a repeated motif in William Hogarth's "Gin Lane," a study of the evils of intemperance in 18th-century England. In the foreground a baby boy falls to his death as his intoxicated mother loosens her hold on him in order to take a pinch of snuff. At far right a second baby is quieted with a glass of gin, which at the time was commonly used as a tranquilizer. Meanwhile a drunken cook (*center background*) seems to be oblivious to a dying infant who has somehow become impaled on his spit, and no concern is being shown about another infant who rests on the ground by the open coffin that awaits his mother.

Checks on Population Growth: 1750–1850

In this period the population of Europe nearly doubled, but without certain checks it would have grown even more. There is much evidence that the checks were the widespread practice of celibacy and infanticide

by William L. Langer

In the span of a mere 100 years, between the 1750's and the 1850's, the population of Europe nearly doubled. Why? Midway through the period Thomas Malthus declared in his famous essay that human fecundity was so great that, if the population grew unchecked, it would increase much faster than the means of subsistence. But Malthus never for a moment supposed that the population would grow unchecked. There were at all times and in all places restrictions on its increase, so that whereas human numbers constantly tended to press on the means of subsistence, and a substantial part of the population was therefore doomed to live in misery on the verge of starvation, ultimate disaster was always forestalled.

The primary checks on population growth recognized by Malthus and by several of his predecessors in the field of population theory were those age-old scourges war, famine and disease. In the days when armies lived off the countryside, little remained for the inhabitants to eat. Furthermore, the filthy army encampments were breeding grounds for disease, with the result that epidemics usually followed in an army's wake. Of course, war was not the only cause of famine and disease; crop failures were frequent. Such failures were usually local, but in the days when transportation was difficult, famine relief was all but impossible. The local population was reduced to eating roots, bark and even grass, and many starved to death.

Disease tended to follow along trade routes, settling primarily in the unsanitary towns. Visitations of the plague came at intervals of 10 years, the worst epidemics often carrying off from a fourth to a third of the population. As late as 1720 a severe outbreak of the plague in southeastern France left 40,000 dead out of a total of 90,000 in Marseilles, the corpses being piled in the streets for lack of men to remove them.

Along with the plague went other lethal diseases. For example, only about four in every 100 persons failed to contract smallpox, a hideous illness that chiefly afflicted children in the first year or two of life. Smallpox was fatal in about one case in seven; in the latter part of the 18th century it was the cause of 10 percent of all deaths. In an expanded version of *An Essay on the Principle of Population*, published in 1806, Malthus noted: "The small-pox is certainly one of the channels, and a broad one, which nature has opened for the last thousand years, to keep down the population to the level of the means of subsistence."

Plague and smallpox were undoubtedly the greatest killers, although tuberculosis and typhus were not far behind. Viewing the pre-Malthusian period as a whole, one can understand that humanity lived in constant dread of war, famine and disease, and that this terrible trio ensured a steady and substantial check on population growth. As Malthus noted, pestilence can sweep off thousands and tens of thousands. Then "gigantic famine stalks in the rear, and at one mighty blow levels the population with the food of the world."

Malthus recognized that in addition to the three major levelers there were other "active and able ministers of depopulation," among them such sexual irregularities as promiscuous intercourse, violation of the marriage vow and improper arts to conceal the consequences of illicit connections. He did not, however, attempt to describe or analyze the role played by these lesser influences. Neither, for that matter, did the many writers who in the wake of the *Essay* participated in the Malthusian controversy. It is my purpose here to examine more closely some of the supplementary checks on population growth and to attempt an evaluation of their importance.

Marriage customs, particularly the prevalence of celibacy, must have been important subsidiary checks on population growth, but the subject is an elusive one. There were plainly many variables, and our knowledge of European marriage in the prestatistical period is both scant and unreliable. This much is certain: the rate of marriage fluctuated everywhere in constant response to economic conditions. A good harvest would invariably produce a rich crop of marriages, and lean years were marked by a sharp decline in new unions.

It can also be said that in general Europeans of the 18th century were marrying at a later age than before. For example, David J. Herlihy of the University of Wisconsin has determined that in late 15th-century Florence more than 90 percent of some 400 upper-class women whose marriage records he examined had married before the age of 20; 50 percent of them were married at the age of 16. Exact data for the 18th century are meager, but it is probably not far from the truth to say that men then married at an average age of 28 or 29. Women married at 25 or 26, and a large proportion of the population never married at all. The lateness of marriage among women meant that their period of fertility was reduced by perhaps a third, so that the custom had a significant effect on population growth.

It should be kept in mind that well into the 19th century marriages for love were the exception rather than the rule in Europe. Wherever property was involved the marriage contract was a business deal concluded by the heads of the families, often with little or no reference to the desires of the marriage partners. Moreover, many upper-class men were

FOUNDLINGS' PROTECTOR, the retired English sea captain Thomas Coram, won royal backing for a home for deserted children that opened its doors in 1741. He is depicted here coming on one of the many abandoned infants whose plight so concerned him.

reluctant to marry at all, according to Malthus, because of "the facility with which they can indulge themselves in . . . illicit intercourse."

Even where the law of primogeniture was not in effect, the nobility strove to maintain their estates intact through inheritance by a single individual. The bulk of the estate usually went to the eldest son, who provided for his mother and, if possible, for his sisters. His brothers, if he was willing to finance their education, went into the professions. Otherwise they went into the church or the army, in which case they remained single unless they were able to woo and wed an heiress; contemporary literature exploited this theme almost *ad nauseam*.

The upper classes restricted marriages other than their own. One of the chief employment opportunities for women in this era was domestic service; even well into the 19th century people of decidedly modest means still employed two or more servants, and the staff of a great manor house of the nobility might number in the fifties. Usually well treated and well paid, the servants had no desire to marry, so that many thousands of women were withdrawn from the ranks of childbearers. Moreover, on large estates, particularly on the Continent, the consent of the master was required for marriage. A landowner was further able to control the population of his holdings by refusing to build cottages for the newly married or even by destroying such tenant housing as existed, thus forcing the inhabitants to seek shelter elsewhere. In the British Isles at the end of the 18th century, one eminent historian has written, "there was throughout the country an open war on cottages." John McFarlan, a Scottish parson, bitterly denounced "the barbarous policy of some country gentlemen who will not suffer the poor to marry, lest they should breed a race of beggars to be supported by the parish." This practice, Sir Frederick Eden noted in *The State of the Poor*, was "the greatest difficulty under which the poor laboured."

Celibacy seems to have been even more common on the Continent than in England. The evidence, which is admittedly sparse, suggests that among women of childbearing age in France 30 to 40 percent remained unmarried and that only some 40 percent of men founded families. Many unmarried men took refuge in the military or the clergy; the spinsters might take up an aunt's role in a brother's household or enter domestic service. Many writers of the time were concerned for the future of France; a modern authority speaks of an 18th-century *crise de nuptialité*.

As in England, the nobility on the Continent controlled the marriages of serfs and other estate workers. Conditions in the Baltic duchies of Mecklenburg provide a classic example. Many of the most intelligent and attractive young women were kept in the manor houses as unmarried servants. The young men were generally conscripted for the army at the age of 22 and obliged to remain single for the six years of their service. In addition, the numbers of the poorer population were held in check by an intentional shortage of housing.

Trade and craft guilds, wherever they still retained power, used their influence and authority to forestall or postpone the marriage of workers. Even the journeymen who had completed their lengthy training were rarely given permission by the guild masters to marry, unless the prospective bride was the widow of a master or an unmarriageable daughter. A great many journeymen therefore never married at all.

Still another factor making for reduced fertility was the trade in mercenary soldiers that was so popular during those times. For centuries the cantons of Switzerland had done a thriving business in hiring out their young men to serve long enlistments in the armies of France, Spain, the Netherlands and various Italian states. Only a few of these men ever returned home and married; the mortality in war was heavy. It has been estimated that over the years the mercenary system did away with 35 to 40 percent of the natural increase in the Swiss population. There were still 20,000 Swiss mercenaries in the French army in 1748 and another 20,000 in the Dutch forces. In the course of the 18th century the Swiss cantons, with a total population of only 1.5 million or so, are thought to have lost 500,000 men on foreign battlefields.

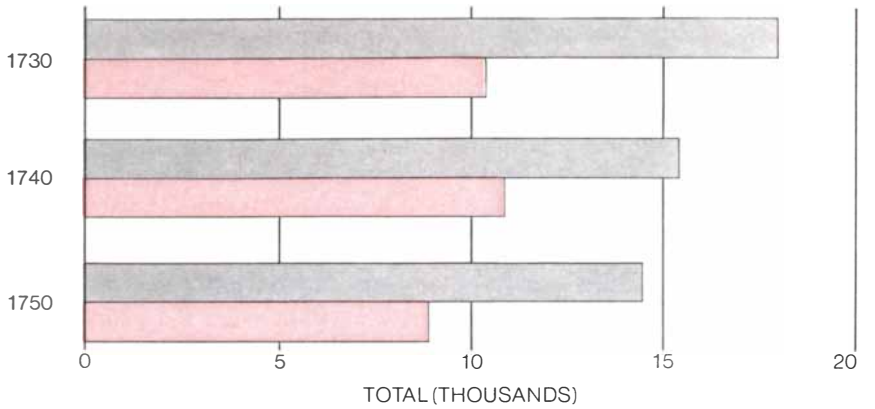
Another significant check on population growth was provided by the legal restrictions imposed on marriage by a number of European states, the German principalities in particular. In the 18th century all governments wanted as large a population as possible because it was believed that the power of a state depended largely on its human resources. The resources they sought, however, were sturdy, industrious farmers and skilled artisans. Not wanting paupers, governments were constantly inventing schemes to get rid of the poor or at least to prevent them from multiplying. The overpopulated German states led in the effort to legally restrict or even prevent marriage among the poor. The most far-reaching laws were those of Württemberg, a region that suffered from chronic population pressure. A series of decrees, beginning in 1712, required official approval of every marriage. Each prospective husband had to give proof of his ability to support a family; the requirement effectively denied paupers the right to marry.

Most of these restrictions were abandoned in the turmoil of the Napoleonic period. They were reintroduced and reinforced early in the 19th century as Europe was seized by fear of overpopulation and alarmed by the growing army of paupers. A number of Swiss cantons and all German states except Prussia and Saxony adopted marriage regulations of varying degrees of harshness. Almost without exception these required a prospective husband to demonstrate that he had not received poor relief during the preceding three years, that he had learned a trade and was now employed, that he had a domicile and that he was a person of good character. Administration of these ordinances was left entirely to local authorities and no leniency was shown the poor.

In Württemberg, where in 1830 there was one marriage to every 121 inhabitants, the rate by 1854 had fallen to one in 236. Yet eminent German economists defended such restrictive legislation on the grounds that no one had the right to produce children whom he was unable to support and who thereby became the responsibility of the rest of the population.

In England much the same position was taken by Malthus, by the chairman of the Poor Law Commission, Nassau W. Senior, and even by John Stuart Mill. Senior actually ordered an inquiry into the marriage regulations of other states and evidently considered the introduction of similar measures in England. Social unrest was so great, however, and the agitation by William Cobbett and others against making marriage a luxury was so violent that only a hint of such a policy crept into the New Poor Law of 1834: male and female paupers who were admitted to workhouses were to be kept rigorously separated, even if they were man and wife, to forestall the propagation of more paupers.

Whether temporary or permanent, voluntary or enforced, celibacy was clearly a factor that limited population growth in precontraceptive times. Equally significant, if not more so, were the methods employed to dispose of unwanted children. Plato and Aristotle, and other ancient authors as well, accepted abortion and advocated infanticide as neces-



MORTALITY RATE was high among abandoned infants raised in English parish workhouses. Of nearly 500,000 christened between 1728 and 1757, more than 60 percent had died by age two. The graph shows christenings (*gray*) and deaths (*color*) in 1730, 1740 and 1750.

sary means of ridding society of infants who were deformed or diseased, and as a means of regulating the size of the population. It is also well known that the exposure of newborn children was practiced by many societies, even in recent times. What is not so generally realized is the extent to which infanticide continued to prevail in Western civilization. In England as late as 1878 about 6 percent of all violent deaths could be classed as infanticides.

The matter was not publicized because the Christian churches regarded it with abhorrence, denounced it along with abortion, contraception and other sexual practices, and induced Western governments to declare abortion and infanticide forms of murder punishable by death in a variety of unpleasantly imaginative ways. Nonetheless, and among the poor in particular, babies were often unwelcome and in any case were easy to replace if it was so desired. We can never know how many women were given dangerous drugs to induce abortion or how many babies were murdered in the first days of life. These crimes were easy to commit and difficult to prove. Because the culprits were rarely discovered, even the harshest penalties—such as death by drowning or burial alive—had little deterrent effect.

The easy methods of committing infanticide included dosing the baby with gin or opiates; starvation and strangulation were often resorted to, and cases of a skull broken by a hairbrush were by no means unknown. A simple and popular method was "overlaying," or smothering an infant who shared a bed with his parents. No doubt this occurred unintentionally when the parents were drunk or careless, but it happened so often that in some countries parents were forbidden to have small children sleep in the same bed with them. Of all procedures the most unobjectionable was simply to leave the infant at some church entrance or in a secluded doorway, in the hope that perhaps someone would rescue him. Most of these abandoned children died quickly of exposure or starvation.

In the 18th century it was not an uncommon spectacle to see the corpses of infants lying in the streets or on the dunghills of London and other large cities. Thomas Coram was only one of an increasing number of humanitarians who found this situation shocking and disgusting. A retired sea captain, Coram spent 17 years of his life enlisting the interest of influential ladies, who finally joined him in a petition to the king to establish a sanctuary "to prevent the frequent murders of poor, miserable infants at their birth [and] to suppress the inhuman custom of exposing new-born infants to perish in the streets."

When Coram's London Foundling Hospital was finally opened in 1741, it immediately became evident that he had underestimated the need. The pressure of applicants was so great that women fought at the hospital gates. Eventually, in 1756, Parliament undertook to provide the Foundling Hospital with funds on the understanding that all children who were offered would be accepted. A basket equipped with a bell was to be hung outside the gate, so that a baby could be left without the mother's being seen, let alone questioned.

The policy of open admissions completely swamped the Foundling Hospital; in the first four years nearly 15,000 children were accepted. It was impossible to find enough wet nurses for such a number and thousands died in early infancy; only 4,400 of the foundlings lived to reach adolescence. The cost to Parliament was 500,000 pounds sterling, and in 1760 the policy was abandoned. Thenceforth only London children were accepted at the Foundling Hospital, and those in limited numbers. In the countryside foundlings were again assigned to the parish workhouses, which Jonas Hanway, a governor of the Foundling Hospital, called "slaughter-houses of infants" because the mortality was well-nigh total. In order to save trouble and money parish officers assigned the infants to paid nurses, who were universally detested and nicknamed "killing nurses" or "she-butchers" because no child ever escaped their care alive.

Infanticide in one form or another steadily increased in England during the 19th century. The statement of Richard Carlile, one of the early advocates of birth control, that "it is a question if infanticide ever prevailed in any country more than in our own" went unchallenged. Because the culprits were rarely discovered, only a few cases reached the courts. The defendants were usually let off with a light sentence; indeed, one of the London coroners, Edwin Lankester, testified that he had never known of a woman's being punished for killing her baby, no matter how flagrant the circumstances. Public sympathy was definitely on the side of desperate women, mostly servant girls made pregnant by their employer or destitute workers forced to resort to unofficial prostitution; deserted by the men involved, they were left to deal as best they could with unwanted children. "It is unhappily true," wrote the physician William B. Ryan in 1862, "that infanticide is not looked upon in the same light as other murders by the public generally.... There is no crime that meets with so much sympathy, often of the most ill-judged kind."

A thick volume of newspaper clippings can be found in the library of the Harvard Law School, most of them from the London press in the years 1861–1863. Together with the extensive report of the Select Committee on Protection of Infant Life in 1871, the clippings provide appalling evidence of the frequency of infanticide in those times. Scores of accounts tell of dead infants found in rivers, canals and drains or lying under the bushes in parks and fields. Coroners' reports show that between 1855 and 1860 inquests were held on 3,900 dead children in the London area, most of them newborn. In 1,120 instances the finding was murder; in 904 others it was "accidental" suffocation. In the 18 months ending in June, 1862, inquests were held on 5,113 dead children throughout England and Wales. The finding was mur-

der in 902 cases, 297 of them in London. In 1862 one of the coroners for Middlesex stated infanticide had become so commonplace "that the police seemed to think no more of finding a dead child than they did of finding a dead cat or a dead dog." The *Morning Star* (June 23, 1863) declared that infanticide "is positively becoming a national institution"; the *Morning Post* (September 2, 1863) termed it "this commonest of crimes."

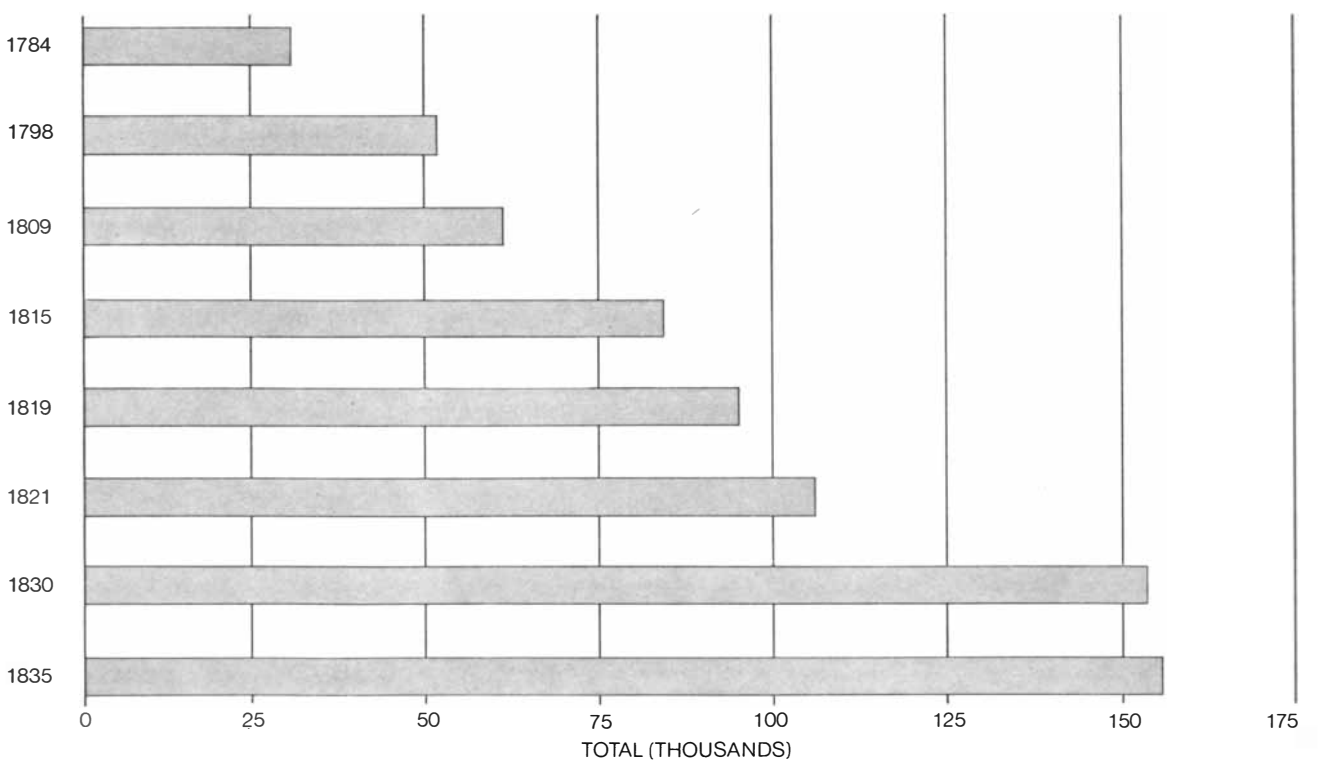
Quite possibly the majority of child murders were perpetrated through baby farms. Though the term "baby farming" hardly antedates Gilbert and Sullivan's *H.M.S. Pinafore,* the institution itself was doubtless of long standing. Women in the factory towns, working outside the home and in no position to care for a child, entrusted their infants to hired nurses—baby farmers—who usually cared for their charges by putting them to sleep with narcotics. Many of them never reawakened. Godfrey's Cordial, a concoction of opium, treacle and sassafras, was a great favorite. In Coventry it sold at the rate of 10 gallons a week—enough for 12,000 doses. In 1870 two baby farmers were brought to trial after 16 of their charges had been found dead. In the same year the bodies of 276 infants were collected in London alone. Under pressure from a newly founded group, the Infant Life Protection Society, Parliament in 1872 finally passed an act requiring baby farms to have a special license and to maintain full accounts of their admissions and deaths.

Infanticide on the Continent was as prevalent as it was in England. Great efforts were made in France and other Catholic countries to master the problem. More than half a century before the Foundling Hospital opened in London, Vincent de Paul, the great promoter and organizer of charities and missions, had interested the ladies of the French court in the plight of unmarried mothers and the related problems of infant exposure and infanticide. He was able to found the Hôpital des Enfants Trouvés, and in due course he secured financial aid from the government, which saw in the care and rearing of abandoned boys an eventual source of manpower for the army and navy.

Before the end of the 18th century similar institutions had been opened in all the major cities of the Continent. In St. Petersburg, Catherine the Great established one of the largest and most lavish foundling centers in 1770 and encouraged the ladies of the court to make it their favorite charity. At all these hospices, as at the London Foundling Hospital, the pressure of numbers rose rapidly until in the late 18th century (which may fairly be called the golden age of seduction) they were hopelessly overburdened with applicants. It is said that some 500 *sages femmes* were engaged in baby farming in Paris alone, and that even so babies continued to be left in alleys and doorways.

A traffic grew up in transporting infants from the provinces to Paris; the practice persisted in spite of numerous decrees forbidding it under heavy penalty. At Valenciennes, for example, a number of contractors made a business of collecting newborn babies from midwives and carting them to Paris. The trip took several days and the infants received no care; hence only exceptional ones survived to reach their destination. As late as the middle of the 19th century the Rouen police reported the case of a woman who between 1843 and 1860 carried a total of 192 babies to Paris in a basket with compartments that would hold four or five at a time. In her later years, keeping up with technological advances, she traveled by railroad; this not only shortened her travel time but also enabled her to reach the Paris hospice at about midnight, a good hour for discreet abandonments.

The literature on the foundling institutions of Paris and other cities is voluminous and scholarly, but it is now almost entirely forgotten. It reveals a precipitous rise in the number of foundlings late in the 18th century and early in the 19th. In France as a whole there was an increase of more than 300 percent in less



HALF-CENTURY RECORD of child abandonments in France shows a fourfold increase between 1784 and 1835. Much of the rise in the decades after 1811 is attributable to Napoleon's decree of that year that encouraged many to abandon their legitimate issue.

than 40 years: from a total of 40,000 *enfants trouvés* in 1784 to 138,000 in 1822. In Paris between 1736 and 1750 about 4,000 babies a year were taken in; in 1765 the figure was 5,000, and in 1780 it was between 6,000 and 7,000.

Napoleon, at the height of his power, determined to make another effort to check the exposure and murder of unwanted babies by making their disposal not only simple but entirely anonymous. On January 19, 1811, he decreed that hospices be set up in every French department and if possible in every arrondissement. Each hospice should have an entrance with a revolving box and a bell, so that the person who left the child could do so without being seen by those inside.

The system was so alluring that it led many parents to abandon legitimate children. Indeed, it is thought that between a fourth and a third of the children left at such hospices were offspring whose parents either could not or would not support them. By 1830 some 270 revolving boxes had been installed in French hospices. They were well patronized. In a single decade (1824–1833) 336,297 infants were consigned to the French hospices and local authorities were staggering under the burden of expense.

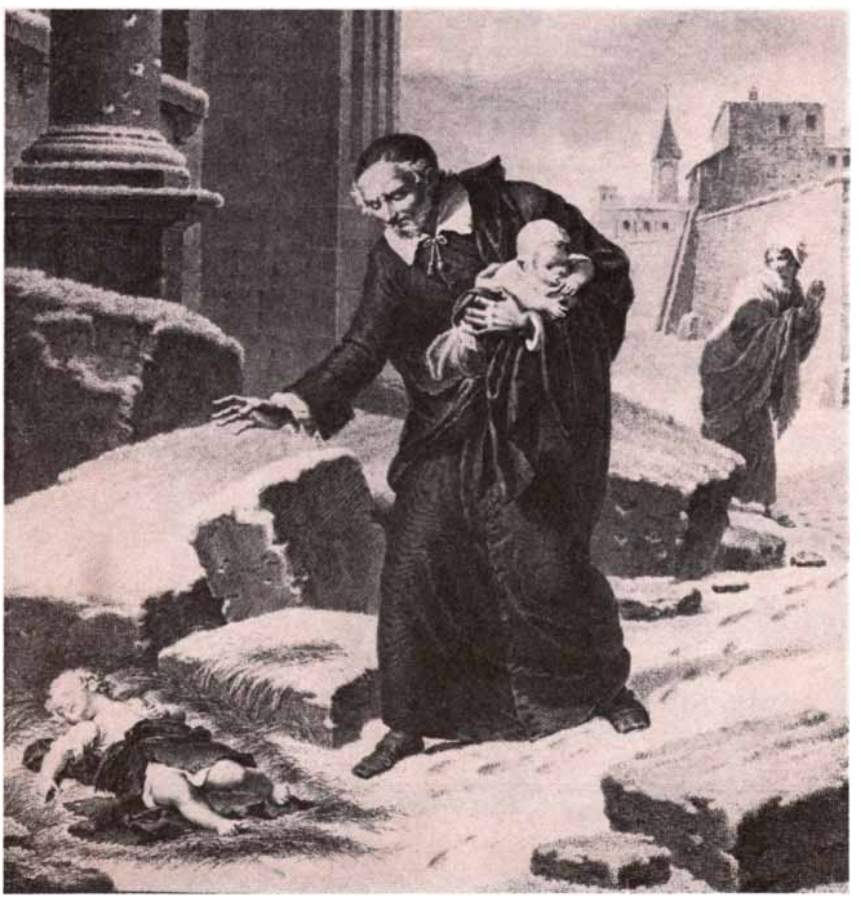
Needless to say, the mortality among the infants was heavy. Many of them were half-dead when they arrived; the rest had to be crowded into ill-ventilated quarters and fed as best the hospice could manage. To find enough wet nurses was impossible, so that the large majority of the infants had to be sent to the provinces for nursing. In the course of being transported, often over long distances and without proper care, most of the foundlings died.

The abundance of information on this overwhelming social problem leaves no doubt that late in the 18th century and early in the 19th fully 80 percent of the foundlings died in their first year, most of them in the first days of life. The Rouen records show that mortality in the hospice there regularly reached and at times exceeded 90 percent. Conditions were somewhat better in Paris. There in 1818 the Hôpital des Enfants Trouvés took in 4,779 babies. Of these, 2,370 died in the first three months and another 956 within the first year, so that the birth-through-12th-month mortality was less than 70 percent. The three winter months, says one commentator, regularly produced "a veritable hecatomb."

There was no mystery about these matters. Mothers who left their babies in the box knew that they were consigning them to death almost as surely as if they dropped them in the river. The general public was understandably appalled. Napoleon's well-intentioned decree amounted in practice to the legalization of infanticide. One writer suggested that the hospices post a sign declaring "Children killed at government expense."

It seems reasonable in the light of this painful record to conclude that infanticide, covert or flagrant, was at least as important as celibacy in checking population growth from the middle of the 18th century to the middle of the 19th. It is also evident that a marked change of attitude with respect to children, particularly the newborn, took place thereafter. What was then commonplace now seems intolerable cruelty. Yet the earlier attitude is not beyond understanding. The newborn bear little resemblance to more mature human beings or even to year-old children. Strong maternal feelings evidently are aroused only on the second or third day after giving birth, when nursing begins. Thus it is not surprising that among so many people at so many different times in history the disposal of unwanted babies has been accepted as a matter of course. In Europe from 1750 to 1850, at any rate, infanticide persisted in spite of all the denunciations of the church and all the penalties of the law.

Studies of celibacy and infanticide as checks on population growth are revealing, yet they have contributed little to an understanding of the phenomenal upsurge in European population that began about 1760 and that must certainly be ranked among the most portentous developments in modern history. The Europe of 1850, with a population of some 265 million, was clearly a very different place from the Europe of a century earlier, with a population of about 140 million. The explanation of this profound transformation has proved to be an intractable problem.



CLERICAL RESCUER of foundlings in the 17th century was the later canonized Vincent de Paul, shown here as imagined by a 19th-century painter, Nicholas Monsiau, in the course of retrieving babies who had been left to perish in the streets of Paris. With the aid of the ladies of the French court, Vincent opened one of the first foundling shelters in Europe.

If one considers the major checks to population growth, it is indisputable that in the century between the Napoleonic Wars and World War I international conflicts were less frequent, less widespread and less lethal than they

EVILS OF EXPOSURE (*left*) are contrasted with the benefits of foundling care (*right*) in a drawing presented by Hogarth to Coram; it was printed as an engraving at the head of the subscription roll for Coram's foundling home. Three victims of exposure are visible: a naked baby by a bush (*left foreground*), a swaddled child (*background*) being put down by his mother, and another child, whose grieving mother kneels in tears nearby, sheltered in the arm of a foundling-home official. The scene among the foundlings is one of industry: the girls are engaging in domestic tasks; boys' work parties are equipped for farming or duty at sea.

had been before that time. Famine too was less frequent and less severe as communications and transportation improved. Contrary to the general view, there were also significant advances in medical science and sanitation, particularly in dealing with the greatest killer after the disappearance of the plague: smallpox. The inoculation of children by the hundreds of thousands with the smallpox virus late in the 18th century and the vaccination of millions more with cowpox following the discoveries of Edward Jenner in 1798 provided a substantial measure of immunity to the disease. This must have substantially reduced the rate of infant mortality, which was a large part of total mortality.

Meanwhile subsidiary checks such as celibacy and infanticide remained in force. Government restrictions on marriages among the poor continued in effect in many German states until they were outlawed by the North German Confederation in 1868. Parental controls over marriage continued even into the 20th century. Moreover, the exposure, abandonment and murder of infants continued to increase along with the growth in population, and foundling hospitals were presently consuming almost half of local government income. Yet it seems clear that checks on population growth that had served their purpose for centuries suddenly proved inadequate to stem the rising tide. How could this be so?

If Malthus was right in arguing that population tends always to rise to the level of available subsistence, one should perhaps seek the answer to this question in some fundamental change in the European food supply that made possible the feeding of more than 100 million new mouths, no matter how poorly. Such a change did in fact take place roughly in concurrence with the European "population explosion." In the middle of the 18th century two imports from America —the potato and maize—began to be cultivated as field crops, the first in northern and central Europe and the second in southern Europe.

Both plants are exceptionally nutritious, easy to grow and rich in yield. Ireland, which pioneered the cultivation of the potato, became the classic example of a country where people married at an early age and raised a family of six or even eight (plus a pig) on a diet consisting almost exclusively of potatoes. By late in the 18th century the same regimen had been adopted in other thickly populated parts of Europe. In Flanders, in the Rhineland, in southwestern Germany and in Switzerland, wherever landholdings were highly fragmented, large families of poor people subsisted on the produce of puny potato patches. Overall the new field crops resulted in an increase of 25 to 30 percent in the food supply available even to the lowest social classes; the sudden expansion in human numbers followed. In the long run two other factors—the development of industrialism and emigration on a huge scale—relieved Europeans of the widespread fear of overpopulation.

This thesis, it must be admitted, has not yet been generally accepted, possibly because it appears too simple and probably because it has not been adequately explored. Economists and demographers like to work with statistics, and they are reluctant to deal with problems of the prestatistical age. They will wrestle manfully with the scant data that can be extracted from parish registers and similar records in an effort to determine birth and death rates, but they can find no statistics on the production of potatoes or maize, and they remain highly skeptical of the value of literary evidence.

It is thus left to the historian, accustomed as he is to working with fragmentary material, to make what he can of the evidence. Unfortunately historians have for the most part ignored population problems; many are still reluctant to accord a decisive influence to the lowly potato.

MATHEMATICAL GAMES

Dr. Matrix poses some heteroliteral puzzles while peddling perpetual motion in Houston

by Martin Gardner

O speculators about perpetual motion, how many vain chimeras have you created in the like quest? Go and take your place with the seekers of gold!

—LEONARDO DA VINCI

A startling letter from Bing Soph, an old friend now living in Houston, arrived in my mail early last August. Soph informed me that an elderly man from Wales, calling himself Llewelyn Hooker, Jr., had created a considerable stir in Houston with his claim to have invented a perpetual motion machine. A small working model of the device was on display in the lobby of the plush Shamrock-Hilton Hotel, where Hooker and his pretty assistant, Miss Jacquelyn Jones, were selling stock for the Hooker Dynamaforce Corporation.

Soph enclosed the company's handsomely printed prospectus. It outlined Hooker's scheme to build a gigantic dynamaforce generator on the Houston Ship Channel. Not only would dynamaforce provide cheap, unlimited power for the area; it also would cut the nation's air pollution in half as soon as the clean dynamaforce motor replaced the dirty internal-combustion engine. The prospectus contained no pictures of Hooker or Jones, but Soph had mentioned that the tall, bearded Hooker had green eyes and a prominent nose, and that Miss Jones's attractive features were unmistakably Eurasian.

I had little doubt that Hooker and Jones were none other than the notorious numerologist Dr. Irving Joshua Matrix and his half-Japanese daughter Iva, but I spent the next hour shuffling around the letters of LLEWELYN HOOKER, JR., to see what else they might spell. Dr. Matrix had a liking for anagrammatic aliases. The hunch paid off. The letters spelled JOHN WORRELL KEELY, a Philadelphia carpenter whose late-19th-century "Keely motor" was the most successful *perpetuum mobile* swindle in American history.

I stuffed some clothes into two cloth traveling bags and telephoned for a plane reservation. Shortly after four the next afternoon I stepped from the hot, humid air of Houston's Main Street into the cool lobby of the Shamrock. Frank Lloyd Wright is said to have remarked when he first entered this lobby: "Now I know what the inside of a jukebox looks like." For me, an ardent Oz buff, it was like walking into the palace of the Emerald City: thick green carpeting, garish green colors everywhere, including the Kelly-green uniforms and the pillbox hats of the busy bellhops.

It was Dr. Matrix and Iva all right, although both pretended not to know me. "Yes, indeed," Dr. Matrix muttered through a bushy Karl Marx beard, his emerald eyes glittering with mild surprise. "I see your column now and then. Do you think *Scientific American* would be interested in an article on dynamaforce?" He ignored a guffaw from a stout man standing behind me, who was wearing cowboy boots and a Stetson hat, long hair, sideburns and a large steer's-head belt buckle with bright ruby eyes. I learned later that he was a prominent physicist from the Houston Space Center.

"Show Mr. Gardner our model, J. J.," said Dr. Matrix.

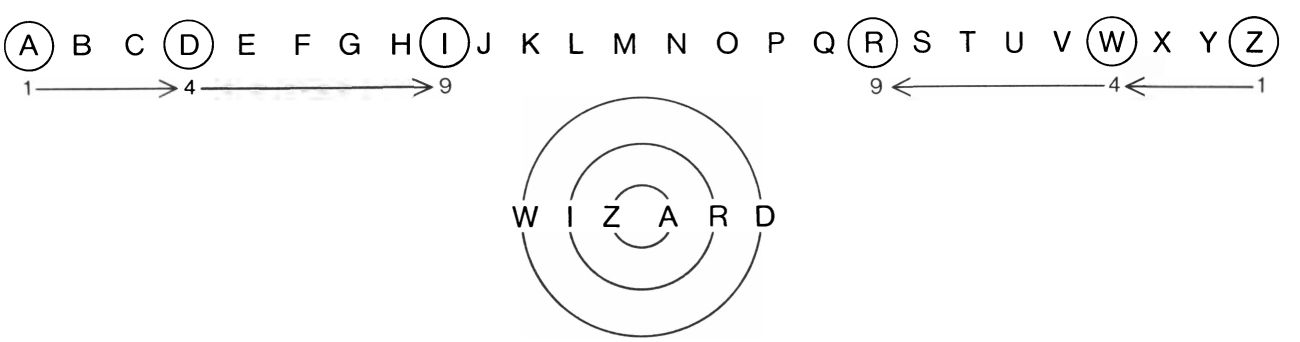
Iva led me by the hand into a small alcove behind the table where she and her father had been sitting. "Please don't give us away," she whispered. "And will you join us for dinner at seven?"

The working model, submerged in a square, vertical tank of water about two feet on each side and 10 feet high, was turning rapidly. Attached to a flexible and hollow belt of plastic were 10 airtight cylindrical glass chambers, each holding a heavy rubber ball that was free to slide with the force of gravity [*see illustration on opposite page*]. The volume of air inside the belt and chambers as a whole obviously remained constant. Because the balls on the right compressed the air, sending it into the chambers on the left where falling balls created suction, it was clear that the chambers on the left displaced more liquid than those on the right. The result was a strong buoyant force on the left that caused the belt and the two wheels to spin perpetually clockwise.

"Isn't it elegant?" said Iva, grinning like the Cheshire cat. She told me that Mrs. Bloomfield Moore, widow of a Texas oilman, had already invested half a million dollars in the project. Dr. Matrix soon hoped to get the same amount from Miss Ima Hogg, a Houston socialite and daughter of a cattle millionaire who was once governor of Texas.

We dined in the Shamrock's Pavilion restaurant, which overlooks the hotel's enormous swimming pool. Iva spoke little while Dr. Matrix and I conversed.

"I like your touch," I said, "of putting 'up' and 'dn' on the piston chambers. It reminds me of a gravity wheel C. L.



The alphabetical symmetry of "wizard"

Stong once pictured in his 'Amateur Scientist' department. The wheel had 9's on the down side. They outweighed the 6's they became on the up side."

"Nine has remarkable inversion properties," said Dr. Matrix, nodding. "Mel Stover, a Winnipeg numerologist, has pointed out that in Roman numerals 9 changes to 11 when turned over, but 9 in the binary system—1001—doesn't change at all. It also stays the same if you write it like this."

Dr. Matrix removed a large gold pen from his striped seersucker jacket. With its felt tip he wrote on my notepad:

nine

"Marvelous!" I exclaimed after turning the pad around.

"Nine and 6, of course, are the digits that made 1961 the year that is the same upside down. You might try this on your readers. It was sent to me by Arthur Hall of Pinner in England. What invertible past year has the largest time lapse between itself and its inverse?"

"Let's see," I mumbled. "The difference between 1,968 and 8,961 is . . . h'm . . . 6,993."

"You can do much better. The answer, by the way, is unique and naturally it turns out to be an important date in world history." He paused while the waiter served us green tea. Three young men at a nearby table seemed to be studying the geometric pattern on Iva's hot pants.

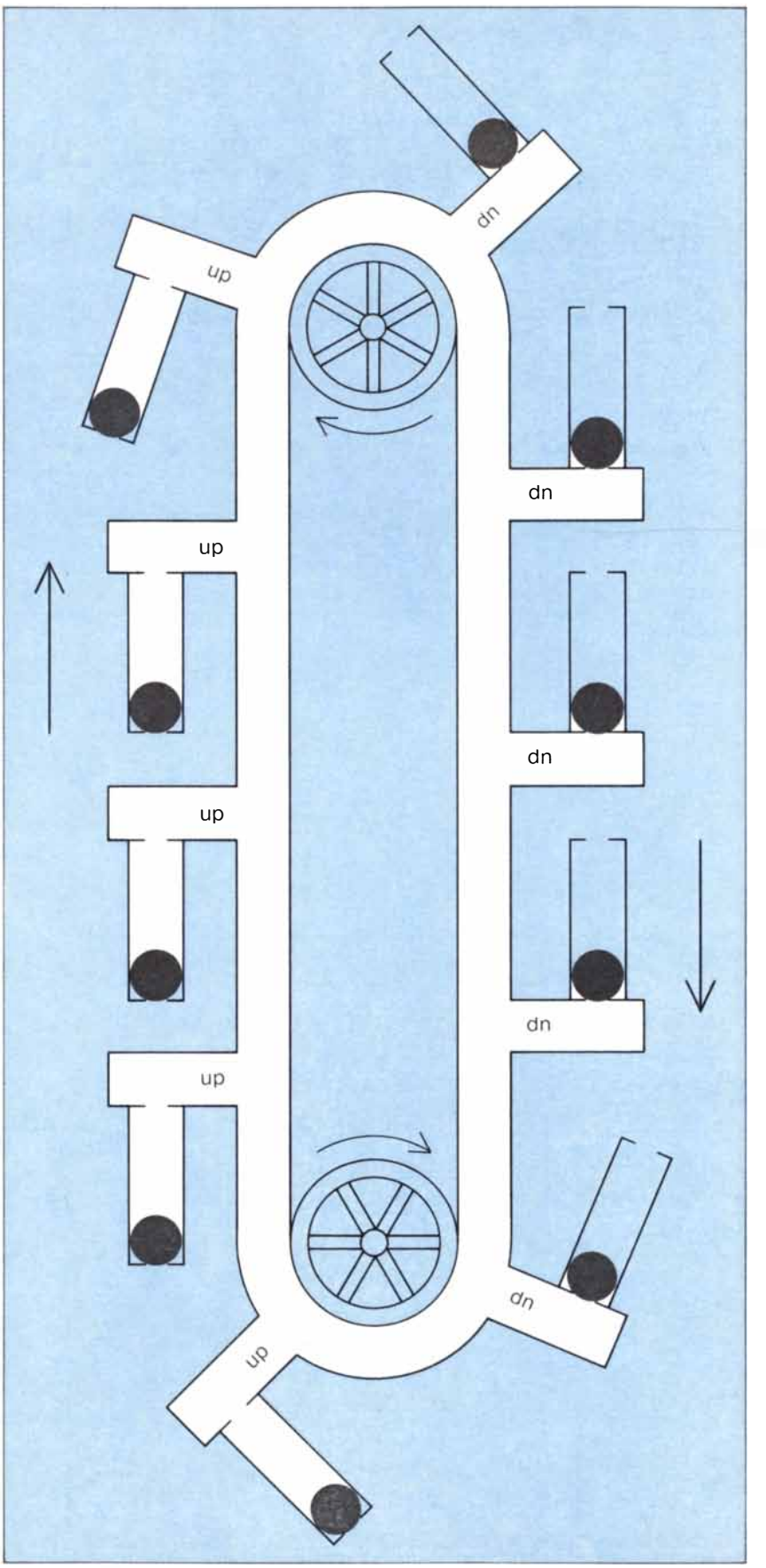
"I was not surprised," Dr. Matrix went on, "to read in one of your columns about Arthur C. Clarke's denial that he intended HAL to stand for IBM." [HAL was the name of the spaceship computer in the film *2001: A Space Odyssey*. If each letter of HAL is moved forward one letter in the alphabet, it becomes IBM. This curious fact had been disclosed by David B. Eisendrath, Jr., in his lively column in *Photo Methods for Industry*, October, 1970.]

Dr. Matrix continued: "Unintended correlations of this sort are commonplace. Mary Scott, a member of the International Wizard of Oz Club, recently observed that a one-step word shift of N.Y., the home state of L. Frank Baum, produces OZ."

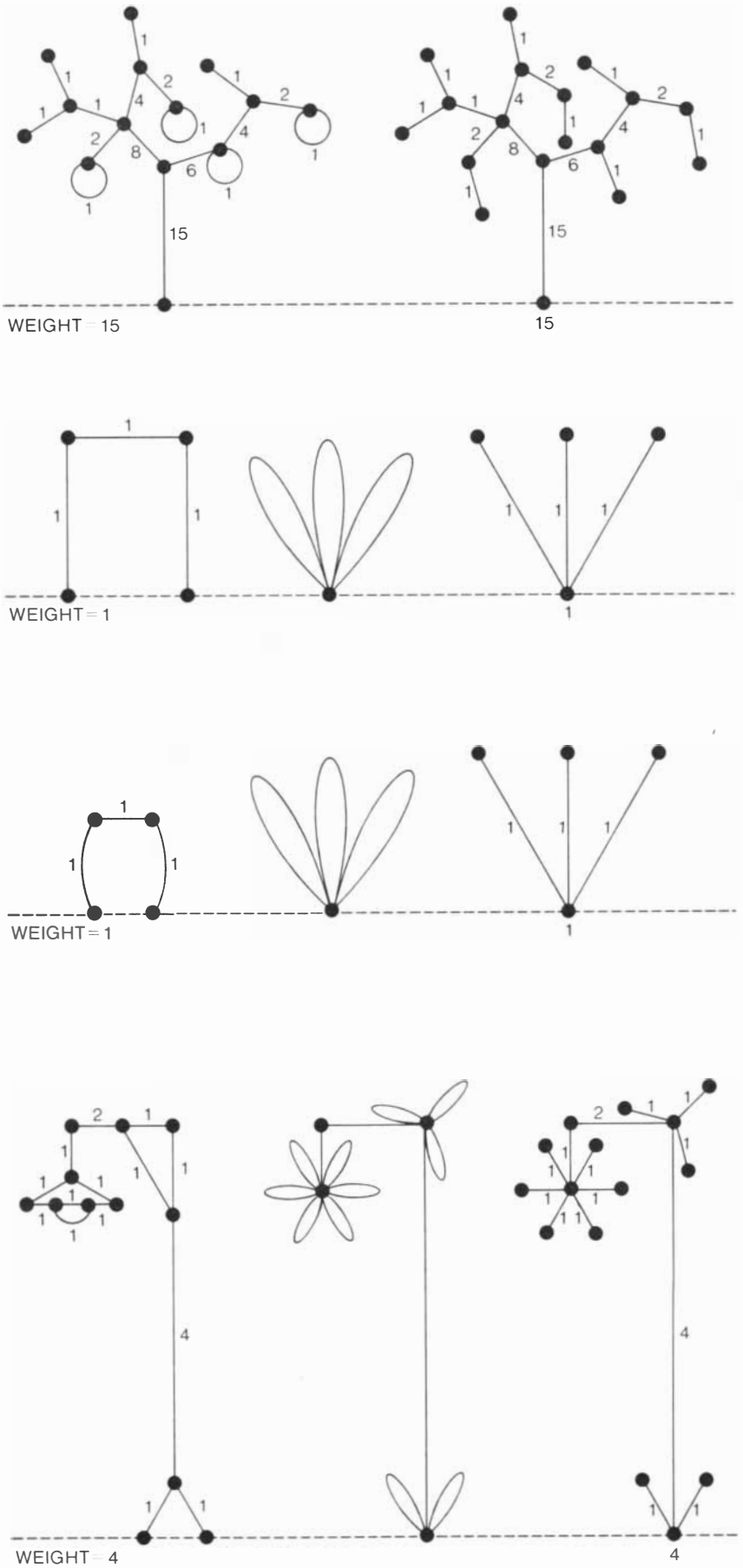
"By Glinda, so it does! Does the word 'wizard' have any numerological significance?"

"Everything does," sighed Dr. Matrix, while Iva's black eyes smiled at me over her teacup. "The word has a fantastic symmetry."

Dr. Matrix lettered the alphabet and



Dr. Matrix' dynamaforce generator



Weighing the Hackenbush apple tree, door, barrel and streetlight

circled the first letter at each end, then the fourth letter from each end and then the ninth letter from each end [*see illustration on page 100*]. They were the letters of "wizard."

"Need I call your attention," he added, "to the fact that 1, 4 and 9 are the first three square numbers?"

"I think, my dear papa," Iva said, "that Gardner would like another problem his readers could work on."

Dr. Matrix tugged on his beard. "Have you noticed the high probability that a randomly selected pair of English words will have at least one letter in common? Red, orange, yellow, green, blue, purple and white all share the letter *E*, but black, the absence of color, does not. Peter Wexler of the University of Essex discovered that the English name for every integer, starting with zero, shares a letter with the next-largest integer. Zero and 1 share *E*, 1 and 2 share *O*, 2 and 3 share *T*, and so on to infinity. There's a line in Longfellow's *Evangeline*, 'Warm by the forge within they watched the laboring bellows.' It contains all the letters in 'Henry Wadsworth Longfellow.' Are you aware that three young rock stars with *J* in their names—Brian Jones, Jimi Hendrix and Janis Joplin—all died in 1970, and that Jim Morrison died in 1971, in the *J* month of July?"

"And the problem?" Iva asked impatiently.

It proved to be a large class of problems. The idea, Dr. Matrix explained, is to look for rare and special examples of what Los Angeles numerologist David L. Silverman calls a "heteroliteral" pair of names. These are names with *no* letter in common. Silverman found, for example, that only one of the 50 states is heteroliteral with respect to its capital. Readers might enjoy searching for it. While doing so they may also discover which letter—there is only one—is not in the name of any state.

What is so rare, Silverman once asked Dr. Matrix when the two met at a numerological convention in San Francisco, as a Friday in June? Silverman meant: What is the only other heteroliteral day-month pair?

"But back to numbers," said Dr. Matrix. "Perhaps your readers can quickly determine the only letter not in the name of any number from zero through 100, yet in the name of every number greater than 100 and less than 200."

After I finished jotting all this down I asked Dr. Matrix if he had any numerological predictions about the 1972 presidential election. Dr. Matrix declined comment. He did, however, show me a

brainteaser from Arthur Hall concerning the digits of 1972. Plus and minus signs, and parentheses, are easily combined with 1972 to obtain expressions equal to 1, 10, 50 and 100:

$$1 + 9 - 7 - 2 = 1$$
$$19 - 7 - 2 = 10$$
$$(1 + 9)(7 - 2) = 50$$
$$1 + 97 + 2 = 100$$

Using only signs for addition, subtraction, multiplication and division (parentheses and brackets are also allowed), how can 9, 7 and 2 each be expressed? The sequence of the four digits in 1972 is not to be disturbed, nor may any digit be used as an exponent.

Iva consented to an evening prowl through the muggy streets of downtown Houston. I thanked Dr. Matrix for having grabbed the tab, and while we pumped hands I said: "It's only fair to warn you that I'm wrestling with my conscience. Your dynamaforce—let's face it—is a colossal dynamafarce."

"Nevertheless," he replied gravely, "like Galileo's earth, the thing does move."

"I'm sure the local police would like to know who you really are."

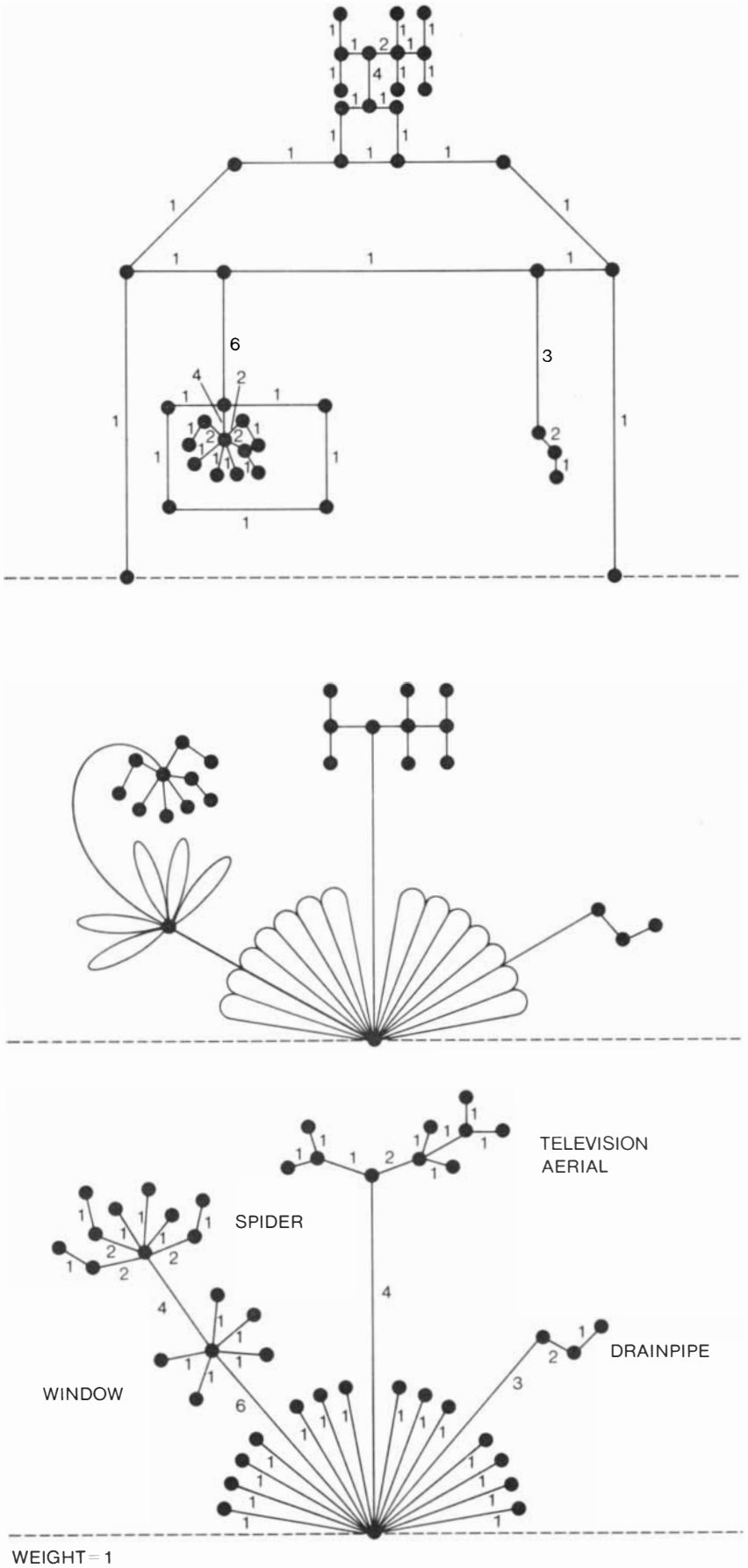
"You have a point there," said Iva, pointing to my head.

"I couldn't possibly fail," said Dr. Matrix, "to disagree with you and Iva less."

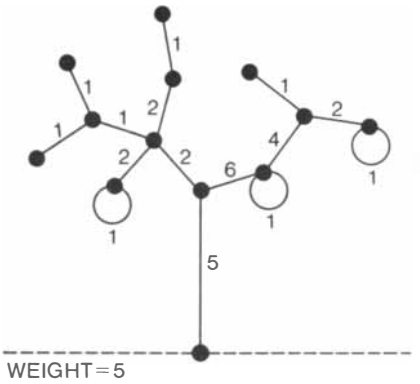
It took me several blocks to figure out what that meant. I spent the night battling my superego. Fortunately no decision had to be made. Next morning, while I was having breakfast with Soph, Hooker and J. J. were seen entering their black Cadillac and speeding off without paying their hotel bill. The dynamaforce model was found to have a tiny battery-driven motor cleverly concealed inside its base.

Early that afternoon I carried my luggage through a jam of people, detectives, reporters and photographers and stepped out of the Shamrock's air-conditioned lobby into a sunbaked inferno. Heat waves shimmered over the spotless concrete. The traffic on Main Street was heavy, and this brought to mind a letter from a reader, George E. Mallinson, who pointed out that the initials of Charles A. Reich, the author of *The Greening of America,* spell CAR—that complicated nongreen mechanism whose engine has become such a sooty albatross around the neck of the world.

Low in the eastern sky, over the oil refineries and chemical factories bordering the Houston Ship Channel, floated a brownish haze, a baleful by-product of



Weighing the Hackenbush house



Apple tree after the winning chop

20th-century seekers of black gold. It was a haze that would take more than dynamaforce to dissipate.

The first problem last month was to explain how the winning strategy in a chessboard version of nim is affected by allowing players to move their counters backward. The answer: It has almost no effect. If the loser retreats, the winner merely advances his opposing counter until the number of spaces separating the two men is the same as before. This preserves the status quo, leaving the basic strategy unaltered. The winner never retreats and, since the chessboard is finite, the loser's retreats must eventually cease. This variation of the game has been attributed to D. G. Northcott and is known as Northcott's nim.

How the various parts (graphs) of John Horton Conway's Hackenbush Homestead are transformed, as explained last month, into apple trees, then trees and labeled is shown in the illustrations on the preceding two pages. The graphs have weights of 15–1–1–4–1, therefore the Homestead's nim sum is 10. The only way the first player can reduce this Grundy number to zero is by lowering the apple tree's weight to 5. "The tree trunk supports two branches of 8 and 6," Conway writes, "and these must be changed to 2 and 6, or 8 and 12, to have nim sum 4. Clearly we must choose the left branch. Climbing the tree, we discover that there is a unique winning move—chop the twig bearing the highest apple on the tree."

This chop lowers the tree's weight (the value of its trunk) to 5 [*see illustration above*]. The graphs now have weights of 5–1–1–4–1, which have a nim sum of zero.

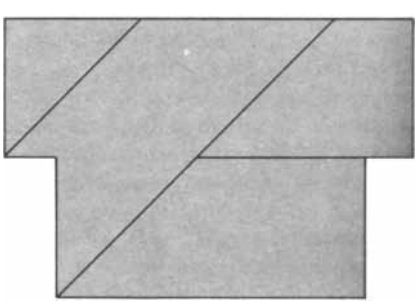
I promised to report on later results concerning the Halma problems of last October. The only improvement on one of the transfer problems was made by James Stuart (who gave no address), Katsumi Takemura of Yokohama and Seiichi Fusamura of Kyoto. They lowered the moves for a diagonal transfer of the three-by-three array, on the order-7 board, from 13 to 12. Octave Levenspiel, a physicist at Oregon State University, tackled the problem of transferring 10 counters from a triangular field on a Chinese-checkers board (its 121 cells are in the form of a six-pointed star) to the directly opposite triangular field. He found a 27-move solution, with palindromic symmetry, which surely must be minimal.

The three-move solution given in November for the Halma solitaire problem involving the order-4 array on an order-6 board apparently not only is fundamentally unique for ending on one of the central cells but also seems to be the only three-move solution that eliminates all but one counter when this last counter can end anywhere on the board. When the order-4 square is at the center of a standard eight-by-eight chessboard, a pretty four-move solution puts the last counter on a corner of the board. And there is a hard-to-find four-move solution, found by George Groth of Chicago, that leaves four counters at the corners of the order-4 square when it is centered on the order-6 field.

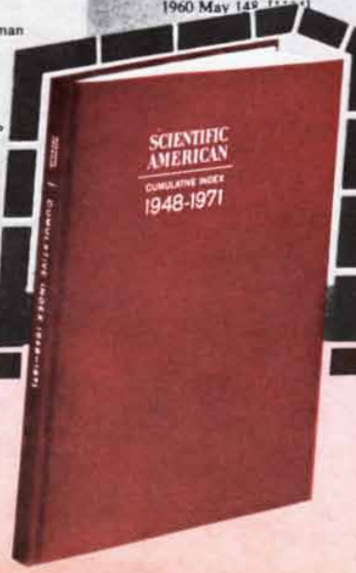
Groth also sent the following results: The order-5 array (on the order-7 board) has four-move solutions that end on any cell originally occupied; the order-6 formation (on the order-8 board) has six-move solutions to any cell formerly occupied, and a five-move solution to the board's corner, and there are two-move solutions for the order-3 array that place the last counter on any cell of the order-5 board's border.

John W. Harris of Santa Barbara, Calif., was the only reader to send results for the order-7 array on the order-9 Japanese chessboard. He found a solution, to the center cell, in seven moves.

An unexpected solution, albeit a fat one, of the old *T*-puzzle given in November was discovered by Manuel R. Pablo [*see illustration below*].



Pablo's solution to the T*-puzzle*



THE AMATEUR SCIENTIST

A simple laser interferometer, an inexpensive infrared viewer and simulated chromatograms

Conducted by C. L. Stong

When a moving object is photographed in ordinary light by time exposure, the resulting image is more or less blurred. Usually such photographs are of little interest to experimenters even though the fuzziness of the image varies with the amplitude of the movement. A comparable photograph made with coherent light, however, yields an accurate measurement of the displacement of the object. For example, a photograph of a vibrating tuning fork that is made with the coherent light of a helium-neon laser can be used for determining to less than a thousandth of an inch the amplitude of movement of the tines.

Displacements can be measured by making a double exposure of an object on a single sheet of film. One exposure is made before the object moves and one is made after it moves. The technique, which is known as speckle interferometry, can also be used to map local deformations in stressed mechanical parts such as the components of telescope mountings, seismometers, optical benches and similar devices. Ulrich Köpf of Fleischmannstrasse 7 in Munich explains the procedure as follows:

"Speckle interferometry resembles conventional holography in some respects but is much simpler to do. LeRoy D. Dickson has presented in these columns several ingenious hints for reducing the sensitivity of holographic apparatus to vibrations [see "The Amateur Scientist"; SCIENTIFIC AMERICAN, July, 1971]. Nevertheless, good holograms are not easy to make. In contrast, a reasonably careful beginner who undertakes an experiment with speckle interferometry can expect success on the first try.

"The technique is based on the speckling or granularity that appears when laser light is reflected by a dull surface such as a painted wall, a sheet of white paper or a roughened piece of metal. The uniform illumination produced by an incoherent source, such as an incandescent lamp, is replaced by a pattern of dazzling granules when a coherent source is used. Each speckle marks a point of constructive interference between waves of coherent light. The speckles are of high contrast. The diameters of the speckles vary statistically, but the mean diameter is determined by the resolving power of the optical system with which the speckles are observed and is approximately equal to the product of the aperture of the pupil of the eye (in the case of a camera, the focal ratio, or *f* number) multiplied by the wavelength of the light. The wavelength of the coherent light emitted by a helium-neon laser is 6.33×10^{-7} meter (6,330 angstroms).

"The pattern of speckles is caused by the diffuse surface texture of the object. When the surface is displaced at a right angle to the direction from which it is viewed, the pattern of speckles moves with it, much as if the speckles were minute spots of paint. The pattern can be recorded on photographic film as a double image. The amplitude of the displacement can be determined by examining the pattern of speckles.

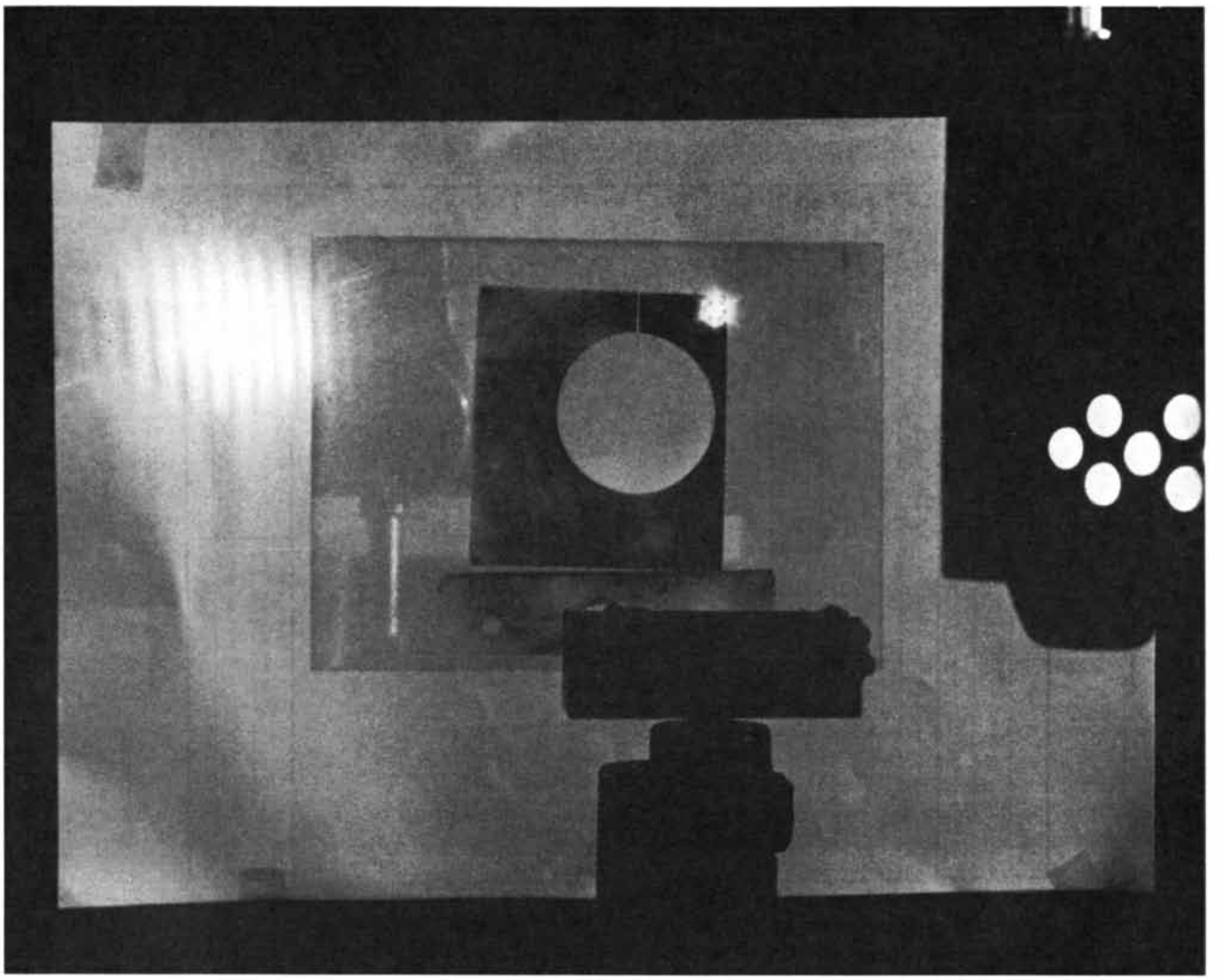
"With these principles in mind, one begins the experiment by flooding an object with the expanded beam of a helium-neon laser. The object might be a simple metal clamp similar to the one shown in the accompanying illustration [*top of page 108*]. The object can be supported by any reasonably stationary base, such as a brick. The beam of laser light can be expanded into a cone with a lens that has a focal length of some four to eight millimeters. I use a 40-power objective lens from a microscope, but a simple plano-convex lens will work as well. The distance between the laser and the object is not crucial, but it should be adjusted so that the cone of coherent light floods all parts of the object. The lens can be held in position by any improvised support that is reasonably rigid. The camera is placed at a distance where the sharply focused image of the object occupies a substantial portion of the photographic negative. The negatives should be of the high-resolution type. I use four-by-five-inch Agfa Gevaert Scientia plates, which are similar to Eastman Kodak 649F plates.

"My exposures are made with a studio camera. After the camera has been focused the aperture is set at a focal ratio, or *f* stop, that varies according to the resolving power of the photographic emulsion and is equal to 1 divided by the product of the resolving power of the emulsion multiplied by the wavelength of the coherent light. (The resolving power of the emulsion is specified by the manufacturer.)

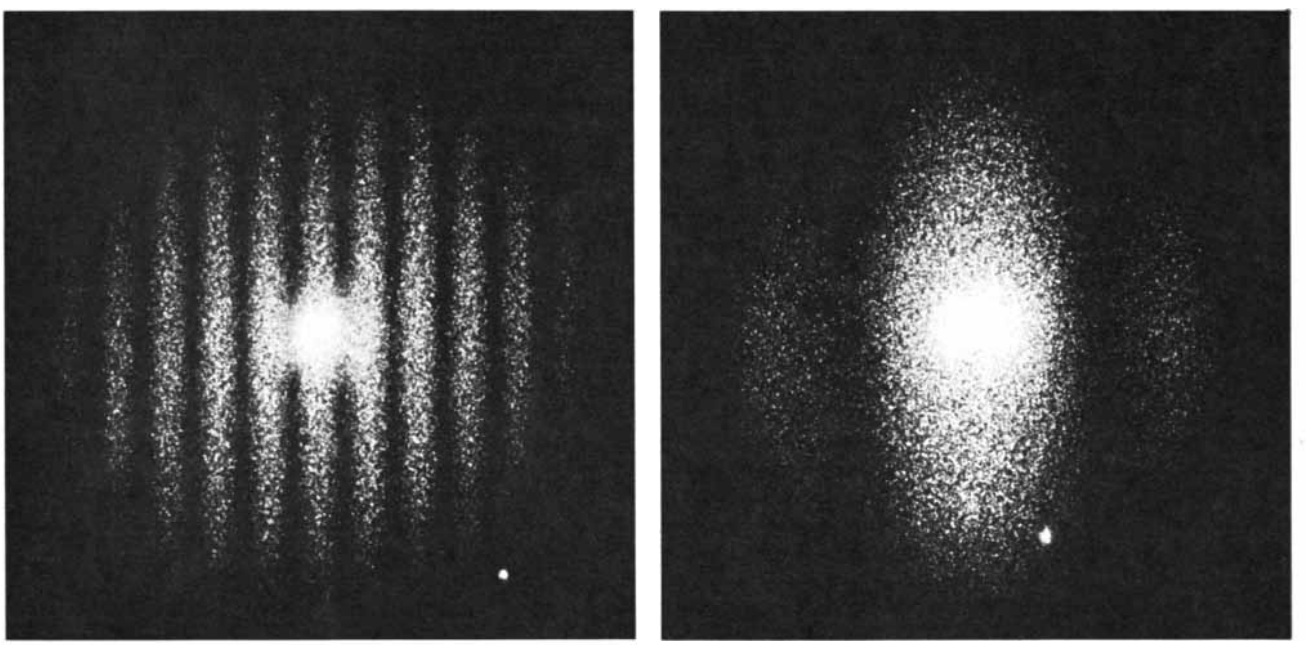
"The exposure interval is determined by flooding the object with laser light and measuring the intensity with a commercial exposure meter. Make the first exposure. Displace the object or otherwise alter its position in whole or in part at a right angle to the direction of the camera. With an object such as the clamp used in my experiment the metal can be warped by heating one side of the device with a small torch. The second exposure is then made on the same negative. The negative records two displaced but otherwise identical patterns of speckles. The negative is developed and fixed according to the procedure recommended by the manufacturer.

"The developed plate resembles an ordinary photographic negative, but the exposed area shows speckles. To detect the displacement and measure its amplitude the experimenter must analyze the complex speckle pattern into its local components by means of a Fourier transform. Do not be dismayed by the prospect of having to carry out this mathematical procedure with paper and pencil. It can be accomplished by an inexpensive analogue computer: a simple lens.

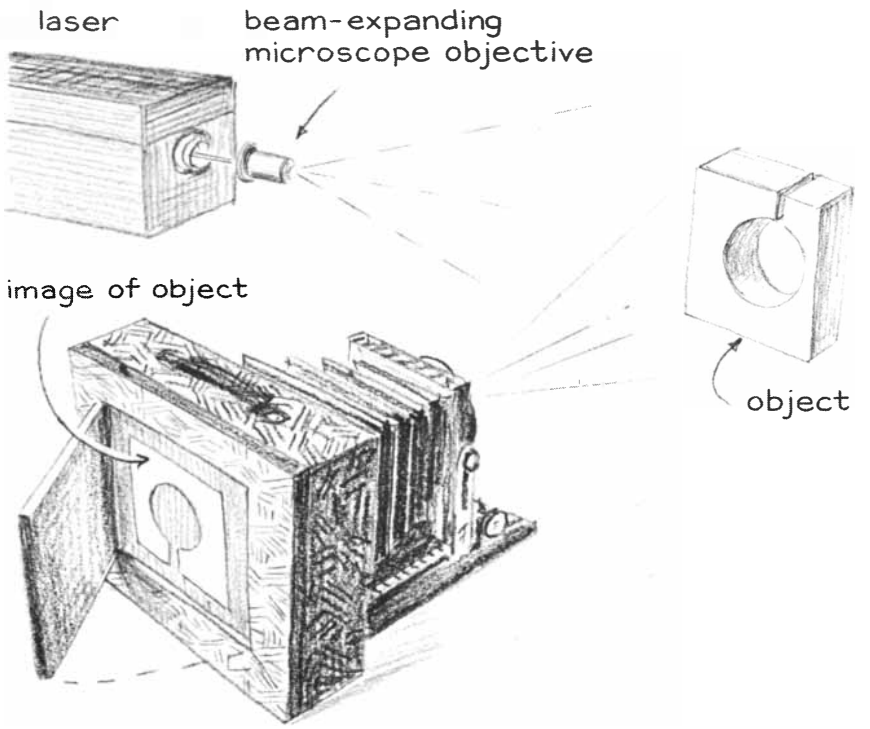
"To make the analysis support the film in the vertical plane by an improvised clamp and direct the laser beam



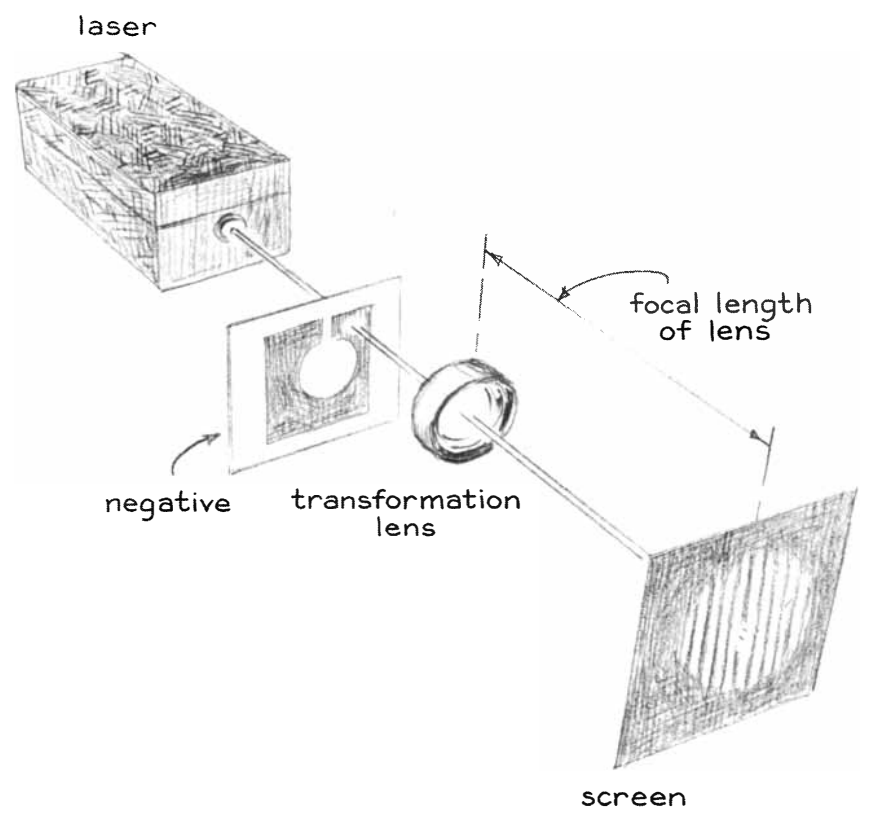
Ulrich Köpf's apparatus for making speckle interferograms



Fringe patterns indicating large displacement (left) *and small displacement* (right).



Equipment for Köpf's experiments



Arrangement for examining the holographic interferogram

through part of the image. Intercept the transmitted beam by the transformation lens adjusted to focus an image on a distant screen [*see bottom illustration at left*]. The image consists of parallel fringes of light and shade. The spacing of the fringes varies inversely with the displacement of the object at the point on the negative through which the laser beam is transmitted.

"Measure the distance d between any pair of adjacent fringes. It is easy to calculate from this known distance the displacement s of the object. The calculation includes the wavelength of the laser light (l), the focal length of the transformation lens (f) and the magnification of the photographic image (m). Usually the image is smaller than the object, hence the magnification is represented by a fraction. To determine the magnification divide the width of the image, as measured with a ruler, by the width of the object. The amplitude of the displacement is calculated by means of the formula $s = l \times f / m \times d$.

"In my experiment with the metal clamp the laser beam was directed through the image at two points: the upper corner, where maximum displacement was expected, and at the thin edge on one side [*see illustrations on preceding page*]. Fringes associated with the upper corner of the part were spaced 6×10^{-3} meter apart. Fringes associated with the thin edge measured 3.8×10^{-2} meter. The focal length of my transformation lens was 3×10^{-1} meter and the magnification of the image was .7. The displacement of the upper right corner of the clamp was therefore $6.33 \times 10^{-7} \times 3 \times 10^{-1} / .7 \times 6 \times 10^{-3} = 46 \times 10^{-6}$ meter, or .0018 inch. The displacement of the edge of the clamp was similarly calculated: $6.33 \times 10^{-7} \times 3 \times 10^{-1} / .7 \times 3.8 \times 10^{-2} = 7 \times 10^{-6}$ meter, or .00028 inch.

"The method is particularly easy to apply in the case of vibrating objects such as a tuning fork because the motion can be photographed by a single exposure. The amplitude of vibration can be measured throughout the length of the vibrating part by directing the laser beam through the photographic negative at a series of points. The laser need not be adjusted for operation in a single mode, as in making holograms, but can oscillate simultaneously in many transverse modes. Local deformations in an object that is stressed but not moved between two exposures are measured by scanning the photographic negative with the laser beam and monitoring the changing fringe distances and directions.

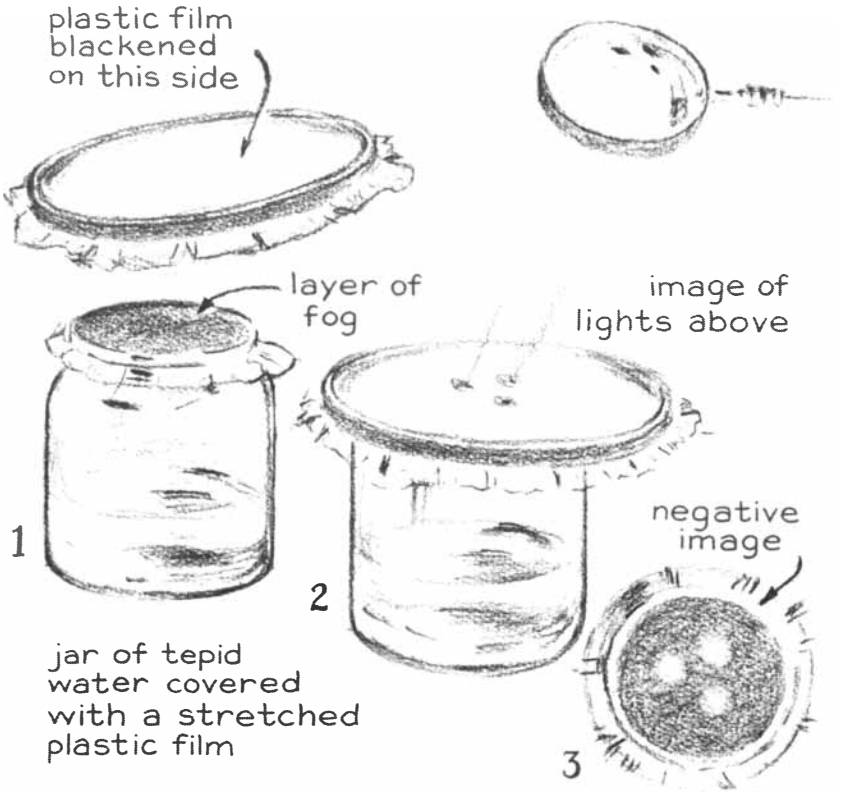
"Displacements occur at right angles to the direction of the fringes. Incidentally, if the transformation lens is removed, the fringes can still be observed provided that the diameter of the beam is less than the fringe separation."

A warning: Laser light is hazardous, particularly to the eye. *Never look into the beam.* When you are using a laser, confine the beam and all targets within an opaque housing.

Roger Baker (Box 7854, University of Texas Station, Austin, Tex. 78712) submits a simple apparatus for viewing images formed by infrared radiation. In principle his device resembles the Czerny evaporograph that was developed at the University of Frankfurt before World War II. In the Czerny apparatus a lens of rock salt focuses an image in infrared radiation on the blackened side of a plastic membrane that is enclosed in a sealed box from which air can be pumped. Rays from the lens enter the box through a window of rock salt. Volatile oil in a heated container at the bottom of the box condenses on the opposite surface of the membrane in the form of a transparent film of iridescent color. Local differences in the temperature of the membrane induced by the focused radiation cause the oil to evaporate from the film nonuniformly.

"The evaporation alters the thickness of the oil film in a pattern that corresponds to the image, which then appears in contrasting color. The colored image can be observed visually or photographically. An exposure of about 10 seconds registers the image of a human being after sunset at a range of 100 yards. Images can be erased by altering air pressure inside the box and thus controlling the rate at which oil is exchanged between the reservoir and the membrane. Baker's evaporograph is much simpler to construct and operate. He discusses it as follows:

"The device consists of a wide-mouthed jar partly filled with ink-stained water and closed by a diaphragm of thin plastic of the kind used for wrapping food. Like the Czerny evaporograph, the device can be used to record and display images formed by heat. Water vapor condenses on the inner surface of the plastic cover. The opaqueness of the condensation varies with its thickness and hence with the temperature of the plastic. An image in infrared radiation that is focused in the plane of the plastic becomes visible in the condensation as a negative image when viewed against the background of water colored with ink. The image can be erased by tipping the jar to wash away the condensation.



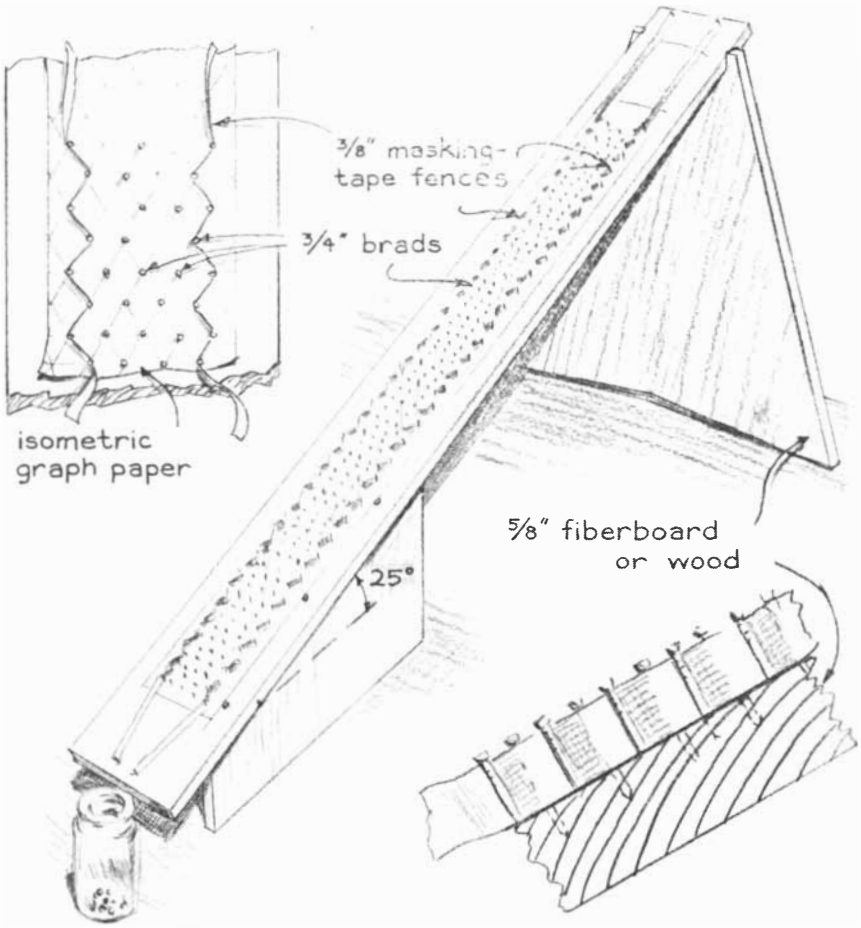
Roger Baker's evaporograph

"The sensitivity of the film to small changes in temperature varies with the way the device is used. For maximum sensitivity I partly fill the jar with a mixture of black ink and water at room temperature and let it stand until the temperature of the solution reaches equilibrium with that of the room. I then cool the metal handle of a kitchen knife or a rodlike piece of metal in ice water and pass it slowly across the top of the jar about an inch above the plastic. Currents of cold air flow down from the metal and cool the plastic to form an even coating of condensation. The temperature of the film changes only slightly because heat liberated by the condensing vapor is largely absorbed by the plastic.

"As in the case of photographic emulsions the density of the condensed film of water droplets varies with both temperature and time. For example, a film of plastic that is cooled one degree Celsius for one second will condense a given amount of water. The same amount of water would condense if the film were cooled .1 degree C. for 10 seconds or 10 degrees C. for .1 second. Conversely, the identical quantity of water will evaporate from the plastic if the temperature is raised .1 degree C. for 10 seconds or .01 degree for 100 seconds.

"The film tends to oppose any change in temperature. The sensitivity of the device to temperature changes in either direction can be demonstrated by coating the film as described and passing a finger lightly but rapidly across the top

Image of a cool penny



Chromatograph simulator made by Ray Parman, Jr.

of the plastic. You can hardly stroke the plastic quickly enough to avoid making a visible streak across the fogged surface where the flow of heat from your finger evaporated the water.

"Removing heat from the plastic similarly encourages condensation. Drop a cool penny or something like it on the plastic. If the plastic is stretched tightly, like the head of a drum, and is inclined slightly, the coin may bounce rapidly across the surface. Each bounce will deposit an image of the coin, including many details of the bas-relief.

"The condensation will store an image for 10 minutes or more if the room temperature is fairly constant, although the droplets gradually increase in size. As the droplets grow, color will appear as a result of optical refraction. The vividness of the color depends somewhat on the angle from which the image is observed.

"The plastic film is transparent and therefore relatively insensitive to infrared radiation. The sensitivity can be increased by covering it with a second film that has been blackened on one side with a coating of soot. I deposit the soot by wrapping a clear sheet of wet plastic tightly around a smooth bottle filled with ice water and passing it through the flame of a candle. The layer of water between the plastic and the glass increases the transmission of heat through the layers and prevents the plastic from reaching its melting temperature. Pinholes will appear in the plastic if it overheats. The smoked plastic is stretched across a supporting ring, such as a small embroidery hoop, and placed black side up over the jar. Air pressure in the jar causes the plastic cover to bow upward slightly, which ensures intimate contact between the two films.

"I have recorded impressions of distant incandescent lamps and other hot objects by focusing the rays on the blackened film with an ordinary magnifying glass. The image is observed by removing the blackened film. The images have not been of high quality. Glass is rather opaque to infrared radiation. I cannot afford a lens of rock salt.

"A concave mirror with a reflecting front surface would work well. I tried to make one of gold resinate, but it cracked as a result of my impatience during the firing procedure. Still, the method is sound. Gold resinate is available from dealers in ceramic supplies. A brilliant front-surface mirror can be made by flowing a thin layer of the resinate over a clear concave lens and baking it. Inexpensive lenses of this type up to two and a half inches in diameter are available from the Edmund Scientific Co., Barrington, N.J. 08007.

"Flow a puddle of the resinate over the clean glass. Drain off the excess by letting the glass stand coated side down on a paper towel. Dry the coating under a 100-watt desk lamp or an equivalent heater. As the coating dries, carefully remove the bead of resinate from around the edge of the lens. Bake the resinate by wrapping the lens loosely in aluminum foil and heating it to approximately 500 degrees C. Cool slowly. For a baking oven I use a covered skillet on a stove. Avoid my mistake of uncovering the lens before it has cooled to room temperature!"

At the beginning of this century the Russian botanist Michael Tswett performed an experiment that was destined to revolutionize the technique of separating mixtures of organic substances into their pure constituents. He extracted a mixture of plant pigments with petroleum ether and poured the solution into a glass tube that had been firmly packed with calcium carbonate. As the fluid trickled through the adsorbent powder each pigment migrated at a characteristic rate. Ultimately the moving pigments separated into distinctly colored zones. By continuing to pass solvent through the powder Tswett could wash the zones completely through the column and recover the pure compounds sequentially. In Tswett's words: "Such a preparation I term a chromatogram, and the corresponding method, the chromatographic method."

Tswett explained that a characteristic force of attraction exists between the particles of each pigment and the particles of calcium carbonate. As a result some pigments are strongly adsorbed by the calcium carbonate and others are adsorbed less strongly. Thermal agitation periodically dislodges the adsorbed particles from the powder. Dislodged particles are swept downstream, readsorbed, dislodged again and so on. A particle that is weakly adsorbed is dislodged more frequently than one that is

strongly adsorbed. It therefore migrates through the calcium carbonate at a proportionately higher net velocity than the more strongly adsorbed particle. As Tswett anticipated, the chromatographic technique has been applied for separating organic substances of all kinds.

To assist students in visualizing the mechanism of chromatographic analysis at the molecular level, Ray Parman, Jr., of Central State University in Edmond, Okla., recently developed an apparatus that displays by analogy a greatly magnified version of the action in two dimensions. The apparatus consists of an inclined trough with a flat bottom that is studded with a pattern of protruding brads in hexagonal array [*see illustration on opposite page*]. The trough functions as the adsorption column. The particles to be separated consist of steel balls in two or more sizes. As the balls roll down the trough they collide with the protruding brads at a frequency determined by the diameter of the balls and the spacing of the brads. The effect is analogous to periodic adsorption. The smaller balls participate in fewer collisions than the larger ones and so migrate at a higher net velocity. As in Tswett's apparatus, the balls become segregated in zones and emerge from the bottom of the trough in lots according to size.

Parman's trough is 36 inches long and two inches wide. It is made of hard fiberboard 5/8 inch thick. As a guide for placing the brads Parman glued graph paper to one side of the strip and coated the paper with clear varnish. Brads were driven into the strip on centers spaced one centimeter apart. Alternate rows were staggered by five millimeters. Parman used 3/4-inch brads driven vertically so that 7/16 inch was exposed. Strips of masking tape 3/8 inch wide were woven between brads at the edges of the array to form the sides of the trough. A few brads were omitted from the pattern at the top of the array to prevent the balls from jamming as they enter the column.

A supplier of balls can be found in larger communities by referring to the classified telephone directory under "Bearings." Parman experimented with balls of four sizes: 1/4, 7/32, 5/32 and 3/32 inch in diameter. The quarter-inch balls cost two cents each; the smaller balls were one cent each. At a brad spacing of one centimeter the cleanest separations are observed with a mixture of 1/4-inch and 3/32-inch balls. A batch of approximately 20 balls can be processed at one time without overloading the column.

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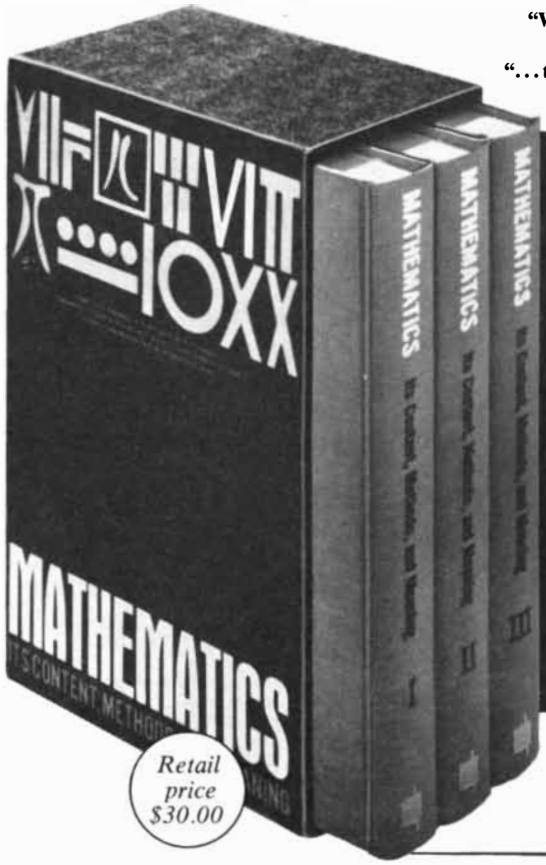

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BOOKS

The depths of the ocean, how the idea of galaxies evolved and other matters

by Philip Morrison

THE FACE OF THE DEEP, by Bruce C. Heezen and Charles D. Hollister. Oxford University Press ($25). The surface of the moon is in plain view. Deficient gravity means no air, but we can bring our own, and the vacuum is no impediment to photons. Thus we know the moon well; men have mapped it in detail and have walked and driven across its plains. The abyss of the sea, with a surface area as big as eight or nine moons, is close at hand. But it is guarded by matter: gravity has clothed it with a fluid shield, at crushing pressures up to hundreds of atmospheres. Seawater is scarcely a translucent screen; our brightest flash lamps, dangling at the end of three or four kilometers of cable alongside a 35-millimeter camera in its pressure case with an inch-thick window, illuminate an area the size of a bed sheet. This striking book, the loving and eloquent work of two pioneers in the field and an up-to-date textual guide to the deep-sea floor (the title seems ambiguous), is an "illustrated natural history of the visible abyss." Almost nothing here lies under the sun; it is a new world, a world ice-cold and dark, not at all that sunlit and colorful shallow sea margin so wonderfully and newly familiar to divers and film makers.

It is only about 20 years since our cameras first saw the floor of the abyss. For a longer time we have fished up samples, the ooze and its creatures here and there encountered by our blind grappling. A couple of hundred thousand photographs now record the abyss, at some 2,000 stations over the whole of the seven seas. About 600 photographs are shown here, with one color sequence (mainly marking the shift from the white, buff and green of the shallower ooze, colors lent by the rain of microscopic shells of surface organisms, to the chocolate of the fine inorganic red clay of the terrestrial basement, where pressure and time slowly dissolve the last limy residues of life). Here is archaeology: an amphora with a skull is shown below four kilometers of the eastern Mediterranean. A newer beverage jar, meant for Coca-Cola, shows up more than five kilometers deep off Cape Hatteras. The "shell-buried cables creep" across the photographs, immobile conduits of information. There is change too; everything falls, and in the end falls to the deep. Rocks and pebbles are rafted to sea on impermanent ice and sink, dust is wind-borne, volcanoes strew their ash; even meteorite debris is microscopically present in samples. There are currents, slow and inexorable, and swift catastrophic landslides that can shear cables, cut canyons and build submarine fans of talus. The "ribs of the solid earth," the outpouring of volcanic material along the great rifts that accompanies the drift of the continents, are not on the scale of these photographs; they can be made visible either by maps or by the happy accident that they come ashore in Iceland and East Africa, where photography—subaerial, not submarine—can exhibit the great faulted landscape. There is mineral wealth: black manganese. Ion by ion the manganese nodules grow, delicately layered, the size of potatoes and cannonballs, strewn over entire landscapes of the abyss, to comprise "the largest mineral deposit on this planet." We cannot hope to mine them as fast as they grow, deep in the ocean, far from land, in the coldest waters and below the most desert surface waters.

The abyss is inhabited, by animals that live on the rain of debris, that mine the ooze for the residue of a sunlit life far above. The dominant animals are ooze-grazing herbivores, the sea cucumbers, known outside the zoologist's shelves as a Chinese delicacy. They are mostly mouse-sized, although some are as big as cats. With their cousins the brittle stars, and a variety of rarer invertebrates, they people the bottoms, "cattle gently grazing on bacterial pastures." See them here by ones and twos, by droves. Most of the pictures show no beasts but rather display the tracks, burrows and furrows, and the intricate droppings of the many creatures of that dark and grassless plain. Some fishes feed on these grazers; some toothed whales dredge the bottom with slack lower jaw, occasionally to catch a cable and drown entangled.

Altogether the volume is a lasting and remarkable novelty; other books have given us some samples of the work and told much of the technical story. This big book is the first compendious and accessible work; it also displays humor and poetry, from Pooh to Pope.

If romance is not dead, these scientists will try to bait some cameras afloat in mid-water in order to attract the extraordinary giant squid, known to be there but never pictured alive. You can see a rare big sleeper shark in deep water, the largest trophy yet taken by the baited "monster cameras" or spied from the little submersibles. There is big game still to hunt in the dark miles down. One footnote (they are generally a rich lode) warns us to expect no living fossils on the bottom. "It appears that the deep sea has undergone a marked cooling during the last 100 million years" and is by no means a particularly stable environment for life. The existing fauna represents more the recent penetration of a variety of forms from the shallower seas into the depths than the survival of a strange and primordial fauna of the abyss.

AN ORIGINAL THEORY OR NEW HYPOTHESIS OF THE UNIVERSE, 1750, by Thomas Wright of Durham. A facsimile reprint together with the first publication of *A Theory of the Universe, 1734*, with an introduction and transcription by Michael A. Hoskin. Macdonald, London, and American Elsevier Inc., New York ($32). THE DISCOVERY OF OUR GALAXY, by Charles A. Whitney. Alfred A. Knopf ($10). Immanuel Kant, a struggling, if precocious, private tutor, read a semipopular monthly published in Hamburg. Out of a book review in that journal he first conjectured the geometry of our universe as we see it now: an unending archipelago of starry islands, within one of which we ourselves dwell.

(Kant's own book was discussed in this space a couple of years ago from the paperback edition issued by the University of Michigan Press.)

The book that Kant read about was Wright's, now presented in handsome facsimile "with upwards of Thirty Graven and Mezzotinto Plates, By the Best MASTERS." Wright was a carpenter's son, apprenticed as a boy to a clockmaker but even then a passionate student of astronomy. He became a private teacher of navigation, then surveyor, map maker and teacher to the gentry, with great success in projects such as "a Large Horizontal Dial for Lord Viscount Middleton... Lady Middleton... study ye use of ye Globes." He wrote several texts on astronomy, but he most delighted in elaborate graphics; he has left us, among much else, an unpublished folio "exhibiting... the various rising and setting of the Sun to all parts of the World" with "near 200" original diagrams and 500 representations of the sun. He published a vast chart (only two copies are known to survive) covering 24 square feet, and a companion book, *Clavis Coelestis*, the key to the heavens. In the present volume, whose drawings and diagrams of both real and fanciful skies are always striking and occasionally darkly and richly beautiful, he discusses the earth within the solar system and the solar system within the fixed stars. Even among the stars he sees order, a great starry ecliptic plane forming the Milky Way. It was this proposal of order that impressed Kant. Wright himself preferred a model of a huge shell of stars, one among many such shells scattered through infinite space, each surrounding some supernatural yet gravitating Eye of Providence. This blend of geometry and theology is characteristic of all his work. His learned editor takes pains to deny Wright any real credit for the first conjecture that our galaxy is a disk of suns, ungenerously stressing Wright's theological bent and his geometric inconstancies. Dr. Hoskin, whose depth of study of Wright's books and manuscripts is unmatched, brought out of hiding a few years back a second volume in which Wright recanted, placing the earth within a solid sky in which the stars were volcanoes! Earlier, however, Wright had touched our truth quite plainly; the consistent mind of Kant saw what hint to pursue and what wild vision to ignore.

Kant's insight—the cosmos of island Milky Ways—was not received within astronomy. It remained a dubious romance of enormous spaces until our own times. The world view we hold today became uniformly accepted only with the work of men and women such as Harlow Shapley and Henrietta Leavitt, Robert Trumpler and Edwin Hubble. In *The Discovery of Our Galaxy* Professor Whitney, a Harvard astronomer with a gift for adroit and engaging prose, recounts the story in a volume of documented narrative whose freshest pages tell of results and ideas put forward only a couple of decades back. It was Shapley, a man of irrepressible energy and wit, who about 1920 first placed our sun in the suburbs of the Milky Way, choosing the great spheroidal system of the globular clusters as the framework of our galaxy. But he was wrong tenfold about the scale of the Milky Way, and he did not admit external galaxies. The regularly pulsing Cepheid variable stars Henrietta Leavitt had recognized in the Clouds of Magellan gave him too large a distance for the large cloud; we know now that there is more than one species of Cepheid variable. This was one false clue. There were two others: the erroneous detection of motion in the spiral nebulas, and the unhappy accident that in 1885 the Great Nebula in Andromeda, the nearest big spiral, produced a supernova far too bright to be a normal nova outside our galaxy. No one had realized that the rare supernovas could in fact be as bright as an entire galaxy. Whitney, a student in the later years of Shapley's department at Harvard, holds that Shapley, "an ambitious young man," could foresee no new achievement to cap his scaling of the Milky Way; he held that the spirals were "secondary creatures, and to measure them would be mere dénouement." "So he became a public man [who] reached beyond science."

It was Hubble, first master of the 100-inch telescope on Mount Wilson, who established the universe of galaxies and that uniform expansion called the Hubble law. He too was an unusual personality: a showman. A boxer of almost professional caliber, a three-letter man in college, a Rhodes scholar, he passed the bar examination but after only a year of practice decided "to chuck the law for astronomy." Writes Whitney: "He knew how to strike a pose." We live in his expanding universe, one solution of the cosmological form of the gravitational equations of Einstein.

Whitney has chosen excellent period diagrams and quite beautiful modern sky photographs, darkly bled off the mat pages, to enrich his book. It is a book for the general reader, demanding little background in science, here and there using analogy to make a basic concept familiar (not always without strain). The epilogue is very up to date, with disarmingly low-keyed accounts of such wonders as quasars, black holes and Seyfert galaxies. For Whitney the universe is unorthodox all according to Hoyle; we shall see. He is preparing a full biography of Hubble, a book eagerly to be awaited.

EAST AFRICAN MAMMALS: AN ATLAS OF EVOLUTION IN AFRICA, VOLUME I, by Jonathan Kingdon. Academic Press ($35). This singularly handsome book is visually without a peer among many years of publishers' output in science. The designer, Tagelsir Ahmed, has given us a volume of the right size and weight, with generous margins and paper that is neither slickly whitened nor blurringly rough. He has justly fulfilled the terms of the work. The book is the work of an artist-scientist; "the drawings and maps are a fundamental part," and the "prime stimulus for the drawings... has been the contemplation of physical beauty in mammals; this is a reward in itself."

Our reward is the hundreds of maps and pencil sketches in an entire gamut of styles, and a number of striking pages of paintings in color, like so many designs by artists of the School of Paris. Across many a page climb and crawl and posture dozens of quick-drawn pottos or pangolins, reminding the reader of the sketchbooks of the old masters. There are fine-lined and careful representations of the bony skeleton of man and gorilla, detailed studies of musculature (even one overlay), marginal drawings and softened renderings of the silky-haired colobus monkey, skulls, faces and sequenced drawings of the jump of a galago, like a strip of motion-picture film. There is a silhouette of the bridge across the Firth of Forth, to compare with the skeletons of quadrupeds. There are small, elegant renderings of the trees of savanna and thicket, of hardpan and multistoried rain forest, like old engravings of cities seen from the waterfront. One can look at chromosomes and electrophoresis patterns of the serum proteins in man and chimpanzee, and coordinate nets with primate-skull profiles superposed on the warp. The "red, white and blue" genital display of the vervet monkey and the white nose and red tail of other forms are presented in comparison studies, with the aim of tracing the origins of these striking signal schemes. Maps abound, informed with the personal graphic alphabet of one sensitive draftsman-artist, mapping the range of a band of 80 chimpanzees or

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the human population of all East Africa compared with the prevalence of the tsetse fly and the reliability of 20 annual inches of rain.

Kingdon has a clear grand aim: he seeks to make an agreeable, broad and complete inventory and introduction to all the mammalian species of East Africa, the region where a million years or so ago our own species emerged among a rich and diverse mammalian fauna. This volume, the first of three, is largely concerned with the primates (including *Homo* and other hominids) "and the peculiar interest their habits excite." Since it is the first volume, it has a set of introductory chapters as background, treating the vegetation and the general environment, the perspective of the long past of geologic time and the foundations of the anatomy of mammals. The author is caught up in the life of field and zoo—"I have kept [the Zanzibar galagos] over long periods"—but he is no stranger to the talk, books and journals of mammalogists. Indeed, it is the very catholicity of the content of his graphics, with his ability to subtly match style and content, that gives his book its unique beauty. There is a bibliography of some 600 titles.

Primates are the stars of Volume I, but the anteaters, the aardvark and the dugong complete the work. Was the Egyptian god Set a tube-snouted aardvark, devouring the moon each month? Will the giant pangolin survive? This beast, feeding on the termites whose mounds it rips open, is threatened by the "purveyor of charms." The overlapping horny scales, a specialized protective armor that may make up a third of the weight of the animal, are popular love charms among the women of Buganda. Bury one suitably under a man's doorstep and he is "incapable of denying his woman's wishes and he will, under the influence of this scale, buy her new dresses or indulge any other of her desires; naturally these are popular charms." A whole pangolin skin is worth a small fortune.

This is a work of analysis, the pencil seeking "to extract from the complex whole some limited coherent pattern" for the mind and the eye. Because the author is an artist he delights the eye; because he is a scientist he goes beyond form and the present to tease out the origins, context and interpretation of form. The second volume will cover the little animals of East Africa, which are the least known; the third volume will treat the large mammals of the region, with a special effort to bring out information relevant to the eventual use of those showy large ungulates as meat-yielders for man. The work as a whole is a luxurious wonder for both the possessor and the user.

TIMES OF FEAST, TIMES OF FAMINE: A HISTORY OF CLIMATE SINCE THE YEAR 1000, by Emmanuel Le Roy Ladurie. Translated by Barbara Bray. Doubleday & Company, Inc. ($10). Professor of history at the University of Paris, this author brings the credentials of a distinguished economic historian. The book he published just before this one (which appeared first in Paris in 1967) was on the Languedoc peasantry. He is one of those specialists in documents "who burrow among archives." His quarry there now is a sound historiography—tested, systematic, detailed and authentic—for the fine structure of climatic change. The climatologists have their ice cores and their thermometer records, and there is a long and inglorious tradition of zealously misapplying clues to past climate in explanations of human history. What Professor Ladurie seeks in this book is to restore the historian's interest in climate for itself, in a document-based history of climate: not overstated, not crudely cyclical and not ignorant of the physical clues.

He pursues the entire topic, presenting what amounts to a valuable critique and summary of many lines of work. For instance, he gives in one of 19 appendixes a set of graphs making visual the data, first gathered in a conference held at Aspen a decade ago, of some 50 chronological series, such as wheat prices in Barcelona and the flowering dates of the cherry trees in central Japan. His own work centers on two sources of data. One is the manuscript dates of the wine harvests of Avignon back 500 years, which he stumbled on in a "huge pile of harvest dates collected by Hyacinthe Chobaut, [a] self-effacing Avignon archivist [who] was one of the true pioneers of the scientific history of European climate." It has been shown that there is an extraordinary detailed inverse correlation, extending throughout the 19th century, between the number of days after September 1 when the wine grapes are brought in and the mean measured local summer temperatures. The other source is the records of the little alpine villages at the foot of the glaciers. In a private archive in Chamonix, for example, we read that in April, 1600, a notary on the Italian side of Mont Blanc had a visit from one Jacques Cochet, who lived near the glacier named Mer de Glace. The French villagers had sent Cochet across the ridge to inquire if the parishioners of Italian Courmayeur had yet asked the Pope in Rome to pray for the withdrawal of the glacier. They had not done so, nor had the glacier drawn back. Three hamlets near there were destroyed between 1600 and 1610; the alpine people were in a panic, one observer wrote in 1616, from "a great and horrible glacier of great and incalculable volume."

There was a "little ice age," a high tide of ice, from just before 1600 up until 1850 or so. The period glacial-terminal landscapes reproduced here display it eloquently. What these small but real changes show—"the worsening of the winters" from 1550 on—seems to come from a mean temperature drop of only about one degree Celsius. From 1850 to 1950 there was a similar phenomenon, only in the other sense; it was an "amelioration" of climate that may now be reversing again. It is these modest variations that are the most likely objects of the historian's inquiry.

This is a richly documented, even rather crowded book. Its auxiliary apparatus, like that of many French works, is not easy to operate. For its intellectual synthesis of historical scholarship and physical science, however, it is notable. Its readability, warmth and constructively skeptical tone mark it as the product of a genuine historian, who knows the strengths and the limitations of how we learn from our fragmentary record of the past, whether from parish journal or tree ring, isotope ratio or moraine debris.

PHOTOGRAPHIC ANATOMY OF THE HUMAN BODY, by Chihiro Yokochi. University Park Press ($12.50). From Rembrandt van Rijn to Somerset Maugham and beyond artists have perceived that the anatomical scalpel cuts two ways. As the blade probes the cadaver, so it searches the emotions of the student. To be sure, shared rational knowledge of the mechanism of the body unites physicians, but they are bound even more into a kind of caste by the residual feelings of their long afternoons among the ruins of the dead. Today we have an old and brilliant tradition of medical illustration, in artful paintings and sharp photographs, that amounts to a kind of paper commentary on the dissecting room, both for the sake of art and for the practical end of supplementing or replacing that costly and dramatic room with the slab tables.

The general reader cannot expect to pass the discriminating judgment of the art critic or the medical pedagogue. For sheer vivid impact, however, this new-

ly Englished version of a successful Japanese atlas of anatomy, now 15 years old, is unmatched. Intended largely for paramedical students, nurses and technicians, it presents both in sharp monochrome and strong color photographs, all blood red and fat yellow, a review of the general structure of the body. Most of the specimens are freshly prepared, not pieces long held in the preserving fluids before dissection and photography. There are also radiographs and photographs of the living, and some magnified shots, diagrams and sequential sections, to gloss the main theme of direct, salient images of the dozen systems of the body teased out and whole.

THE SCIENCE OF MATTER: A HISTORICAL SURVEY, selected readings edited by M. P. Crosland. Penguin Books ($4.95). A HISTORY OF MEDICINE, selected readings edited by Lester S. King. Penguin Books ($5.75). These two paperbound anthologies present fresh and attractive, if somewhat staccato, excerpts from the entire range of their respective domains. *The Science of Matter* offers more than 160 samples, averaging a couple of pages each; *A History of Medicine,* a thinner volume, wider in scope and somewhat more conventional, gives us a couple of dozen readings some 10 or 12 pages in length. The editorial comment is helpful and readable throughout. Matter is examined through the eyes of its students from Aristotle to C. N. Yang, usually, although not always, in citations of contemporaneous work. In 1654 Walter Charleton estimated the size of atoms by the volume of air rendered pungent by a grain of frankincense; the number of atoms in the volume was at least 10^{18}. Forty years later Edmund Halley reckoned that the gold layer on gilded drawn silver wire was less than a fifth of a micron thick, and "even in this exceeding thinness, very many of those atoms may still lie one over the other."

The medical anthology begins with Hippocrates and Galen and ends with a 1967 paper reporting the experience of a couple in Indiana whose gold wedding bands induced a long-lasting irritation of the skin of the fingers. It turned out the gold had been reworked from radon-containing gold implants used in tumor therapy.

These books are enjoyable, but they are not cheap. It is too bad the publishers could not at that price include more graphic material. A few line diagrams begin to enliven the atomic text, but there is nothing in the medical volume save words.

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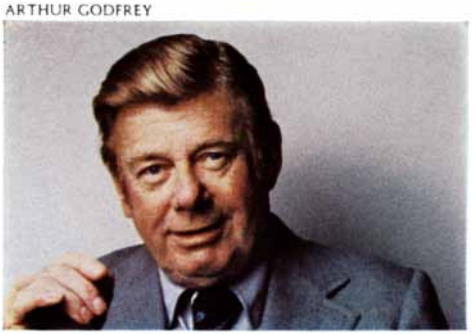

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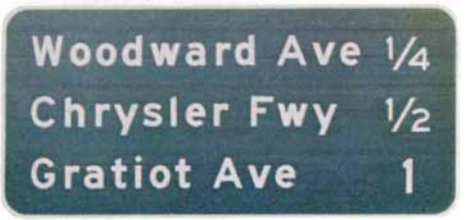

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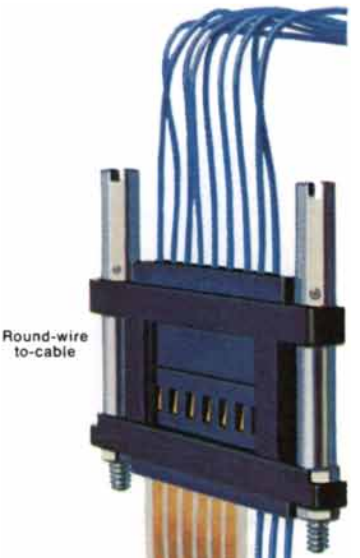

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