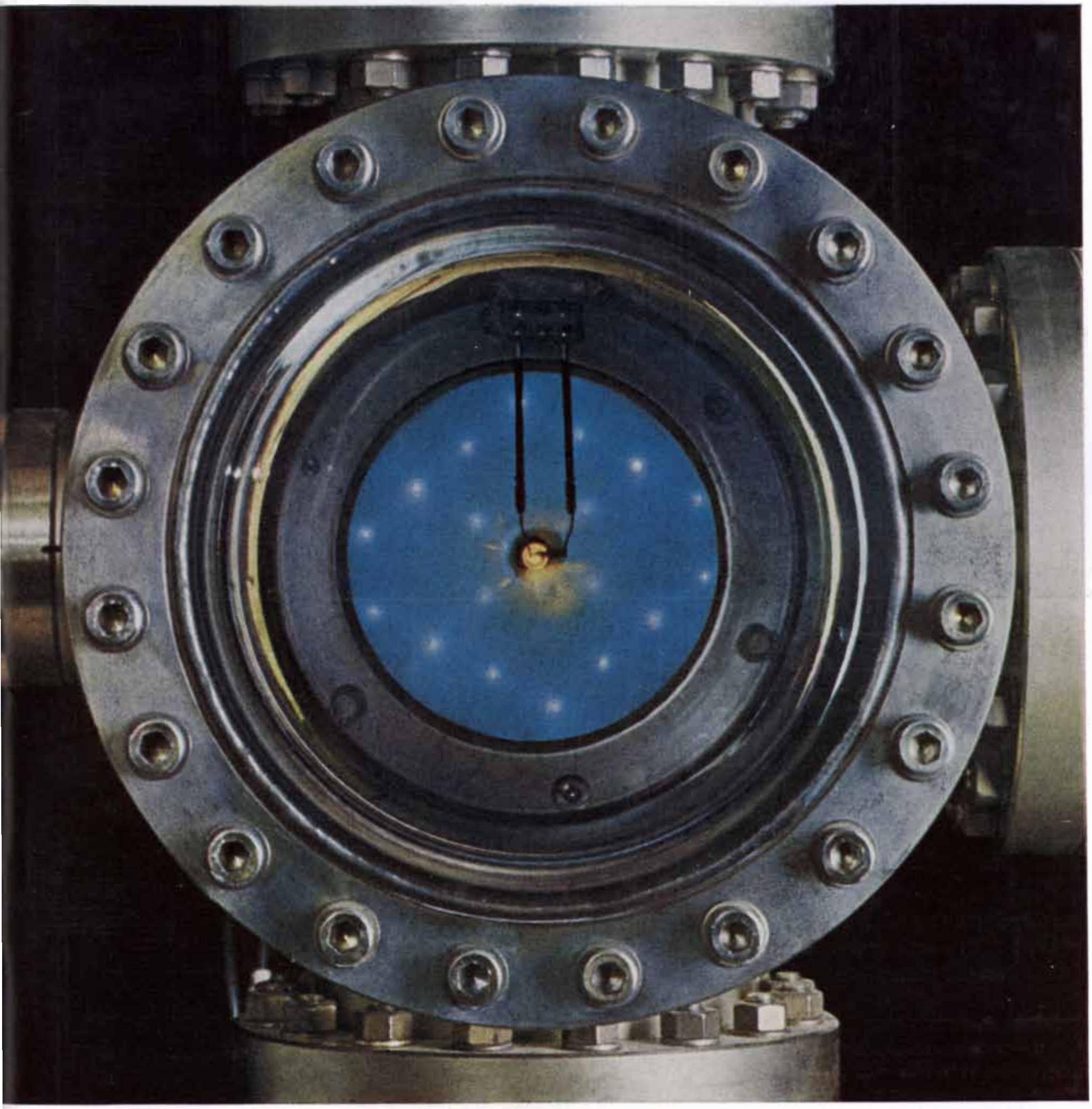
SCIENTIFIC AMERICAN

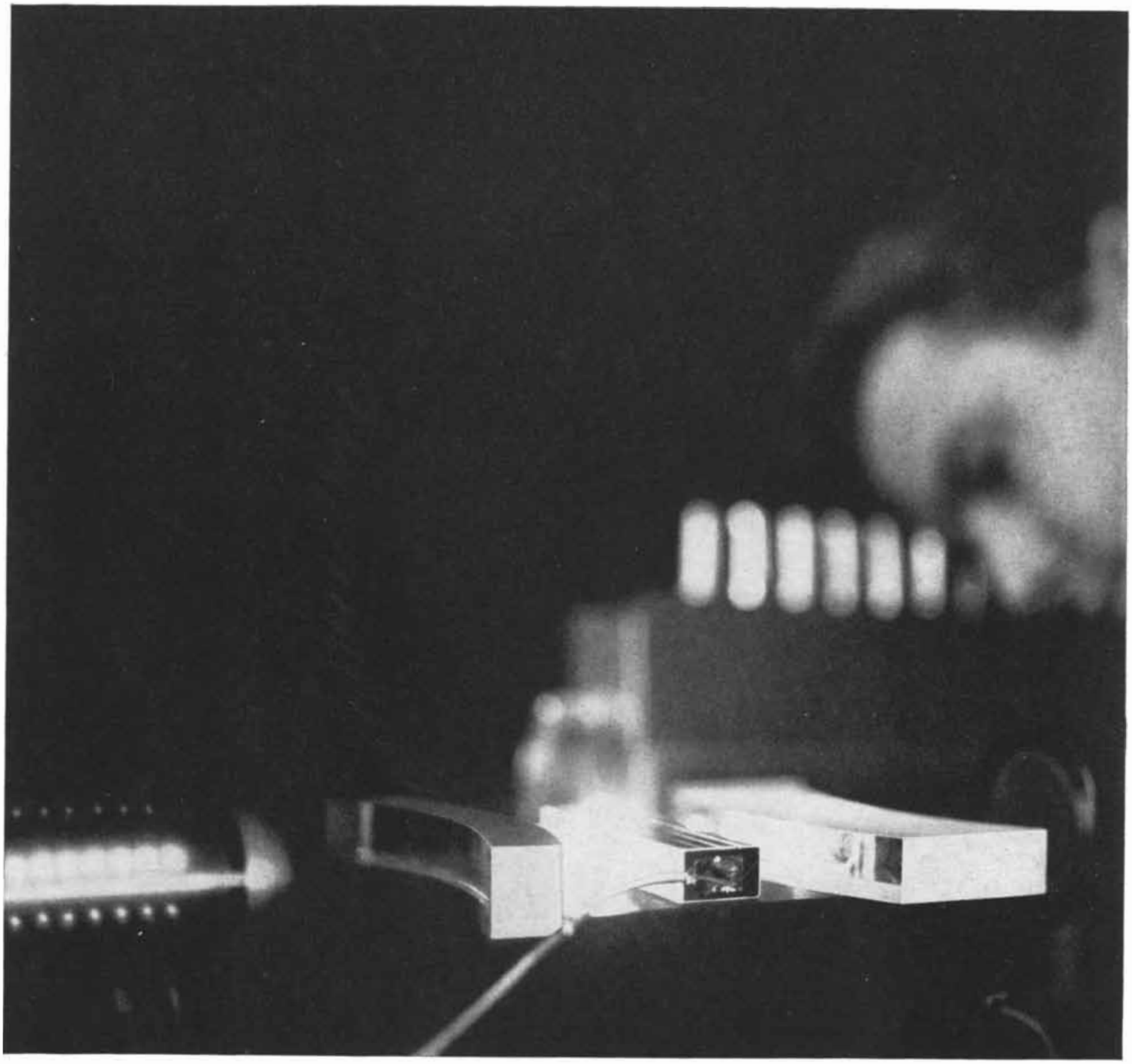


THE STRUCTURE OF CRYSTAL SURFACES

SIXTY CENTS

March 1965


LOUVRE



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Established 1845 **SCIENTIFIC AMERICAN** March 1965 Volume 212 Number 3

ARTICLES

DEPARTMENTS

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THE COVER

The photograph on the cover shows the pattern of low-energy electrons diffracted from the surface of a crystal of tungsten on which oxygen atoms are adsorbed. The pattern appears on the fluorescent screen of an instrument built by Varian Associates and photographed in the laboratory of Lester H. Germer at Cornell University. Germer is a coinventor of the instrument and the author of "The Structure of Crystal Surfaces," which begins on page 32. Each white spot in the pattern represents the diffraction of electrons from parallel rows of atoms on the surface of the crystal being examined. Knowing the wavelength of the incident electrons, one can calculate from the pattern the arrangement of atoms on the surface.

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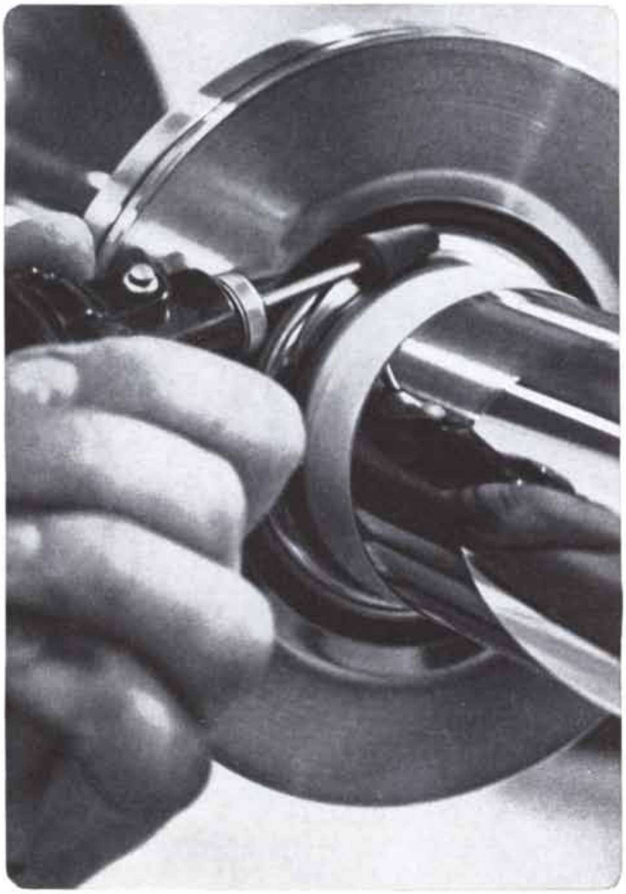

LOOK WHAT THEY'RE DOING WITH DIAMONDS

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LETTERS

Sirs:

I feel compelled to take issue with some of the assertions made by Sir Julian Huxley in his letter [Scientific American, January] attempting to rebut the severe but not unfair criticisms of his book by A. E. Mirsky. It seems scarcely credible that a serious scientist can see no need for more detailed knowledge of human genetics than is now available to embark on a program of genetic improvement of mankind. Sir Julian seems to be convinced that he knows exactly what kind of genetic endowment will be best for mankind and just how to proceed to achieve this goal. What he is pleased to call "the modest and voluntary methods suggested by H. J. Muller and myself," i.e., artificial insemination of women by the sperm of donors selected (by whom?) for this purpose, is certainly not free of objections on genetic grounds, even if it were acceptable on psychological and sociological grounds. Sir Julian's letter seems to imply that the "modest" methods he so enthusiastically recommends has been endorsed also by R. A. Fisher, Bernhard Rensch, Ernst Mayr, George Gaylord Simpson and even Charles Darwin; this is simply not true. Eugenics was in the past compromised by hasty programs and rash promises of its overenthusiastic supporters, and it is liable to be hampered again by the proposals made in the name of so-called "humanism." Eugenics is not synonymous with humanism; humanism has no meaning unless it signifies an appreciation of human dignity, which is not overabundant in Sir Julian's "Essays of a Humanist."

Theodosius Dobzhansky

The Rockefeller Institute
New York, N.Y.

Sirs:

I read with displeasure A. E. Mirsky's review of Sir Julian Huxley's "Essays of a Humanist" [Scientific American, October, 1964] and his reply in your January issue to Sir Julian's letter. Unless Dr. Mirsky holds that intelligence needs to be discouraged, I should like to point out to him that while the detection of genius may be too difficult for the tests of our psychologists, the detection of stupidity is a task that comes within their scope. And if the number of stupid people is to be decreased, it is unnecessary to decide whether the children of stupid parents are stupid because of an unfavorable combination of genes or because they are raised in a stultifying environment. The task in either case is to persuade stupid people not to become parents.

George Milwee, Jr.

Nashville, Tenn.

Sirs:

In his reply to Sir Julian Huxley, A. E. Mirsky states that "before man can embark on a program of eugenics he will need far more knowledge and wisdom than he possesses today." The need for more knowledge is incontrovertible, but the statement unfortunately seems to imply that man, lacking knowledge and wisdom, is not currently embarked on such a program. This widely prevalent view exists only by grace of verbal camouflage. That the medical use of insulin, to take one example, is usually described as the alleviation of diabetes in no way changes the fact that it is also a potent program to increase the frequency of diabetogenic genes in the population. Since such measures are increasing exponentially with the progress of medicine, we are actively engaged at the present time in selecting for biochemically and surgically supported survival as against fitness. The result of selecting for survival in a less and less demanding environment is well exemplified by the tapeworm.

Although Dr. Mirsky stresses that it is difficult to determine what to select for, at least this one particular program meets virtually no opposition.

That an increase in knowledge inevitably leads to an increase in responsibility is not something we have recently learned from the atomic bomb but is a truism that has descended to us from antiquity. An act is criminal or not depending on whether the perpetrator was aware, or could reasonably be aware, of its consequences. Until recently the birth of a child with Duchenne's muscular dystrophy was, in the technical sense, an "act of God." It is now possible to detect the heterozygous females who carry the defective gene on their X chromosome, so that the brief and miserable existence of the offspring, being predictable, is the responsibility of the parents. . . .

One must recognize, of course, that meeting such responsibilities is as subversive to sexual morals as the doctrine that the earth is not flat is to some theologies. On the other hand, the exact shape of the geoid may be of less ultimate significance to the human race than its genetic constitution.

MARTYNAS YČAS

Upstate Medical Center
State University of New York
Syracuse, N.Y.

Sirs:

In their debate over the book review Mirsky correctly identifies some instances of logical inconsistency and lack of care in Huxley's argument. Mirsky fails, however, to recognize the other horn of the dilemma. He perceives the perils of authoritarianism, of racism and the lack of conclusive means of identifying desirable and undesirable hereditary traits. Against these dangers must be placed the grave consequence of the present do-nothing policy. Muller has described our mounting "genetic load" of deleterious genes that results from modern technological aids to survival and reproduction of even the poorer specimens. He points out that a gene that "harms its possessor only a little does an amount of damage to the population comparable to that done by a gene having drastically injurious effects."

The most probable outcome of this dilemma is that future political, economic and scientific developments will enforce some form of eugenics on men before they can reach the kind of definitive social knowledge Mirsky demands. The oppressive overpopulation that looms ahead will certainly lead to both quantitative and qualitative controls. Indeed, any kind of world crisis, especially war, would create almost irresistible pressures for selection because under starvation and acute shortages the survivors could scarcely afford the luxury of drones. Even technical competition with the U.S.S.R. and China, if it continues to sharpen, will generate pressures for quality improvement. Finally, Mirsky implied that science may achieve control over the chemistry of heredity before eugenics is realized. If so, his difficulty will not be escaped. Unpleasant decisions will still remain as to which genes to "correct" and what kind of corrections to make.

How will this selection be made? How will it be carried out? Certainly the I.Q. and other standard tests, education and performance under formalized instruction are not definitive criteria of innate capacities. Yet we may expect continuing efforts to improve the material conditions of life and intellectual opportunities for all who can take advantage, as well as improvements in devices to detect the various human abilities. If and when the selection must be made, hopefully it will be conducted in a humane manner on the basis of the best evidence and judgement—similar to the sterilization laws of the more progressive states. It will encourage and reward reproduction among those with demonstrated capacities, while using similar techniques to discourage reproduction among those with minimal ability. Should gene manipulation be achieved, these tentative and pragmatic decisions will have to be made, perhaps aided by some experimental alterations of heredity conducted on a voluntary basis.

BRUCE STEWART

Michigan State University
East Lansing, Mich.

Sirs:

What deeply bothers me regarding the debate between Sir Julian Huxley and A. E. Mirsky on whether or not we are ready to apply eugenics is that Mirsky seems to have accepted Huxley's premise that the prime question here is only one of sufficient scientific data. The all-encompassing ethical consideration of whether or not any man or group of men ever have the right to tell any other man or group of men whom to marry or how many children to have has been purposefully subordinated, if not entirely overlooked. When all the major evidence on eugenics is finally in, Huxley's ideology will still have to answer for the fact that he advocates applying science with soldiers. Overpopulation is certainly a crucial and geometrically growing problem in our world, but a larger problem is and will be that most human beings, residing even 1,000 miles apart, will not allow each other to live. Could it be because at the root they believe in the efficacy of force rather than mind?

Homo sapiens is that unique species with a fully conscious, rational faculty; to forgo that faculty and treat its members as so many cattle shows a latent cynicism for science as well as a patent disregard for morality. Those scientists who protest so much their desire to "improve the species" either possess a subconsciously different desire or have in mind the wrong species.

Paul G. Neimark

Editor-in-chief
New Classics House
Chicago, Ill.

Sirs:

I am surprised that Martin Gardner, in his column on tetrahedrons ["Mathematical Games," February], described the caltrop without giving its name. Or is he counting readers?

J. A. Amy

Downer's Grove, Ill.

Sirs:

I can only reply by paraphrasing Dr. Johnson: "Sheer ignorance, sir." *The Oxford English Dictionary* defines the caltrop as "an iron ball armed with four sharp prongs or spikes, placed like the angles of a tetrahedron, so that when thrown on the ground it has always one spike projecting upwards: Used to obstruct the advance of cavalry, etc."

Martin Gardner

Hastings-on-Hudson, N.Y.

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MARCH, 1915: "The decisive factor in the titanic struggle which is sweeping to and fro over the plains of Poland and East Prussia is not General von Hindenburg nor Grand Duke Nicholas but General Locomotive. After giving due credit to the strategical skill of the German and Russian generals, to the wonderful military efficiency of the German army and to the traditional stubbornness and bravery of the Russian infantry, it has become evident during the first six months of the great war that the fundamental determining condition of success, for one side or the other, is the propinquity of the contending armies to the network of military railroads which approaches and everywhere covers the German frontiers. In East Prussia, Russia has already suffered the two greatest defeats in her history, and in each case the defeat has been mainly due to the ability of von Hindenburg to concentrate rapidly against the enemy an overwhelming force which was rushed there over the admirable German system of railroads."

"The last annual report of the Mount Wilson Observatory states that all the larger parts of the mounting for the 100-inch reflector (which will be much the largest telescope in the world) will probably be assembled at the Fore River shops, where they have been constructed, in time to permit shipment to Pasadena *via* the Panama Canal early this year. The circular steel building and dome will probably be completed next summer so that the mounting may be set on the pier in the autumn. Meanwhile good progress has been made with the capital task of grinding and figuring the great mirror."

"We are in receipt of a letter from Mr. E. B. Stiles of Manchester, Iowa, in which he writes: 'I notice that in a recent issue of *Scientific American* you make mention of the death of Charles M. Hall, of aluminium fame. You might be interested to know that it was the reading of *Scientific American* that first interested Mr. Hall in a method of extracting aluminium from the clay earths. I distinctly remember being at his father's home in the fall of the year 1880, when he was about 16 years of age. One Sunday afternoon, in taking a walk with him, he explained to me that there was a valuable metal contained in the clay which abounds in northern Ohio, with many of the qualities of copper, and that if a cheap method of extracting the same could be found, the metal would be of very great use in the arts. Although he was a little older than myself, I expressed my incredulity, but he assured me that he had read about the matter in *Scientific American* and it could be depended upon. I think there is no question but that beginning with his perusal of *Scientific American* when he was a mere boy, he never gave up his determination to find a method for the production of aluminium until he, while still a very young man, succeeded in his purpose.'"

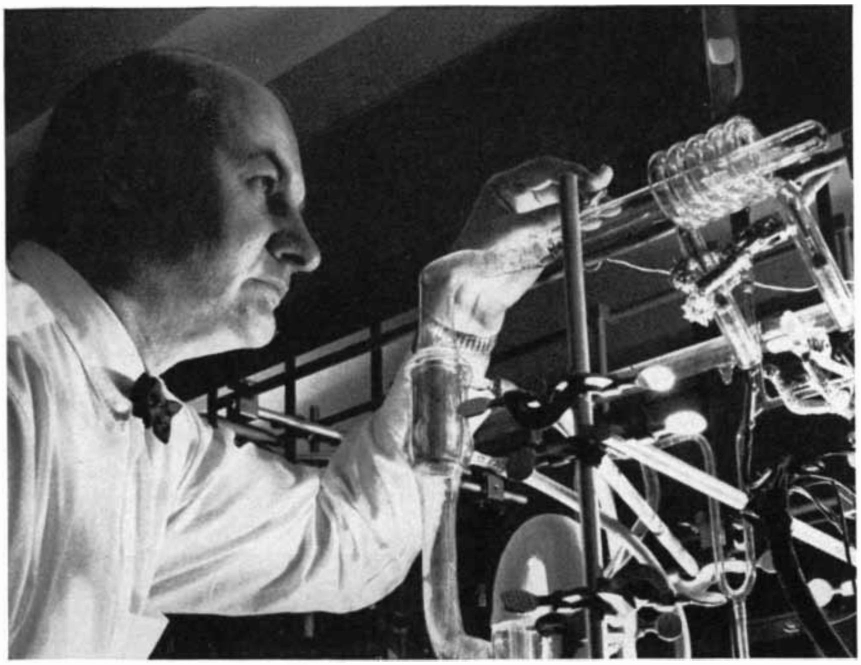
"The Hon. Bertrand Russell has written a preface to a new translation of the late Henri Poincaré's *Science and Method,* in which he sympathetically sets forth the significance of Poincaré's work in this age. One must endorse his estimate of Poincaré's writings. 'It has the freshness of actual experience,' Mr. Russell asserts with justice, 'of vivid intimate contact with what he is describing.... His wit, his easy mastery and his artistic love of concealing the labor of thought may hide from the non-mathematical reader the background of solid knowledge from which his apparent paradoxes emerge. Often behind what may seem a light remark there lies a whole region of mathematics which he himself has helped to explore.'"

Scientific American.

MARCH, 1865: "On Sunday morning at three o'clock the wires of the Western Union Company were connected with the Pacific lines and communication was established direct between New York and San Francisco. Though the weather was bad, rain falling at the time at many points on the route, the wires worked well and a considerable amount of business was transacted. The distance is nearly 3,000 miles and the difference in time about four hours. This is unquestionably the longest circuit ever

Report from

BELL LABORATORIES



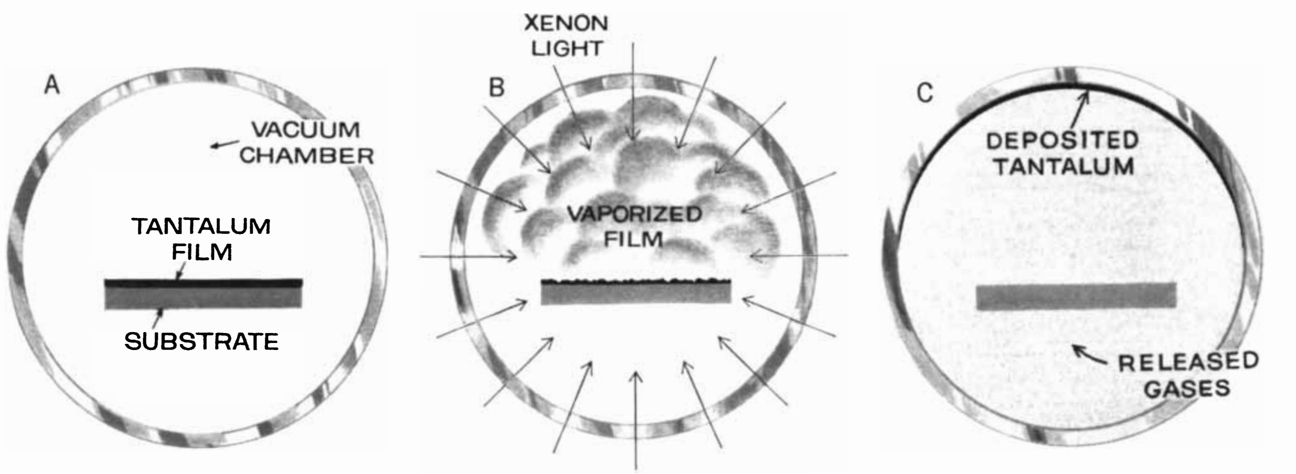
Chemist W. G. Guldner examines apparatus for "flashing" thin-film samples to remove gases for analysis. Helical tube is xenon flash surrounding vacuum chamber indicated in drawings below.

"FLASHING" THIN FILMS FOR QUANTITATIVE ANALYSIS

In making tantalum thin-film circuits, the tantalum is deposited on a substrate. Nitrogen is added during the deposition to form tantalum nitride, which helps stabilize resistance and capacitance values. After a film is formed, one then needs a quantitative analysis of the amount of nitrogen and other gaseous elements it contains.

A new technique has been developed at Bell Laboratories to perform this analysis quickly and accurately. As shown in the photograph above and in highly simplified form in drawing A, a sample of a film on its substrate is placed in a glass vacuum chamber. This chamber, surrounded by a xenon flash tube, is then subjected to a one-millisecond flash of light. As indicated in drawing B, the light energy is selectively absorbed by the film and has little effect on the substrate or on the walls of the glass chamber. The film is vaporized, and the temperature is high enough to dissociate the tantalum nitride.

Drawing C illustrates the chamber after the flash. Tantalum atoms have been driven to the inside walls of the chamber and are there condensed. Most of the released nitrogen and other elements are now in gaseous form within the chamber. These are pumped out for analysis by gas chromatography or other means.



Bell Telephone Laboratories
Research and Development Unit of the Bell System

worked, and the fact that such length of wire was telegraphed over in one circuit is a notable event in the history of telegraphy."

"Mr. Thomas Cook, correspondent of the New York *Herald*, writes as follows from Fort Fisher:—'The enormous shells of the monitor were thrown with unerring precision at so short a range, every one exploding with effect. Not a shot was wasted from this vessel. Although she fires but slowly, she accomplished infinitely more in attacking such a work than all the rest of the fleet combined. With her it is a perfect matter of indifference whether the fort responds or not, and at every discharge cartloads of sand are shoveled out of the wall of the fort.' "

"A strange discovery, if true, has just been made at Pompeii. The *Italia* of Naples states that a fountain has been discovered there covered with zinc. It is added that this is the first time that the said metal has been found at Pompeii. We should think so, for though the ore was known to the Romans, metal was not extracted from it, so far as our knowledge goes, until the 16th century by Paracelsus."

"M. H. Tresca has communicated a paper on the flow of solids under pressure to the French Academy, in which he details experiments to show that 'solid bodies can, without change of condition, flow after the manner of liquids, if sufficient pressure is exerted on them.' Mr. Tresca thinks that operations of this kind may explain cases of intrusion of one rock into another."

"Of the new lines in London probably the most remarkable is that proposed under the name of the Waterloo and Whitehall Railway. This is a pneumatic line, not for the conveyance of parcels only, not an iron tube like the gigantic pipe between the Post Office and Euston Square; it is an extension of the plan that has been for some time exhibited in operation in the grounds of the Crystal Palace at Sydenham. The tunnel admits about a full-sized omnibus carriage, which is impelled by the pressure of the atmosphere behind the vehicle, produced by lessening the density of the air in front. It is an underground railroad worked without locomotives. The proposed line will run in a tunnel under the Thames and open a communication between Whitehall and Waterloo Station, near Vine Street."

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THE AUTHORS

MAURICE A. GARBELL ("The Jordan Valley Plan") is president of the firm of Maurice A. Garbell, Inc., consulting aeronautical engineers and meteorologists, and of the Garbell Research Foundation, both in San Francisco. He received the degree of Doctor of Mechanical and Industrial Engineering from the Institute of Technology in Milan in 1938. For 23 years he has served various U.S. Government agencies and several private firms as an independent consultant. Among his numerous inventions are a "stall-safety wing," which is in use on propeller-driven and turbojet aircraft, and a meteorological instrument (in use by the Atomic Energy Commission) for the precise measurement of wind direction. Garbell was the author of the article "The Sea that Spills into a Desert" in SCIENTIFIC AMERICAN for August, 1963.

LESTER H. GERMER ("The Structure of Crystal Surfaces") is visiting professor of physics at Cornell University. He was graduated from Cornell in 1917, just in time to serve in World War I. Thereafter he obtained master's and doctor's degrees at Columbia University. For many years Germer was a research physicist at the Bell Telephone Laboratories, retiring in 1961. During much of that time he studied the opening and closing of electrical circuits; he estimates that such events "occur more than one million times per second in the telephone switching offices of the U.S." With his recent work on crystal surfaces Germer has returned to a field in which, as he puts it, he "made some preliminary contributions many years ago." One may assume that this refers to his work with C. J. Davisson that led to the discovery of the wave properties of the electron, for which Davisson (together with G. P. Thomson) received a Nobel prize.

BRIAN B. BOYCOTT ("Learning in the Octopus") is reader in zoology at University College London. He is a graduate of Birkbeck College London, which he attended while employed as a laboratory technician at the National Institute for Medical Research. After a short time lecturing in zoology at University College he spent five years as a research assistant in the anatomy department, returning to the zoology department in 1952. Boycott writes that in addition to his investigations of the octopus he is "currently working on the vertebrate retina and changes in the structure of the brain of hibernating mammals." Although he bears a surname that has entered the language as both a common noun and a verb, he is not related to the Captain Charles Boycott whose activities were responsible for the origin of the word.

LAURENCE J. CAHILL, Jr. ("The Magnetosphere"), is associate professor of physics at the University of New Hampshire. He is a native of Maine and a graduate of the United States Military Academy. After leaving West Point in 1946 he spent eight years in the Air Force, first as a fighter pilot and then as a physicist in the Air Research and Development Command. Cahill resigned from the Air Force in 1954 and entered the State University of Iowa, where he received master's and doctor's degrees. He went to the University of New Hampshire in 1959 as assistant professor of physics and has been there since except for 14 months with the National Aeronautics and Space Administration in Washington. "I join my family whenever I can," he writes, "in sailing on the Maine coast and in skiing wherever we can find snow."

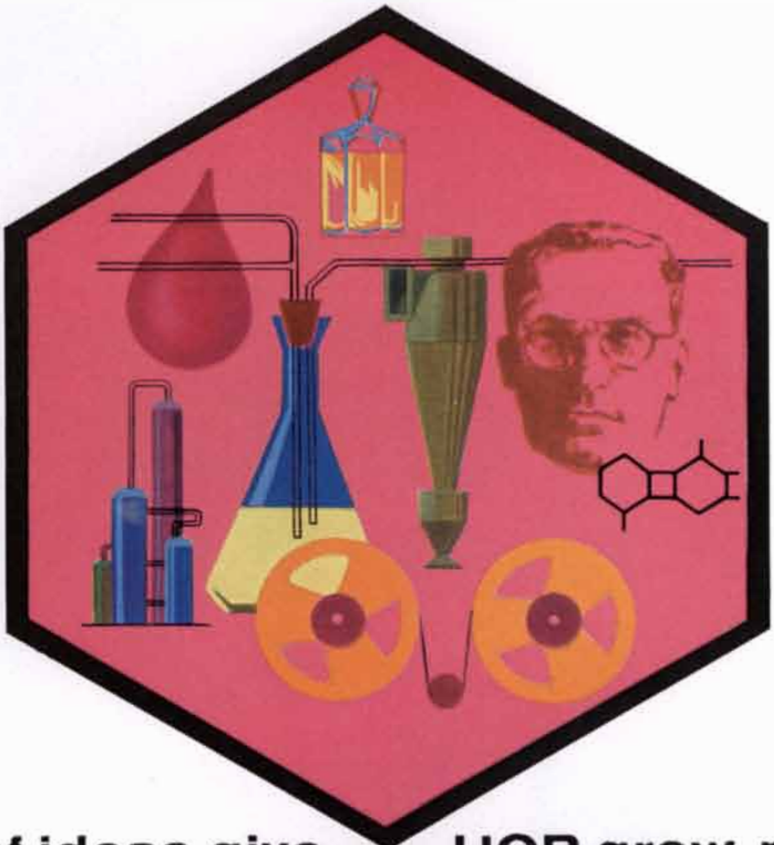
KEITH R. PORTER and CLARA FRANZINI-ARMSTRONG ("The Sarcoplasmic Reticulum") are respectively professor of biology at Harvard University and an investigator at University College London. Porter, a native of Nova Scotia, was graduated from Acadia University in 1934 and obtained a Ph.D. at Harvard in 1938. He was with the Rockefeller Institute for 22 years before joining the Harvard faculty in 1961. Mrs. Franzini-Armstrong was born and educated in Italy and then worked with Porter at Harvard before going to University College, where she is "working on the mechanism of contraction of crab muscle fibers." She is expecting her first child this month.

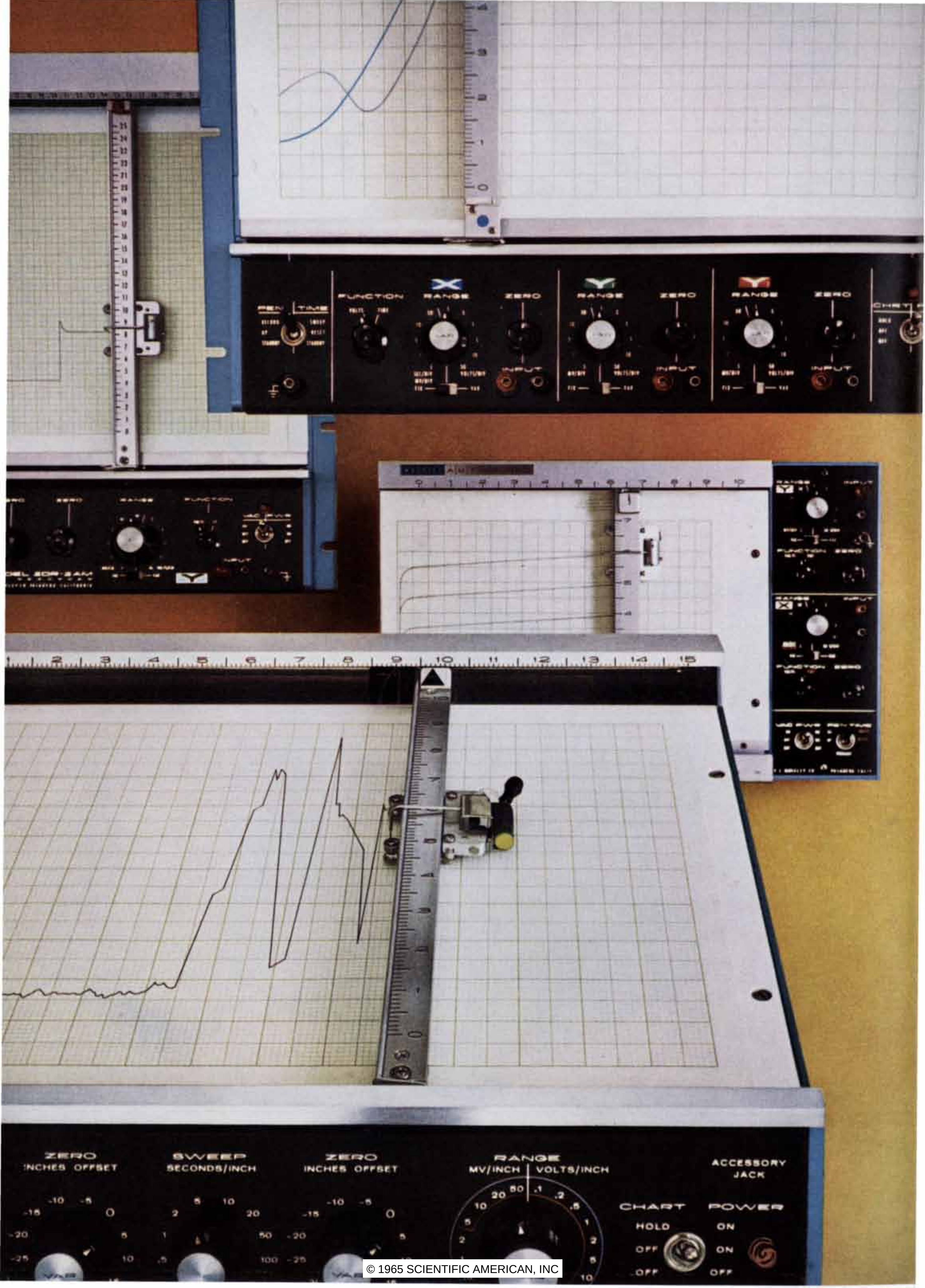
PETER F. OSTWALD ("Acoustic Methods in Psychiatry") is associate professor of psychiatry at the University of California School of Medicine in San Francisco, from which he was graduated in 1950. He also did his undergraduate work at the university. From 1951 to 1956 he was a resident in psychiatry at New York Hospital, returning then to the University of California School of Medicine. Ostwald reports that a childhood interest "in communication with sounds led to the study of music and to violin-playing" and that "during adolescence I became interested in psychoanalysis and decided to go into medicine." In addition to his teaching and research he maintains a private practice of psychiatry. He writes: "My interest is in psychotherapy as a way to explore and modify emotional problems, and I am curious to find out how scientific techniques can be developed and applied to the study of the doctor-patient relationship."

ROBERT A. CHIPMAN ("De Forest and the Triode Detector") is professor of electrical engineering and chairman of the department of electrical engineering at the University of Toledo. He is a native of Canada and was graduated from the University of Manitoba in 1932. Thereafter he went to England for graduate work at the University of Cambridge, where he received a Ph.D. in 1939. Chipman taught at McGill University for 11 years before going to Toledo in 1957. Concerning the history of electrical science he writes: "Attempts to fill in a historical background as one teaches electrical physics or electrical engineering quickly reveal the fragmentary and disconnected state of the documentary reports on the history of most electrical topics." Chipman's current interest is "the development of wireless telegraphy in the U.S. from 1895 to 1910 or 1915, a period of chaos and confusion, in many respects more comic than productive."

FRANCIS H. HARLOW and JACOB E. FROMM ("Computer Experiments in Fluid Dynamics") are investigators at the Los Alamos Scientific Laboratory. Harlow was born in Seattle and received his entire university education there at the University of Washington, where he obtained a Ph.D. in 1953. That same year he went to Los Alamos, where he is currently involved with theoretical work on numerical methods for fluid dynamics studies. Fromm, who is from Colorado, did undergraduate work at the University of Colorado and graduate work at the University of California at Los Angeles. He has been at Los Alamos since 1956; he reports that his current work is "numerical study of the Bénard Problem (thermal convection through a horizontal layer of fluid)."

MARTIN J. KLEIN, who in this issue reviews a collection of Lord Rutherford's papers and two books about Rutherford, is professor of physics at the Case Institute of Technology.





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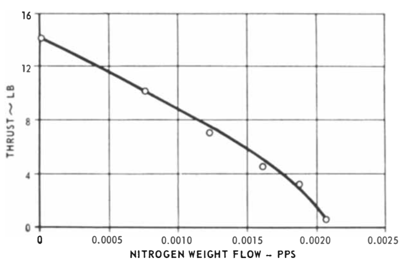
Variable thrust rocket engine for space vehicle attitude control

An efficient and simple means of producing variable thrust capability has been one of the significant objectives in the continuing search for optimal space vehicle attitude control techniques. Current techniques for variable thrust levels require complex mechanisms or a series of size staggered units at each station. Bendix Research Laboratories has demonstrated a variable thrust attitude control liquid bipropellant rocket engine. The engine is of simple design, and is capable of good throttling accuracy and high fuel efficiency utilizing fixed injector and chamber geometry.

The Bendix engine can be operated in a proportional mode (50-1 throttling range), in a pulse mode (5 millisecond response), or in a combination proportional-pulse mode to obtain an extremely wide dynamic range of integrated impulse. These new techniques result in a state-of-the-art advancement for space vehicle attitude control, velocity vernier control, drag compensation or any such application requiring a wide range of precise thrust control.

The Bendix design embodies a vortex combustion chamber. The need for a new combustion chamber design was dictated by the conflicting requirements for combustion stability during throttling and for fast response during pulse operation; the vortex combustion chamber design meets both requirements and results in a shorter and more compact envelope which is easier to integrate into a vehicle structure. For example, a 25 pound thrust unit with the vortex combustor, having a characteristic length (L*) of 7 inches, has shown stable efficient combustion with a characteristic velocity (C*) equal to 93% of the theoretical value. In addition, the Bendix design minimizes heat soak-back problems by isolating the combustion zone from the exterior walls.



Thrust turndown—typical performance

A companion on-off, electropneumatic two-stage valve was provided as an integrated assembly with the vortex combustor. Response time of 0.005 second was realized from signal initiation to 90 percent of rated thrust for engines in the 10 to 100 pound thrust class. The integrated package was designed to anticipate all of the response compromising considerations, such as line dynamics, stagnation volumes and electrical power demand. The two-stage design results in a typical control power requirement of 3 watts for a 50 pound thrust engine.

Throttling is accomplished by controlled injection of an inert gas into the liquid fuel and oxidizer ahead of the combustion chamber injectors. The inert gas displaces the liquids and throttling of propellant flow is proportional to the amount of inert gas injected. Stable efficient combustion is maintained over the throttling range.

For space vehicle attitude control, this integrated package provides a high degree of flexibility in choosing the best control law and adaptive logic, and eliminates the need for use of complicated designs or multiple thrust level engines.

Bendix Research embraces a wide range of technology including acoustics, nuclear, solid-state physics, quantum electronics, mass spectrometry, photoelectronics, electron beam and tube technology, measurement science, applied mechanics, energy conversion systems, dynamic controls, systems analysis and computation, navigation and guidance, microwaves, digital techniques, data processing and control systems. Motivation: to develop new techniques and hardware for The Bendix Corporation to produce new and better products and complete, integrated, advanced systems for aerospace, defense, industrial, aviation, and automotive applications. Inquiries are invited. We also invite engineers and scientists to discuss career position opportunities with us. An equal opportunity employer. Write Director, Bendix Research Laboratories Division, Southfield, Michigan.

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The Jordan Valley Plan

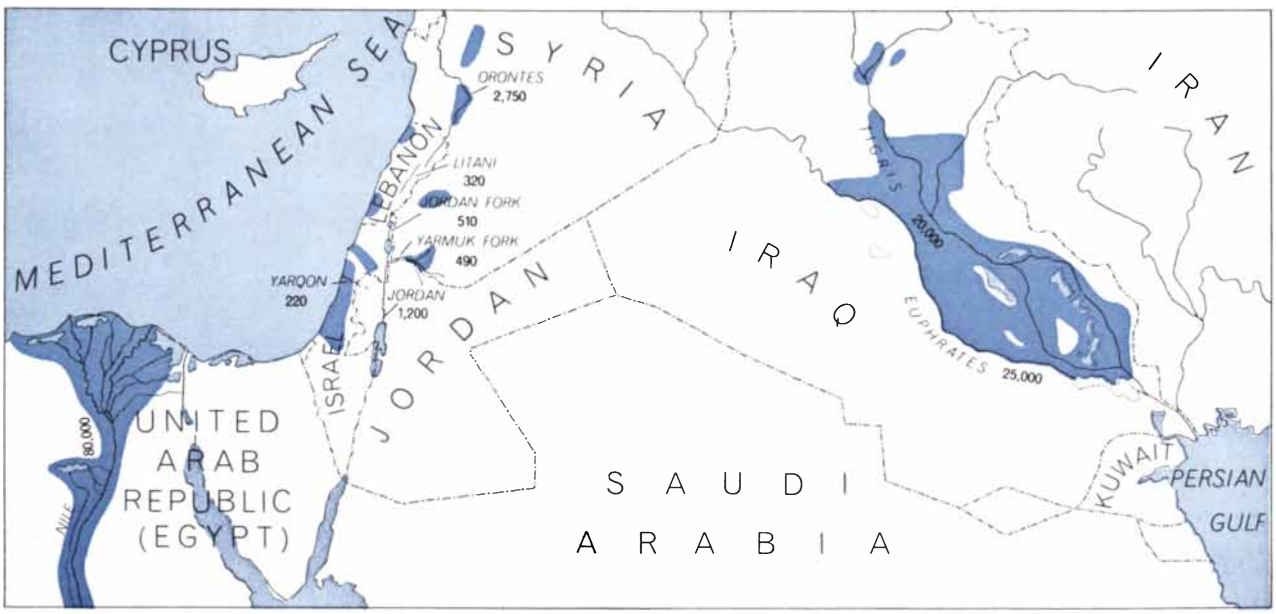
The historic region at the eastern end of the Mediterranean is especially suited to a unified development of water resources. Some advances have been made in spite of Arab-Israeli tensions

by Maurice A. Garbell

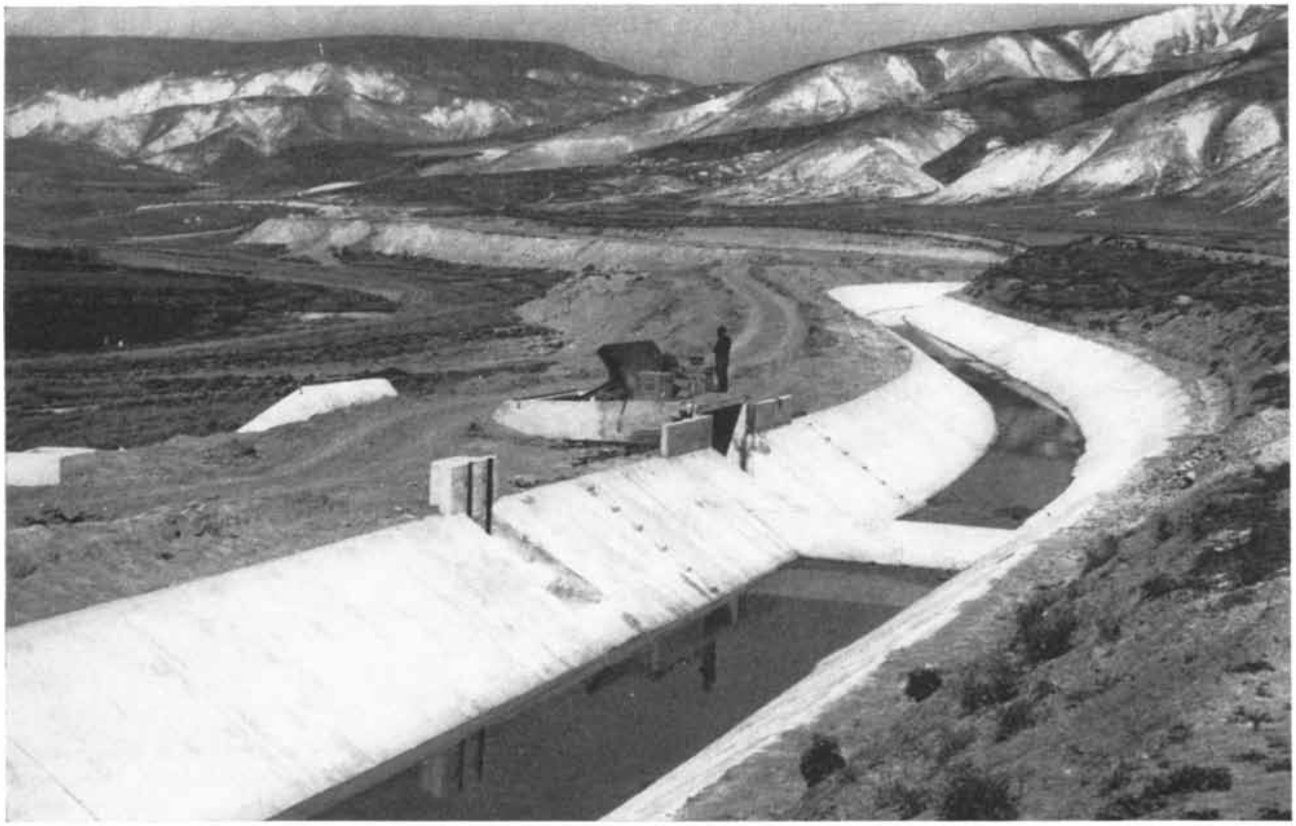
It is an irony of history that semi-desert conditions now prevail in much of the region once known as the Fertile Crescent. At the time of the Roman and Byzantine empires these lands just east of the Mediterranean supported a population substantially larger than they do today. Moreover, the earlier peoples had on the whole a higher standard of living than most of the present inhabitants.

The degradation of the region came about almost entirely because of human discord and neglect. The ancient peoples had ingeniously developed the lands of the Fertile Crescent by the intelligent use of meager water resources. Their technique was mainly efficient storage of water in cisterns and in open reservoirs, supplemented by well-planned irrigation, terracing and tree planting. Then invaders laid waste to the region and a long decline set in. A succession of indolent and mutually intolerant peoples allowed the cisterns and reservoirs to fall into ruin, the irrigation channels and the terraces to crumble, the trees to be cut down, the low vegetation to be destroyed by sheep and goats and the land to be scoured by erosion.

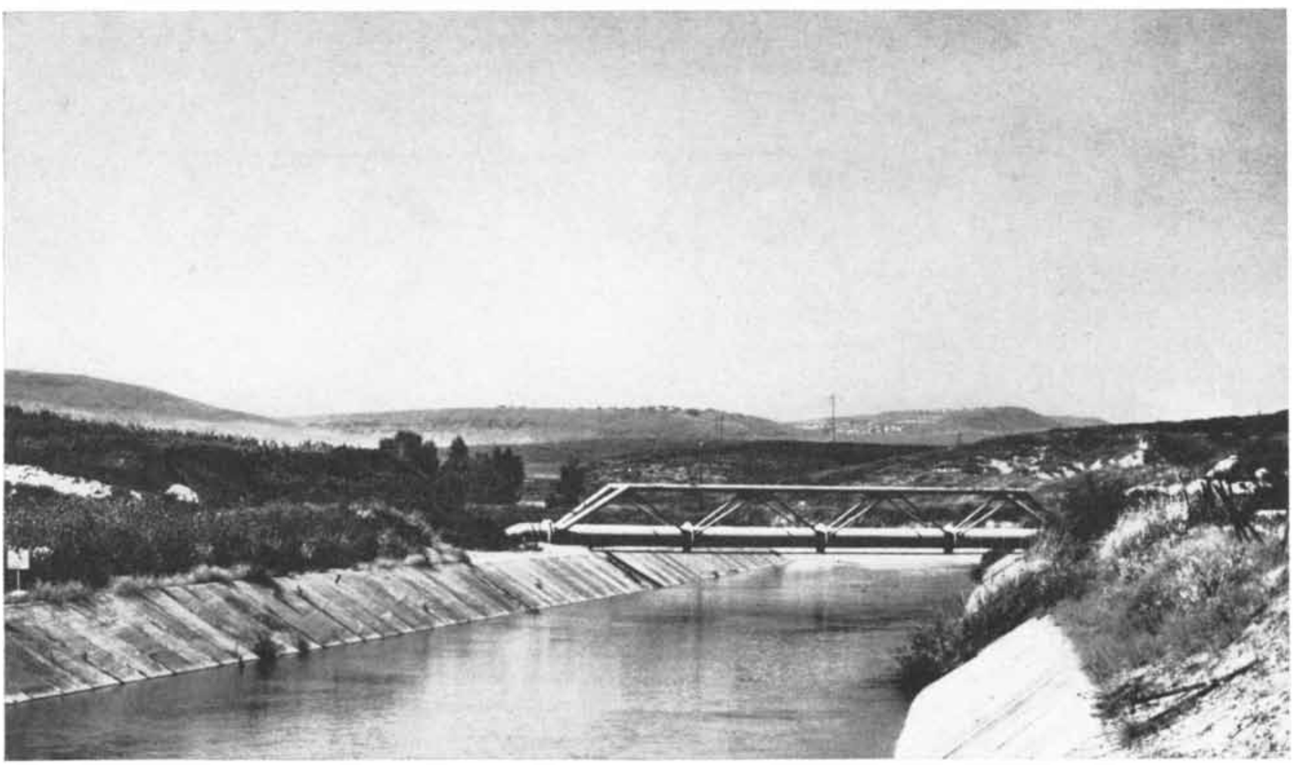
Only in recent years has any systematic effort been made to arrest the de-



WATER SITUATION IN MIDDLE EAST is summarized. The number with the name of each major river shows the river's average annual flow in millions of cubic meters. The portions of the map in dark color indicate regions that are under irrigation.



JORDAN'S GREAT YARMUK PROJECT takes water from the Yarmuk River and channels it into a canal system that carries it southward to irrigate farmlands along the River Jordan, which is itself unsuitable for irrigation because it flows below sea level and is markedly saline. Shown above is a completed portion of the canal system, which takes its name from the main East Ghor Canal.



ISRAEL'S NATIONAL WATER CARRIER PROJECT includes various works designed to use fresh water from the upper Jordan River and to reduce the salinity of Lake Tiberias. Shown here is a portion of the conduit carrying saline effusions from the region toward their ultimate destination in the Dead Sea. Israel is diverting the flow of several saline springs that once fed into the lake.

cline and to restore a flourishing agriculture by modern techniques of conservation and water distribution. Israel in particular is making remarkable progress in this direction [see "The Reclamation of a Man-made Desert," by Walter C. Lowdermilk; SCIENTIFIC AMERICAN, March, 1960]. More recently the Hashemite Kingdom of Jordan has likewise begun to develop its water resources. Because of their common hydrographic endowment both nations must depend primarily on the waters that flow into the River Jordan. Lebanon and Syria are also affected, although less significantly, because some of the Jordan's headwaters originate in those countries.

Logic would prescribe that the most effective use of the water resources in such a situation would be made by a common undertaking, similar to the Tennessee Valley Authority, directed toward the unified development of a jointly held and mutually needed river system. Indeed, several such plans for the Jordan valley were integrated into a unified plan that gained the technical agreement of the parties concerned but was not adopted explicitly by the Arab participants because of the political impasse between Israel and the Arab nations. Even so, Israel and Jordan have managed to proceed individually with aspects of the plan—aspects that are in fact virtually dictated by the hydrography of the region. Lately, however, the situation has become fraught with the danger of open conflict. The danger arises from the declared intent of the Arab nations to divert several of the Jordan's headwaters before those waters reach Israel. Such an action would violate the concepts of the unified water plan I have mentioned. Israel has asserted that she would take serious measures against such a move.

It appears likely that political efforts to ease this situation may soon be undertaken, perhaps by the United Nations. It is desirable that the geographic, hydrographic and technological considerations involved be broadly understood. For the remainder of this article, then, I shall discuss mainly these subjects.

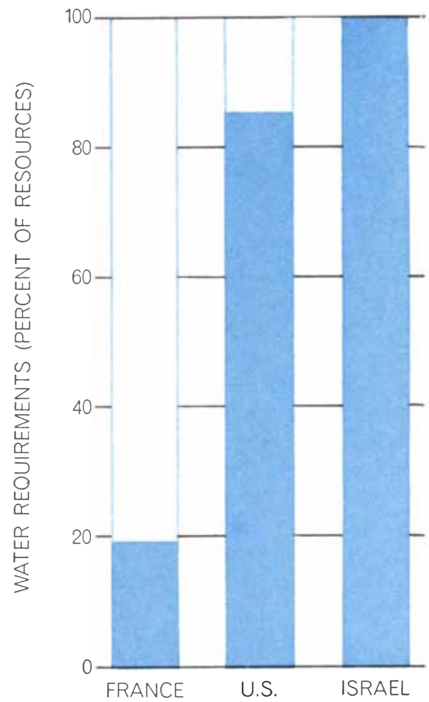
The major components of the Jordan River system are the Jordan itself and the Yarmuk River [*see illustration on next page*]. It is useful, however, to consider the system in three parts. One I shall call the Jordan River Fork, by which I mean the waters north of the point at which the Yarmuk joins the Jordan. The second part is the Yarmuk, and the third is the Jordan south of the Yarmuk-Jordan confluence.

The Jordan River Fork is the product of three creeks that come together in Israel after originating mainly in several perennial springs on the western and southern slopes of Mount Hermon, which bestrides the border between Lebanon and Syria. From west to east the creeks are the Hasbani, which rises in Lebanon and also flows for about a mile in Syria before entering Israel; the Dan, which is entirely in Israel, and the Baniyas, which rises in Syria. The Hasbani has an annual flow of 150 million cubic meters; the Dan, 240 million, and the Baniyas, 120 million. Below the confluence of the three creeks, which occurs at about 230 feet above sea level, the Jordan River Fork flows into Lake Huleh, where its volume is further augmented by springs. Emerging from Lake Huleh, the fork tumbles to 650 feet below sea level at its entrance to Lake Tiberias, which is the Sea of Galilee of the Bible and is called Yam Kinneret by the Israelis. South of Lake Tiberias the fork continues in a shallow gradient for about four miles to the confluence with the Yarmuk.

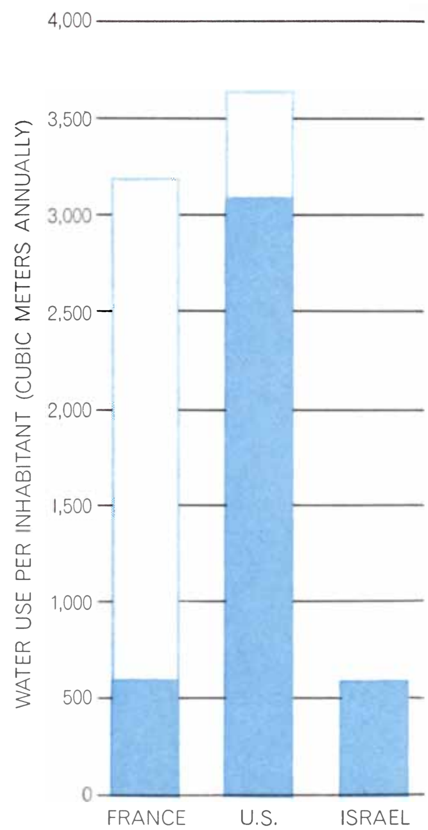
The Yarmuk River originates in a widely spread system of winter wadis and perennial springs in the Horan Plain of Syria. The river forms the border between Syria and Jordan for some 20 miles and then becomes the border between Jordan and Israel for eight miles until it joins the Jordan River. Unlike the Jordan River Fork, the Yarmuk has no natural storage basins such as Lake Tiberias.

Each of these major tributaries of the River Jordan is markedly seasonal, carrying a much larger natural flow in winter than in summer. For example, the maximum natural winter flow of the Yarmuk is about 62 cubic meters per second and the minimum summer flow about 7.6 cubic meters per second. This variation is attributable to scant snow storage, which occurs only on the main massif of Mount Hermon, and to the almost total absence of precipitation during the summer in the source regions of both the Jordan River Fork and the Yarmuk. During the course of a year, however, each of these two tributaries discharges about 500 million cubic meters of water into the River Jordan.

South of the confluence of the Jordan River Fork and the Yarmuk, the River Jordan forms the boundary between Jordan and Israel for about 20 miles before it enters Jordan. Thereafter it continues southward some 40 miles to



WATER REQUIREMENTS as projected for 1975 are shown for three nations in differing situations, which are indicated below.



RANGE OF SITUATIONS is from France, with much water and low demand, to Israel, with little water and heavy requirements. Open bars show resources; solid bars, use.

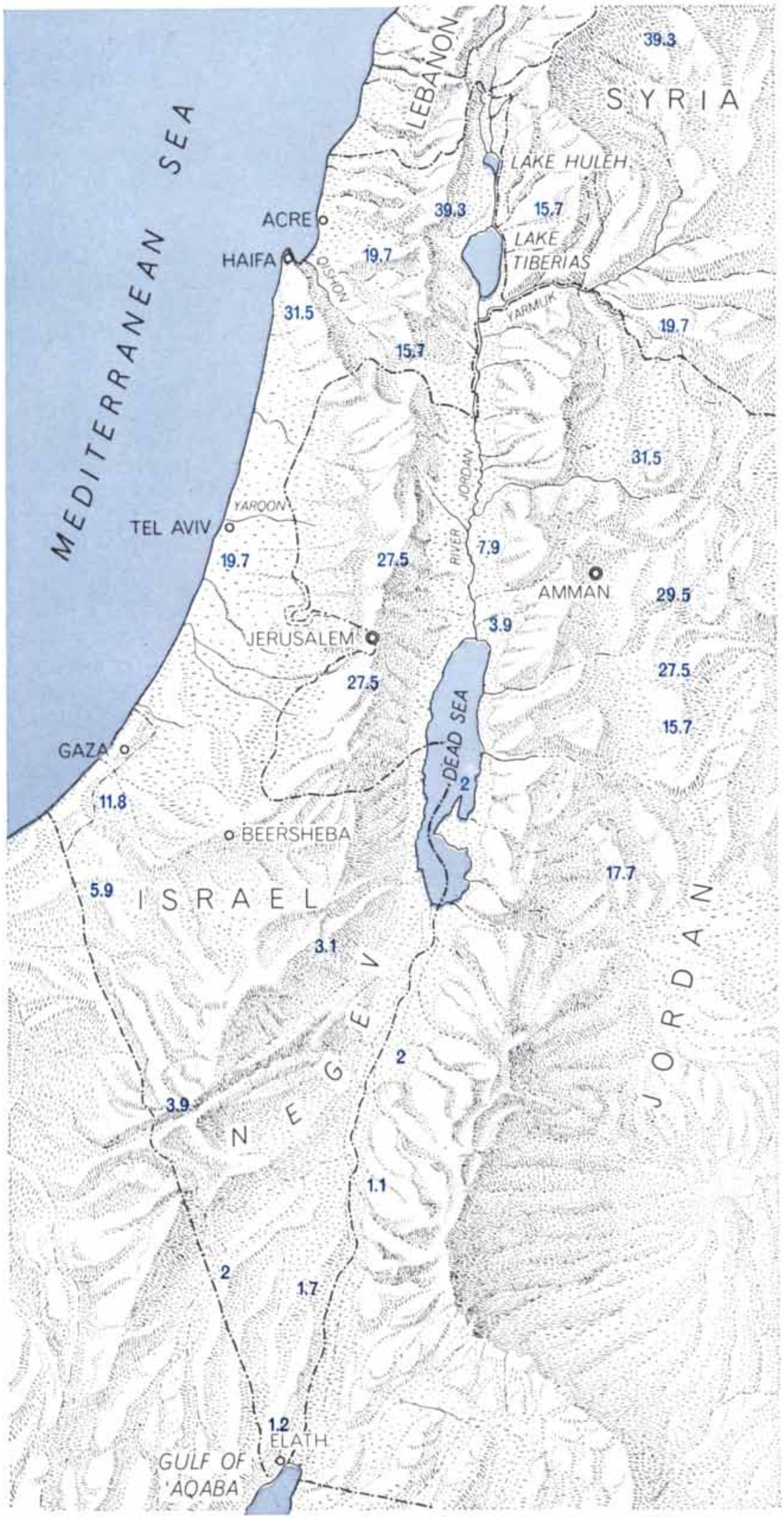
the Dead Sea. Along its course the Jordan receives irregular storm runoff from several winter wadis, so that at the Allenby Bridge near Jericho the average natural annual flow of the river is 1.2 billion cubic meters.

One geographical feature of the region is particularly significant. The Jordan valley is no ordinary valley produced by geological folding or erosion. It is a deep rift: part of a huge crack in the crust of the earth. This crack cleaves the Asian-African land bridge to depths far below sea level; at the Dead Sea bottom, which is 2,600 feet below sea level, the rift forms the deepest inland sink in the world. South of the Dead Sea the same rift contains the Red Sea, and as it winds through Africa it forms the East African Rift Valley, with its many large lakes and depressions.

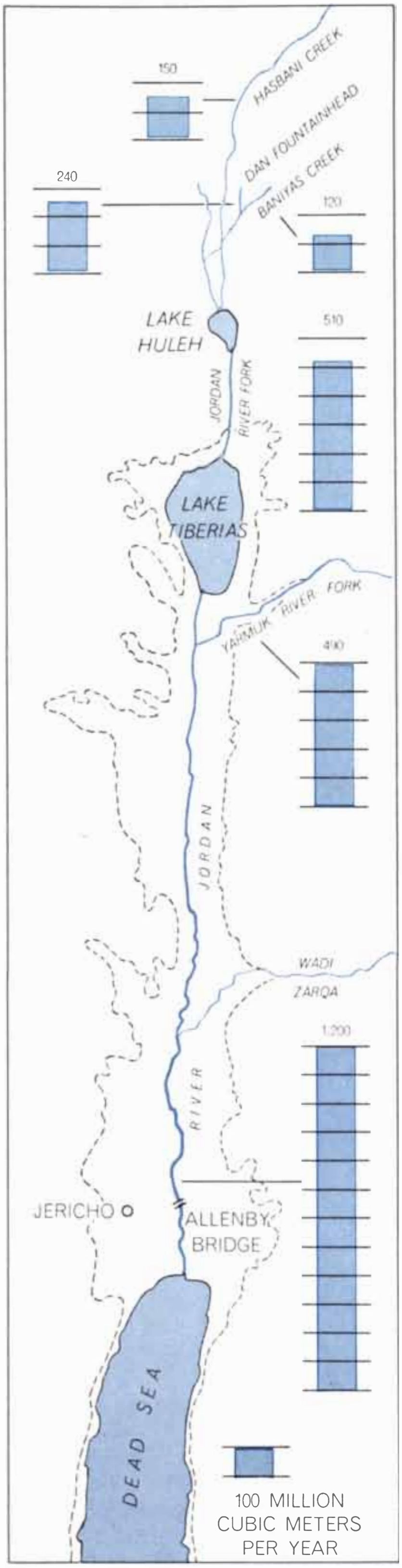
As a result of this unusual geomorphic feature the entire River Jordan south of the Jordan River Fork–Yarmuk confluence flows below sea level. So does most of the Jordan River Fork, beginning at a point just south of Lake Huleh. On the other hand, the Yarmuk and its tributaries are almost entirely above sea level.

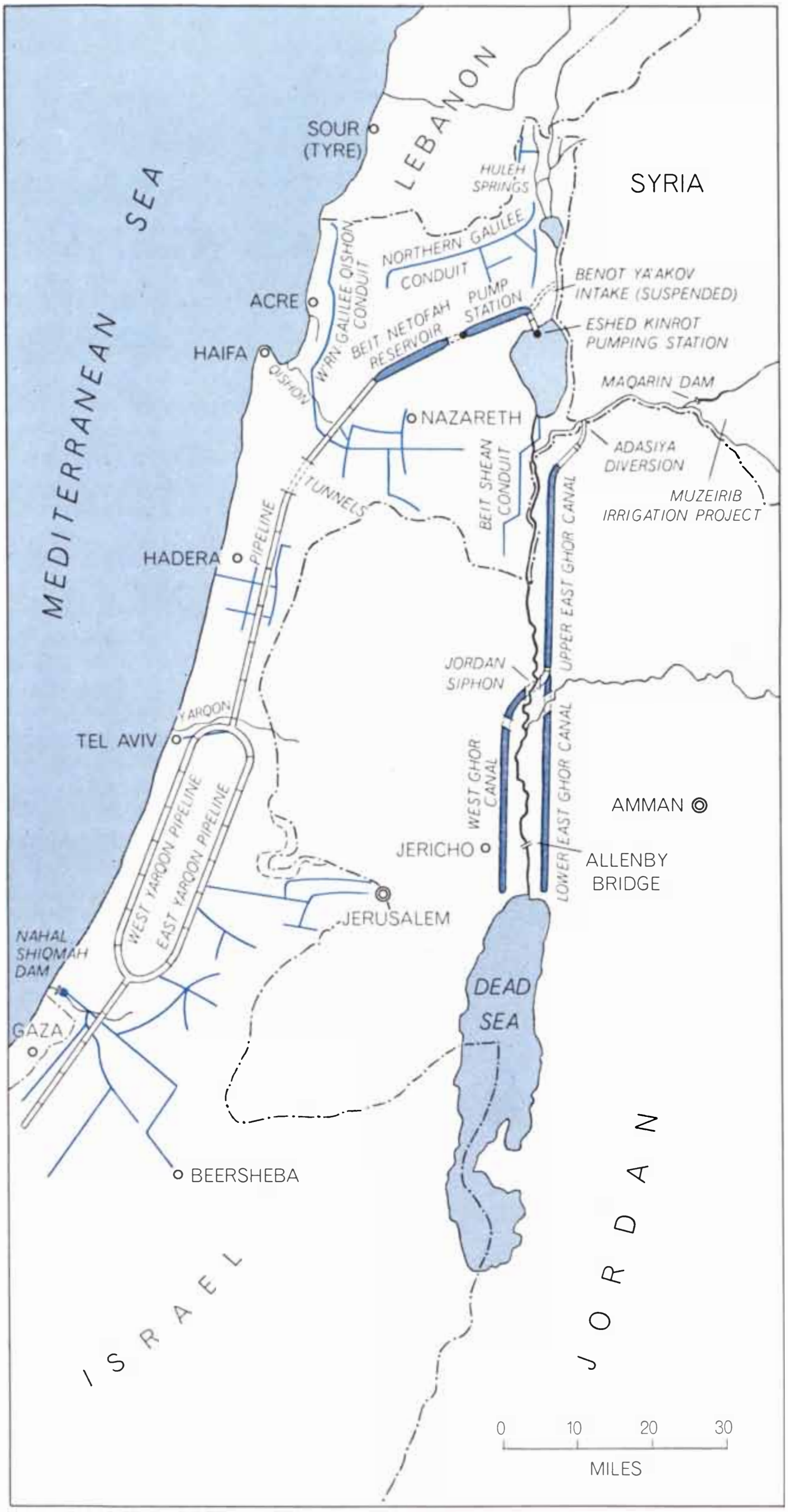
Certain consequences important to the development of the water resources of the Jordan River system arise from this situation. One is that the Jordan, flowing far below sea level and with a shallow gradient, is unable to provide any appreciable amount of irrigation by gravity to agriculture along its banks. Moreover, being below sea level, the Jordan and much of the Jordan River Fork receive heavy infusions of salt, mostly from subterranean springs. Such springs deliver an annual discharge of 160,000 tons of chlorine in the basin of Lake Tiberias and an additional 180,000 tons between the lake and the Dead Sea. (The figures are given in terms of chlorine to provide a common denominator for the several chlorides involved.) These saline infusions would render the water of the Jordan intolerable for most human uses were it not for the diluting action of the fresh water of the Yarmuk.

These facts prescribe two broad concepts that any equitable plan for the development of the Jordan system would seem compelled to follow. The first is the use of the fresh water of the Yarmuk to supply trunk-line canals within the Jordan valley. Such canals would run parallel to the River Jordan but would be uphill from the arable land along the river. Carried through



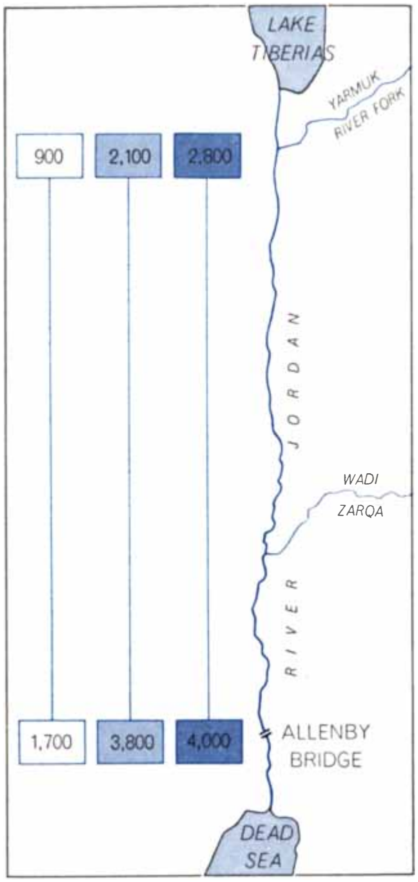
GEOGRAPHICAL SETTING of the Jordan Valley Plan is shown on this map. The River Jordan flows partly along the Israel-Jordan border and partly in Jordan; its major tributary, the Yarmuk River, forms in part the Jordan-Syria border and in part the Israel-Jordan border. The headwaters of the River Jordan rise in Israel, Lebanon and Syria. The numbers in color show the average annual precipitation (in inches) in various parts of the region.



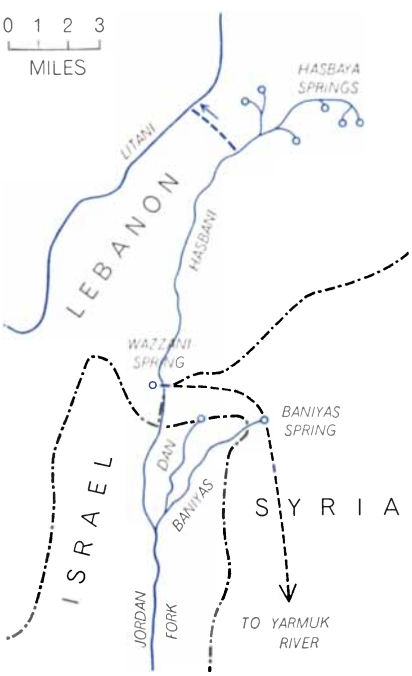


MAJOR FLOWS of water in the Jordan River system are indicated by the colored bars. The total at Jericho is higher than the sum of the Yarmuk and Jordan River Fork contributions because of winter storm flows.

SEPARATE WORKS undertaken by Jordan and Israel to develop the resources of the Jordan River system are depicted. Jordan's works draw on the waters of the Yarmuk River and are used mainly for irrigation. Israel draws from Lake Tiberias, which receives most of its water from the upper Jordan. The Israeli works are partly to supplement existing water supplies and partly to carry water far south into the Negev for irrigating new farmlands.



SALINITY of River Jordan in parts per million at two sites is shown for 1962 (*white*); with Yarmuk project operating (*light color*); with Israeli works added (*dark color*).



POSSIBLE DIVERSIONS of Jordan headwaters as discussed by Arabs are indicated.

the farmlands by subsidiary canals, the water would serve both for irrigation and for leaching salts out of the soil before draining into the Jordan. The salts would be carried by the river to the Dead Sea.

The second concept involves the separation of the fresh water of the Jordan Fork from the saline infusions occurring in Lake Tiberias and south of it. If this were not done, the water would continue to be spoiled by the admixture of brines while coursing wastefully to the Dead Sea. The fresh water thus taken from the Jordan Fork could be used for irrigation of arable lands along the Jordan or carried far south to the northern Negev, which has a potentially fertile soil of the loess type that is now virtually useless for lack of water.

These basic concepts underlie several of the plans that have been drawn up for the development of the Jordan River system. The concepts figured in a proposal made in 1944 by the American conservationist Walter C. Lowdermilk. His proposal was a forerunner of others that embodied similar concepts. One such plan was "The Unified Development of the Water Resources of the Jordan Valley Region," prepared in 1953 at the request of the UN. This plan, drawn up by Charles T. Main, Inc., under the direction of the Tennessee Valley Authority, is sometimes called the Johnston Plan because it formed the basis for extensive negotiations conducted between the Arabs and the Israelis from 1953 to 1955 by the late Eric A. Johnston, who went to the Middle East as a special ambassador at the request of President Eisenhower.

Johnston also took into account plans prepared separately by Israel and Jordan. He incorporated features of all of them into what became known as the Unified Water Plan, which sought to recognize the right of each riparian state to a fair share of the available waters. Jordan, Syria and Israel were regarded as riparian states concerned with both the Yarmuk and Jordan Fork waters, and Lebanon was recognized as a fourth party at interest with respect to the Jordan Fork. The plan called for about 60 percent of the water to be available to the three Arab states, with the rest to be assigned to Israel. It gave Lebanon and Syria the full amounts specified by their governments for the irrigation of farms in the headwater region, and it gave Jordan the water required for the irrigation of all its irrigable lands. The U.S. offered to provide up to $200 million toward the execution of the plan.

In October, 1955, Johnston reported that "Israel and her Arab neighbors—Lebanon, Syria and Jordan—now recognize the Jordan Valley Plan as the only logical and equitable approach to the problem of developing a river system that belongs, in some part, to all of them." He added: "They have made it clear to me that, in the main, the technical and engineering aspects of the plan... are now satisfactory to them." Johnston expressed the view that the negotiations had reached the "one-inch line."

Unfortunately they advanced no further. Although the technical experts on both sides had signified agreement with the plan and Israel had indicated a readiness to ratify it, the political committee of the Arab League deferred its decision and sent the policy paper back to the technical committee.

Interestingly the failure of the plan to obtain formal approval has not meant its total abandonment. Most of the work done by the nations individually since 1958—by Jordan and Syria to draw on the Yarmuk and by Israel to draw on the Jordan Fork—has followed closely the basic provisions of the Unified Water Plan. In effect the plan has proved to be largely self-enforcing because of the physical facts on which it is based. The two major projects undertaken since 1958, both with financial support from the U.S., are the Jordanian Great Yarmuk Project and the Israeli National Water Carrier Project [*see illustration at right on preceding page*].

The Great Yarmuk Project is principally a Jordanian venture, but it is being carried out in cooperation with Syria. It is based on a plan prepared by the Harza Engineering Company of Chicago. The project has three distinct phases, which I shall discuss by the names most frequently used in referring to them.

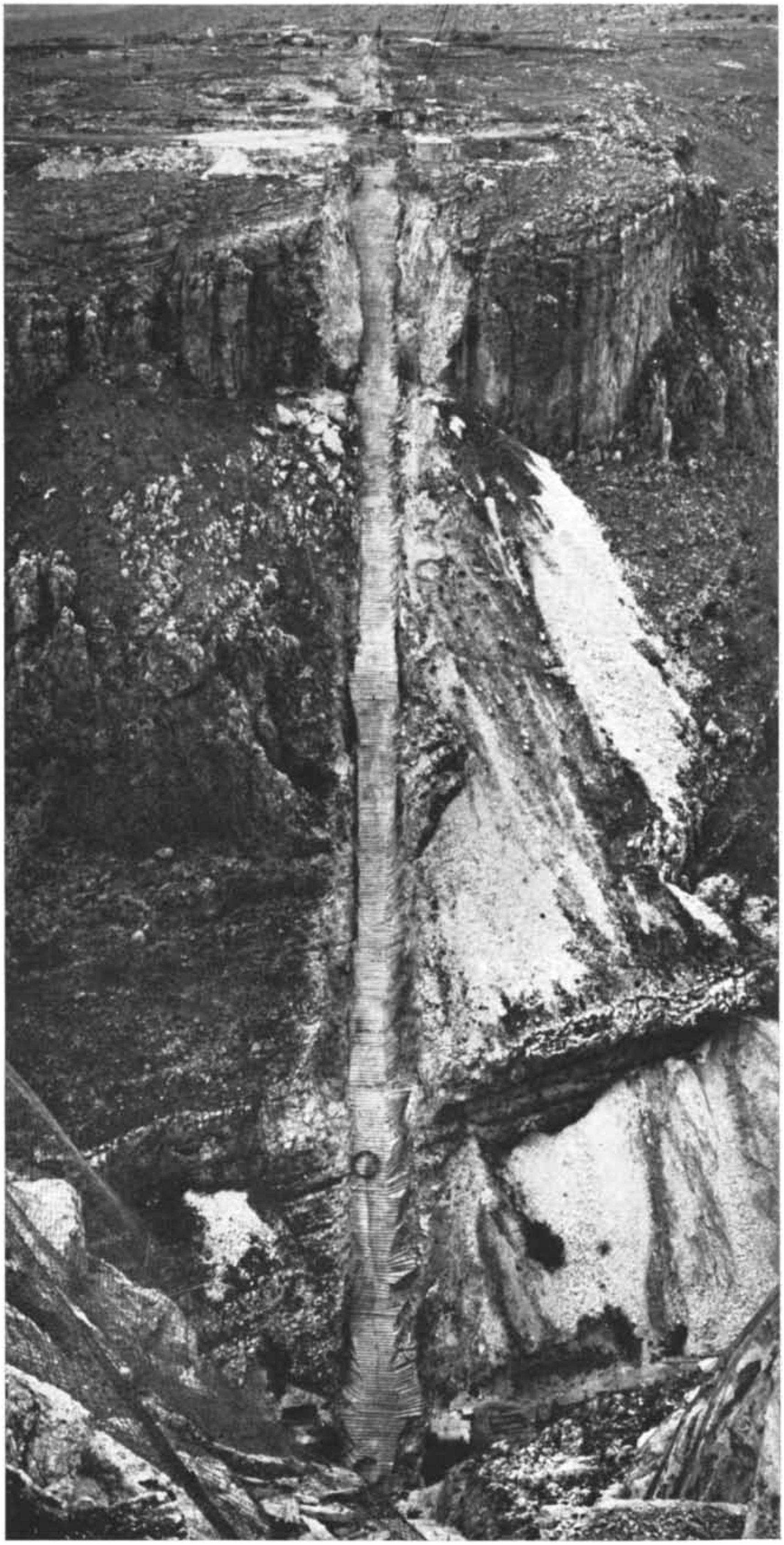
The El-Muzeirib phase, designed to deal with the large variation between the winter and summer flow of the Yarmuk, is a headwater irrigation program to provide controlled winter irrigation and expanded summer irrigation in the El-Muzeirib region of Syria. It is of major importance to the agriculture of a dry and remote part of southern Syria. This undertaking has already brought about 7,500 acres under irrigation and will eventually encompass about 16,500 acres. The total withdrawal of water will be some 70 million cubic meters, which is substantially in agreement with the Unified Water Plan.

The Upper East Ghor Canal phase is a Yarmuk diversion affecting the summer flow at Adasiya in Jordan, where the river begins to form the Jordan-Israel border. Water diverted there is channeled along the foothills of the eastern Jordan valley to irrigate some 30,000 acres of previously marginal and undeveloped land between the Yarmuk and the Wadi Zarqa, which is about half of the distance from the Yarmuk-Jordan confluence to the Dead Sea. This joint undertaking of the Jordanian government and the U.S. Operations Mission to Jordan, financed by the U.S. to the extent of about $15 million, was substantially completed in 1963. Its principal feature is the 42-mile Upper East Ghor Canal.

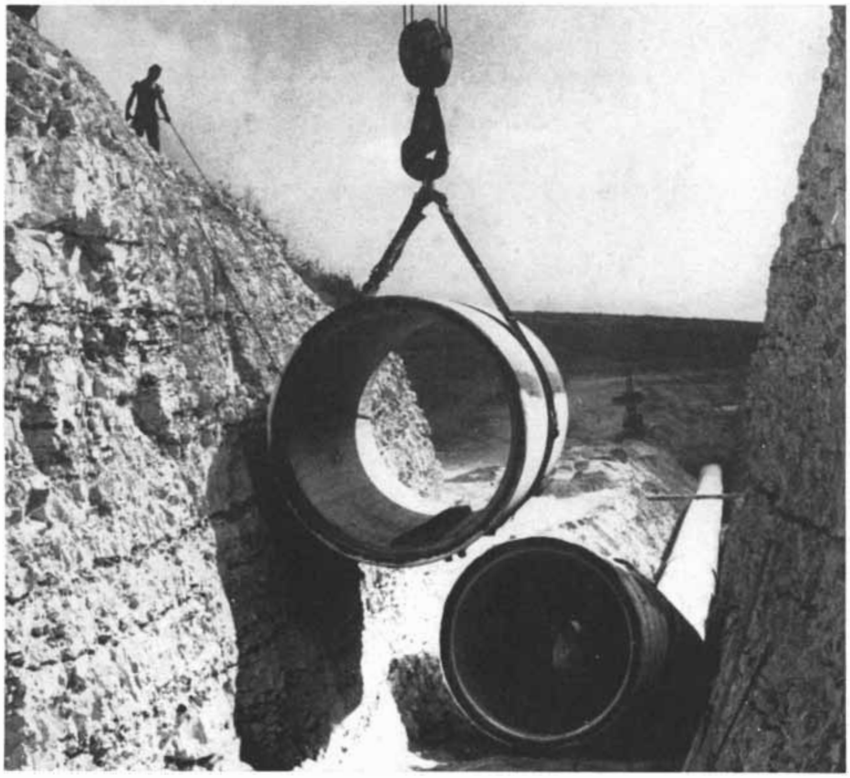
As a result of the diversion of water from the Yarmuk by the Jordanian undertaking, amounting to 150 million cubic meters a year, certain problems have arisen along the Yarmuk and the Jordan downstream from the diversion. Although the Israeli villages along the Yarmuk are enabled to draw a flow of water approximately equal to what they have drawn in the past, the task of utilizing the water has become complex. Israel used to take its share from a fairly ample stream; now it has the difficult and costly task of deriving the same share from a shallow rivulet, trickling at levels below the previously installed intake-strainers. Another problem is that the Yarmuk diversion has already increased the salinity of the River Jordan to so great a degree that the Jordan's water can no longer be used for irrigation by Jordanian farmers along the east bank. Jordan is moving to provide them with a substitute by building branch canals from the Upper East Ghor Canal.

The Maqarin Dam phase of the Great Yarmuk project involves the impounding and controlled release of the total winter flow of the Yarmuk by means of a dam to be constructed at Maqarin on the Jordan-Syria border. This phase also involves an extension of the East Ghor Canal into two branches south of Wadi Zarqa, one branch to extend along the eastern face of the Jordan valley and the other along the western face. The entire undertaking is now in the early stages of development, aided by substantial funds from the U.S. Agency for International Development.

Both hydroelectric power and irrigation will be provided by the water



"INVERTED SIPHON" carries the trunk line of Israel's water project down to a deep wadi, under the bed of the wadi and up the other side. In spite of its name it has no siphoning action but instead carries water by contained fall on the down side and by the resulting force on the up side. "Inverted" means that the apex of the structure is at the bottom.



TRUNK-LINE PIPE, 108 inches in diameter, is laid by Israeli workmen. Israel's trunk line carries water from Lake Tiberias in a combination of canals, pipelines and tunnels.

stored behind the dam. The power will be shared by Jordan and Syria; most of the irrigation waters will go to Jordan. These waters will be distributed through the two extensions of the Upper East Ghor Canal (the extension west of the Jordan receiving its water by means of a pipeline passing beneath the bed of the saline river) and will irrigate some 125,000 acres of hitherto parched land along the banks of the lower River Jordan.

Israel's National Water Carrier Project, partly new and partly old, extends from the Jordan Fork through nearly the full length of the country, including also some east-west extensions and branch networks. The philosophy of its design derives from certain characteristics of the nation's water economy. One is the marked variation in rainfall, both geographically and in time. Geographically the variation is from 40 inches a year in the mountainous Upper Galilee region to about 16 inches in the coastal plain, eight inches in the northern Negev and 1.25 inches at the southern end of the country. The north has a longer winter precipitation season and a smaller year-to-year and storm-to-storm variation than the south; indeed, the typical desert "drought or deluge" situation in the south may in unusual years result in entire winters being rainless. Another characteristic of the nation's water economy is an abundance of water at low elevations (some below sea level) in the north and a deficiency in the south on irrigable lands 250 to 650 feet above sea level. A third characteristic is a preponderance of population and unused arable land in the dry south and a higher degree of current use of existing arable lands in the amply watered north. Concomitantly the potentially fertile lands of the dry Negev offer the attraction of a smooth topography that makes them particularly suitable for mechanical cultivation.

Three major parts of the National Water Carrier system were built some time ago and so do not arise directly from the Unified Water Plan. The Yarqon-Negev part, completed in 1955, is fed by wells east of Tel Aviv and provides 270 million cubic meters of water a year for the city and for the irrigation of the potentially fertile lands south of the city in the Lakhish area, which had been a neglected badland for nearly 2,000 years. Another part captures the flow of northern Galilean creeks, formerly lost to the Mediterranean Sea, to irrigate the inner portions of the Esdraelon Valley. The third part is the system that drains the area around Lake Huleh; this work eliminated a malarial swamp, improved the land and enriched the flow of the Jordan Fork.

The National Water Carrier Project was designed to coordinate these and other existing systems. It had other objectives as well. One was to extend irrigation farther southward in the Negev by augmenting the existing water projects with a flow of water from the Jordan Fork. Another was to stabilize the water economy of the central coastal plain, where pumping had caused an alarming drop in the water level of the two principal subterranean aquifers and had produced an equally objectionable advance inland of the underground saltwater front.

To accomplish these purposes Israel has undertaken the construction of a large trunk line to take water from the Jordan Fork and carry it as far as 125 miles south. The carrier was designed in accordance with the water allocation of the Unified Water Plan. Technologically the undertaking is impressive. It raises water from 692 feet below sea level to 120 feet above sea level by pumps, and then it carries the water southward (with some additional raising) in a line of canals, pipes nine feet in diameter and tunnels drilled through mountains.

Originally Israel planned to take water directly from the Jordan Fork at Benot Ya'akov, which is between Lake Huleh and Lake Tiberias. It is also above sea level, so that the project could have been designed to let excess winter flows descend to Lake Tiberias for storage and generate electric power in the process of descent. Because Benot Ya'akov is in the demilitarized zone between Israel and Syria, however, Syria protested to the UN when Israel began work on the intake and the hydroelectric facilities in 1953. A debate ensued in the Security Council, and Israel suspended work pending the outcome. In 1954 a resolution for the resumption of the work carried a majority in the Security Council but was vetoed by the U.S.S.R. Israel stopped all work at Benot Ya'akov and undertook the planning of an alternate intake.

That intake is at Eshed Kinrot on Lake Tiberias and is therefore below sea level. As a result Israel has had to use electricity to raise water from the lake without the compensating factor of electricity generated by the water in its descent to the lake. From the intake three pumps, each rated at 23,000 kilowatts and having a capacity of 6.75 cubic meters a second, lift the water 812 feet through a penstock 1.3

miles long. The penstock feeds into a canal that carries the water 11.5 miles to an operational reservoir at Beit Netofah. Along the route the canal crosses two deep wadis by means of buried crossover pipelines known locally as inverted siphons [*see illustration on page 29*]. Actually they do not involve the siphon principle of suction; the function of the structure is merely to let water fall down one side of the wadi and, as a result of hydrostatic pressure, rise again to the original free level on the other side. Before reaching Beit Netofah the water goes into an intermediate reservoir at Tsalmon, where another pumping station lifts the water from 122 feet above sea level to the level of the Netofah Valley at 482 feet. There three more pumping units maintain the canal-discharge rate of 20 cubic meters a second. At the Beit Netofah reservoir the water enters the nine-foot pipe, which carries it 48 miles interrupted only by the one-mile Shimron tunnel through the Nazareth Range and two tunnels through the Carmel Range—Menashe-A tunnel, four miles long, and Menashe-B, 1,100 feet.

When the trunk line is fully in operation in 1970, it will carry an average water flow of 320 million cubic meters a year. That is well within the share of the Jordan-Yarmuk system allotted to Israel by the Unified Water Plan. It amounts to 1.3 percent of the total river flow in the four countries encompassed by the Jordan River system.

An accessory to the trunk-line undertaking is the use of Lake Tiberias as a storage reservoir, which has necessitated some work designed to reduce the salinity of the lake. In the natural state of the lake the salinity is approximately 350 parts per million, compared with 20 to 30 parts per million for the water of the Jordan Fork at the point of entrance to the lake. Although a salinity of 300 parts per million can be tolerated for many agricultural uses, it is too high for the irrigation of the citrus groves that abound in Israel and produce a major export crop.

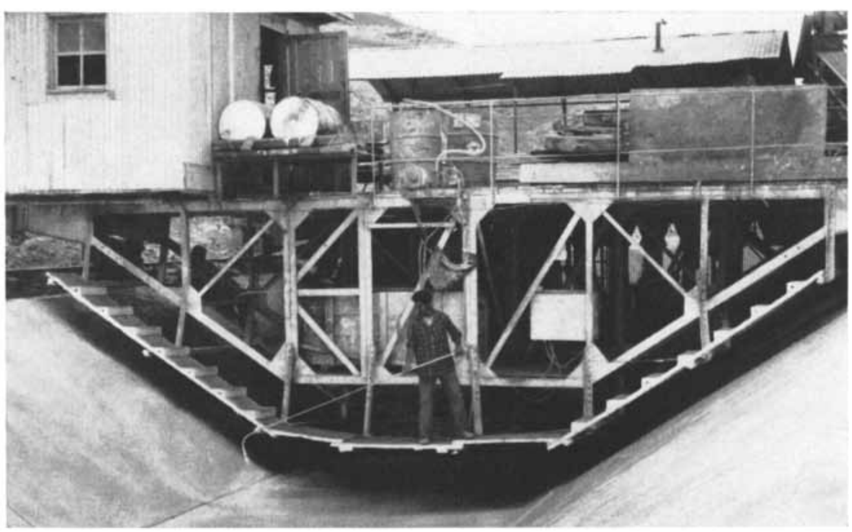
The saline effusions come about equally from shore springs and underwater springs, some of the latter issuing through fissures 3,000 feet or more below water level. A survey by Tahal, the Israeli Water Development Agency, revealed that many of the shore springs actually carried fresh water and only became saline through contact with soil layers containing soluble minerals. These layers proved to be at fairly shallow depths and rather close to the lake. Tahal therefore has undertaken to capture the fresh water before it reaches the soluble minerals. Deep saline springs, on the other hand, are being captured by drilling. All captured saline effusions are carried off in a canal and ultimately deposited in the Dead Sea. Tahal foresees that in about 10 years the combination of saline withdrawals and the steady flow of fresh water from the Jordan Fork into the lake will reduce the salinity of the lake to a mean value of about 130 parts per million. Then the water drawn into the trunk line will be suitable for unlimited irrigational use in citrus groves.

As a result of withdrawals of fresh water from the Jordan Fork and the Yarmuk, Israel has had to take some steps to continue providing usable water to the flourishing Beit Shean agricultural region in the vicinity of the Jordan-Yarmuk confluence, because that region had depended on water from the rivers for irrigation. Israel has built a special canal network to supply the region with water from the Jordan Fork. In addition Israel is continuing to release the quantities of fresh water agreed to by the technical conferees in 1955 from Lake Tiberias into the River Jordan for the use of Jordanian farmers. This action conforms with the Unified Water Plan.

In January, 1964, a few months before Israel began withdrawing water from the Jordan Fork into the National Water Carrier system, the leaders of the nations that constitute the Arab League held a "summit" conference in Cairo. From that meeting emerged the plan to divert some of the Jordan's headwaters from Israel. As subsequently outlined in general terms by Arab spokesmen, the plans call for diversion of the Hasbani Creek in Lebanon into the Litani River, the flow of the Wazzani springs near the Hasbani into the Baniyas Creek and the Baniyas into the Yarmuk [*see bottom illustration on page 28*]. A second meeting of the Arab leaders last September produced a decision for "immediate work" on diversion projects.

Any such undertaking would be costly and time-consuming. It also would be contrary to the concepts of the Unified Water Plan and inconsistent with traditional international headwater rights of a historically established downstream user. It therefore seems unlikely that serious diversionary moves will be made immediately. Still, an Arab-Israeli encounter over water could occur at any time through misunderstanding.

If Israel and Jordan are able to proceed with their separate efforts to carry out the concepts of the Unified Water Plan, the time will soon be at hand when all the fresh-water resources of the Jordan River system will be put to effective use. At that stage the only practicable addition to the supplies will be large-scale desalination of seawater. Whenever desalination becomes necessary—or desirable if the cost can be reduced to a level comparable to that of obtaining fresh water from other sources—the waterworks already built by Israel and Jordan will be useful for receiving and distributing the desalinated water as a welcome supplement to a supply already hard pressed by expanding agricultural and industrial activities.



EAST GHOR CANAL is shown receiving a curing compound during construction. Jordan plans extensions of the canal along both the east and the west sides of the Jordan River.

The Structure of Crystal Surfaces

By using low-energy electrons as a probe a new instrument can disclose the configuration of atoms on the surface of a crystal. The technique has revealed structures of unexpected complexity

by Lester H. Germer

When we look at the bare surface of a metal or other homogeneous solid, we usually assume that we are seeing nothing more than an exposed section of the bulk material below the surface. Indeed, it was long thought that the properties of a surface could be adequately understood by examining the structure and properties of the bulk material. Not only did surfaces seem to promise few surprises but also there was no effective means of studying them.

The recent development of an electron-diffraction technique for studying surfaces happily coincides with the recognition that many important properties of materials are largely determined by surface structure. These properties include electronic behavior, corrosion (including resistance to corrosion) and catalysis. The last phenomenon presents a particular challenge. Although the industrial application of catalysis annually yields chemical products worth many billions of dollars, little is known about catalytic mechanisms except that the desired reactions take place on surfaces.

In attempting to describe the electronic behavior of solids, complex and elegant theories have been built up by ignoring surface structure altogether and assuming that surfaces are simply mathematically smooth planes. Early theories of thermionic and photoelectric emission were of this kind. The theories served well in their day, but most solid materials are crystalline and it is now recognized that various crystal faces have quite different properties. Even when this fact has been taken into account, the naïve assumption is usually made that the atoms in a given surface plane have the same arrangement as the atoms in a parallel plane inside the crystal. This simple view is often adequate, but it is occasionally quite wrong. The very existence of a surface requires that the atoms in it have no neighbors on one side. The forces acting on them are therefore unsymmetrical and might be expected to modify their arrangement. Recent work has shown that this is often the case.

One of the most significant facts about real surfaces is that they quickly become dirty; a freshly cleaved crystal soon adsorbs foreign atoms on its surface. Where and how these atoms are adsorbed must be strongly influenced by the positions of the atoms of the clean surface. It seems likely that adsorption on actual surfaces is quite different from that envisaged in most present theories.

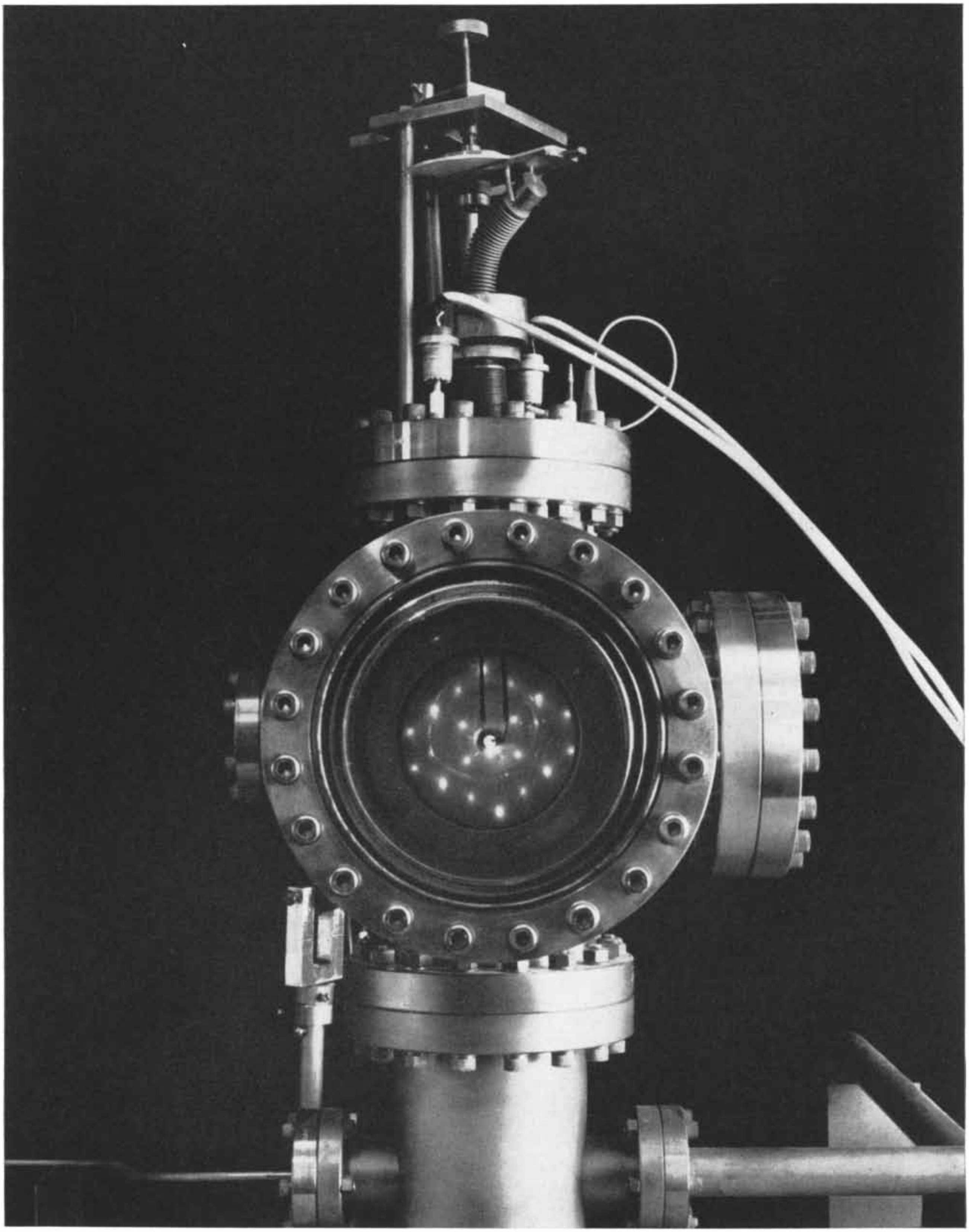
If surfaces are so important, how can one explore their structure? It is well known that the periodic arrangement of atoms inside a crystal can scatter electromagnetic waves and produce diffraction patterns much as a ruled grating produces a diffraction pattern when it scatters light. Just as diffraction patterns can disclose the arrangement of atoms inside a crystal, they can also disclose the arrangement of the atoms that compose the surface of a crystal. The spacing of the atoms varies in different directions, with the result that there can be many diffraction beams that add up to the observed diffraction pattern.

To obtain an atomic diffraction pattern the incident waves must be shorter than the spacing between the most widely separated rows of atoms on the crystal surface, a spacing that is commonly less than three angstrom units. These requirements are met not only by electromagnetic waves such as X rays but also by "matter" waves, that is, subatomic particles such as neutrons and electrons, which can be regarded interchangeably as particles or waves.

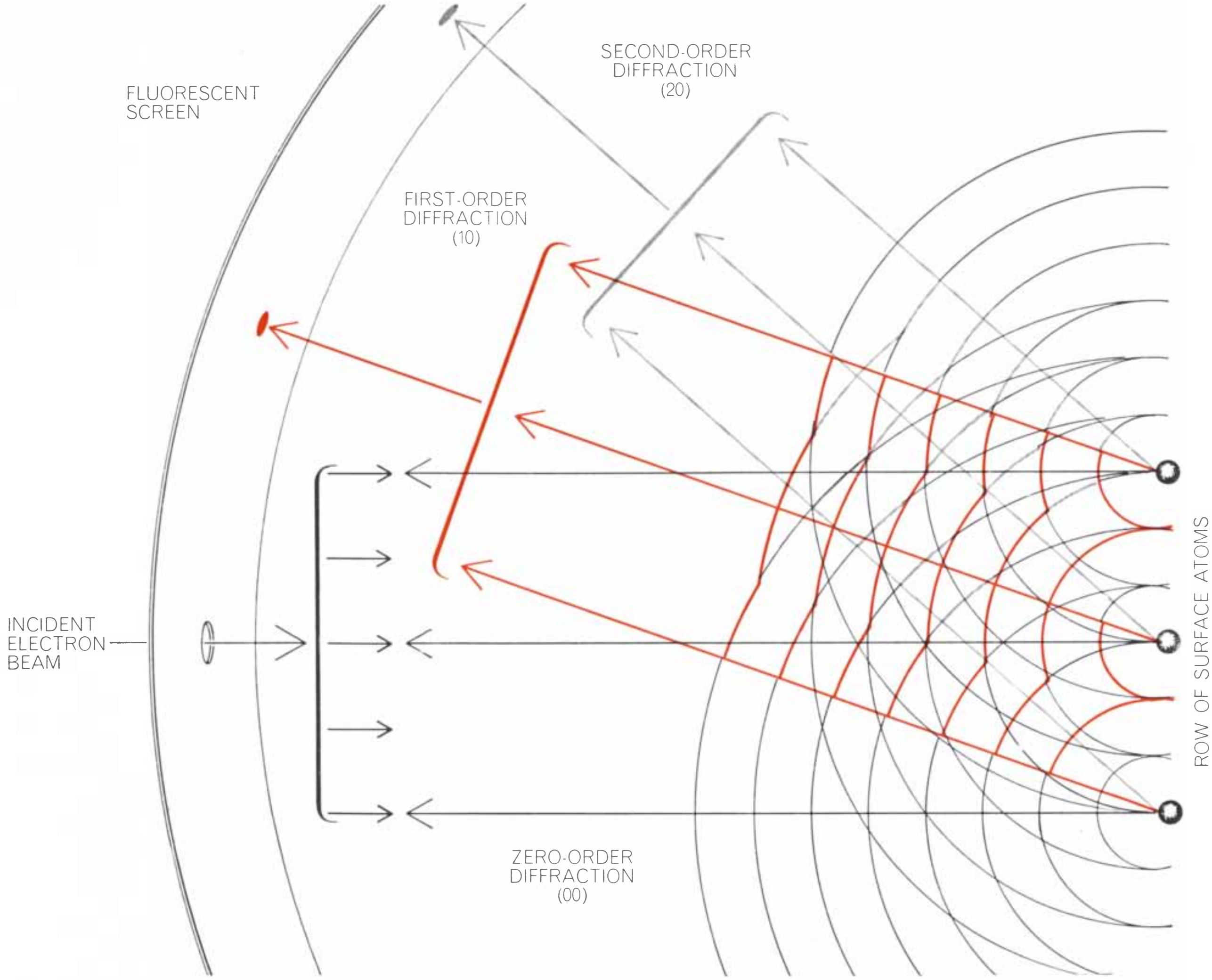
For studying surfaces X rays cannot be used because they penetrate many thousands of layers of atoms. Neutrons are more penetrating still. Light waves and ultraviolet radiation are readily reflected (and diffracted) from a surface, but their wavelengths are much too long. The ideal probe is a beam of slow electrons, which can be adjusted in penetrating power by altering the electrons' energy; this can easily be made so low that the electrons barely penetrate even the topmost layer of atoms of a crystal surface.

The discovery that electrons behave as waves and produce diffraction patterns when they interact with the atoms in a crystal was made in 1927 by C. J. Davisson and me at the Bell Telephone Laboratories and independently in Britain by Sir George Thomson. The electrons used by Sir George had energies of around 50,000 electron volts, enough to penetrate more than 100 layers of atoms, but the electrons we used had energies in the much lower range of from five to 500 electron volts. Although the more energetic electrons have been widely used since 1927 to study the near-surface regions of crystals, their penetrating power is so great that they yield no information about the topmost layer of atoms.

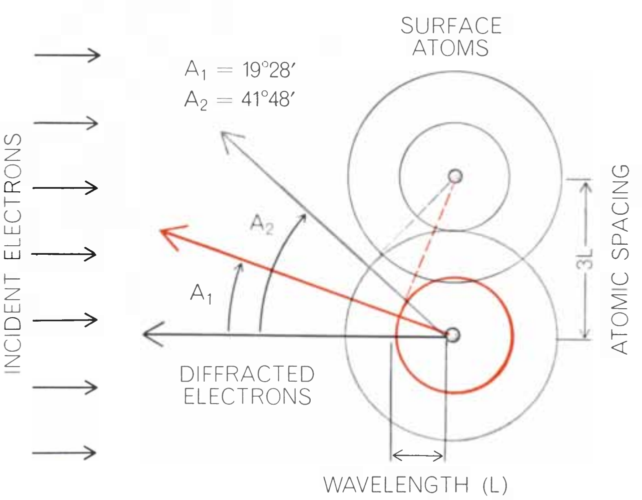
For electrons in the lower energy range between five and 500 volts the penetration is limited to the outer layers of atoms, and the diffraction pattern of electrons scattered back from the crystal discloses the surface structure. The detection of these electrons, however, presents practical problems. In our early experiments the diffracted electrons

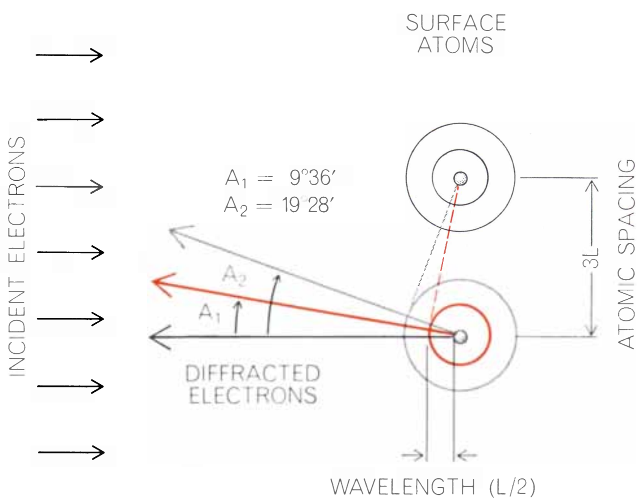


LOW-ENERGY ELECTRON-DIFFRACTION instrument makes visible on a fluorescent screen the pattern of electrons that rebound from the surface of a crystal. This pattern, which is the same as the one shown on the cover of this issue, is produced by electrons diffracted from the surface of a tungsten crystal that is half-covered by a single layer of oxygen atoms. When this much oxygen is present, the tungsten atoms on the surface of the crystal rearrange themselves as depicted in the diagrams at the bottom of page 39. The instrument shown here was built by Varian Associates and was photographed in the author's laboratory at Cornell University. The instrument was conceived by the author in collaboration with E. J. Scheibner and C. D. Hartman of the Bell Telephone Laboratories.



WAVELIKE BEHAVIOR of electrons creates intense spots on a fluorescent screen where the waves reinforce each other constructively. The specific angles at which this reinforcement occurs depend on the wavelength of the incident electrons and the spacing of atoms on the surface of the crystal being examined. Only electrons diffracted with full energy are accelerated and allowed to hit the screen. A fine-mesh wire grid (not shown) stops electrons of lower energy. Electrons of "zero order" diffraction normally strike the hole in the screen that admits the incident beam, but by turning the crystal slightly they can be shifted to one side and made visible.





DIFFRACTION ANGLES vary with the wavelength of the incident electrons. The diagram at left shows the angles for first- and second-order diffraction when the wavelength is a third of the atomic spacing. To shorten the wavelength the voltage of the incident beam is raised. When the wavelength is reduced to a sixth of the atomic spacing, the diffraction angles become smaller, as shown at right.

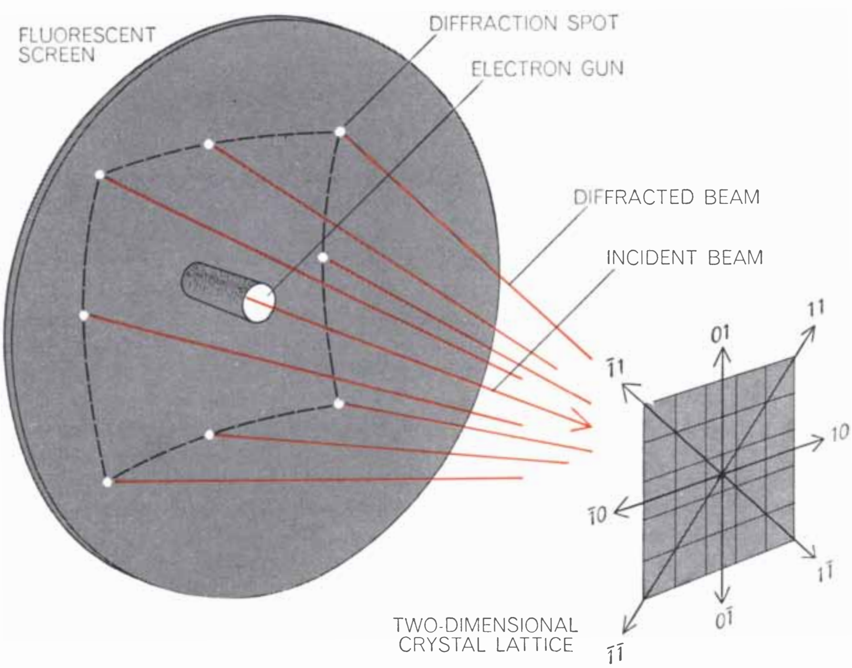
were collected by a simple bucket arrangement invented by Michael Faraday and commonly called a Faraday box. The electrons flowed from the box along a wire and were measured by a galvanometer or electrometer. This straightforward method has been used successfully for more than 35 years by H. E. Farnsworth and his co-workers at Brown University.

In an instrument that is now coming into wide use the diffraction pattern is made to appear on a fluorescent screen. This method was pioneered in 1934 by W. Ehrenberg, who carried out his experiments at the Physikalisches Institut of the Technischen Hochschule in Stuttgart; in 1960 a practical instrument was built by E. J. Scheibner, C. D. Hartman and me at Bell Laboratories. The photograph on the cover of this issue of *Scientific American* shows the fluorescent screen of an instrument of this type in my present laboratory at Cornell University.

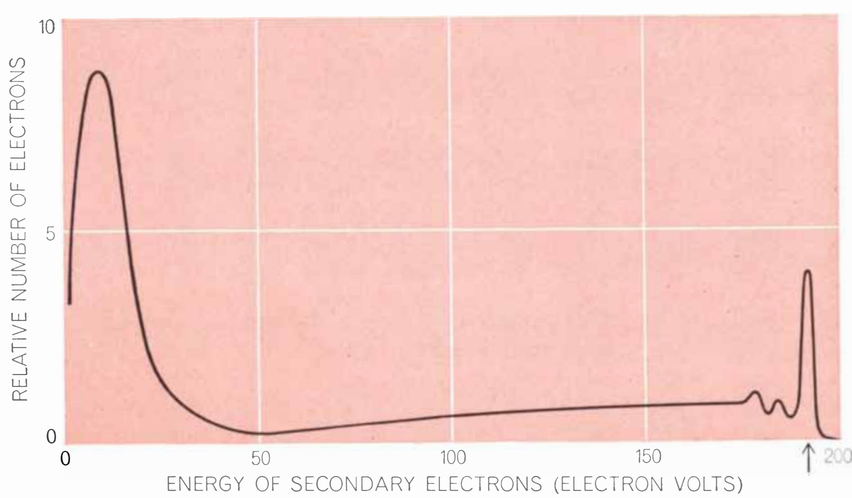
In this instrument the electron beam originates behind a spherically curved fluorescent screen, passes through a small hole in its center and strikes a crystal suspended at the screen's center of curvature. Immediately in front of the screen are two fine-mesh, closely spaced wire grids. The one nearer the crystal serves as a shield to keep stray electric fields from deflecting the electrons from a straight path. The second grid has a negative charge that is just sufficient to repel electrons that have lost some of their original energy and thereby prevents them from reaching the fluorescent screen. About 1 percent have not lost energy and pass through the second grid. A high positive potential on the screen itself accelerates these electrons so that they strike the screen with an energy of 5,000 electron volts. If the diffracted electrons were not accelerated in this way, they would lack the energy needed to make the screen fluoresce, but if all the electrons, regardless of energy, were accelerated, they would produce a general haze that would tend to obscure the diffraction pattern. The pattern on the screen can be photographed or the brightness of individual luminous spots can be measured with a photometer.

The illustrations on the opposite page show how the diffraction patterns are related to the wavelength of the incident electrons and to the spacing between atoms at the surface of the crystal. Although the waves ripple out in all directions from each atom, their interference is completely constructive only in certain directions where the crests of waves coincide. The spots on the fluorescent screen define the angles of constructive interference. From these angles and the wavelength of the incident electrons one can calculate the spacing of atoms in the crystal surface. When the structure of the surface is simple, it is easy to calculate a two-dimensional "unit mesh" that establishes the atomic configuration of the surface.

At present some of the experiments of greatest interest involve the adsorption of foreign atoms on a clean surface and the catalytic reactions in which the surface somehow promotes the interaction of foreign atoms and molecules. Before such studies can be made one must obtain a crystal whose surface is perfectly clean and one must be able to keep it clean long enough to carry out the desired experiment. This requires that the crystal be cleaned and maintained in a very high vacuum. As a rule molecules that strike a clean



COMPLETE DIFFRACTION PATTERN shows how electrons are diffracted from horizontal, vertical and diagonal rows of atoms in the surface of a crystal. The crystal depicted has a two-dimensional lattice containing a simple square or rectangular mesh. The two digits used for identifying the directions taken by diffracted electrons are called Miller indices.



ENERGY OF SCATTERED ELECTRONS varies from almost zero to that of the incident electrons in the primary beam (*arrow*). About 1 percent of the incident electrons are scattered without loss of energy and only these are retained for producing a diffraction pattern. The rest, if not removed, would partly obscure the pattern and confuse interpretation.

surface stick to it and constitute a contaminating film.

When a surface is exposed to air, each atom on the surface is struck about a billion (10^9) times a second by air molecules. To reduce the number of hits and the consequent contamination to a tolerable level the density of gas molecules at the surface must be reduced by a factor much greater than 10^9. The unit commonly used for measuring low pressures is the torr, which is slightly more than a thousandth (10^{-3}) of standard atmospheric pressure. The vacuum needed for low-energy electron diffraction work is around 10^{-9} or 10^{-10} torr.

In experiments involving the adsorption of a gas it is important that the gas brought in contact with the crystal surface be pure. Pure gases are readily obtainable; the main problem is to keep them from becoming contaminated once they have been introduced into the electron-diffraction apparatus. The interior of the apparatus has a wall area of some 10,000 square centimeters and is a major source of contamination. There is the constant bugbear that an experimental gas may interchange with gas adsorbed on the walls of the vacuum chamber and thus liberate it. A single layer of atoms released from a square centimeter of surface will exceed by a factor of more than 10,000 the number of atoms or molecules contained in a liter of gas at 10^{-9} torr. Since the experimental apparatus has a volume of 15 liters, an interchange need involve a layer of gas one atom thick on only a hundredth of a square centimeter of surface to contaminate by 50 percent the experimental gas held at a working pressure of 3×10^{-8} torr.

Finally, the contamination problem is aggravated by the necessity of using hot filaments, usually of tungsten, to produce a beam of electrons. A new tungsten filament is inevitably coated with carbon atoms, probably in the form of hydrocarbons. When heated in a high vacuum in the presence of oxygen, the filament can evolve thousands of liters of carbon monoxide (measured at 10^{-8} torr) before all of the carbon is removed. Yet the situation is not as hopeless as this account makes it seem; the required gas purity can be maintained by continuous pumping combined with a continuous inflow of the experimental gas.

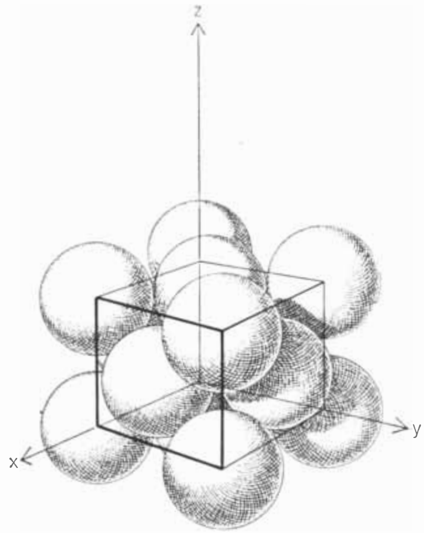
Cleaning a crystal surface presents another set of problems. Different treatments are required to clean metals, semiconductors and crystals of various inorganic salts. Semiconductors and salt crystals can sometimes be cleaved after being placed in a vacuum, and this is often the method of choice when it can be done.

For crystals that cannot be cleaved in a vacuum, heat is always a necessary part of the cleaning treatment, but by itself it is rarely sufficient. It is supplemented by chemical cleaning and by "sputtering," a method first applied to this problem by Farnsworth, in which contaminating atoms are knocked off the surface by bombardment with positive ions (atoms from which one or more electrons have been removed). An effective ion for sputtering is that of the inert gas argon.

One of the most difficult surfaces to clean is the surface of a single crystal of iron. Heating alone cannot be used to clean the surface because at 900 degrees centigrade (a relatively low temperature in this work) the crystal structure of iron changes, with the result that the original single crystal is broken up into many small crystals and a usable diffraction pattern can no longer be obtained. Milder heating is not very effective for cleaning; moreover, it makes carbon atoms, which are always present, diffuse to the surface from the interior of the crystal. Although the carbon atoms can easily be removed by having them react with oxygen, this treatment leaves the crystal coated with oxygen atoms. The obvious method of removing the oxygen by having it react with hydrogen, which works with some metals, is not successful with iron.

The cleaning of iron has been successfully accomplished by Arthur J. Pignocco of the United States Steel Company's Applied Research Laboratory at Monroeville, Pa. He starts with a crystal that of necessity has a considerable amount of carbon on its surface but very little inside. By careful sputtering with argon ions he removes the surface carbon atoms without driving the argon atoms deep into the surface. This is followed by a gentle heat treatment that removes the embedded argon atoms and allows the displaced iron atoms to fall back into their proper place in the crystal structure.

One of the simplest and most common of all crystalline arrangements of atoms is the structure known as face-centered cubic. As one might expect, crystals with this structure produce some of the simplest diffraction patterns. The series of diagrams at the top of these two pages shows a basic unit of the structure and the three simplest surfaces that can be exposed by cutting sections through it. These faces, named according to the way they intersect a three-dimensional set of axes, are known as the (111) face, the (100) face and the (110) face. When listed in this order, they indicate surfaces with a decreasing density of atoms.

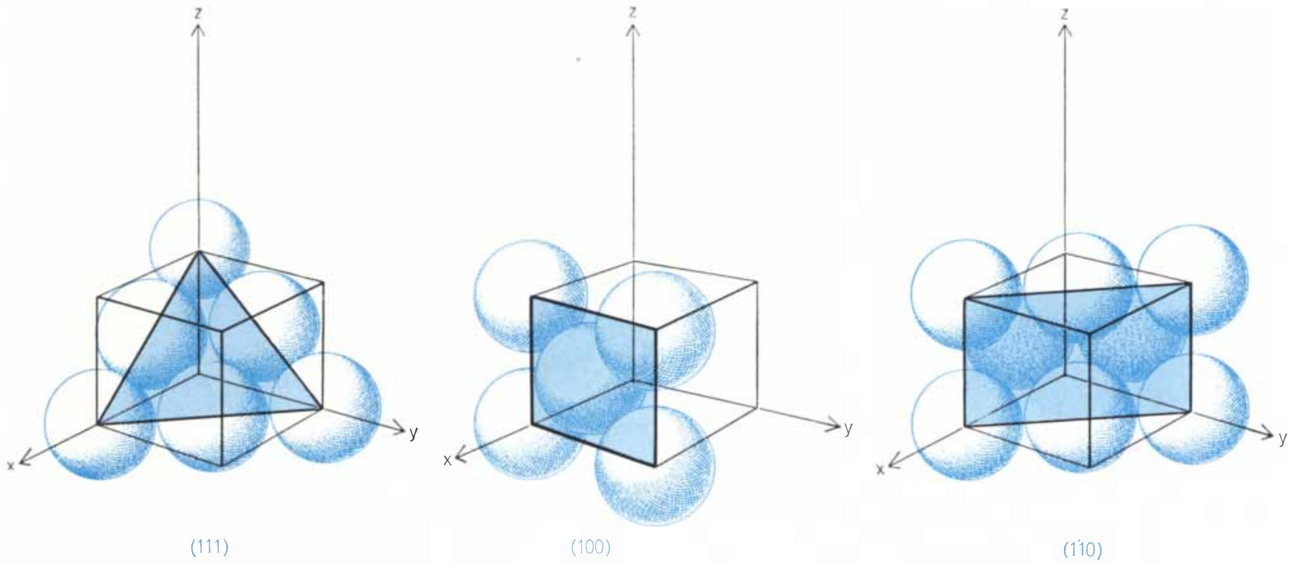


ATOMIC ARRANGEMENT in a crystal of nickel is that known as face-centered cubic:

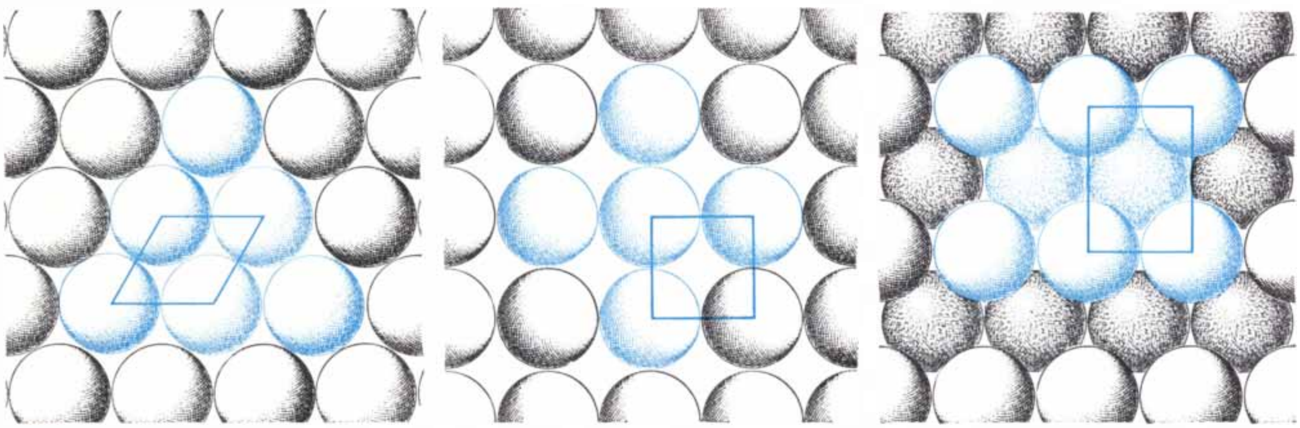
Each of the surfaces is made up of a repeating pattern of atoms that extends indefinitely in two dimensions [*see middle illustration on opposite page*]. One can think of the atoms as arranged in long, parallel, equally spaced rows. In each surface configuration one can find a unit mesh that maps out the whole surface when the mesh is shifted in two dimensions.

When a beam of electrons strikes such a surface of atoms, the rows act like the parallel ruled lines of an optical diffraction grating. The electron waves diffracted from the two-dimensional mesh of atoms produce a series of intense spots that represent diffraction from all possible parallel rows of surface atoms. The patterns produced by the (111), (100) and (110) faces of a nickel crystal, which is one of many metals with the face-centered cubic structure, are shown at the bottom of the opposite page below the structural diagrams of the three faces. Given such diffraction patterns, one can work backward and calculate the arrangement of surface atoms. The scale of the structure is determined by the spacing between the nearest neighbor atoms, which for nickel is 2.49×10^{-8} centimeter, or 2.49 angstroms.

From the low-energy diffraction patterns of the (111), (100) and (110) faces

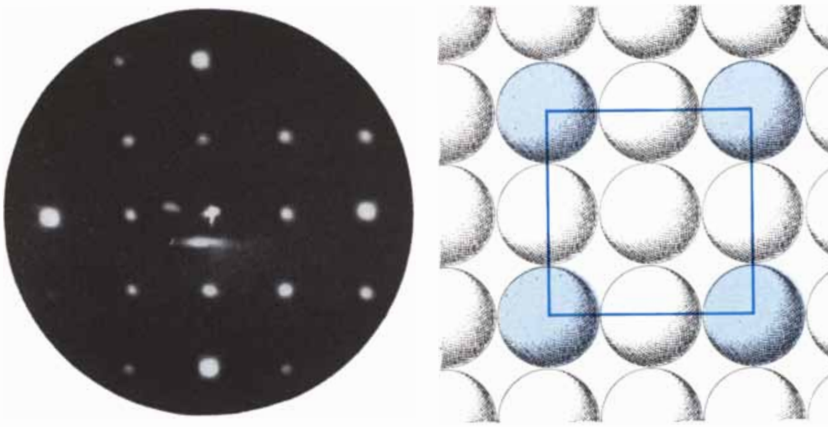


a cube with an atom in each corner and an atom in the center of each face (*left*). The planes that make the three simplest surfaces are labeled according to the way they intercept three coordinates (*x, y, z*). They are shown in decreasing order of atomic density.



THREE SURFACES OF NICKEL correspond respectively to the (111) face, the (100) face and the (110) face, whose derivation from a face-centered cube is illustrated directly above each surface. The three shapes drawn in outline (*diamond, square and rectangle*) represent the "unit mesh" for each face. This is the smallest unit that will reproduce the whole surface when shifted in two directions.

DIFFRACTION PATTERNS OF NICKEL are shown for each of the three surfaces illustrated in the ball models directly above. In the pattern for the (111) face (*left*) the spots are farther apart than those in the other two patterns, which shows that the atoms on the (111) face are more densely packed than those on the other two faces. In the pattern for the (100) face (*middle*) the spots form a square array, evidence that the unit mesh is square. In the pattern for the (110) face (*right*) the short spacing between horizontal rows coincides with the longer side of the rectangle in the unit mesh. The energy of the incident electrons used in making these diffraction patterns was about 85 electron volts in each case. The photographs were made by A. U. Mac Rae of Bell Laboratories.



OXYGEN ADSORBED ON NICKEL leads to a rearrangement of the atoms on the surface and yields a diffraction pattern (*left*) in which the square array on the (100) face is just half the size of that for the same face when the nickel is clean. (The clean face is shown in the middle pattern at the bottom of the preceding page.) Evidently the unit mesh on the surface of the crystal is now twice the size of the mesh when only nickel atoms are present. The adsorption of enough oxygen atoms to fill a quarter of the top layer causes this reconstruction of the nickel surface. The new unit mesh is outlined in the drawing at right. The location of oxygen atoms (*color*) is conjectured. The photograph was made by Mac Rae.

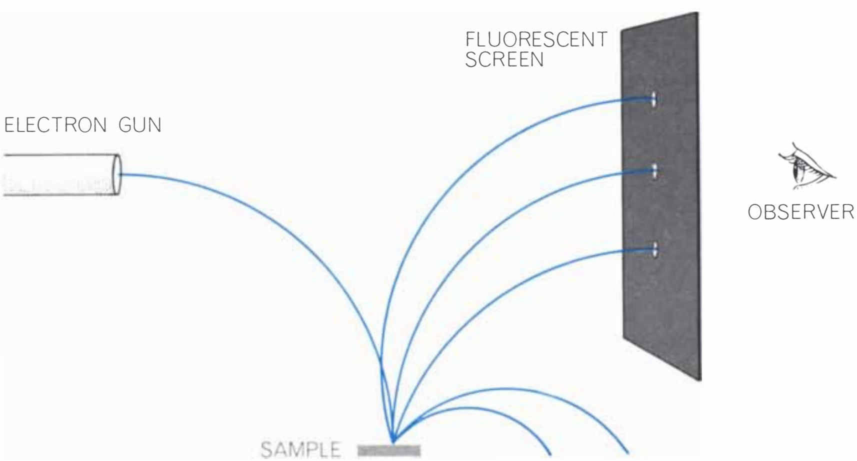
of a clean nickel crystal one can conclude immediately that the arrangement of atoms in each of these surfaces is exactly the same as that in a parallel plane of atoms in the body of the crystal. This one-to-one relation has been found for all metals studied so far. In metalloids such as silicon and germanium, however, the arrangement of surface atoms does *not* correspond to that of the interior; this has also been found to be the case for the crystals of some chemical compounds.

The locations of spots in diffraction patterns produced by nickel surfaces are easy to account for. As the voltage of the electron beam is increased the diffraction spots move closer together in a way that corresponds directly to the decrease in electron wavelength that attends the voltage increase. At the same time, however, all the spots change in intensity, and these changes are not so readily interpreted. As the beam voltage is raised the incident electrons penetrate deeper into the crystal and the diffracted waves that arise from the more deeply buried atoms interfere with the waves diffracted from the surface atoms. If the interfering waves are in step, they reinforce each other and produce more intense spots; if they are out of step, they tend to cancel and the spot intensity is reduced. From these intensities it should in principle be possible to calculate the depth of penetration of the electrons and the relation of atoms in the surface to those below, but unexpected difficulties have sometimes arisen in interpreting the observed intensity changes.

If one has been able to produce clean nickel surfaces and has obtained diffraction patterns such as those shown on the preceding page, one may wish to see what happens when the surfaces are exposed to oxygen. We shall limit our discussion to the (100) face. As one watches the fluorescent screen of the diffraction instrument while oxygen is admitted into the vacuum system containing the nickel crystal with its (100) face exposed, one sees first the diffraction pattern of the clean (100) face. Gradually a number of diffuse streaks appear superposed on the pattern. Soon they coalesce into new sharp spots with the spots of the original pattern still present and apparently unchanged [*see top illustration at left*]. The entire new pattern now forms a square array just half the size of the original array. This shows that the unit mesh on the surface is now twice the size of the original mesh when only nickel atoms were present. It can be shown that the new mesh contains atoms of both nickel and oxygen. The atomic arrangement and unit mesh is illustrated in the model next to the diffraction pattern.

The structure of the model implies that oxygen adsorption causes complete rearrangement of nickel atoms on the crystal surface. Moreover, the rearrangement begins when only a partial layer of foreign atoms one atom thick has been adsorbed. Such a reconstruction of the surface has been observed in many other experiments and often occurs when the foreign atoms are strongly held.

Nickel surfaces have been studied more intensively than those of any other metal, not only because nickel is unusually simple but also because it is known to have an "active" surface and is widely used as a catalyst. Recently tungsten surfaces have also begun to receive much attention. One reason for this interest is the possibility of building ion-jet engines for space propulsion by accelerating ions produced on a tungsten surface. At Cornell I began the study of tungsten surfaces with Richard M. Stern about three years ago; the study is being continued with John W. May. We have been concerned with reactions involving adsorbed layers



ANOTHER ELECTRON-DIFFRACTION METHOD, devised by C. W. Tucker of the General Electric Research Laboratory, uses a magnetic field to bend both the incident and the diffracted electrons through an angle of 90 degrees. Electrons that have lost energy are forced into short-radius curves and are thus prevented from reaching the fluorescent screen.

of carbon, carbon monoxide, oxygen and hydrogen.

Tungsten may be the easiest of all metals to clean because of its high melting point. Yet even it requires some care. This can be seen from the series of three diffraction patterns below, which show a (110) tungsten surface in various stages of cleaning. The diffraction pattern from a badly contaminated surface appears at the left. After the crystal was heated for only a few minutes at about 1,000 degrees C. in oxygen at a pressure of 5×10^{-8} torr, the diffraction pattern was that shown in the middle (and also on the cover of this issue). Most of the oxygen was then removed from the vacuum chamber by pumping the chamber down below 10^{-9} torr and the crystal was raised to 1,700 degrees for a few seconds. This vaporized the oxygen that had been adsorbed on the tungsten surface. After this treatment the surface produced the diffraction pattern shown at the right in the illustration.

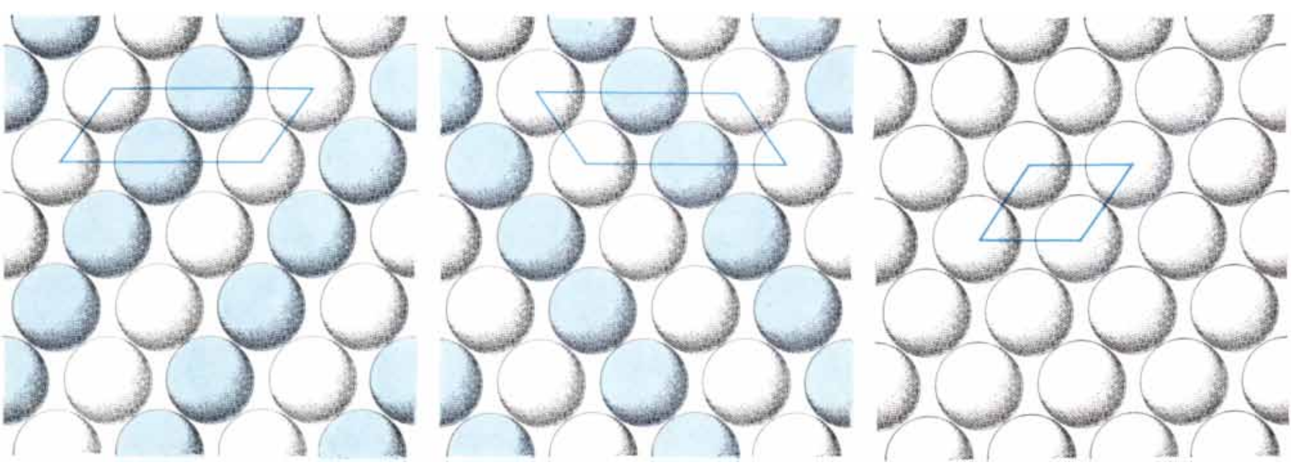
Tungsten has a very simple crystal structure, body-centered cubic, and an ideal (110) plane of this structure would give just this diffraction pattern. Thus the pattern provides evidence that the surface had now been cleaned. This conclusion is supported by the fact that intense heating of the crystal produced no further change.

The arrangement of surface atoms on the clean crystal and the arrangements of atoms that exist on two different regions of the oxidized and partially cleaned surface are shown in atomic models below the diffraction patterns on this page. Evidently the oxygen treatment was essential for obtaining a clean surface. It appears that the original contaminant, which was so easily burned off by oxygen, may simply have been carbon.

Apart from metals, the crystal surfaces most intensively studied by this diffraction technique are those of the semiconductors germanium and silicon. The interest in these elements is of course due to their importance in transistors and other solid-state devices. Various faces of these crystals were studied first by Farnsworth and his co-workers at Brown and later by James J. Lander and John A. Morrison at Bell Laboratories.

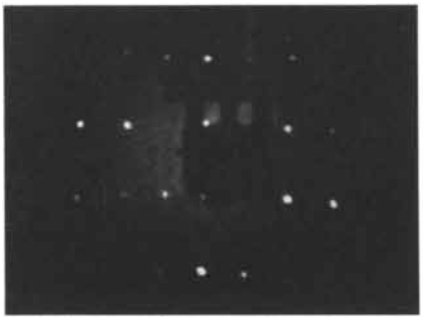
These investigators have found that

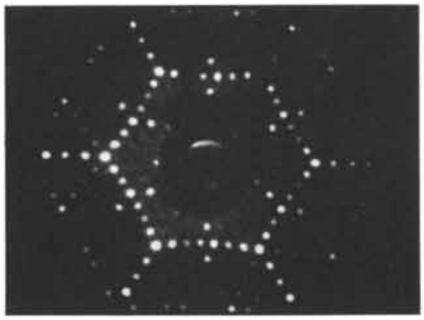
TUNGSTEN SURFACE at different stages of cleaning is shown in these three diffraction patterns. The patterns depict the (110) face of the crystal when it was bombarded with electrons having an energy of 75 electron volts. The pattern at left shows the badly contaminated surface before cleaning. The chief impurity is probably carbon. When the impurity was burned off by a short exposure to oxygen at 1,000 degrees centigrade, the reconstructed surface containing both oxygen and tungsten atoms yielded the pattern in the middle (and also on the cover of this issue). When the oxygen was removed by a very brief heating at 1,700 degrees, the diffraction pattern at right resulted. The diffraction patterns were obtained by the author and his colleague John W. May at Cornell University.

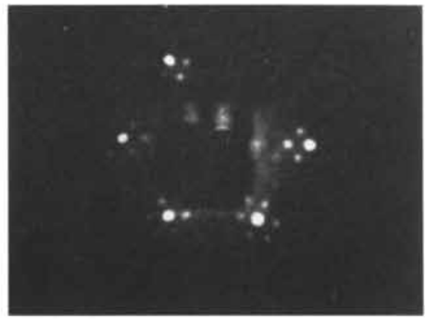


MODELS OF TUNGSTEN SURFACE represent the clean (110) face at right (below its diffraction pattern) and two arrangements for the reconstructed surface whose diffraction pattern is in the middle above. The reconstructed surface is presumed to contain equal numbers of tungsten atoms and oxygen atoms (*color*) in two independent mirror-image arrangements (*left and middle*).

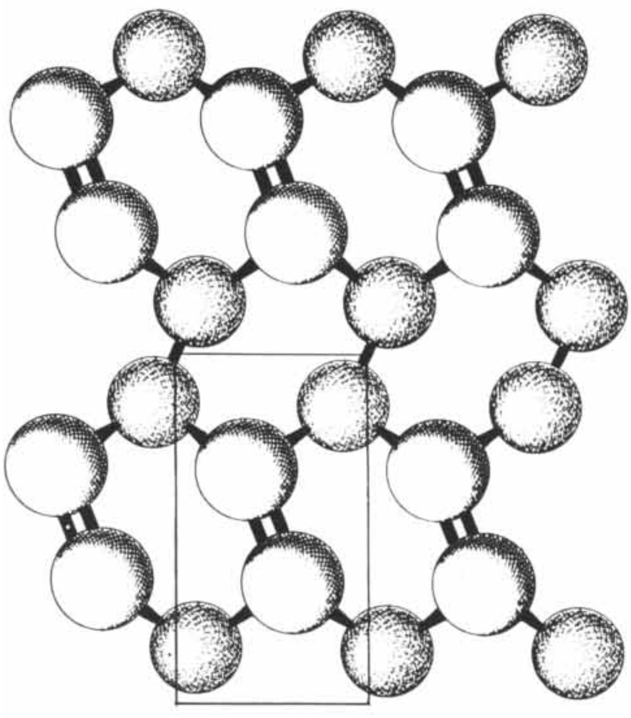
when any surface of a germanium or silicon crystal is perfectly clean, its structure is profoundly modified by the lack of symmetry in the forces acting on the surface atoms. The phenomenon apparently does not occur at metal surfaces. At a clean surface of silicon or germanium there are dangling chemical bonds that evidently can be satisfied by joining up with neighboring atoms in various complex arrangements. Often for the same clean surface there is more than one stable structure, determined by previous history such as cleavage in a vacuum, heat treatment subsequent to cleavage and heat treatment subsequent to etching. Some changes induced by heat are reversible and some are not. Examples of diffraction patterns from clean silicon surfaces, with suggested structures that account for the patterns,

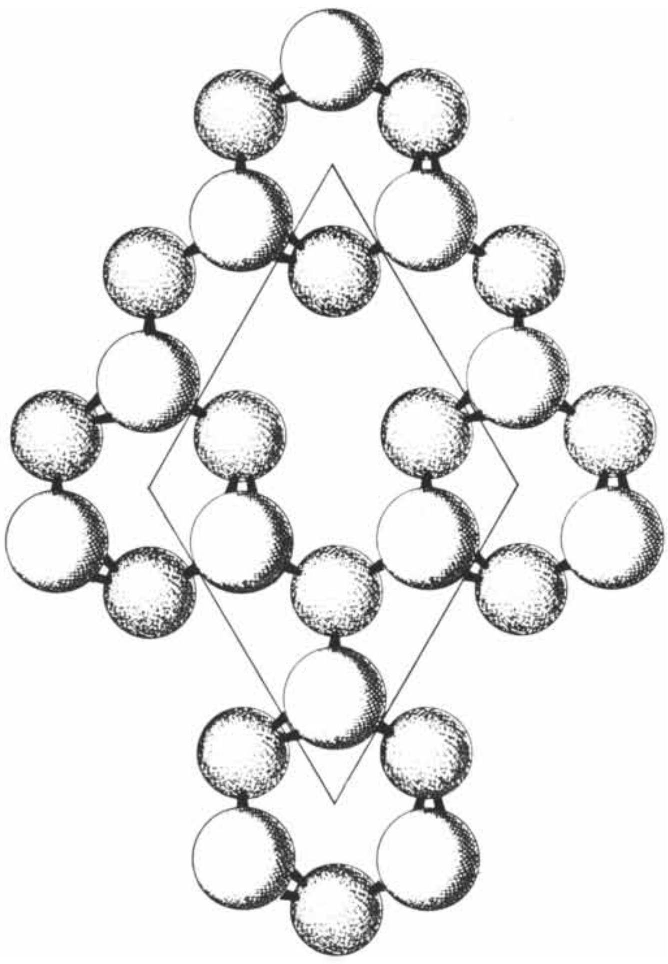






CLEAN SURFACE OF SILICON can produce various diffraction patterns depending on how the crystal has been treated. The pattern at left of the (111) face of silicon was made by a crystal freshly cleaved in a vacuum. After a brief heating, which removed some of the stresses left in the surface, the pattern in the middle resulted. After lengthy heating the apparently more stable surface produced the pattern at right. The middle pattern is called the "seven structure" because seven spots compose each edge of the hexagon. In the right pattern there are only five spots per edge (not all of them clearly visible); it is therefore called the five structure. The patterns were obtained at Bell Laboratories by James J. Lander and John A. Morrison. An atomic arrangement that may correspond to the freshly cleaved silicon surface and a possible building block of the five and seven structures are illustrated below.





TWO KINDS OF SILICON STRUCTURE have been proposed to explain the three kinds of diffraction pattern shown above. The freshly cleaved surface, which exhibits a rectangular unit mesh, may have the atomic structure at left. Both the five and seven structures, which are produced by heat treatment, must have diamond-shaped unit meshes. The atomic building block at right may form an essential part of these surfaces. All three silicon surfaces are so complex that structures are difficult to deduce.

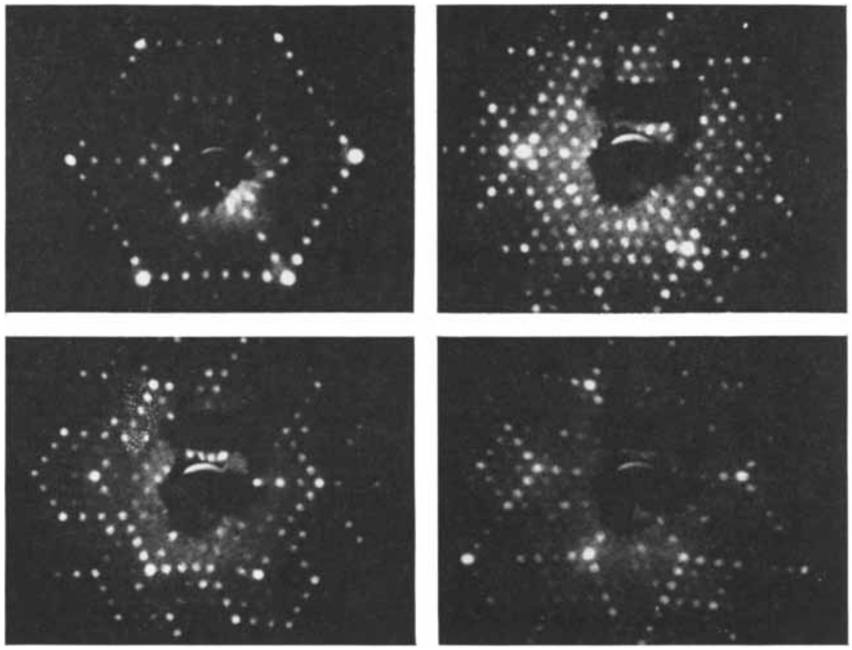
are illustrated on the opposite page.

Lander and Farnsworth and their co-workers have studied the effects of depositing various foreign atoms on silicon and germanium surfaces. These atoms have included hydrogen, oxygen, iodine, bromine, phosphorus, aluminum, calcium, barium, indium, molybdenum, mercury, lead, tin and gold. In many cases the resulting surfaces have a structure of great complexity, and some undergo curious transformations when they are heated.

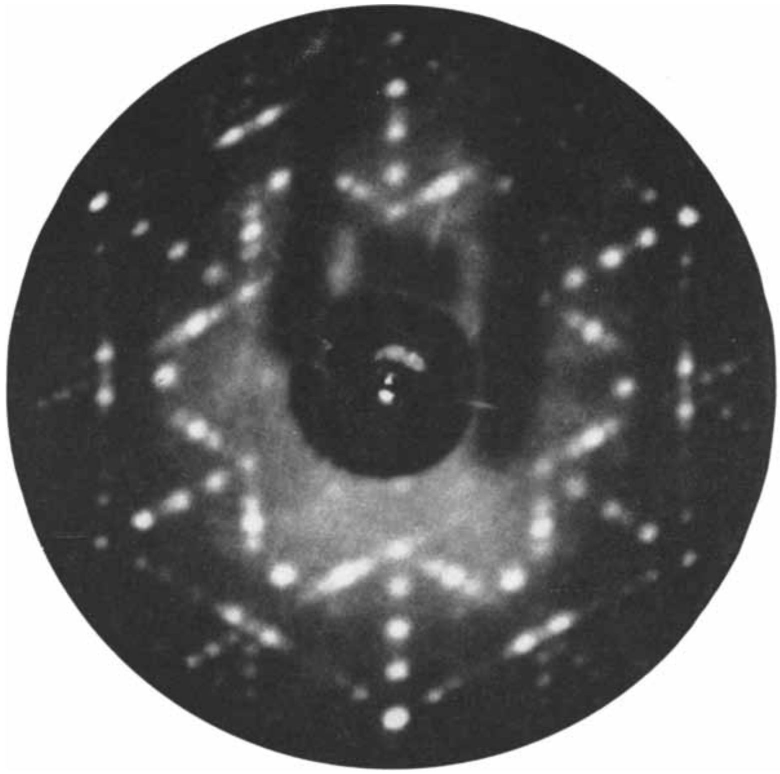
Other investigators have studied the surfaces of a number of two-element compounds. Among these are some of the alkali halides and some metal oxides, as well as more exotic compounds such as gallium arsenide (which has interesting semiconductor properties and also emits an intense monochromatic light beam when it is fashioned into a solid-state laser).

It is probably evident to the reader that this article has been concerned with techniques that are still being rapidly developed. Thus far low-energy electron diffraction has uncovered more questions than it has answered. Why, for example, do metal surfaces have atomic structures that are the same as those found inside the crystal whereas silicon and germanium do not? Of what scientific importance is the discovery of surface reconstruction caused by adsorption?

These and similar questions stand as a challenge to physicists, some of whom seem to believe that aggregations of matter and energy of intermediate size are no longer particularly interesting. There is a growing feeling that the chief frontiers of physics are soon to be relegated to the very small and the very large—those regions smaller than an atomic nucleus and larger than a star. (The marvelously complex organizations of intermediate size that we classify as living are too complex for physicists to understand.) For a few years, at least, some physicists may find it interesting to learn more about surfaces—arrangements of matter at an intermediate level of size that have not yet been studied effectively. The tools for such study have been available for almost 40 years but have been neglected for all this time. Since many of the most important physical and chemical events take place on surfaces, extension of knowledge about them will surely advance many fields of science, including, very likely, the study of life.



CHANGE IN BEAM VOLTAGE causes a change in the pattern of diffracted electrons, as shown in this sequence by Lander and Morrison. The crystal surface is that of partially annealed silicon, the same surface depicted in the middle pattern at the top of the opposite page. The pattern shown there was produced with the incident beam set at 58 volts. Here the beam voltages are 33 (*top left*), 72 (*top right*), 82 (*bottom left*) and 112 (*bottom right*).



MYSTERIOUS DIFFRACTION PATTERN was produced by the adsorption of an unknown gas on the (111) surface of a nickel crystal while it was left standing in Mac Rae's diffraction apparatus at Bell Laboratories over a weekend. The adsorption occurred while the vacuum system was being held at the extremely low pressure of 4×10^{-10} torr. A clean (111) surface would have only the six spots that form the corners of the large hexagon (*see pattern at left at the bottom of page 37*). The many spots inside the hexagon indicate a two-dimensional structure with a unit mesh 10 times that of the clean surface. Study of this structure is hampered by imperfect understanding of the diffraction process.

LEARNING IN THE OCTOPUS

The animal cooperates readily in laboratory experiments. Tests of its capacities before and after brain surgery lend support to the idea that there are two kinds of memory: long-term and short-term

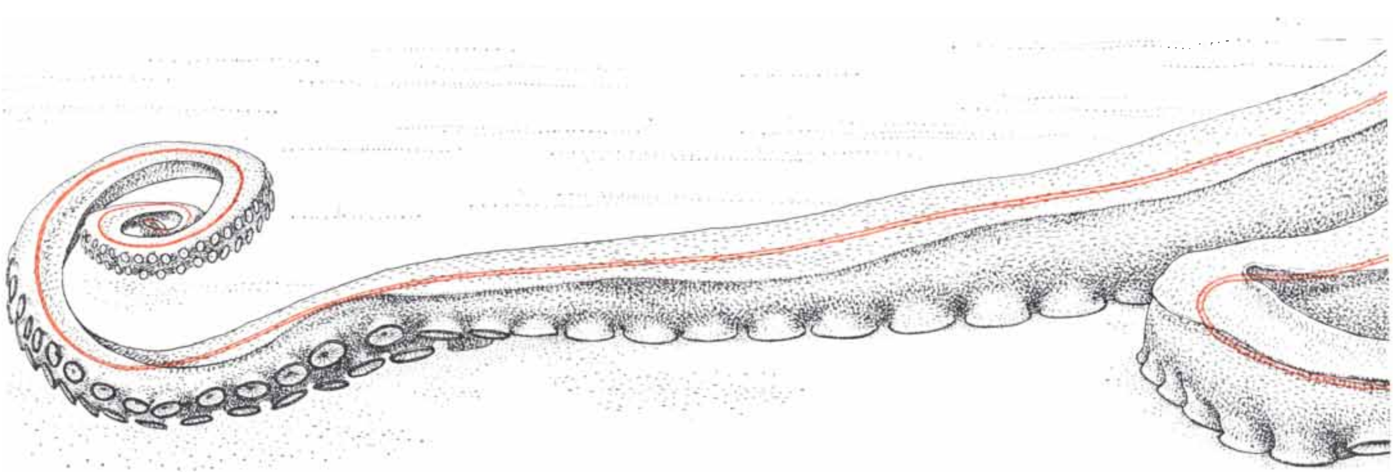
by Brian B. Boycott

In recent years a number of British students of animal behavior, of whom I am one, have done much of their experimental work at the Stazione Zoologica in Naples. The reason why these investigations have been pursued in Naples rather than in Britain is that our chosen experimental animal—*Octopus vulgaris*, or the common European octopus—is found in considerable numbers along the shores of the Mediterranean. *Octopus vulgaris* is a cooperative experimental subject. If it is provided with a shelter of bricks at one end of a tank of running seawater, it takes up residence in the shelter. When a crab or some other food object is placed at the other end of the tank, the octopus swims or walks the length of the tank, catches the prey with its arms and carries it home to be poisoned and eaten. Since it responds so consistently to the presence of prey, the animal is readily trained. It is also tolerant of surgery and survives the removal of the greater part of its brain. This makes the octopus an ideal animal with which to test directly the relation between the various parts of the brain and the various kinds of perception and learning.

There are many unanswered questions about such relations. We now know a great deal about conduction in nerve fibers, transmission from nerve fiber to nerve fiber at the synapses and the integrative action of nerve fibers in such aggregations of nerve cells as the spinal cord; we are almost wholly ignorant, however, of the levels of neural integration involved in such long-term activities as memory. We can still quote with sympathy the remark of the late Karl S. Lashley of Harvard University: "I sometimes feel, in reviewing the evidence on the localization of the memory trace, that the necessary conclusion is that learning is just not possible!"

It was J. Z. Young, then at the University of Oxford, who first began to exploit the possibility of using for memory studies various marine mollusks of the class Cephalopoda. Shortly before World War II he undertook to work with the cuttlefish *Sepia officinalis.* In a simple experiment he and F. K. Sanders removed from a cuttlefish that part of the brain known as the vertical lobe. They found that a cuttlefish so deprived would respond normally—that is, attack—when it was shown a prawn. If the prawn was pulled out of sight around a corner after the attack began, however, the cuttlefish could not pursue it. The animal might advance to where the prawn had first been presented, but it was apparently unable to make whatever associations were necessary to follow the prawn around the corner. One might say it could not remember to hunt when the prey was no longer in sight. Young and Sanders found that surgical lesions in certain other parts of the cuttlefish's brain did not affect this hunting behavior.

In 1947 I had the privilege of joining Young in his studies. Financed by the Nuffield Foundation, we began



COMMON EUROPEAN OCTOPUS (*Octopus vulgaris*) is the experimental animal the author and his fellow-workers in Naples use for their investigations of perception and learning. The animal's brain (*in color between the eyes*) is about two cubic

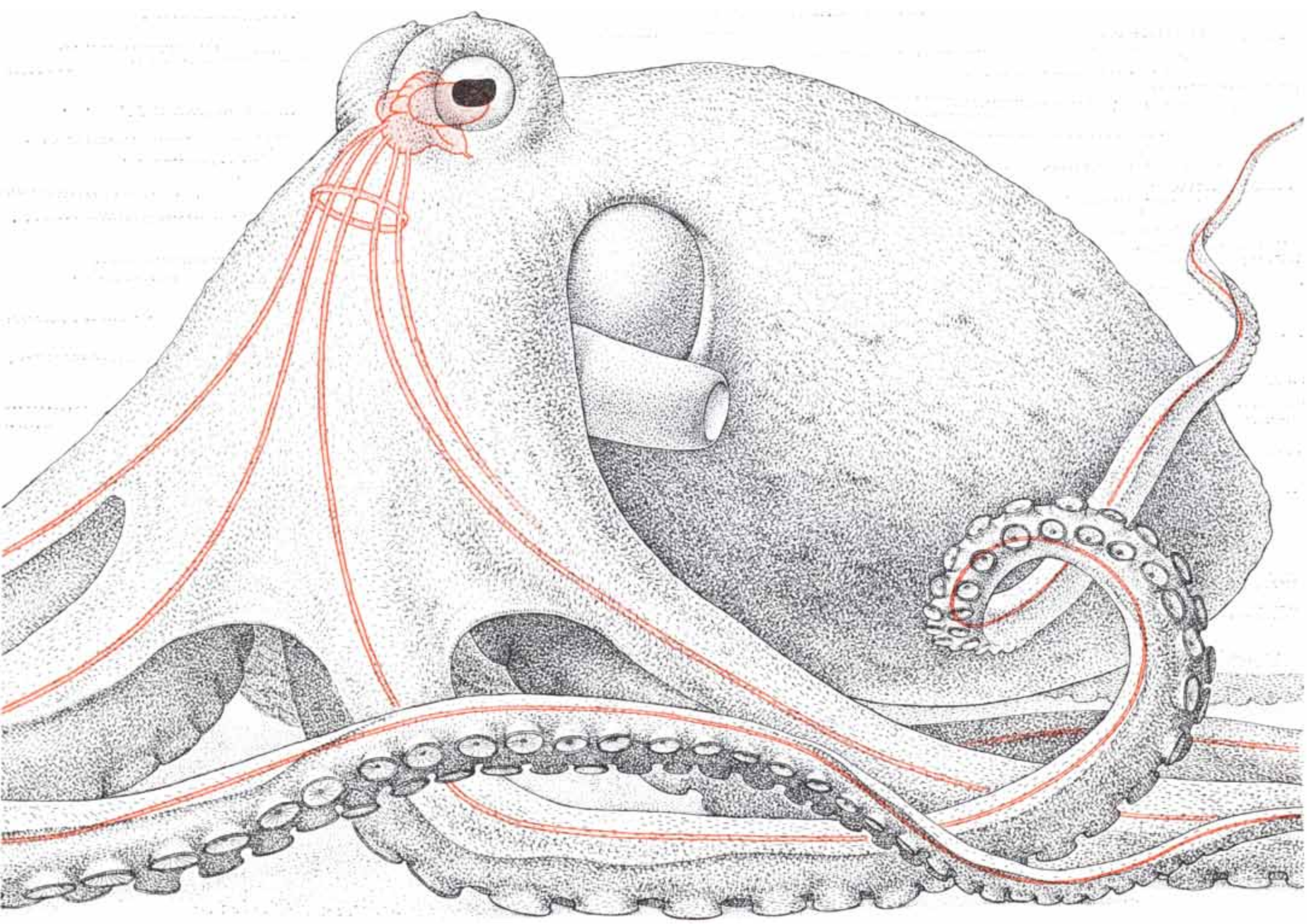
work at the Stazione Zoologica, where both seawater aquariums and *Octopus vulgaris* were in abundant supply. The octopus was chosen in preference to the other common laboratory cephalopods—cuttlefishes and squids—because they do not survive so well in tanks and are less tolerant of surgery. At Naples today, in addition to Young's associates from University College London, there are investigators from the University of Oxford led by Stuart Sutherland and from the University of Cambridge led by Martin J. Wells, all going their various ways toward using the brains of octopuses for the analysis of perception and memory. At present most of the work is financed by the Office of Aerospace Research of the U.S. Air Force.

In our early experiments we attempted to train octopuses to do a variety of things, such as taking crabs out of one kind of pot but not out of another, to run a maze and so on. Our most successful experiment was to put a crab in the tank together with some kind of geometric figure—say a Plexiglas square five centimeters on a side—and give the octopus an electric shock when it made the normal attacking response. With this simple method we found that octopuses could learn not to attack a crab shown with a square but to go on attacking a crab shown without one [*see bottom illustrations on pages 46 and 47*]. Or we could train the animals to stop taking crabs but to go on eating sardines or vice versa. The purpose of these experiments was to elucidate the anatomy and connections of the animal's brain and relate them to its learning behavior.

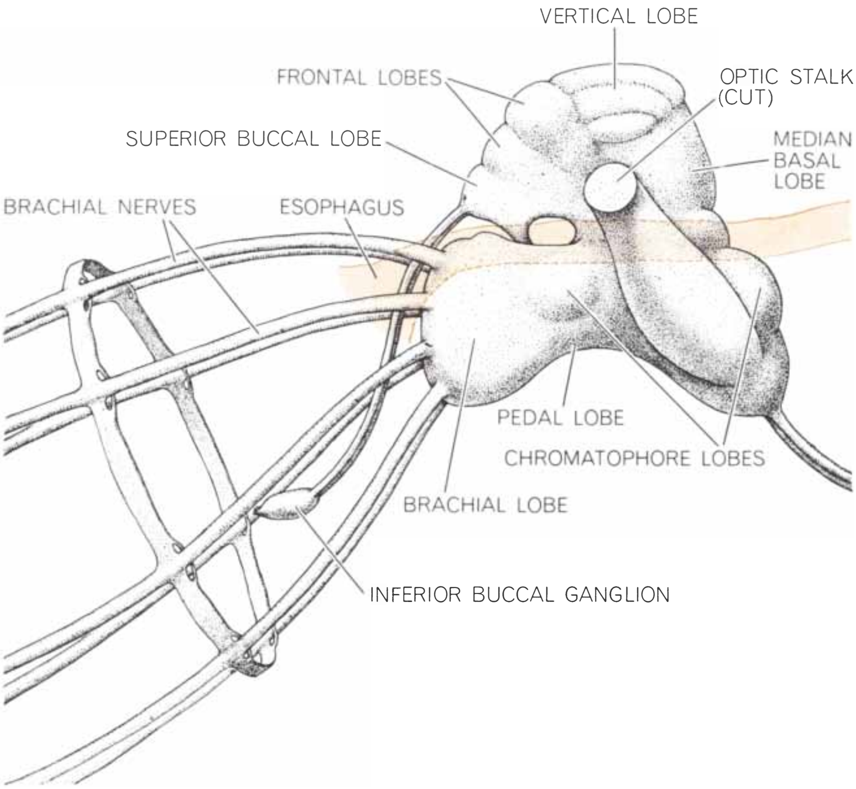
Like the brains of most other invertebrates, the brain of the octopus surrounds its esophagus [*see illustrations on next page*]. The lobes of the brain under the esophagus contain nerve fibers that stimulate peripheral nerve centers, for example the ganglia in the arms and the mantle. These peripheral ganglia contain the nerve cells whose fibers in turn stimulate the muscles and other effectors of the body; through them local reflexes can occur. When all of the brain except the lobes under the esophagus is removed, the octopus remains alive but lies at the bottom of the tank; it breathes regularly but maintains no definite posture. If it is sufficiently stimulated, it responds with stereotyped behavior.

A greater variety of behavior can be obtained if some of the brain lobes above the esophagus are left intact. For instance, the upper brain's median basal lobe and anterior basal lobe send their fibers down to the lower lobes and through them evoke the patterns of nerve activity involved in walking and swimming. Above these two lobes are the vertical lobe, the superior frontal lobe and the inferior frontal lobe; their surgical removal does not result in any defects of behavior that are immediately obvious.

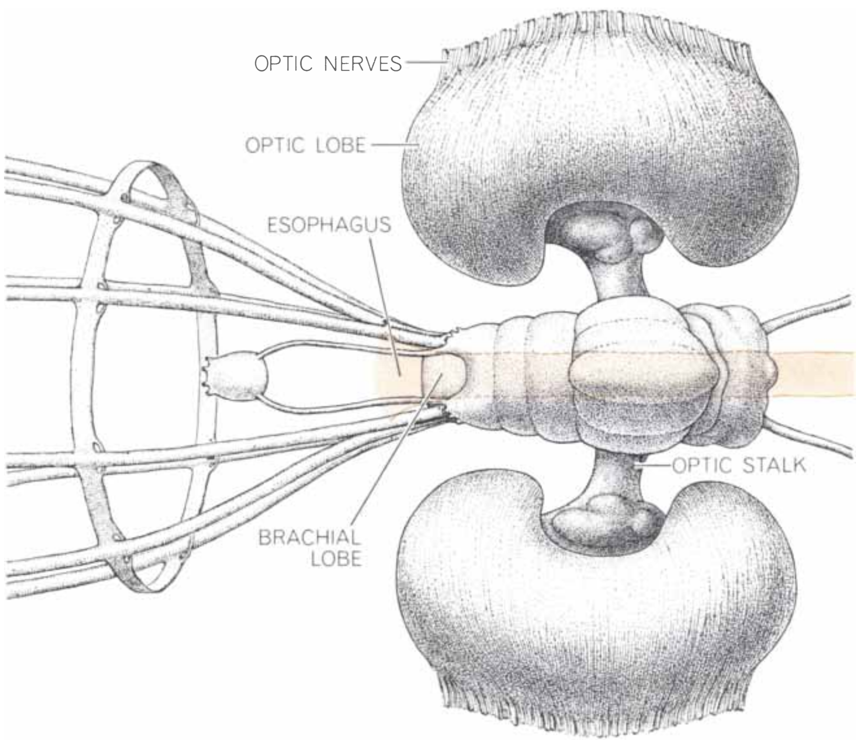
It is with these three lobes and the two optic lobes—which lie on each side of the central mass of the brain—that this article is mostly concerned. Using the electric-shock method of training



centimeters in size; the basket-like structure below it is composed of the eight major nerves of the arms, some of which are also outlined in color. The octopus adapts readily to life in a tank of seawater and can be trained easily through reward and punishment.



OCTOPUS BRAIN is shown in a side view with the left optic lobe removed (*see top view of brain below*). The labels identify external anatomical features of the brain and its nerve connections. As is the case with many other invertebrates, the brain of the octopus completely surrounds the animal's esophagus. Excision of the entire upper part of the brain is not fatal, but the octopus's behavior then exhibits neither learning nor memory.



TOP VIEW OF BRAIN relates the two large optic lobes and their stalks to the central brain structure situated above and below the octopus's esophagus (*color*). Combined, the mass of the two optic lobes roughly equals that of the brain's central structure; the fringe of nerves at each lobe's outer edge connects to the retinal structures of the octopus's eyes.

we soon found that, as far as visual learning goes, removing either the vertical lobe, the superior frontal lobe or both, or cutting the nerve tracts between these two lobes, left the octopus unable to learn the required discriminations (or, if they had already been learned, unable to retain them). Since operations on other parts of the brain—performed on control animals—had no effect either on learning or on previously learned behavior, we seemed to have demonstrated that the vertical lobe and superior frontal lobe of the octopus brain are memory centers. In a sense they are, but this is an unduly simple view; in a recent summary of findings Young has listed no fewer than six different effects caused by the removal of or damage to the vertical-lobe system alone.

Karl Lashley, who studied the cerebral cortex of mammals, concluded that, in the organization of a memory, the involvement of specific groups of nerve cells is not as important as the total number of nerve cells available for organization. A similar situation appears to hold true in the functioning of the vertical lobe of the octopus brain; there is a definite relation between the amount of vertical lobe left intact and the accuracy with which a learned response is performed [*see top illustration on page 48*]. This seems to suggest that, at least in the octopus's vertical lobe and the mammalian cerebral cortex, memory is both everywhere and nowhere in particular.

Some of the difficulties such a conclusion presents may be due to a failure to distinguish experimentally between the two constituents of a memory. Whatever its nature, a memory must consist not only of a representation, in neural terms, of the learned situation but also of a mechanism that enables that representation to persist. A distinction must be made between the topology of what persists (the coding and spatial relations involved in the memory of a particular animal) and the mechanisms of persistence (the neural change that is presumably the same in the memory of any animal). Indeed, it may be that some of the theoretical confusion in the study of memory arises from the fact that experiments showing a quantitative relation between memory and nerve tissue tell us something about how the neural representation of memory is organized but nothing about how the representation is kept going.

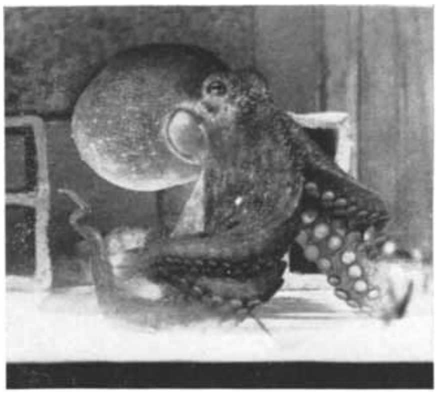
In our experiments demonstrating that an octopus deprived of its vertical lobe could not be trained to discriminate between a crab alone (that is, reward) and a crab accompanied by a geometric figure and a shock (that is, punishment) our groups of trials were separated by intervals of approximately two hours. When we spaced the trials so that they were only five minutes apart, however, we found that such animals were capable of learning [*see bottom illustration on page 48*]. Using the number of trials required as a criterion of learning, we found that these animals attained a level of performance as good as that of normal animals trained with longer time intervals between trials.

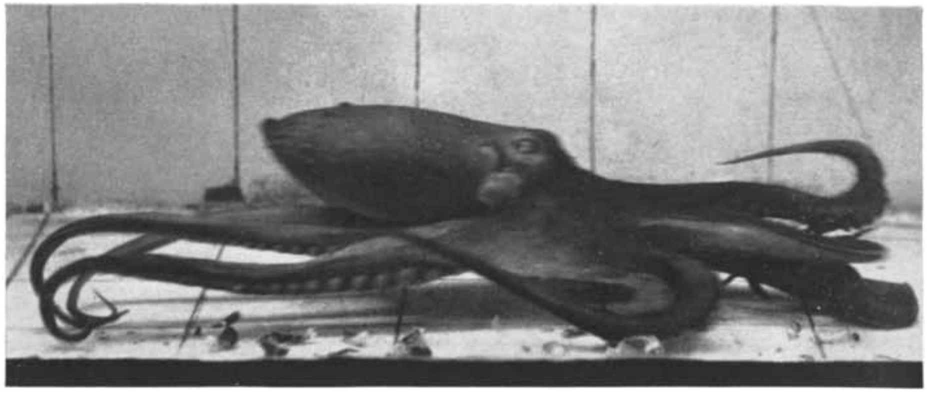
One significant difference remained: a normal octopus has a learning-retention period of two weeks or longer, but animals without a vertical lobe had retention periods of only 30 minutes to two hours. These observations suggest that the establishment of a memory involves two mechanisms. There is first a short-term, or transitory, memory that, by its continuing activity between intervals of training, leads to a long-term change in the brain. If there were no reinforcement, the short-term memory would wane; with reinforcement it keeps going and so induces the long-term—and by implication slower—changes that enable a brain to retain memories for long periods.

In 1957 Eliot Stellar of the University of Pennsylvania School of Medicine pointed out the parallels between our results with invertebrates and the unexpected discovery of a similar effect in man by Wilder Penfield, Brenda Milner and W. B. Scoville of the Montreal Neurological Institute. Epileptic patients who have been treated by surgical removal of the temporal lobes of the brain score as well in I.Q. tests after the operation as they do in tests before the onset of epilepsy. They remember their past, their profession and their relatives. They cannot, however, retain new information for more than short periods. Articles can be read and understood, but they are not remembered once they are finished and another topic is taken up. A relative may die but his death goes unremembered after an hour or so. This surgery involves the hippocampal system of the human brain; its effects seem to suggest that, although man's cerebral cortex incorporates a long-term memory system, the hippocampal system is essential to the establishment of new long-term memories.

Today a considerable body of behavioral and psychological evidence favors the separation of memory into short-term and long-term systems. At the neurological level this distinction has brought about a reaffirmation of the role in memory of what are called self-reexciting chains. A few years ago the concept of such chains had gone out of fashion because it had been found that neither convulsive shocks nor cooling the brain to a temperature so low that all activity ceased would abolish learned responses. It is now known that if such treatments are given during the early stages of learning—that is, before a memory is fully established—they have an effect; supposedly this is because they have interfered with the more active part of the process. As the surgical operations for epilepsy indicate, a long-term memory system is intact after removal of the temporal lobes. A short-

SAGITTAL SECTION stained with silver reveals some of the structures in the octopus brain. Broken lines (*color*) show the route of the esophagus, the boundary between the upper and lower parts of the brain. Labels identify eight lobes in the upper brain and four in the lower; experiments before and after surgical removal show that the vertical lobe (*top right*) plays a role in visual learning and that the inferior frontal lobe (*top left*) is one of two involved in tactile learning. The statocyst (*bottom right*) is not a part of the brain; it is one of the twin organs responsible for the octopus's sense of balance. Magnification is 15 diameters.



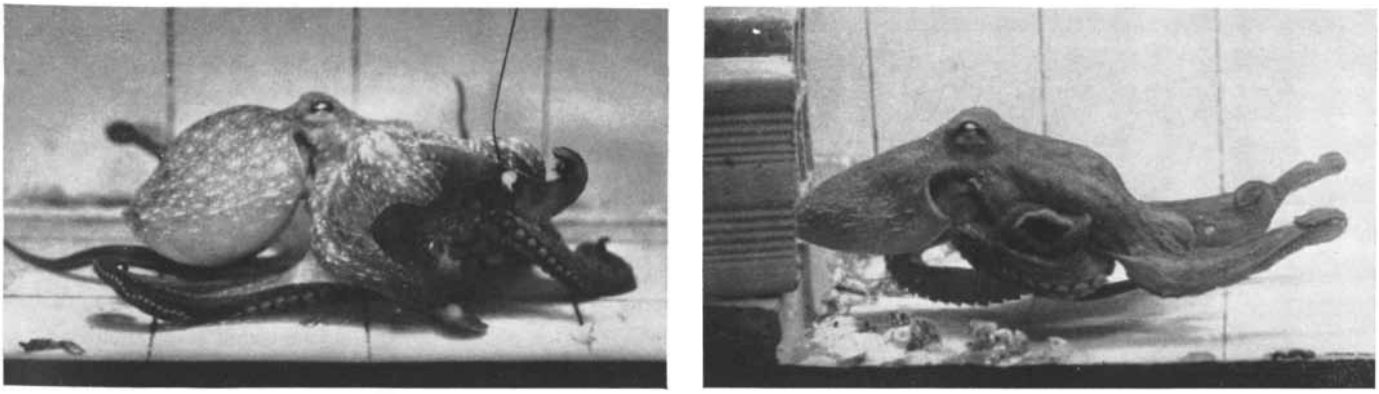


UNSCHOOLED OCTOPUS leaves the shelter at one end of its tank (*first photograph*) and walks toward the bait at the opposite end. The advancing animal uses only one of its eyes to guide it. When the bait, a crab, is in range, the octopus throws its leading

term memory system must also remain, however, because the patients can remember new information for short periods, particularly when they use mnemonic devices. On the basis of this interpretation it would appear that the hippocampal system may have the role of linking the two memory mechanisms—whatever that may mean.

For octopuses in our training situation it seems at first that when the vertical lobe of the brain is removed, the long-term memory system of the animal is completely abolished, leaving only the short-term system. We obtain a different result, however, if instead of showing such an animal a crab with or without a geometric figure we present it with figures only, rewarding it with a crab for an attack on one figure and punishing it with a shock for an attack on another. Under such conditions an octopus without its vertical lobe can learn the required discriminations and retain them. At least two conclusions can be drawn from this kind of result. The first is that the vertical lobe is essential to the memory system if the learned response involves a change in what might be termed innate behavior toward an object as familiar to an octopus as a crab. The second is that a long-term memory system for some responses

TRAINED OCTOPUS is cautious in its approach when a crab and a geometric figure are presented together (*first photograph*). If the animal seizes the crab, it receives an electric shock (*note darkened region at the base of the arm in second photograph*). As



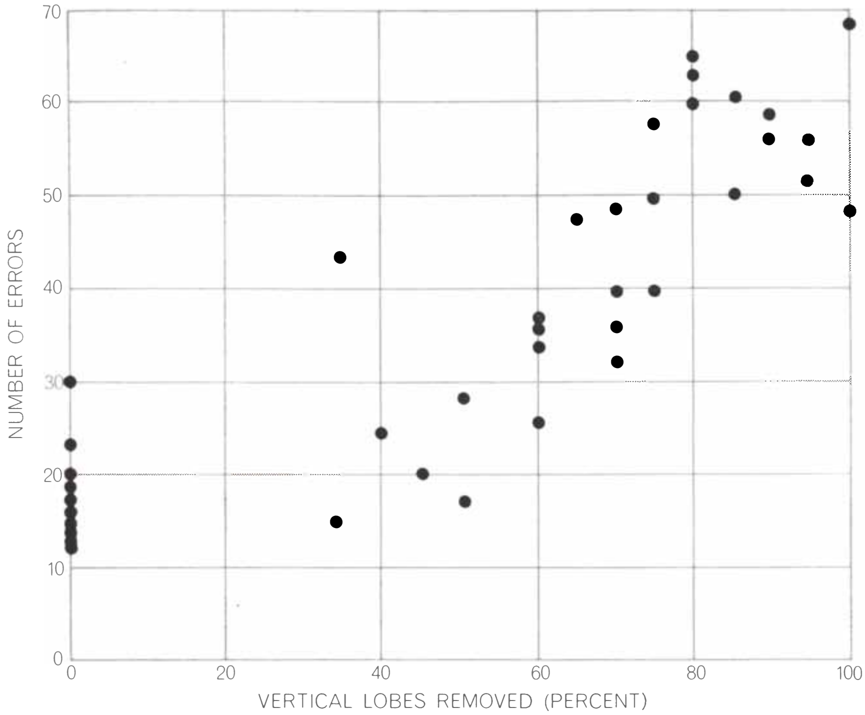
arms forward to seize it (*second photograph*). Next it tucks the crab up toward its mouth (*third photograph*). The octopus then returns to its shelter (*fourth photograph*), where it kills the crab with a poisonous secretion from its salivary glands and eats it.

can be maintained in the absence of the vertical lobe.

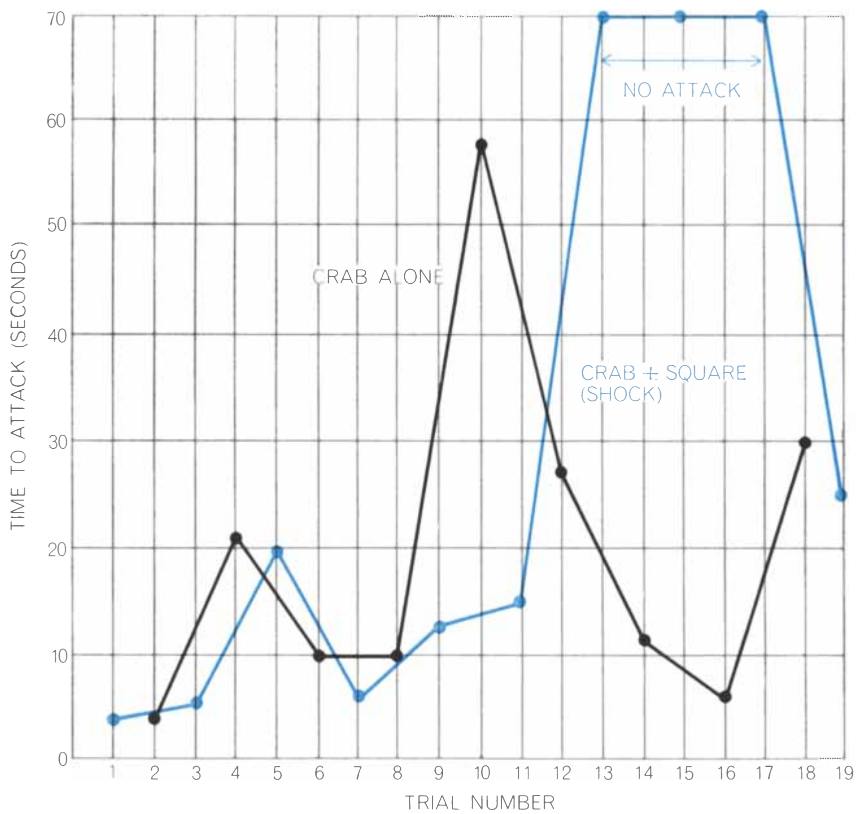
Since we do not know (and probably never will know because it is so difficult to rear *Octopus vulgaris* from its larval stage) whether the octopus's response to a crab is learned or innate, our studies over the past eight years have involved experiments in which reward or punishment is given only after the animal has responded to an artificial situation, that is, the presentation of a figure of a given size, shape or color. It has been shown that animals without a vertical lobe can learn to attack unfamiliar figures for a reward, although they do so more slowly than normal animals. Once they have learned to attack such figures these octopuses retain their response for as long a time as normal animals do. If octopuses without a vertical lobe are required to reverse a learned visual response, however, they find it particularly difficult. When a shock is received for attacking a figure that formerly brought a reward, the animals can still learn to discriminate, but they make between four and five times as many mistakes as normal animals; moreover, their period of retention is shorter.

In addition to its large visual system

training continues, the octopus will often not even leave its shelter when crab and figure are presented (*third photograph*). If crab and figure are brought near a fully trained animal, it pales and pumps a jet of water at them (*fourth photograph*).



CONTRAST IN PERFORMANCE of normal (*far left*) and surgically altered octopuses shows that the number of errors increased more than threefold as larger and larger portions of the brain's vertical lobe were excised. This finding supports the conclusion that the organization of memory depends primarily on the number of brain cells available.



ABILITY TO LEARN can be demonstrated by an octopus deprived of the vertical lobes of its brain, provided that the trials are only a few minutes apart. In the example illustrated, little learning was apparent during 12 alternating exposures to negative and positive stimuli. Thereafter three successive negative stimuli were avoided by the octopus.

the octopus has a complex chemotactile sensory system. Most of the investigation of this system has been done by Martin Wells and his wife Joyce. By applying methods similar to those used for training the animals to make visual discriminations, they have been able to show that tactile learning in the octopus is about as rapid as visual learning. Octopuses have been trained to discriminate between a live bivalve and a counterfeit one consisting of shells of the same species that have been cleaned and filled with wax. They can discriminate between a bivalve with a ribbed shell and another species of comparable size but with a smooth shell. Just recently Wells has found that octopuses can detect hydrochloric acid, sucrose or quinine dissolved in seawater at concentrations 100 times less than those the human tongue can detect in distilled water. Presented with artificial objects, they can distinguish between grooved cylinders and smooth ones, although they cannot distinguish between two grooved objects that differ only in the direction in which the grooves run [*see illustration on opposite page*]. After intensive training they can discriminate a cube from a sphere about 75 percent of the time.

Through each arm of an octopus, which is studded with two rows of suckers, runs a cord of nerve fibers and ganglia. In these ganglia occur local reflexes along the arm and between the rows of suckers. It is supposed that, when the octopus makes a tactile discrimination, the state of excitation in the ganglia above each sucker is determined by the proportion of sense organs excited, and the degree to which these sense organs are stimulated determines the frequency with which nerve impulses are discharged in the fibers running from the ganglia to the brain. Learning in the isolated arm ganglia is probably not possible. Wells has found that for tactile learning to occur the upper brain's median inferior frontal lobe and subfrontal lobe are necessary. Damage to these regions of the brain does not affect visual learning, and for that reason the two lobes have often been used as the sites for control lesions in the investigation of visual learning.

The role of the median inferior frontal lobe seems to be to interrelate the information received from each of the octopus's eight arms; if the lobe is removed and one arm is trained to reject an object, then the other arms continue to accept the object. Without the subfrontal lobe the animals cannot even learn to reject objects by touch. As in the case of the vertical lobe in visual learning, the retention of small portions of the subfrontal lobe allows adequate learned performance. Wells believes that as few as 13,000 of the five million subfrontal-lobe cells may be sufficient for some learning to occur. The subfrontal lobe is structurally very similar to the vertical lobe; it must be considered the vertical lobe's counterpart in the chemotactile system. Removal of the vertical lobe nonetheless has an effect on chemotactile discrimination, mainly in the direction of slowing the rate at which learning occurs.

This account has discussed the main lines of work on memory systems that have been carried out with octopuses as experimental animals, together with some comparisons with human memory. Recently Young has summarized all the work on the cephalopod brain of the past 17 years and has devised a scheme of how such brains may work in the formation, storage and translation of memory into effective action.

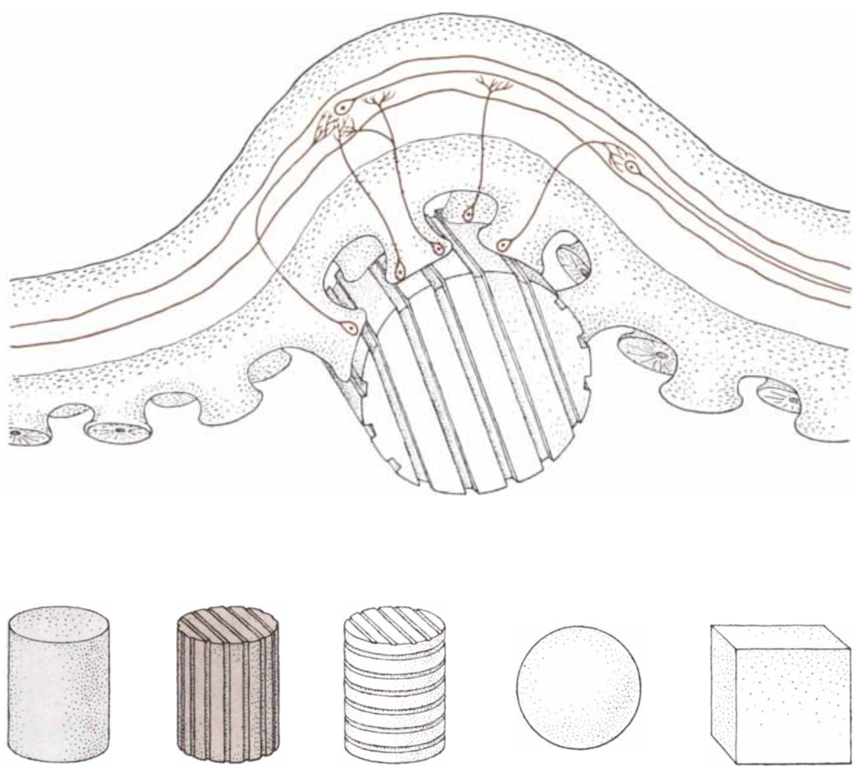
Young proposes that in the course of evolution chemotactile and visual centers developed out of a primitive taste-and-bite reflex mechanism. As these "distance receptor" systems evolved, providing information as to where food might be obtained other than that received from direct contact, there came to be a more indirect relation between a change in the environment and the responses that such a change produced in the animal. As this happened, signal systems of greater duration than are provided by simple reflex mechanisms also had to evolve; learning had to become possible so that the animal could assess the significance of each distant environmental change.

Suppose, for example, a crab appears at a distance in the visual field of an octopus; as a result of what can be called "cue signals" there arises in the octopus brain a system for producing "graduated commands to attack." This command system will be weak at first but will grow stronger with reinforcement. The actual strengthening process will vary according to the reward or punishment met at each attack, because the outcome of each attack gives rise to a "result" signal. Such signals condition the distance-receptor systems that initially cued the attack—in the present example, the visual-receptor system. These result signals become distributed throughout the nervous tissue that carries a record of a particular event.

There is, of course, a delay between the moment the cue signals are received in the brain and the moment the result signals arrive. If the result signals are to produce the appropriate conditioning of memory elements, the address of these elements, so to speak, has to be held to allow correct delivery of the information of, say, taste or pain. In the brain of the octopus each optic lobe contains "classifying" cells, among them vertically and horizontally oriented sets of nerve fibers that are presumably related to the vertical and horizontal arrangement of elements in the retina of the octopus's eye. These classifying cells form synapses with "memory" cells in the optic lobes that in their turn activate the cells that signal either attack or retreat. According to Young's hypothesis, each of the memory cells at first has a pair of alternative pathways; the actual neural change during learning consists in closing one of the two pathways. This closing may be accomplished by small cells that are abundant in these learning centers and that can perhaps be switched on so as to produce a substance that inhibits transmission.

Suppose an attack has been evoked by means of this system; the memory cells activate not only an attack circuit but also a circuit reaching the vertical lobe of the upper brain. The signals indicating the results of the attack, such as taste or pain, arrive back and further reinforce the memory cells in the optic lobes, which have been under the influence of the appropriate pathways set up in the vertical lobe during the time interval between the cue signal and the result signal [*see illustration on next page*].

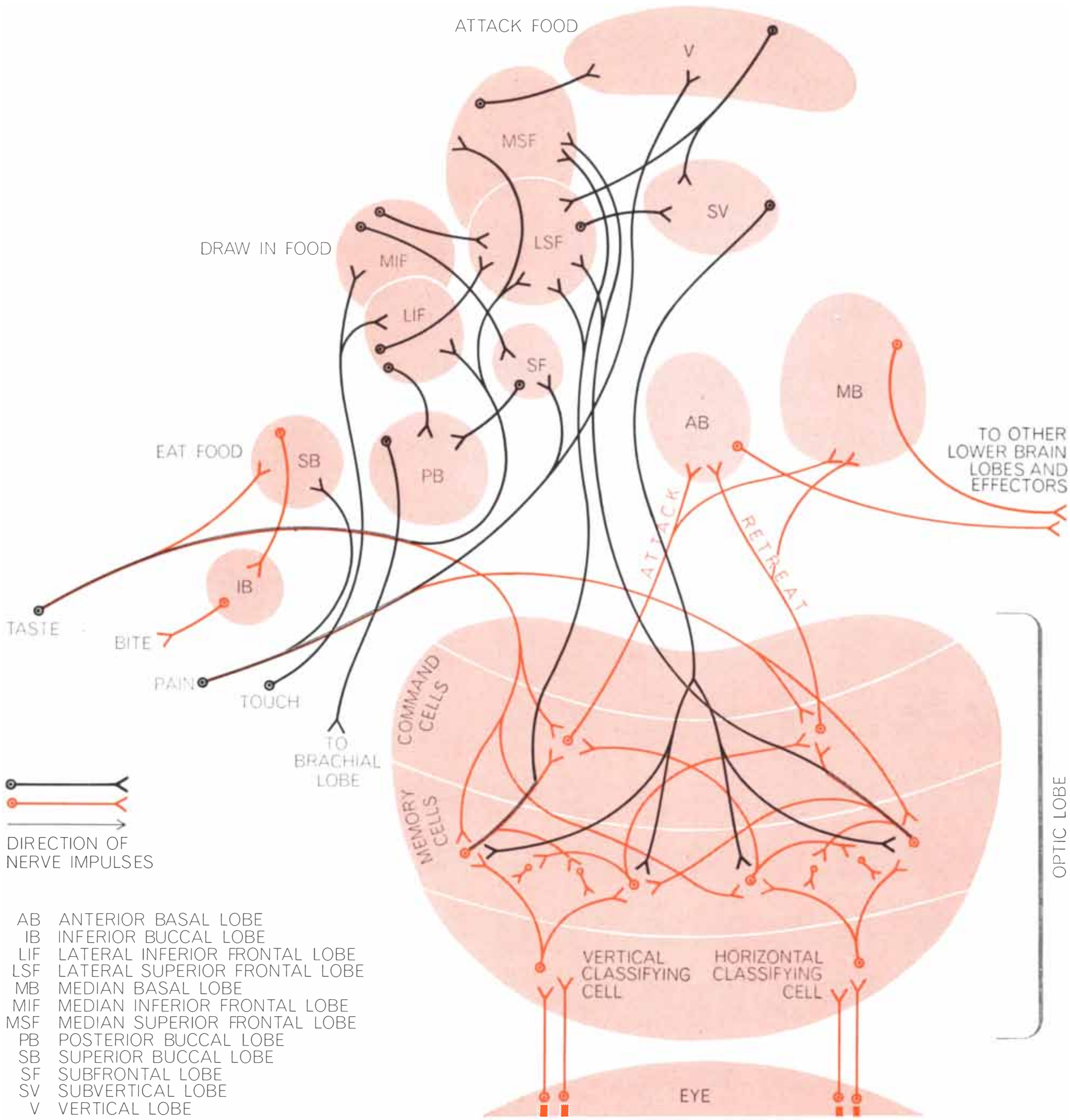
The hypothesis that the actual change represented by memory is produced by the small cells agrees with the fact that these cells are also present in the part of the brain that was shown by the Wellses to be the minimum necessary for tactile memory. Young suggests that the small cells were originally part of the primitive taste-and-bite reflex system, serving the function of



LEARNING BY TOUCH in the octopus was investigated by presenting objects with a variety of shapes and textures. In the case of a grooved cylinder (*top*) only the sense organs in contact with the surface are excited; those resting over the grooves remain inactive. Thus the octopus can learn to discriminate between a smooth cylinder (*gray*) and a grooved one (*color*), and even between a cube and a sphere; it cannot, however, discriminate between two cylinders that differ only in the orientation of the grooves.

temporary inhibition. The evolution of the memory consisted in making the inhibition last longer. The sets of auxiliary lobes associated with the memory system arose to allow for various combinations of inputs to be set up, to be combined with the signals that report the results of actions and finally to be "delivered to the correct address" in the memory.

There is much that is speculative about this description, but the fact remains that both the visual and the tactile memory systems of the octopus embrace sets of brain lobes arranged in similar circuits. This organization provides opportunities for study of the memory process that are made more challenging by Young's conviction that comparable circuits exist in the brains of mammals, including man.



DUAL NATURE OF MEMORY can be traced out on an exploded view of the octopus brain. Circuits leading from the optic lobe (*color*) are the first to be activated on receipt of a visual cue by the lobe's classifying cells. The cue is then recorded in the memory cells and relayed to the command cells; the latter induce the octopus to attack or retreat. If an attack is rewarded, the returning "result" signal will reinforce a memory that registers the initiating cue favorably. If, instead, the attack brings pain, the reinforced memory will register the cue unfavorably and any similar cues encountered in the future will be channeled to the circuits governing retreat rather than attack. Additional circuits (*black*) connect the memory and command regions of the optic lobe to various lobes of the upper brain; thus each event and its outcome are also recorded and reinforced in these nervous tissues. In due course what appear to be the long-term components of the memory system become localized in individual upper brain lobes.

Kodak reports on:

a new plate that will go far . . . encoding 2000 x 490 documents coolly . . . a very selective compound

The trouble with astronomers

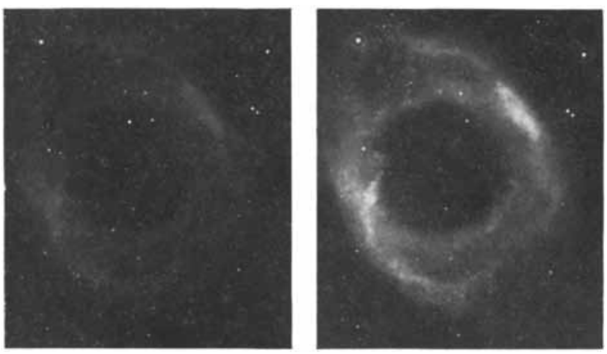
Astronomy has probably done more for us than we have done for astronomy.

Some of the deepest chemical and physical underpinnings that support us as we cheerfully manufacture $\$n \times 10^8$ worth of photographic materials this year were driven down to bedrock because astronomers were analytical-minded users of photographic materials, though unable to match boardwalk tintype artists for volume of consumption.

The trouble with astronomers is still their paucity. Yet here we go, proudly announcing the KODAK Special Plate, Type 080-01, that halves exposure time for the faintest of stars, nebulae, and their spectra, or alternatively, establishes new extremes in faintness. Since, in the class of observations where it is not extraneous light that imposes the limit, penetration is bought with exposure time and focal length, and since the world supply of telescope time on serious focal lengths defines a rather cozy little customer-community of astronomical frontiersmen, questions of commercial sanity might well be raised.

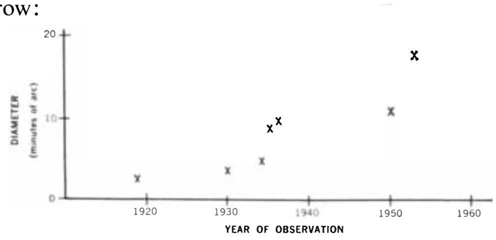
No, the explanation is not so simple as that this emulsion research will soon pay off in shooting cowboys on dimly lit saloon sets for TV. A deeper understanding now reveals weakness in conclusions drawn from studies of fast films designed for other purposes than to distinguish threshold light signals from darkness. That the earthlier applications of photography use fractional-second exposures instead of hours is only part of the difference.

With rival claims now reassessed, photographic detection has been restored to its former eminence in the astronomical observatory. How can we now possibly stand it to refrain from jumping in? To whom shall the astronomers turn if not to us?



Kitt Peak National Observatory recorded the very large and faint planetary nebula NGC 7293 in Hα light with (left) the former best choice, KODAK Spectroscopic Plate, Type 103aE, and (right) the new KODAK Special Plate, Type 081-01, an "E"-sensitized version of our new breed.

Not many men pull on their shoes in the morning with the thought, "Today I'll ship something that will probably expand the visible universe." It's fun to make a galaxy like Messier 32 grow:



This business, yielding a revenue inverse to its cosmic scope, is conducted by Special Sensitized Products Division, Eastman Kodak Company, Rochester, N.Y. 14650.

Information at the fingertips

Compared with fish, fats, fuel, or anything else you can think of, information is now the most *dignified* commodity in which to traffic—to sell, buy, gather, generate, blend, arrange, process, refine, filter, weigh, store, retrieve. We want you to think of us in association with the two last named. Better yet, think of our RECORDAK MIRACODE System. It can reward your interest by bringing your domain abreast of the age without loss of your cherished sense of financial reasonableness.

See Miss 1966, a well educated girl contributing to the soundness of society in a dignified, cool, pleasant way. The console at her left as she coolly retrieves from your RECORDAK MIRACODE System holds 490 film magazines each containing up to 2,000 documents, the proper one of which will appear on the screen (and even in the hand) within seconds in response to an interrogation punched on the keyboard.

The news is of healthy, continuing growth at the underneath part of the iceberg. Down below, where the massive problems are found of encoding usefully and rapidly 2000 × 490 documents—that's where the coolness of the retrieval is determined.

That's where, for example, you may now install our new accessory that makes a common card punch translate Hollerith holes into the proper signals to lay down photographically on the film a code describing the document image or images it precedes. This code can, of course, extend to whatever depth is wanted for precision of response to those cool fingertips.

This kind of talk grows complicated all too quickly. To set up a situation where it can be better pursued in the necessary detail, address your own kind of inquiry about the RECORDAK MIRACODE *System to R. F. Beckwith, Recordak Corporation, 770 Broadway, New York 10003 (Subsidiary of Eastman Kodak Company).*

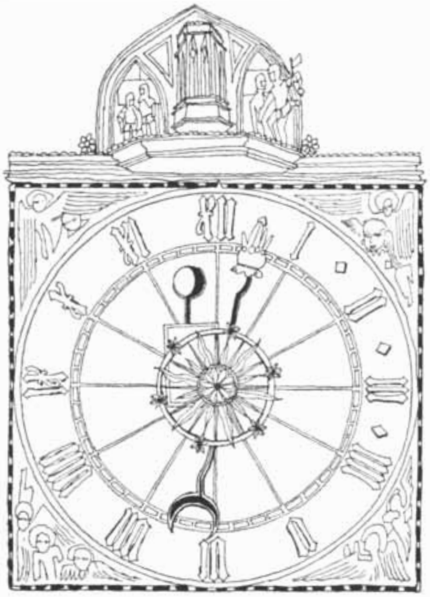
Glycine picker

Should an occasion arise where it is desired to pick the glycine out of a protein hydrolysate, attention is drawn to a 1935 paper in *J. Biol. Chem.* (*10*, 317). It reports that *Potassium Oxalatochromate* forms an insoluble complex with glycine and only glycine among all amino acids.

Sorry to have waited till now to offer the compound. It is available as EASTMAN *9256 from lab-supply dealers or from Distillation Products Industries, Rochester, N. Y. 14603 (Division of Eastman Kodak Company). So are many thousand other* EASTMAN *Organic Chemicals. Send to same address for "List No. 43."*

This is another advertisement where Eastman Kodak Company probes at random for mutual interests and occasional commerce with those whose work has something to do with science

SCIENCE AND



Extended Symmetry

The mystery presented by the multiplicity of "elementary" particles seems to be rapidly reaching a climax and perhaps even a solution. The idea is gaining ground that all the known particles can be grouped into a few large families and that within each of these "supermultiplets" all the particles can be regarded as the mathematical equivalents of one another. This method of grouping particles arose with the "unitary symmetry" theory called SU(3), also known as the eightfold way (see "Strongly Interacting Particles," by Geoffrey F. Chew, Murray Gell-Mann and Arthur H. Rosenfeld; SCIENTIFIC AMERICAN, February, 1964). Within the past six months a still more comprehensive ordering scheme called SU(6) has won broad support. SU(6) refers to a special unitary group whose algebra is based on six components and yields even bigger supermultiplets than SU(3) does.

The SU(3) theory showed how particles that vary in certain basic properties (isotopic spin and hypercharge) can be regarded as members of a supermultiplet, provided that they are alike in other basic properties (ordinary spin and parity). The most familiar particles that can be grouped in this way are the nucleon doublet (the neutron and proton), three sigma particles, two xi particles and a lambda particle, which together constitute a supermultiplet with eight members—an octet. Another supermultiplet of 10 members—a decuplet—met SU(3) requirements but was lacking its 10th member at the time it was proposed. When the missing particle—the omega minus—was discovered a year ago, the prestige of SU(3) was greatly enhanced. The theory that postulated these groupings had been developed independently in 1961 by Murray Gell-Mann of the California Institute of Technology and Yuval Y. Ne'eman of Tel Aviv University.

The SU(6) theory rehabilitates an idea proposed nearly 30 years ago by Eugene P. Wigner of Princeton University. Wigner had suggested that the forces inside the atomic nucleus might be largely independent of the spin of the nuclear components. The idea, which had only limited success in predicting the properties of nuclei, has now been applied to the subnuclear particles themselves. The eight-member and 10-member supermultiplets are characterized by different amounts of spin angular momentum. Particles in the eight-member group have 1/2 unit of spin; those in the 10-member group have 3/2 units of spin. Both groups, however, have positive parity. In the SU(6) theory the difference in spin provides the key to grouping the octet and decuplet into a still larger supermultiplet in which spin itself is regarded as a secondary property, like charge, hypercharge, isotopic spin and mass. In the SU(6) counting system the octet and decuplet form a supermultiplet not of 18 members but of 56. The explanation is that each particle in the octet has two spin states, for a total of 16 states, and each particle in the decuplet has four spin states, for a total of 40 states; 16 plus 40 equals 56. According to the symmetry operations of SU(6) the 56 members of the supermultiplet can transform into each other.

Other supermultiplets that similarly transform under SU(6) have 20, 35 and 70 members. Supermultiplets of 35 or 56 members can accommodate most of the well-established particles. A 35-member family can be formed by grouping 17 of the known mesons that have negative parity. Eight have a spin of zero, therefore only one spin state each; nine have a spin of one, or three spin states each. The total is eight plus 27, or 35, spin states.

One unexpected triumph of SU(6) is that it accounts for the ratio of the magnetic moment of the neutron to that of the proton, which is −1.91/2.79, or −.68. According to SU(6) it should be −2/3, or −.67.

SU(6) can be regarded as a marriage of SU(3) and Wigner's spin-independence concept. In a mathematical sense SU(3) treats all the particles as if they were composites of three fundamental particles, which Gell-Mann has called "quarks." (Various groups have been hunting the quark, so far without success; it may exist only as a useful mathematical fiction.) In SU(6) it is assumed that each quark has two spin states, so that six states are available for forming the particles actually observed. The smallest supermultiplet of six objects taken three at a time is a set of 20. Sets of 35, 56 and 70 consist of more elaborate combinations of the six quark states taken three at a time.

The authorship of the SU(6) theory is shared by a number of workers. The first statement of the theory was published by Feza Gürsey of the Middle East Technical University in Ankara and Luigi Radicati of the Scuola Normale Superiore in Pisa while the two men were visiting the Brookhaven National Laboratory last summer. Other early statements of the theory were made by B. Sakita of the University of Wisconsin and independently by George Zweig of the California Institute of Technology. Others who helped to develop the theory were Abraham Pais and M. A. Baqi Bég of the Rockefeller Institute and Virendra Singh, now at the Tata Institute of Fundamental Research in Bombay.

In its early version SU(6) could accommodate only the static properties of particles, and many physicists doubted that it could be extended to cover the behavior of moving particles. For this purpose it would have to be expressed in a form consistent with the special theory of relativity. Significant success in this direction now seems to have been achieved by two groups. One consists of Abdus Salam, J. Strathdee and R. Delbourgo, working at the International Centre for Theoretical Physics in Trieste. The other group consists of Pais and Bég, who reported their results at the January meeting of the American Physical Society in New York. The relativistic version of SU(6) may permit the approximate prediction of scattering probabilities in various particle reactions—predictions that have heretofore been very difficult. There is also a possibility that the symmetry groups will be still further enlarged to form even bigger supermultiplets.

A Place for the Mohole

It has been decided where to dig the Mohole. After a six-year search for the ideal spot at which to drill a hole through the earth's crust to the underlying mantle, earth scientists have selected a site in the Pacific Ocean 100 miles north of Hawaii. At the chosen site the sea is some 14,000 feet deep and the ocean floor is an estimated 17,000 feet above the mantle, so that the surface-to-mantle distance is a relatively short 31,000 feet.

The prospective site for the Mohole and six sites for testing purposes, also in the Pacific, were recommended to the National Science Foundation, which is in charge of the Mohole project, by a Selection Committee of the National Academy of Sciences. A site near San Juan, Puerto Rico, that had received consideration was finally ruled out because it lay within a hurricane belt. Another, near Antigua, was vetoed because the distance from sea level to the mantle was 35,000 feet, the estimated limit of a practical drilling regime.

Breakthrough in Test Detection?

Recent developments suggest that a solution to the problem of detecting underground nuclear tests, or at least a substantial improvement in capability for dealing with the problem, may be at hand. The key development is the installation by the U.S. of a large detection system in Montana. In addition a group of seismologists from several nations agreed at a recent meeting sponsored by the Royal Society of London that with such equipment it should be possible to distinguish an underground test from an earthquake. If reliable detection could be established, the way might be opened to include underground tests in the treaty banning nuclear testing.

The Montana installation is called LASA, an acronym for "large-aperture seismic array." It consists of 525 buried seismometers arranged in 21 star-shaped clusters. Each cluster occupies about a square mile, and the 21 clusters are arranged in a circle some 125 miles in diameter. The underlying idea is that recording a seismic event on many detectors, which are arranged to cover both a considerable geographic area and several wavelengths of seismic energy, will provide a basis for judging the nature of the event against the constant background of subterranean noise caused by various natural phenomena and human activities. In other words, the objective of the array is to provide a better signal-to-noise ratio for any event of interest than can be obtained now.

LASA, which is being installed by the Advanced Research Projects Agency of the Department of Defense, is part of Project Vela, the U.S. effort to improve the detection of nuclear tests. The $10 million installation is an outgrowth of five similar but much smaller arrays already operating in Oregon, Utah, Tennessee, Arizona and Oklahoma. Project Vela officials hope the concept of the Montana array will improve by a factor of five to 20 the capability of present apparatus, which can detect an underground nuclear explosion of about one kiloton in granite and 20 kilotons in soft rock.

The Great Quasar Hunt

The task of identifying quasi-stellar radio sources, or quasars, which include the brightest and most distant objects in the universe, has been greatly accelerated by the completion of a new catalogue that provides accurate positions for more than 400 radio-emitting objects of all types. How many of them will prove to be quasars remains to be seen, but some guesses run as high as 30 percent. Until the data in the catalogue were compiled reliable positions for radio sources were so scarce that fewer than 15 of them had been identified as quasars from their appearance on photographic plates. With the aid of the catalogue the number of suspected quasars has been increased to about 60; the prospect is that as many more may be identified in the next few months.

The new catalogue, which is not yet published, represents more than a year of observations made with the new 300-foot radio telescope at the National Radio Observatory in Green Bank, W.Va. The observers were Ivan Pauliny-Toth, Campbell M. Wade, Jr., and D. S. Heeschen. The big Green Bank instrument can be pointed only along a line running north and south. As a radio source drifts across this line its radio output is recorded. The known declination of the telescope and the time at which the signal reaches a maximum provide a position that has a probable error of only 15 seconds of arc.

Provided with such positions, Allan R. Sandage and Philippe Veron of the Mount Wilson and Palomar Observatories have been inspecting sky-survey plates made with Palomar's 48-inch Schmidt telescope. The plates are made in pairs to record the blue and red regions of the spectrum separately. To qualify as a potential quasar a stellar object must be in the right position and emit strongly in the blue. When such an object is found, Sandage inspects it photoelectrically with the 200-inch reflector to see if it has the strong ultraviolet emission that is characteristic of a quasar.

The final step is to record the full spectrum of the object to see if its spectral lines display a red shift. A red shift indicates that the object is receding as part of the general expansion of the universe; the greater the red shift, the more remote the object. Although quasars are intrinsically bright, they are so distant that only four have yielded spectra whose red shifts are well established. One of the four appears to be the most distant object in the universe. A fifth may be even more distant, but its spectrum, which contains only one faint line, cannot be unequivocally interpreted. Most of the red-shift determinations have been made by Maarten J. Schmidt of Mount Wilson and Palomar.

Because quasars are such strong ultraviolet emitters it seemed possible to make an optical search for them without reference to the catalogue of radio positions. Such a search can be conducted by making a double exposure on a single photographic plate. One exposure is made in the ultraviolet part of the spectrum; the plate is then shifted slightly and a second exposure is made in the yellow region. When the developed plate is inspected, objects with strong ultraviolet emission stand out vividly. Using this method, Sandage has found an unexpected number of objects that imitate quasars. Since they do not coincide with any of the known radio sources, he refers to them as interlopers.

It has been suggested that the interlopers are "silent" quasars—quasars that have either not yet started to emit radio energy or have passed their peak. Sandage suspects, however, that most of them will turn out to be a peculiar type of star in the outer regions of our own galaxy; he is pursuing the optical search to test his hypothesis. What pleases optical astronomers is that the quasar search is now symmetrical: they are turning up objects that radio astronomers must examine. It used to be the other way around.

Fourth Test of General Relativity

A radio astronomer at the Lincoln Laboratory of the Massachusetts Institute of Technology has proposed a fourth test of Einstein's general theory of relativity. Writing in a recent issue of *Physical Review Letters,* Irwin I. Shapiro outlines a plan for bouncing radio waves off Mercury or Venus when it is on the far side of the sun from the earth and recording the echoes. According to the general theory, such waves should be slowed down by a tiny amount as they travel through the gravitational field of the sun. By measuring the changes that occur in the interval between the transmission of a radio wave and its reception back on earth when the wave passes near the sun, Shapiro and his colleagues hope to verify this relativistic effect of the sun's gravitation.

In some respects the new test resembles a technique that has been employed many times since 1919 to verify another prediction of the general theory. By measuring the apparent displacement of stars in the sky when they lie close to the limb of the sun during a solar eclipse, it has been possible to detect the predicted bending of starlight by the sun's gravitational field. The two other successful tests of the general theory involve slight changes in the rotation of Mercury's elliptical orbit and the "gravitational red shift" of spectral lines observed in the spectra of the sun and a few very massive stars; the gravitational red shift has also been observed on earth in experiments utilizing the Mössbauer effect.

"Whiskers" in Quantity

A process that makes high-strength "whiskers" of silicon carbide available in quantity has been announced by the Carborundum Company. Previously whiskers, which are tiny, single-crystal fibers of various materials, had been grown only in laboratories, and efforts to scale the process up for quantity production had been unsuccessful. The Carborundum Company has not disclosed the details of its process, saying only that "no problems are foreseen in scaling up to whatever capacity demand will warrant." The company puts the tensile strength of its silicon carbide whiskers at three million pounds per square inch; as is the case with the whisker form of many materials, that is far higher than the strength obtainable with large pieces of the material.

Crystals of certain nonmetals such as silicon carbide have high strength because of the strong forces between their atoms. Such crystals tend, however, to be brittle. Recent efforts to develop high-strength materials for use in structures have concentrated on putting nonmetal fibers in a metal matrix, thereby combining the high strength of the fibers with the relative lack of brittleness of the metal (see "Fiber-reinforced Metals," by Anthony Kelly; SCIENTIFIC AMERICAN, February). Problems still remain, however, notably the problem of placing the fibers or whiskers in a suitable matrix. Officials of the Carborundum Company said they hoped their process would advance research on such problems by making whiskers available in whatever amounts an experimenter may desire.

Oldest Rocks?

Analysis of the relative abundance of strontium isotopes in samples of rock from a group of islets halfway between South America and Africa indicates that the rock may be 4.5 billion years old, roughly a billion years older than any heretofore studied. The rocks nearest in antiquity are a South African granite with an isotope age of 3.2 billion years and a Minnesota granite with an age of 3.3 to 3.5 billion years.

The islets, a Brazilian possession known as St. Peter and St. Paul Rocks, lie on the Mid-Atlantic Ridge near the Equator; they have long interested geologists because they are composed entirely of the rock peridotite. In theory peridotite is a major component of the mantle, that deep layer of plastic rock that is buried by miles of the earth's crust and that surrounds the earth's core. It has been speculated that the islets are surface exposures of this primordial layer.

Five peridotite samples from the region were analyzed in 1964 by the Isotope Geology Group of the Carnegie Institution of Washington to determine the ratio of strontium 87 (the decay product of rubidium) to strontium 86 (the common isotope) in their contents. One sample substantially exceeded the other four both in the proportion of strontium 87 and in the quantity of undecayed rubidium present. Stanley R. Hart, the principal investigator, emphasizes that the analysis is subject to an error of as much as 25 percent; he nevertheless believes it is possible that the sample is a fragment of outer mantle, chemically unaltered from the time of its formation some 4.5 billion years ago.

"Eyeless Vision" Unmasked

The flurry of interest among Soviet psychologists in women who demonstrated "second sight" by "reading" with their fingertips, elbows and toes has ended. The ladies do not have "eyeless vision" after all. An article in *Literaturnaya Gazeta*, recently translated by Albert Parry of Colgate University, makes it clear that at least some Soviet psychologists were suspicious from the start, just as most U.S. psychologists and all accomplished magicians were when they heard of the "phenomenon." The Soviet investigators have now established that the ladies were cheating: they peeked.

"Eyeless vision" appeared in the Soviet press in the summer of 1962, when 22-year-old Rosa Kuleshova was reported to be able to "read" print while blindfolded by moving a fingertip over the lines. An epidemic of other examples followed. Nina Kulagina gave a demonstration that a Soviet parapsychologist called "a great scientific event." Lena Bliznova "read" with her fingers not quite touching the page and described a picture covered by a stack of books. In the U.S. *Life* published a report on "dermo-optical perception." Richard P. Youtz of Barnard College reported that a Michigan woman, Patricia Stanley, could distinguish colors with her fingers in absolute darkness.

As the *Literaturnaya Gazeta* article points out, although there have been reports of eyeless vision at least since the 18th century, it has never been claimed by a blind person—"although they should have been the very first to discover and perfect this ability so important to them." The article describes a thorough investigation of Nina Kulagina at the Bekhterev Psychoneurological Scientific Research Institute in Leningrad. Carefully controlled tests were mixed with those in which there was an opportunity to peek or eavesdrop; the woman scored well only when she could cheat. "There were no miracles whatsoever," reported the head of the institute. "There was ordinary hoax." The author of the article observed a demonstration by Rosa Kuleshova. "I had the impression that Rosa peeked," he wrote. Peeking is easy, according to those who understand "mentalist" acts. It is virtually impossible to devise a blindfold that does not leave a tiny aperture on each side of the nose.

THE MAGNETOSPHERE

Satellite measurements indicate that the earth's magnetic field is confined to a definite volume of space shaped somewhat like a teardrop with a tremendously long tail

by Laurence J. Cahill, Jr.

The magnetic field of the earth is commonly represented in textbooks as a symmetrical array of lines of magnetic force centered on the earth's magnetic polar axis. The overall configuration of the lines resembles the undistorted dipole field set up by an ordinary bar magnet, and the analogy is often carried to the point of depicting a giant bar magnet buried at the center of the earth. In the absence of any external influences such a field would extend indefinitely into interplanetary space, becoming gradually weaker with distance from the earth.

Since 1958 direct measurements of the outer reaches of the earth's field by means of artificial satellites and rocket probes have convinced many geophysicists that this simple picture of the earth's magnetic field must be drastically revised. Far from being free of external influences, the geomagnetic field is continuously buffeted by a "wind" of electrically charged particles emanating from the sun, distorted by electric currents circulating in the radiation belts that girdle the earth and perhaps modified still further by a variable interplanetary magnetic field. The net result of all these influences is a geomagnetic field shaped somewhat like a teardrop with a tremendously elongated tail. Instead of extending outward indefinitely, the field appears to be confined to a definite volume of space, called the magnetosphere, that is surrounded by a fluctuating but discrete boundary layer, called the magnetopause. Analysis of the data provided by the satellite measurements has progressed to the stage at which the broad outlines of the magnetosphere can now be mapped with reasonable accuracy. Meanwhile theorists have been able to construct several alternative working models to account for the complex interactions that take place both in and out of the magnetosphere between charged particles and magnetic fields.

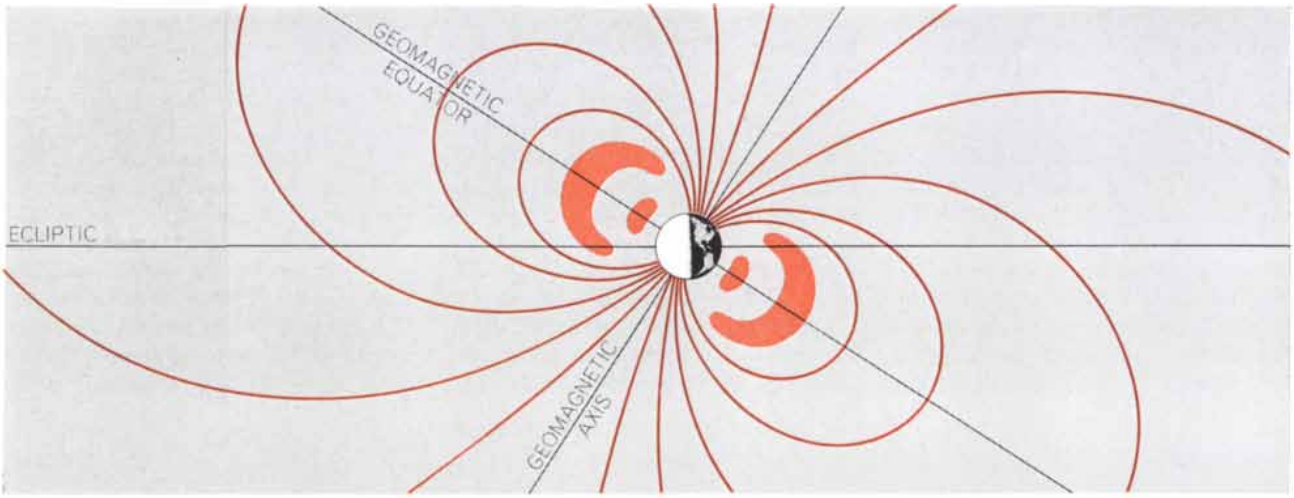
An Early Model

The first suggestion that the geomagnetic field was confined to a definite volume of space by a thin boundary layer was made some 30 years ago. Observers had noted that large flares on the surface of the sun were often followed a day or two later by severe magnetic storms on the earth. Such storms generally begin with a sharp increase in the strength of the geomagnetic field over much of the earth's surface. From this evidence the British geophysicist Sydney Chapman and his colleague V. C. A. Ferraro reasoned that the worldwide increase in field strength might be caused by the compression of the geomagnetic field. They proposed in 1931 that the agent of the compression was an electrically neutral cloud of protons and electrons (now called a plasma) ejected by the sun in the course of a solar flare. In order to account for the delay between the visual observation of a solar flare and the occurrence of a geomagnetic storm, they calculated that such a cloud must travel through space at a speed of about 1,000 kilometers per second.

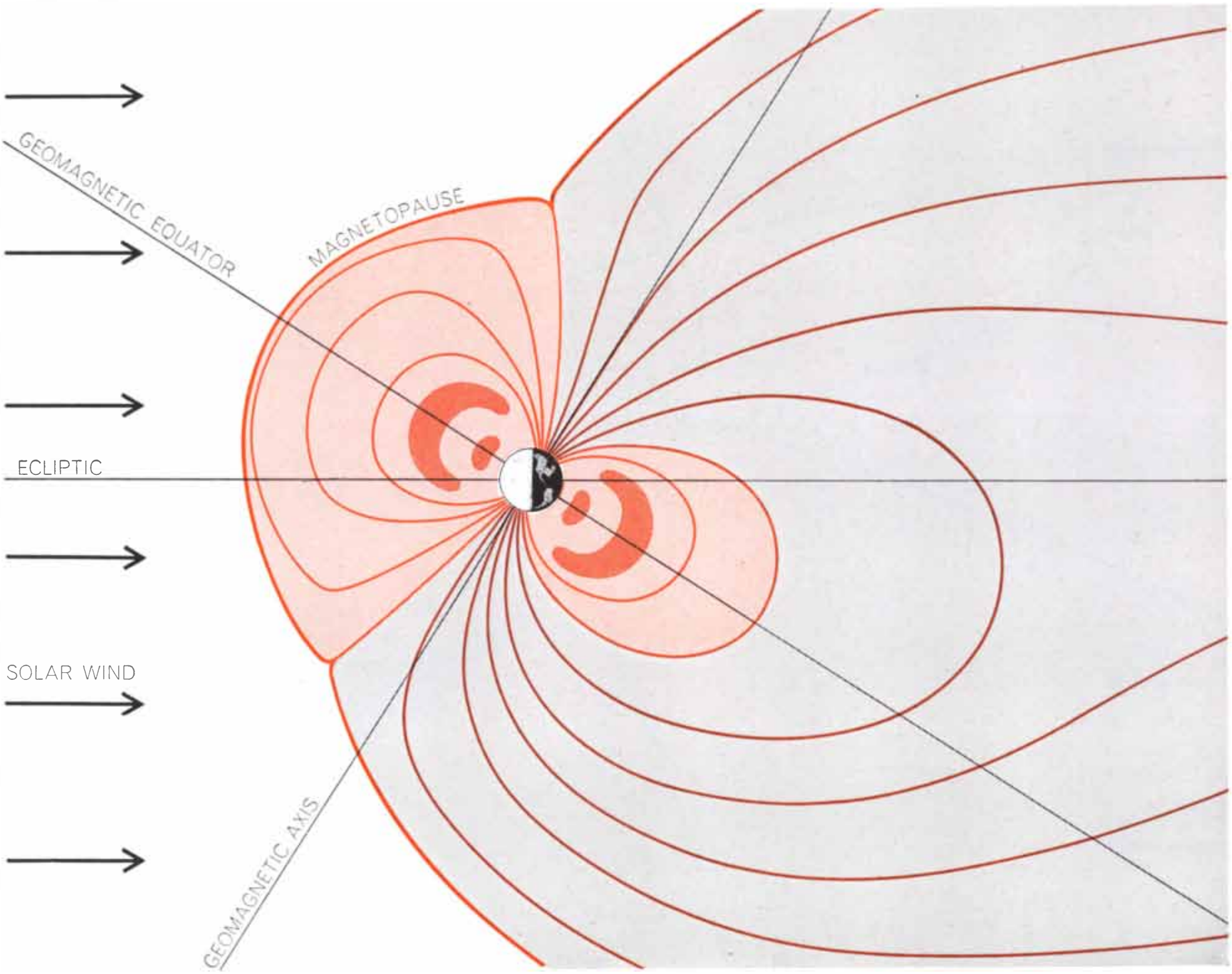
In the model put forward by Chapman and Ferraro an electric current is induced in the plasma cloud as it first encounters the outer magnetic field of the earth; this current is analogous to the current induced in a metal sheet when it is thrust into a magnetic field. In either case the "right hand" rule for the flow of current in a conductor moving in a magnetic field is employed to determine the direction of the induced current [*see illustration on page 61*]. A current induced in this way in the plasma cloud would in turn set up its own magnetic field, which would cancel the normal geomagnetic field in the cloud and strengthen the normal field in the region between the cloud and the earth. The cloud would continue to advance until its forward momentum was expended in compressing the geomagnetic field. The resultant boundary would remain at an equilibrium position as long as the flow of plasma in the cloud was constant. Successive surfaces of plasma would arrive at the boundary and be reflected from it by the same mechanism.

Years later it became evident that plasma is more or less continuously emitted by the sun [see "The Solar Wind," by E. N. Parker; SCIENTIFIC AMERICAN, April, 1964]. Solar flares and sunspot activity apparently produce stronger gusts in the otherwise steady wind of plasma, and the magnetopause moves in and out in response to these gusts. Some details of the interaction of the solar plasma and the geomagnetic field contained in the original model proposed by Chapman and Ferraro are now known to be incorrect. Nonetheless, the model has allowed quantitative predictions to be made as to the location and shape of the magnetopause. In general these predictions have been in close agreement with the satellite measurements. The model remains extremely useful as a first approach to the actual situation.

According to the original Chapman-Ferraro theory and later models derived from it, the pressure of the solar wind pushes the geomagnetic field closer to the earth on the earth's sunlit side and bends the polar-field lines back toward the tail on the earth's dark side. The



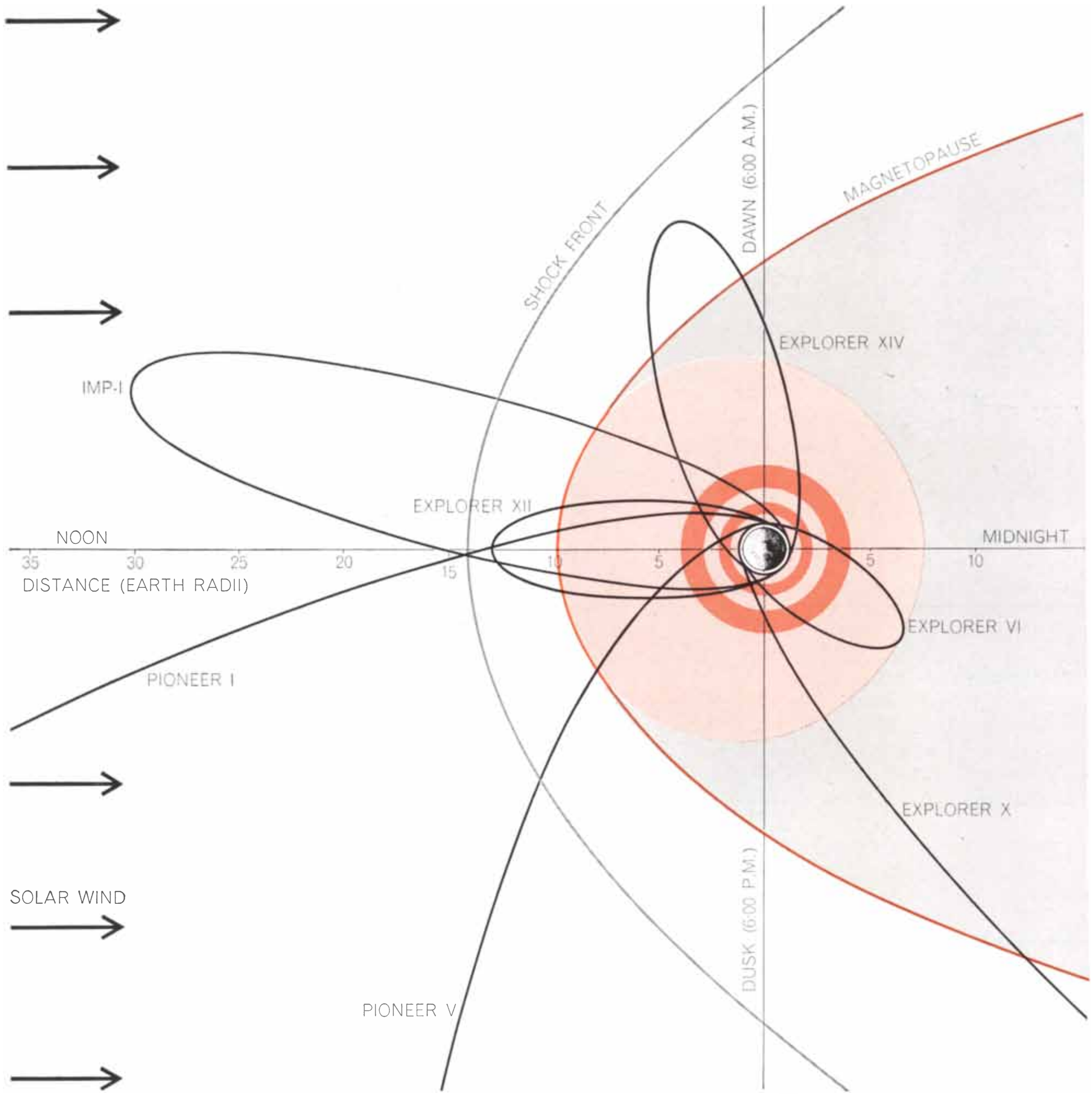
UNDISTORTED DIPOLE FIELD, similar to that set up by an ordinary bar magnet, would exist around the earth in the absence of any external influences. Such a geomagnetic field would extend indefinitely into interplanetary space, becoming gradually weaker with distance from the earth. The density of the lines of magnetic force is proportional to the strength of the field. The inner and outer Van Allen radiation belts, which respectively consist of high-energy protons and high-energy electrons, are shown in color.



ACTUAL GEOMAGNETIC FIELD is distorted by a variety of external influences, the chief being the "wind" of electrically charged particles emanating from the sun (*arrows*). As a result the field is confined to a definite volume of space, called the magnetosphere, that is surrounded by a fluctuating but discrete boundary layer, called the magnetopause. The inner magnetosphere (*colored area*) remains more or less symmetrical around the earth's magnetic polar axis. The solar wind bends the polar-field lines back toward the tail on the dark side of the earth. The magnetosphere is depicted during winter in the Northern Hemisphere, when the angle between the geomagnetic axis and the solar wind is at a maximum; at this time the distortion of the magnetosphere is also at a maximum.

plasma is most effective in compressing the magnetosphere where the direction of plasma flow is perpendicular to the surface of the magnetopause. In the simplest situation, where the plasma is assumed to be streaming radially from the sun in straight lines, the point of maximum compression is on the line that connects the center of the earth to the center of the sun. Away from this point the plasma strikes the magnetopause at less than a right angle and the pressure is correspondingly reduced. The pressure is zero where the flow of plasma is tangent to the magnetopause just beyond the dawn and dusk meridians. By estimating the density and velocity of particles in the solar wind, it was possible to predict that the magnetopause must lie somewhere between five and 10 earth radii from the earth on the earth-sun line, with an increase of 30 to 40 percent near the dawn and dusk meridians. (The radius of the earth is roughly 4,000 miles.)

On the dark side of the earth, where the forward momentum of the solar plasma is no longer effective in compressing the magnetosphere, the size and shape of the magnetosphere are more difficult to predict. At first it was thought that the thermal pressure of the solar plasma, brought about by the random motions of individual particles and equal in all directions, would confine the tail of the magnetosphere and that the lines of force originating in the polar regions of the earth would be closed by this pressure within a few tens of earth radii in the antisolar direction. In most of the more recent models, however, the tail of the magnetosphere ex-



INITIAL TRAJECTORIES of the seven artificial earth satellites and rocket probes mentioned in this article are projected on the earth's geographic equatorial plane in a view looking down on the North Pole. The satellite orbits remain fixed in relation to the stars, but as the earth travels around the sun the orbits appear to rotate around the earth toward the west (*clockwise*) at approximately one degree per day. Positions in longitude with respect to the sun are commonly indicated in terms of the local time meridian.

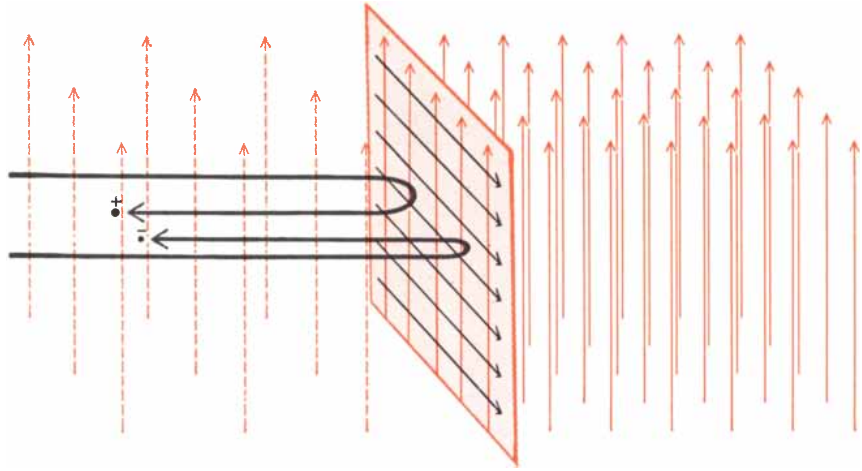
tends to great distances on the dark side of the earth or is not closed at all.

The Satellite Data

The first measurements of the outer regions of the magnetosphere were made in 1958 with instruments carried in the space probe *Pioneer I* [*see illustration on opposite page*]. With instruments that could measure the geomagnetic field only in a direction perpendicular to the spin axis of the satellite, Charles P. Sonett, then at the Space Technology Laboratories, and his colleagues found that the measured field was reasonably close to an undistorted dipole field between three and seven earth radii but was much stronger and fluctuated widely between 12 and 14 earth radii. Near 14 earth radii a sudden decrease in the strength of the field was observed.

Two years later *Pioneer V*, carrying similar instruments, traversed the outer magnetosphere along the 3:00 P.M. local time meridian. The results were similar to those obtained on the earlier flight: a gradually decreasing field out to eight earth radii, a strong, fluctuating field beyond 10 earth radii and a decrease to a weak, presumably interplanetary field somewhere between 15 and 20 earth radii. If the decreases in field strength observed beyond 14 earth radii were interpreted as the magnetopause, these distances were considerably greater than the Chapman-Ferraro model had predicted.

In March, 1961, James P. Heppner of the National Aeronautics and Space Administration's Goddard Space Flight Center installed a magnetometer experiment in the satellite *Explorer X*, which was launched toward the rear of the magnetosphere along the 9:00 P.M. meridian. On this flight both the strength and the direction of the geomagnetic field were measured. The field beyond eight earth radii was distorted, as though the lines of force were being pulled away from the earth, and the strength of the field was higher than predicted. The field remained fairly steady, however, out to 21 earth radii, where it abruptly decreased in strength from 20 gammas to about 10 gammas. (A gamma is a unit of magnetic-field strength equal to a hundred-thousandth of a gauss.) At this point the direction of the field also changed abruptly and a plasma detector on the spacecraft observed high-velocity plasma for the first time. The strength and direction of the field continued to fluctuate by large amounts beyond 21 earth radii. The appearance of plasma, together with the sharp field changes, constituted convincing evidence that the spacecraft was passing through the magnetopause at this point. Later in the flight the plasma disappeared and reappeared several times; each time the absence of plasma coincided with a steady magnetic field of about 20 gammas pointing away from the earth. When plasma was recorded, the magnetic field was stronger and more erratic than that expected in interplanetary space. The simplest interpretation of these events is that the satellite traveled outward approximately parallel to the extended tail of the magnetosphere, and that the magnetopause moved back and forth past the satellite in response to changes in the solar wind.

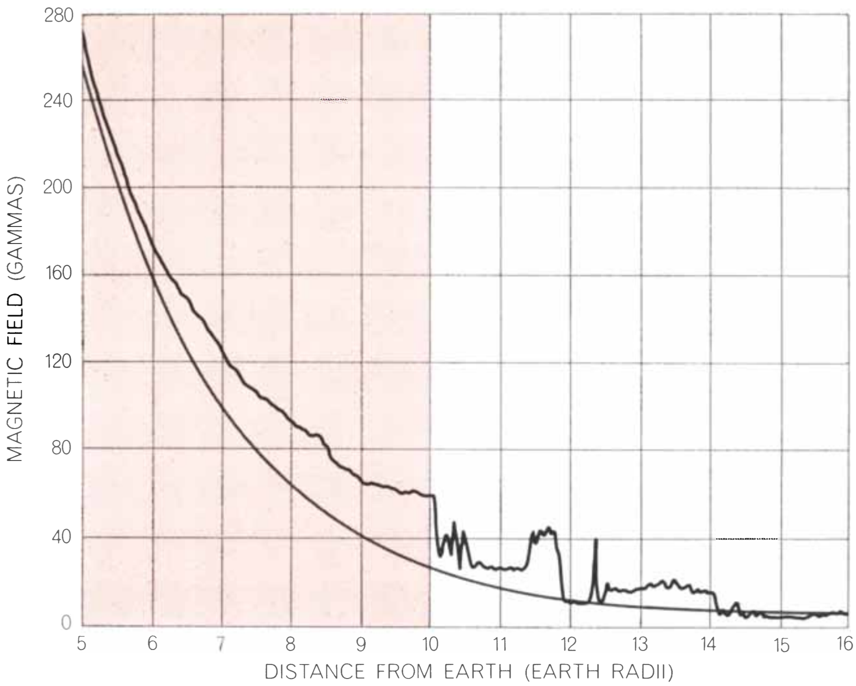


COMPRESSIONAL MECHANISM put forward in 1931 by Sydney Chapman and V. C. A. Ferraro explained how an electrically neutral cloud of protons and electrons (now called a plasma) ejected by the sun in the course of a solar flare could compress a part of the geomagnetic field and thereby cause a magnetic storm on the earth. As the plasma cloud first encounters the outer magnetic field of the earth, the individual protons and electrons are reflected by a force perpendicular to both the magnetic field and the direction in which the particles are moving. The motions of numbers of protons and electrons constitute an electric current (*black arrows*), which in turn sets up its own magnetic field (not shown here). The induced field cancels the normal geomagnetic field in the cloud (*left*) and strengthens the normal field in the region between the cloud and the earth (*right*). The cloud continues to advance until its forward momentum is expended in compressing the geomagnetic field.

Later in 1961 *Explorer XII* was launched into a highly elliptical orbit with an apogee beyond 13 earth radii. At the University of New Hampshire several students and I, with the assistance of Erick Schonstedt of the Schonstedt Instrument Company and with support from NASA, had prepared a magnetometer experiment for this satellite. One orbit per day was completed during the 102-day lifetime of the satellite, so that extensive observations of the outer magnetosphere were provided under a variety of solar and geomagnetic conditions. The apogee was initially near the noon meridian, but as the earth moved around the sun the orbit of the satellite remained fixed in space; as a result the angle between the major axis of the orbit and the noon meridian increased by about one degree per day toward the west.

The magnetopause was recorded on many passes by *Explorer XII* as a sudden, large shift in field direction and a corresponding decrease in field strength, with large fluctuations in both quantities. The strength of the field just inside the magnetopause was found to be double the value predicted for an undistorted dipole field; this was in agreement with the compression mechanism put forward in the Chapman-Ferraro model. The field outside the magnetopause was not zero, however, as the Chapman-Ferraro model had predicted; it was comparatively strong (10 to 50 gammas) and exhibited large fluctuations both in strength and direction. The distance from the magnetopause to the earth was typically about 10 earth radii near the noon meridian, although there was a considerable movement of the magnetopause from day to day. The closest observation of the magnetopause was at a distance of 8.2 earth radii. Away from the noon meridian this distance became greater, but day-to-day fluctuations tended to obscure the general increase. After three months, when the satellite was near the dawn meridian, the magnetopause was seldom observed, an indication that it was beyond 13 earth radii.

Explorer XIV, launched in October, 1962, also carried a magnetometer ex-



TYPICAL SATELLITE MEASUREMENT of the strength of the geomagnetic field between five and 16 earth radii from the earth on the sunlit side is represented in this graph by the jagged black curve. The smooth black curve is the hypothetical dipole-field strength. Below five earth radii both curves rise smoothly to about 50,000 gammas at the surface of the earth. (A gamma is a unit of magnetic-field strength equal to a hundred-thousandth of a gauss.) Between five and 10 earth radii the measured field is stronger than the predicted field; at 10 earth radii, where the magnetopause is located, the strength of the measured field is nearly twice that of the predicted field. Beyond the magnetopause an irregular, fluctuating field appears to extend out for another four or five earth radii, where a second, shock-front boundary is located. Beyond the shock front the records show a weak interplanetary field.

periment prepared at the University of New Hampshire. This satellite had an apogee of 16 earth radii, which was initially on the 7:00 A.M. meridian, but as the earth proceeded along its solar orbit the satellite's orbit appeared to move back slowly into the tail of the magnetosphere. Since the magnetopause was detected only occasionally during the first month of the flight, it was probably beyond 16 earth radii for most of this time. In general the outer regions of the magnetosphere appeared to be more disturbed than they were on the sunlit side of the earth. Substantial fluctuations in both strength and direction were observed, but the average direction was close to that predicted by the Chapman-Ferraro model. After a month the magnetopause was no longer observed and the satellite was presumed to be inside the tail of the magnetosphere.

Late in 1963 another elliptical-orbit satellite was launched, this time with an apogee near 30 earth radii. This was the first of a series of Interplanetary Monitoring Platforms, designed to carry instruments beyond the magnetopause to investigate cosmic rays, plasma and the magnetic field in interplanetary space. The *IMP-1* magnetometer experiment, prepared by Norman F. Ness of the Goddard Space Flight Center, succeeded in obtaining the first unambiguous measurements of the strength and direction of the interplanetary magnetic field. The satellite also penetrated the magnetopause twice every four days. Again the magnetopause was found to be about 10 earth radii from the earth near the noon meridian, with this distance increasing to approximately 14 earth radii near the dawn meridian. The *IMP-1* apogee distance of 30 earth radii also allowed observations of the magnetopause well beyond the dawn meridian. Along the 5:00 A.M. meridian, for example, the magnetopause was observed on several occasions at about 16 earth radii from the earth.

The Structure of the Magnetopause

On the basis of all these measurements it is possible to state with some assurance that the magnetosphere extends to approximately 10 earth radii from the earth on the earth's sunlit side and stretches back at least 30 earth radii on the earth's dark side. In contrast the magnetopause itself appears to be less than 100 kilometers thick. Compared with the total size of the magnetosphere, the magnetopause can be visualized as having the relative thickness of the skin of an apple. Within this thin boundary layer the strength of the geomagnetic field drops abruptly and the direction of the field shifts by as much as 180 degrees. According to the Chapman-Ferraro model, a ribbon-like layer of electric current flows from west to east inside the magnetopause. When viewed in cross section, the lines of magnetic force form loops around this layer of current [*see illustration at left on page 64*]. At the center of the loops the magnetic field set up by the current layer drops to zero. This zero-field point is called an "O type" neutral point from the configuration of the surrounding magnetic-field lines. The existence of such a structure might be verified by observing the changes in the direction of the magnetic field as a satellite passes through the current layer. Bengt Sonnerup of the Royal Technological Institute in Stockholm, while visiting our laboratory recently, found evidence of the field-loop structure in the *Explorer XII* magnetopause data. In other cases, during magnetic disturbances on earth, he found field directions in the magnetopause opposite to those predicted by the Chapman-Ferraro model.

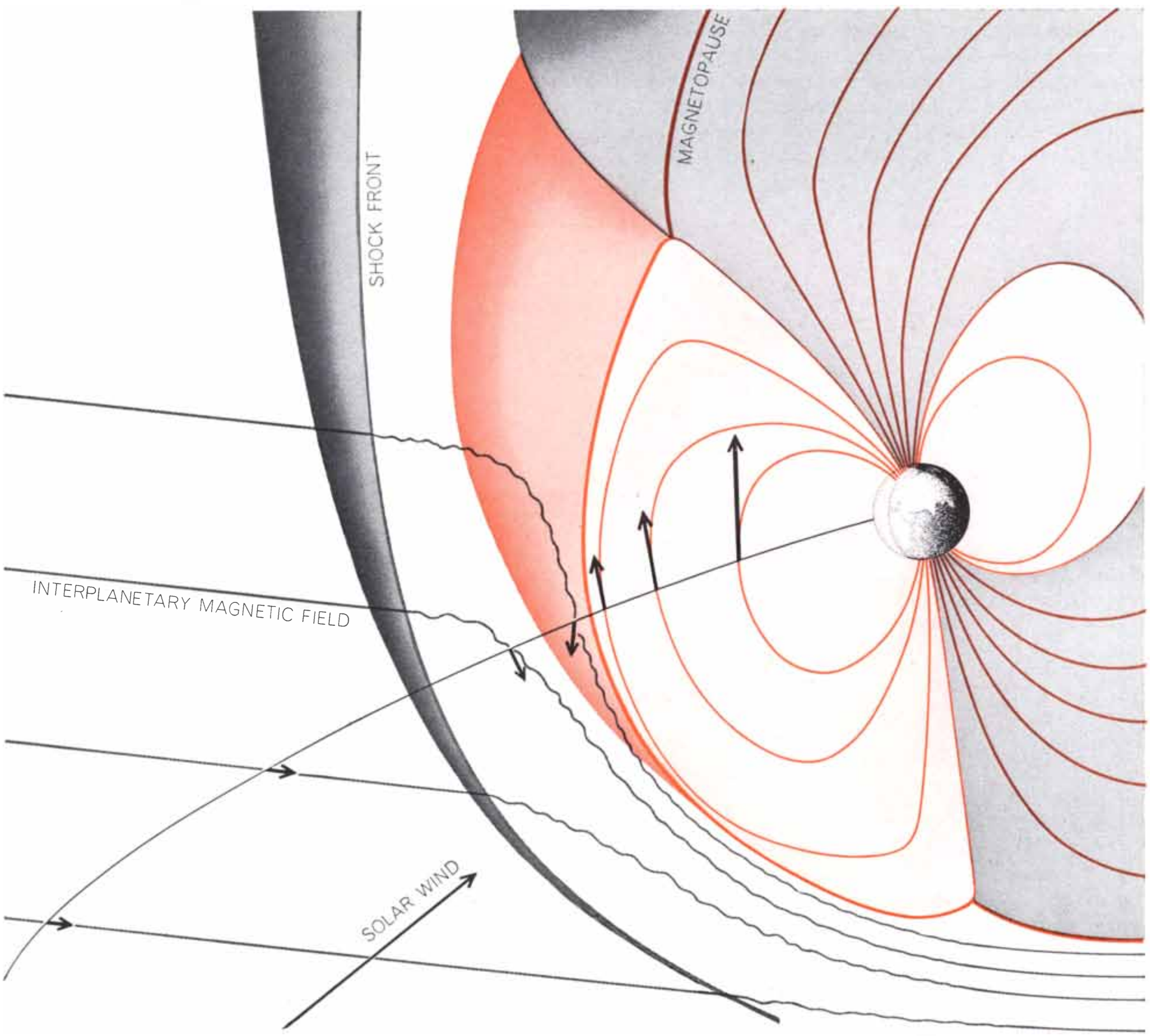
The Shock Front

In early studies of the magnetosphere it was assumed that the interplanetary magnetic field was negligible and that immediately outside the magnetopause the solar plasma would have no magnetic field associated with it. More recent studies of the solar wind and of cosmic rays from the sun, however, suggest that a spiral magnetic field, five to 10 gammas strong near the earth, extends from the sun. The measurements of *Explorer X* and *Explorer XII* demonstrated that beyond the magnetopause the magnetic field did not go to zero but fluctuated between 10 and 50 gammas. *Pioneer I* and *Pioneer V* also recorded an irregular, fluctuating field between 10 and 20 earth radii from the earth. In this "transition region" the weak interplanetary field is apparently compressed and distorted in some way as it is carried around the magnetosphere [*see illustration on opposite page*].

One explanation of this unexpected finding, offered independently by several theorists, is that a shock wave may form in the flow of solar plasma around the magnetosphere that is analogous to the shock wave formed in the supersonic flow of a compressible gas around a solid object. According to this analogy, a shock wave would form some four or five earth radii upwind of the leading edge of the magnetopause. In ordinary gas dynamics such a shock wave is not expected to form in flow around an obstacle unless the obstacle is large compared with the average distance traveled between collisions by gas molecules within the flow. When this condition is met, the molecules act collectively as a fluid and not as individual particles. The flow of solar plasma around the magnetosphere does *not* satisfy this condition, however; the "mean free path" traversed by a plasma proton before it collides with another proton is estimated to be roughly 100 million kilometers, whereas the diameter of the magnetosphere is on the order of 100,000 kilometers.

An alternative mechanism for the formation of a shock front in the solar plasma is provided by the interplanetary magnetic field. Protons in the solar plasma trace out circles with a radius of several hundred kilometers as they gyrate around the interplanetary lines of force. Under certain circumstances this distance can be considered to be analogous to the mean free path between collisions in an ordinary gas flow. Thus the interplanetary magnetic field can cause the plasma particles to act collectively as a fluid.

The field transition observed at 14 earth radii by *Pioneer I* and between 15 and 20 earth radii by *Pioneer V* was apparently the postulated shock front. *Explorer X* and *Explorer XII* did not travel far enough beyond the magnetopause to reach this second boundary. The *IMP-1* satellite, with an apogee of 30 earth radii, penetrated the shock front repeatedly, and on a series of passes late in 1963 and early in 1964 it mapped not only the magnetopause but also the second, shock-front boundary of the magnetosphere. The *IMP-1* results are in general agreement with the predicted changes in plasma flow and field properties at the shock front. The magnetic



INTERPLANETARY MAGNETIC FIELD is compressed and distorted as it is carried around the magnetosphere in the transition region between the magnetopause and the shock front. The plasma protons in the solar wind are bound in spirals around the interplanetary lines of force and therefore can act collectively as a fluid in this region. The trajectory of a typical satellite is shown penetrating the magnetopause and the shock front. Arrows along the trajectory indicate the direction and strength of the measured field.

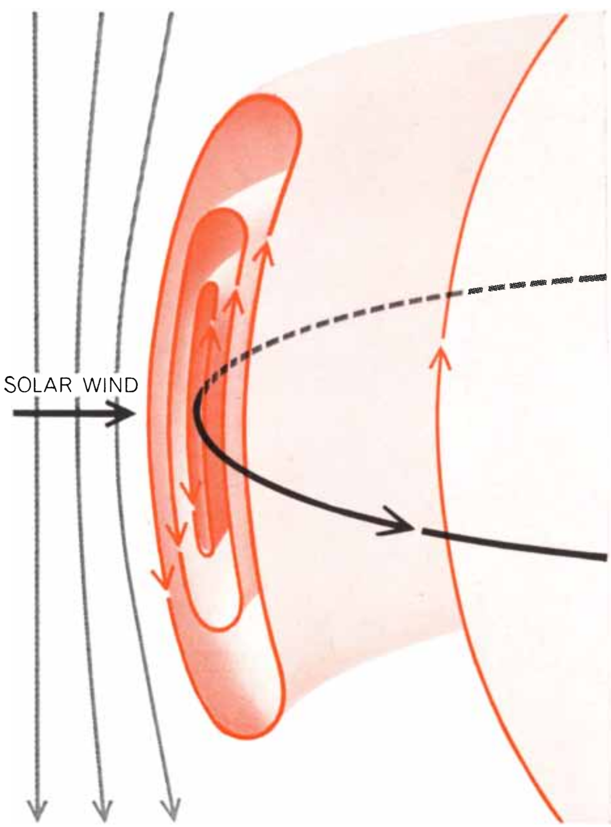
field between the magnetopause and the shock front was found to be stronger than it is in interplanetary space and the velocity of the solar plasma was found to be lower. The plasma no longer arrived only radially from the sun but entered the plasma detectors from all directions. In addition electrons with energies of several thousand electron volts were observed in the transition region, whereas solar-wind electrons rarely have energies higher than a few electron volts. This suggested that some of the original kinetic energy of the plasma protons is transferred to the electrons at the shock front.

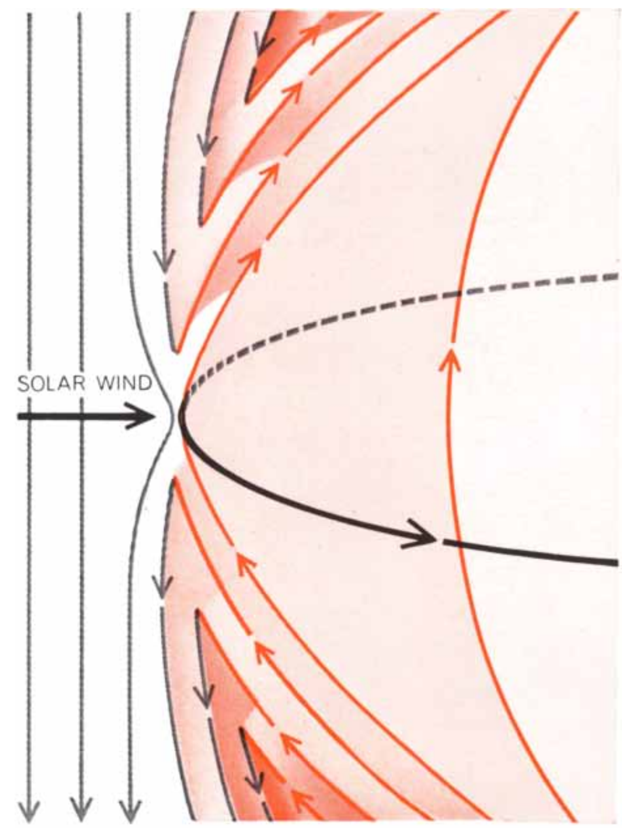
Inside the Magnetosphere

The satellite measurements have shown that the pressure of the solar wind distorts the lines of magnetic force inside as well as outside the magnetopause. Immediately inside the magnetopause, where the geomagnetic field is weakest, the distortion is large, but even close to the earth the fluctuations of the magnetopause have some effect on the geomagnetic field. When the magnetopause moves in and out rapidly, oscillations are set up in the outermost lines of force and consequently in the plasma particles bound to these lines. The oscillations travel inward through the plasma-filled magnetosphere as magnetohydrodynamic waves [see "Electricity in Space," by Hannes Alfvén; SCIENTIFIC AMERICAN, May, 1952]. Abrupt compressions or expansions of the entire magnetosphere had been assumed to be responsible for the worldwide fluctuations in surface field strength known as "sudden impulses" [*see middle illustration on opposite page*]. Recently Atsuhiro Nishida, working at our laboratory with data from *Explorer XII*, noted sudden impulses inside the magnetosphere between five and 10 earth radii from the earth and, a minute or two later, corresponding impulses in the ground records. This confirmed the notion that sudden impulses originate near the magnetopause. The delay time also yielded a crude estimate of the average propagation velocity of magnetohydrodynamic waves through the magnetosphere.

Periodic magnetic disturbances with periods from a fraction of a second to several minutes have also been recorded in ground-level magnetograms. These too are thought to originate in the outer magnetosphere. Two types of long-period magnetohydrodynamic waves have been observed at satellite altitudes. The simpler type is a compressional wave, much like a sound wave in air. The wave propagates across the field lines and consists of alternating zones of compressed and expanded lines of force; it is observed as a sinusoidal fluctuation in field strength with little or no fluctuation in direction. Compressional waves with amplitudes of five to 10 gammas have been observed by satellites, but it has not yet been possible to identify the same waves in the ground records.

A second type of long-period magnetohydrodynamic wave propagates in a direction parallel to the field lines. The





CLOSED MODEL of the magnetosphere is derived from the original Chapman-Ferraro model, in which a ribbon-like layer of electric current (*black curve*) is assumed to flow from west to east inside the magnetopause. When viewed in cross section, the lines of magnetic force form loops around this layer of current. At the center of the loops the magnetic field set up by the current layer drops to zero. This zero-field point is called an "O type" neutral point from the configuration of the surrounding lines of force.

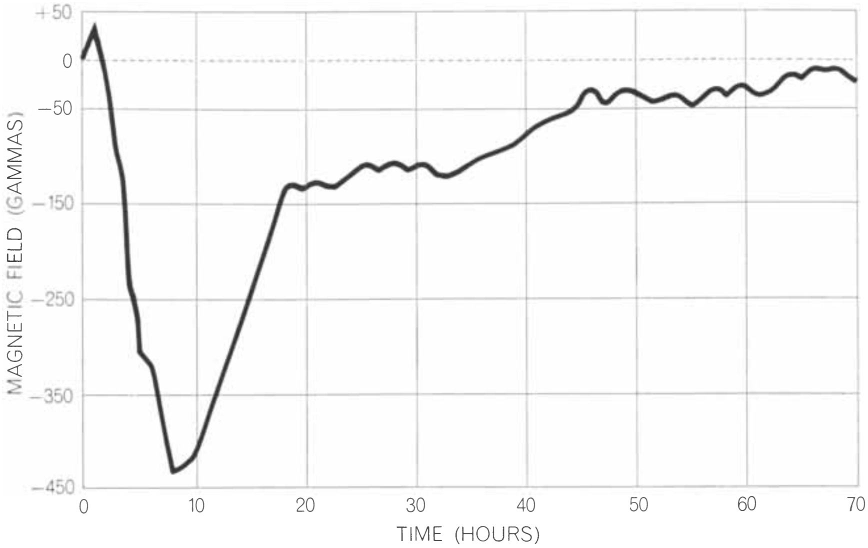
OPEN MODEL of the magnetosphere was first proposed by James W. Dungey of the Imperial College of Science and Technology in 1961. If the interplanetary magnetic field were parallel but opposite to the earth's field at the nose of the magnetosphere, the field lines approaching the earth from interplanetary space might connect with the outer lines of the magnetosphere at an "X type" neutral point in the magnetopause. In both illustrations on this page the interplanetary magnetic field is represented by gray arrows.

disturbance vector is perpendicular to the magnetic field and rotates around the lines of force as the wave progresses. Evidence of these transverse waves was first noted on the earth in the auroral zones. The waves have now been identified in the satellite measurements, first by Paul J. Coleman, Jr., of the University of California at Los Angeles, working with data from *Explorer VI*, and then more conclusively by V. L. Patel of our laboratory, working with the complete vector-field measurements obtained by *Explorer XII*. Both compressional and transverse waves were detected recently in the *Explorer XIV* data with periods ranging from 20 to 45 minutes and with amplitudes of 10 gammas. The immense size of the magnetosphere makes possible the generation and propagation of magnetohydrodynamic waves with extremely long periods and correspondingly long wavelengths. Satellite magnetometer experiments make it possible to study these unusual waves, which cannot be duplicated in the confines of a ground-level laboratory.

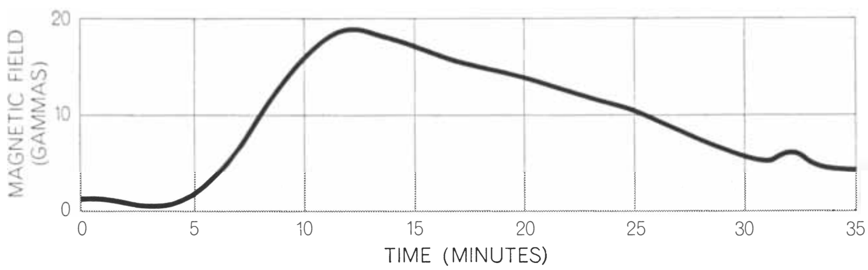
It is generally thought that magnetohydrodynamic waves in the magnetosphere have a considerable influence on the trapped particles there, possibly accelerating the particles from lower to higher energies and also decelerating the particles, or changing their trajectories in such a way that they are lost in the atmosphere. Particles trapped in the changing outer regions of the magnetosphere exhibit large fluctuations in population, particularly at times of magnetic disturbance.

The energy density of particles trapped in the lower Van Allen radiation belts also changes by significant amounts, sometimes quite rapidly. A complete evaluation of the relation between magnetohydrodynamic waves and particle acceleration requires observation of particles of all energies and waves of all frequencies. This has not yet been accomplished and remains one of the most interesting and fundamental problems of the magnetosphere.

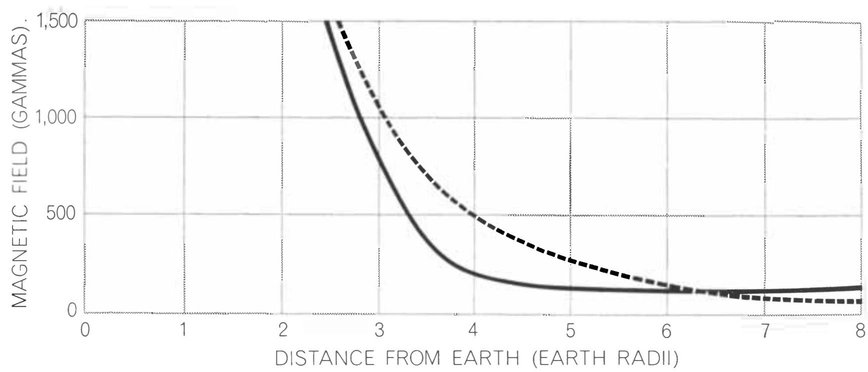
In their original model Chapman and Ferraro attempted to account for the weakening of the geomagnetic field during the main phase of a magnetic storm by an electric current of protons and electrons completely encircling the earth at a distance of several earth radii. This ring of current is now thought to be produced by the motions of the charged particles trapped in the earth's field. The main phase of a geomagnetic storm occurs when the number or energy of the trapped particles is increased. This



LARGE GEOMAGNETIC STORM, recorded at Honolulu on February 11, 1958, exhibited the four distinct phases characteristic of this type of disturbance. During the initial phase of the storm, which lasted for two hours, the strength of the magnetic field at the surface of the earth increased by about 50 gammas above the prestorm level. During the main phase the field strength dropped abruptly by more than 400 gammas. Rapid recovery phase was completed some 18 hours after storm began. Slower recovery phase lasted for several days.



POSITIVE "SUDDEN IMPULSE" is a lesser magnetic disturbance frequently observed at the surface of the earth. Similar impulses have been recorded at satellite altitudes, starting one or two minutes earlier than the corresponding ground impulse and having a slightly larger amplitude. Negative sudden impulses are also common. These fluctuations in the strength of the geomagnetic field are presumably caused by sudden compressions or expansions in the magnetosphere in response to increases or decreases in solar-wind pressure.



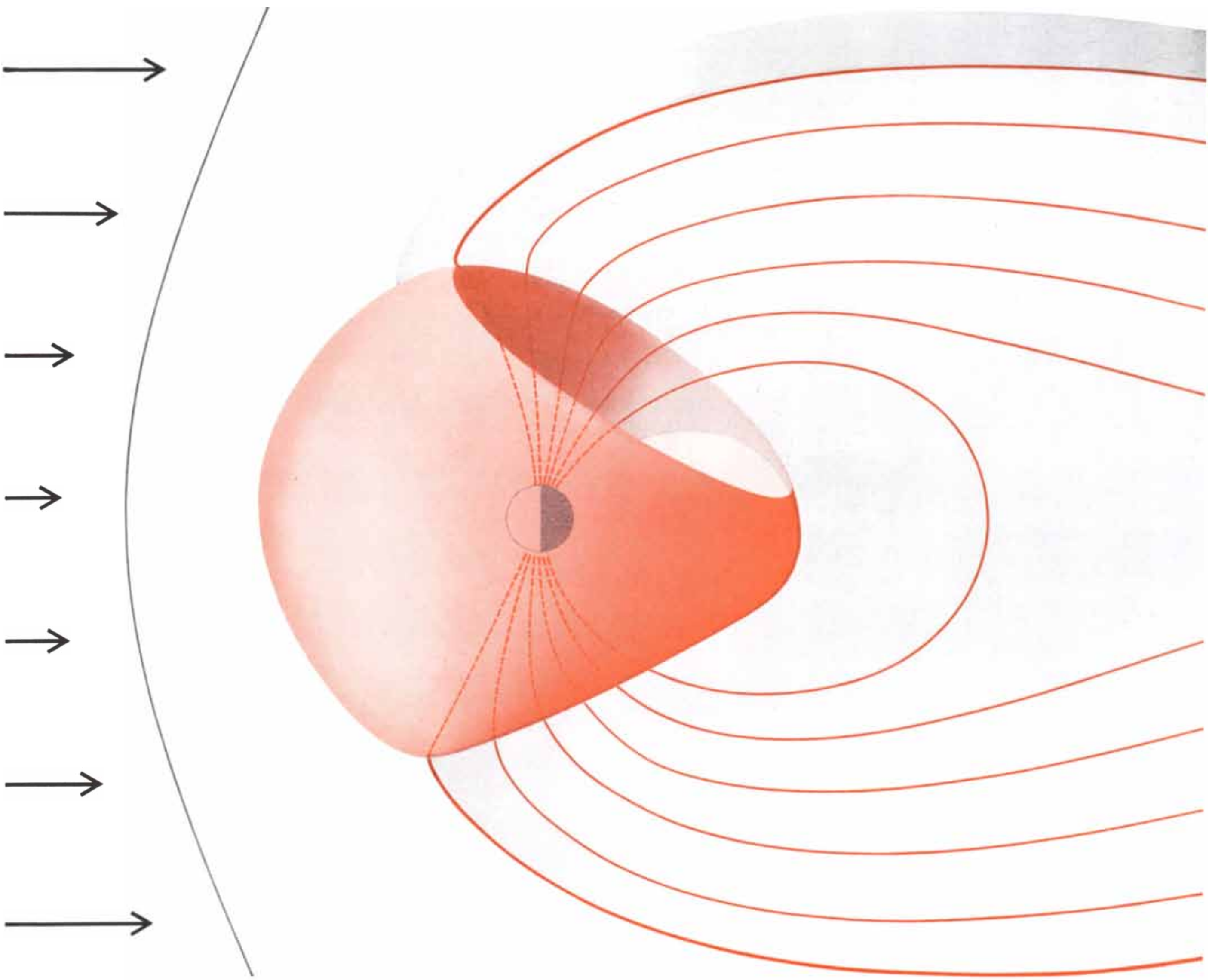
RING CURRENT encircling the earth at a distance of several earth radii is produced by the motions of the charged particles trapped in the earth's field. The main phase of a geomagnetic storm occurs when the number or energy of the trapped particles is increased. This produces a decrease in the strength of the magnetic field between the current and the earth and an increase in strength above the current. The strength of the prestorm field is shown by the broken line; the solid line shows the calculated effect of the ring-current field.

causes a decrease in the strength of the magnetic field between the current and the earth, but at altitudes above the current the field should increase in strength [*see bottom illustration on preceding page*].

Early measurements by Heppner, with the *Vanguard III* satellite, indicated that the current system responsible for the main-phase decrease in strength was beyond two earth radii. *Explorer VI* measurements by Edward Smith of the Space Technology Laboratories indicated that the current was beyond four earth radii on the dark side of the magnetosphere. Between six and eight earth radii, during several passes of the same satellite, a considerable decrease below the predicted field strength was observed, corresponding to the field changes expected near the center of a ring current. In the course of the *Explorer XII* observations from August to December, 1961, several magnetic storms occurred, and no weakening of the field was recorded between the magnetopause and four earth radii. At four earth radii the field was observed to increase in strength during the main phase of several storms at the same time that a decrease was observed on earth. This suggested strongly that the ring current was between two and four earth radii on the sunlit side of the magnetosphere.

So far no flux of particles intense enough to produce a main-phase decrease in the strength of the magnetic field recorded on the earth had been found in the magnetosphere. Then Leo Davis of the Goddard Space Flight Center detected a particularly intense flux of protons, with energies greater than 100,000 electron volts, in an experiment carried in *Explorer XII*. The protons detected by Davis and his colleagues were at a distance of between two and four earth radii. During a storm on September 30, 1961, Davis observed a threefold increase in the flux of protons above the prestorm level. This was accompanied by an increase in the magnetic-field strength at about four earth radii, which was noted in the *Explorer XII* magnetometer record. The particles detected by Davis are apparently still not intense enough to produce the observed main-phase decrease; there must be even larger numbers of particles with energies lower than those detected.

Explorer XIV provided measurements during a time of very low magnetic activity deep in the tail of the magneto-



THREE-DIMENSIONAL VIEW of the magnetosphere shows the doughnut-shaped inner magnetosphere (*color*), which contains the stable, low-energy trapped particles and can be considered as being defined by them. Lines of force originating in the north and south polar caps thread the hole of the doughnut and remain inside the tail of the magnetosphere. In most recent models the tail extends

sphere. The orbit in January, 1963, was near the 1:00 A.M. meridian, on the opposite side of the tail from *Explorer VI*, which had been launched some years earlier. On several occasions a weakening of the field below the predicted strength was observed between five and eight earth radii. The weaker readings were obtained only when the satellite passed very close to the geomagnetic equatorial plane. An intense flux of low-energy electrons was also seen in this region by Louis A. Frank of the State University of Iowa in another experiment on the same satellite. Since the magnetic activity was so low (there had been no significant magnetic storm for several weeks prior to these measurements), it appeared that the flux of low-energy particles and the weak region near the geomagnetic equator are permanent features of the tail of the magnetosphere.

to great distances on dark side of the earth or is not closed at all. Magnetosphere is shown during fall in Northern Hemisphere.

Syun-Ichi Akasofu of the University of Alaska has suggested that certain features of the main phase of large magnetic storms require two regions of electric current above the earth. The first part of the main phase consists of the greatest weakening of the field and a fairly rapid recovery from the minimum value. After the rapid recovery the strength of the field continues to increase, but at a slower rate; it often takes several days to regain its prestorm level. Perhaps two currents are involved, one of which decays rapidly, the other over a longer period. The weakening of the field observed between five and eight earth radii by *Explorer XIV* may be due to a more or less permanent current caused by a large population of low-energy electrons. At times of magnetic storms the particle population may increase and the field become still weaker. The persistence of this region of particles, even at a time of comparatively low magnetic activity, suggests that the current due to these particles may be partially responsible for the slowly decaying recovery phase of large magnetic storms.

Another unexplained phenomenon of the magnetosphere closely related to magnetic storms is the aurora. Auroras are observed most frequently in two circular zones around the north and south magnetic poles. The northern auroral zone passes through Alaska and south of Hudson Bay. Auroral displays are enhanced at times of high solar activity and consequent magnetic disturbance on earth. At these times the auroral zones appear to move southward; auroras are sometimes seen as far south as Florida.

It has been assumed that auroral displays result from the excitation of atmospheric molecules above 100 kilometers by charged particles precipitated from the trapped-particle belts. In 1957 Carl McIlwain, then at the State University of Iowa, detected some protons, but principally electrons, with rocket-borne instruments launched through a visible auroral arc. Brian J. O'Brien, using the Iowa laboratory's *Injun* satellites that had been launched in low-altitude polar orbits, observed particles descending to auroral altitudes at times of auroral displays. In the outer regions of the magnetosphere particle fluxes vary widely from day to day, and the magnetopause is observed to move back and forth with great rapidity.

It seems plausible, then, that the auroral radiation is somehow related to these less stable outer regions of the magnetosphere. Unfortunately the observed particle populations of the outer regions would be depleted in a few minutes to provide the flux necessary to sustain the aurora. The incoming solar plasma provides a much higher density of particles—if these particles can somehow penetrate the magnetopause. The energy of the electrons in the solar wind, only a few electron volts, is much lower than that of the auroral electrons.

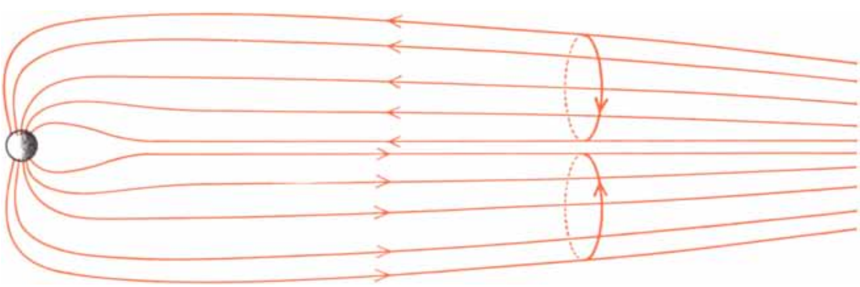
Electrons with energies of several thousand electron volts were found in the transition region by John Freeman at Iowa with *Explorer XII* data, and more recently in experiments on the *IMP-1* satellite. Particles of the requisite energy appear to be present just outside the magnetopause. The neutral points on the front side of the magnetosphere might provide entry to the auroral zone for these electrons, since the computed neutral-point field lines reach the earth near, but somewhat above, the auroral zones on the noon meridian. The auroral displays on the dark side of the earth are not explained, however, by entry of auroral-energy electrons on the sunlit side. In a closed, teardrop-shaped magnetosphere the field lines from the nighttime auroral zone are buried deep within the tail of the magnetosphere.

Some Recent Models

Models of the magnetosphere must account for the considerable body of experimental data that is rapidly accumulating. The sunlit side of the magnetosphere, near the Equator, is well defined by experiment. The stretched-out field lines in the tail have been observed by *Explorer X*, *Explorer XIV* and *IMP-1*. The *Explorer XIV* and *IMP-1* measurements indicate that the tail of the magnetosphere is controlled by the solar wind and is symmetrical, not about the geomagnetic equatorial plane but more nearly about the continuation of the earth-sun line behind the earth. *Explorer X* and *IMP-1* results suggest that the tail of the magnetosphere flares out and extends to 40 earth radii or beyond. In spite of all these measurements the polar region and the distant tail remain comparatively unexplored, and it is here the various models differ. Complete models must explain two vital problems of the magnetosphere: auroras and magnetic storms.

The simplest model, mentioned earlier in this article, predicts a teardrop-shaped magnetosphere with a fairly short tail closed by the thermal pressure

CONVECTION OF PLASMA within the magnetosphere is represented in this "closed tail" model. Plasma moves to the rear along the surface of the magnetosphere tail and returns up the center of the tail, pulling the polar-field lines with it. The ends of the field lines, which connect to the earth's auroral zones, set up ionospheric electric currents in polar regions. Motion of plasma is indicated by colored arrows in tail; colored arrow on earth shows corresponding movement of ends of polar-field lines. Black arrow shows rotation of earth.



"DOUBLE-BARRELED" TAIL is formed at great distances from the earth in this model proposed recently by Alexander J. Dessler of Rice Institute. A polar-field line originating just above neutral-point line in each hemisphere forms boundary of a separate tube of field lines in the tail as earth rotates. Lines from north polar region point toward earth; south-pole lines point away. Thus solar-wind plasma has direct access to entire auroral zones.

of the solar plasma. The geomagnetic field is completely enclosed by the magnetopause and solar plasma is completely excluded. The magnetic-field lines from the polar regions always remain on the dark side of the earth. A line of force extending from the northern neutral point in the plane of the geomagnetic polar axis and the earth-sun line passes over the surface of the magnetosphere tail in the midnight meridian and returns to the neutral point in the Southern Hemisphere. In 12 hours this same line follows a much shorter path well within the interior of the magnetosphere tail. All lines originating at higher latitudes in the polar cap remain within the magnetosphere tail and never reach the magnetopause. The lines that originate at latitudes below the neutral point rotate with the earth and trace out the doughnut-shaped inner magnetosphere, fatter in the front of the earth than in the rear [*see illustration on preceding two pages*]. The inner magnetosphere contains the stable, trapped particles and can be considered to be defined by them. Polar lines thread the hole of the doughnut. Most recent models agree with this simple scheme on the sunlit side of the magnetosphere and in the inner, toroidal portion. They differ in the shape of the tail or the distance to which it extends.

An alternative to the closed magnetosphere model was first described by James W. Dungey of the Imperial College of Science and Technology in London in 1961. He suggested that under certain conditions the interplanetary magnetic field may join the earth's field. This could occur, according to Dungey, if the interplanetary field is parallel but opposite to the earth's field at the nose of the magnetosphere. In this case field lines approaching the earth from interplanetary space might connect with the outer lines of the magnetosphere at an "X type" neutral point in the magnetopause [*see illustration at right on page 64*]. Once connected, the outer field lines of the magnetosphere, with the magnetosphere plasma anchored to them, would be pulled to the rear by the advancing solar plasma. This model was introduced to explain several puzzling phenomena observed in the polar regions even during magnetically quiet conditions. The geomagnetic field in the polar regions is often disturbed, and a special system of ionospheric electric currents has been postulated to account for the behavior of these polar disturbances. Electric currents flow from east to west along the auroral zone in the dawn hemisphere and from west to east in the dusk hemisphere; the return flow is across the polar cap. In Dungey's model the polar-field lines carry plasma rearward within the magnetosphere. Plasma returns to the front of the magnetosphere with field lines that connect to the auroral zones. Motion of the plasma extends with the field lines down to ionospheric levels and establishes the polar ionospheric currents.

A model put forward by W. Ian Axford and Colin O. Hines of the University of Chicago describes the same sort of plasma flow through the magnetosphere but attributes it to viscous interactions of the exterior plasma flowing past the boundary and the plasma within the magnetosphere. In both of these models plasma returns toward the earth along the center of the tail.

Alexander J. Dessler of Rice Institute has recently proposed a model that includes division of the tail at great distances into two separate tubes of magnetic-field lines [*see bottom illustration at left*]. Lines from the north pole point toward the earth, and the south-pole lines point away. The field lines from the auroral zones form the boundary of these tubes, and thus the solar-wind plasma has direct access to the entire auroral zones. Solar-wind electrons accelerated in the transition region to auroral energies are free to spiral along these boundary lines to the earth's upper atmosphere. As with most of the recent models some of these features are speculative, whereas others are based more firmly on experimental evidence. Further analysis of the existing satellite records, together with the launching of new experiments, should fill some of the gaps and narrow the range of possible models. Meanwhile the magnetosphere continues to provide a unique laboratory for the study of large-scale interactions of charged particles and magnetic fields.

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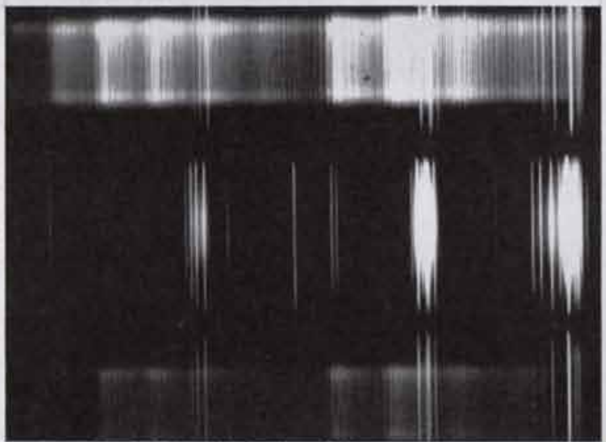
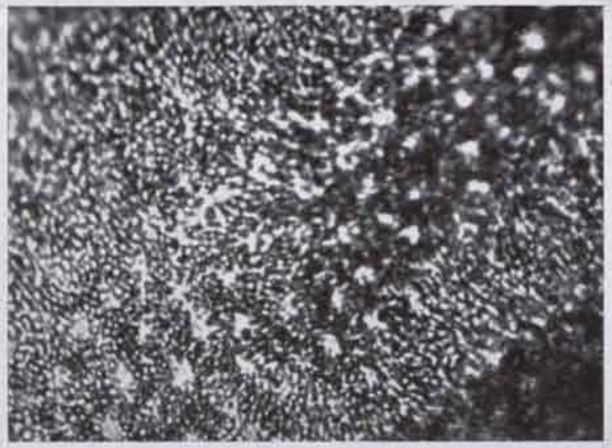


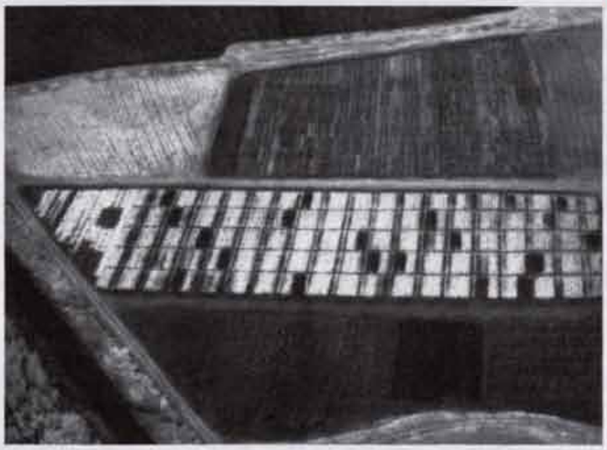
Picture made by Dr. T. Wentink, Jr., Avco/RAD.

A

B



C



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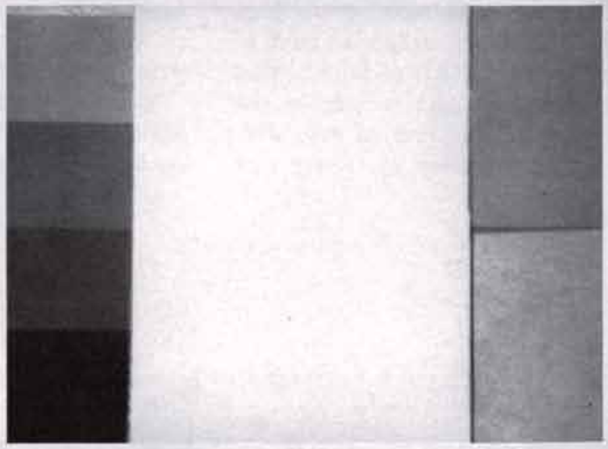

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Also, if your picture requires special or elaborate equipment, Type 413 film saves you the risk of having to set it up twice. **Picture B,** for example, a microspectrograph of the cones of the retina, required the use of infrared lighting because visible light causes bleaching of the pigments. The scientist who took it saw his results immediately and knew he had a perfect picture while his set-up was still intact.

While on-the-spot recording is the most important advantage of this remarkable new film, it isn't the only one. Type 413 film is also three times as sensitive as conventional infrared films. Its A.S.A. equivalent speed is 800 without filters. Since this permits faster shutter speeds and smaller lens apertures, the film is ideal for applications like aerial photography. In **Picture C** — an aerial shot of a potato field used for plant pathology testing—you can see how clearly the film was able to record the fungus-infected areas (dark rectangles) using an extremely fast exposure setting. Shot was made at f/32 and 1/300th of a second.

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Because of these advantages Type 413 film will have wide use in almost every field of industrial and scientific photography. In laser research, spectrographic analysis, specialized industrial photography where heat is a factor, plant pathology, general medical research—wherever there is a need to investigate the infrared.

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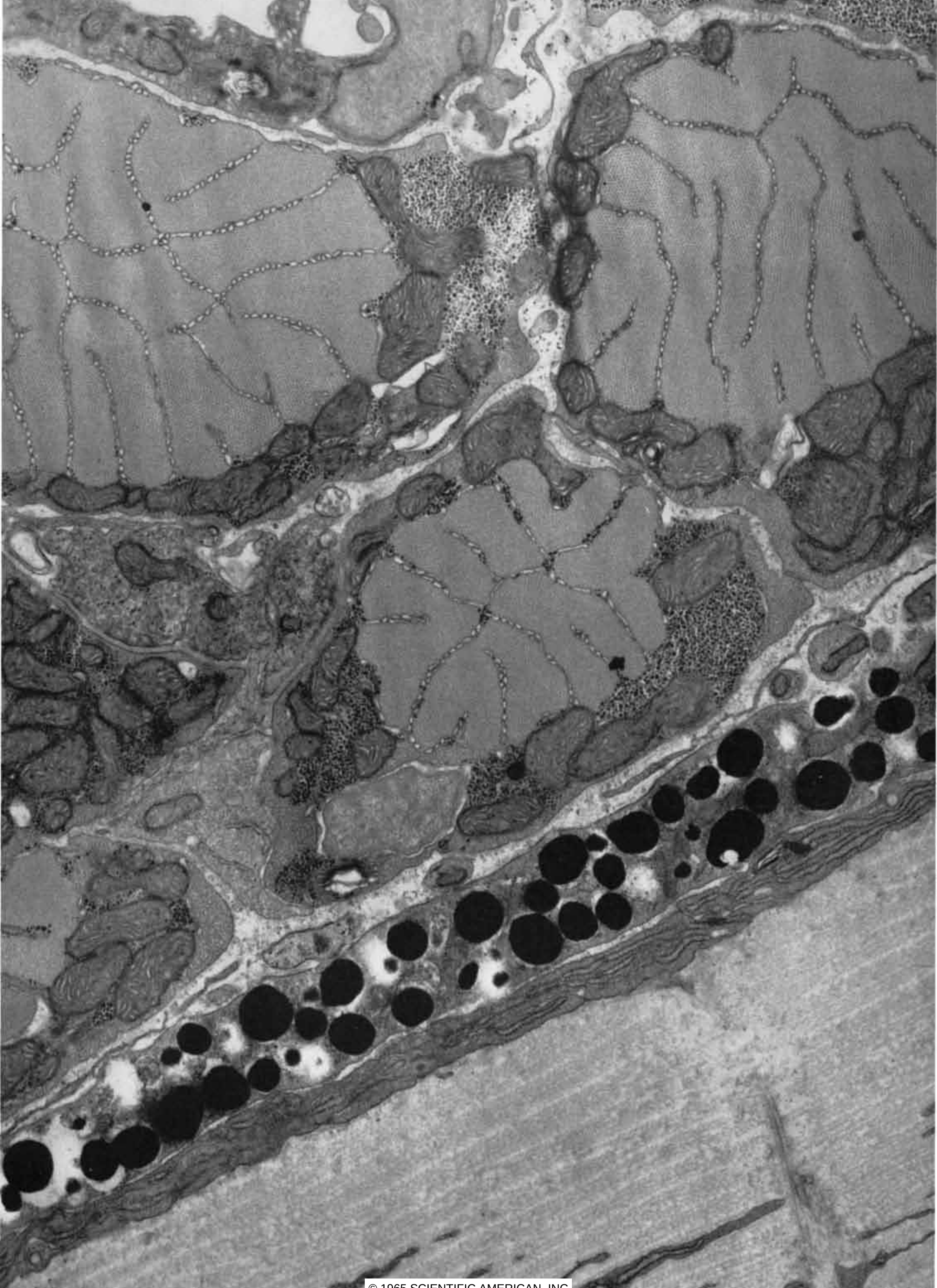


THE SARCOPLASMIC RETICULUM

High-resolution electron micrographs reveal that this complex network of tubules and sacs inside the striated muscle fiber performs the functions of rapid telegraphy, plumbing and supply

by Keith R. Porter and Clara Franzini-Armstrong

The structure of a muscle fiber, like the structure of a flower, tells a revealing story. Its form and the organs that compose it offer important clues to how muscle functions. In recent years examination of the fine structure of the striated muscle fiber, made possible by the electron microscope, has shed new light on the mystery that physiologists and biochemists have been investigating for nearly a century: the question of how the muscle cell translates chemical energy into the mechanical work of contraction. Most of the studies have focused on the contraction process itself [see "The Contraction of Muscle," by H. E. Huxley, SCIENTIFIC AMERICAN, November, 1958, and "How Cells Move," by Teru Hayashi, SCIENTIFIC AMERICAN, September, 1961]. This article is concerned with an equally intriguing part of the question: communications within the muscle cell.

The process of contraction is complex and calls for the coordinated action of many elements in the cell. How does the cell manage to direct the performance of all these elements so that they work together? Messages must be transmitted to all of them simultaneously, and metabolic materials must be delivered to many different points at just the right time. New studies with the electron microscope have now identified the system that evidently performs these services in the striated muscle cell. It is a network of extremely fine channels known as the sarcoplasmic reticulum.

We must begin by examining the general anatomy of the striated muscle cell. (This kind of muscle fiber, characteristic of skeletal muscles, has received much more study than those of the "smooth" muscles because it shows its structure and action more clearly.) The striated fiber gets its name from crosswise bands that show up plainly under the microscope [*see illustration on page 76*]. Each fiber is a long cell enclosed in a sheath called the sarcolemma. It is made up of a large number of ribbon-like filaments, called myofibrils, that are packed closely together in the cell. A series of broad crosswise bands marks each fibril. These are alternately dark and light. The dark band is called the *A* band (for anisotropic) and it is interrupted in its midsection by a narrow, less dense stripe called the *H* band; the light band, called *I* (for isotropic), is similarly divided across its middle by a dark stripe called the *Z* line. The individual myofibrils vary somewhat in diameter and cross-sectional shape, but the striations of all of them are in register, so that the bands run across the whole fiber.

The myofibril is the functional unit of muscle action: the contraction of a muscle fiber is produced by the collective and coordinated shortening of the many myofibrils composing it. This at once indicates a problem of communication, which is made more difficult by the fact that all the fibrils must be excited simultaneously. The electrical stimulus, or "action potential," that triggers a fiber to contract travels along the outside surface of the membrane sheathing the fiber. The distance from the outside to the center of the fiber is of the order of 50 microns (50 thousandths of a millimeter). This means that if the whole group of fibrils is to shorten simultaneously, there must be some sort of telegraphic system that conveys the message rapidly to the inner fibrils. What is more, the myofibrils not only need to get the message; they must also receive energy-supplying substances—adenosine triphosphate (ATP) and creatine phosphate—during the relaxation phase of the contraction-relaxation cycle and get rid of waste products. Thus they prepare for the next contraction, which may follow in a small fraction of a second. All of this implies the existence of a system capable of performing the functions of rapid telegraphy, plumbing and supply. Where in the muscle cell, densely packed with myofibrils, is there room for such a distribution system?

It is now known to reside in the narrow spaces between the myofibrils, which are filled with the cytoplasmic fluid of the muscle cell called the sarcoplasm. Many years ago light microscopists noticed that in muscle stained with silver fine strands seemed to run through the sarcoplasm in a delicate network. What purpose this system might serve was far from obvious, and its discovery was dismissed as unimportant until a few years ago, when it

TRANSVERSE SECTION through the tail of a black mollie, a small aquarium fish, shows several muscle fibers (*large gray circular areas*). The fibers are divided into rectangular segments, called myofibrils, which are arranged more or less radially in the fibers. The chainlike strings of small white circles that divide the myofibrils from each other are tubules of the sarcoplasmic reticulum. Darker gray objects around fibers are mitochondria. Tiny black dots mixed in with mitochondria are particles of glycogen. Between the muscle fibers and the skin of the tail (*bottom right*) is a layer of pigment (*large black spots*) that gives the fish its characteristic color and its name. The enlargement is approximately 22,000 diameters. All the electron micrographs in this article were made by the authors.

was reexamined with the electron microscope. It then became plain that the fine strands of the light image were tubules and sacs associated to make up a highly organized network connected in a precise fashion to the pattern of bands composing the myofibrils.

This network—the sarcoplasmic reticulum—varies considerably in details and complexity in various muscles and species of animals, but it has general features common to all of them. The tubules run parallel to the myofibrils in the spaces between them and also transversely around the fibrils. At certain places some of the tubules fuse and form a sac that girdles each fibril and also winds its way among the fibrils so that it provides a transverse channel across the whole fiber. These transverse channels occur at the level of the *H* band and also at the level of the Z line of each myofibril segment, or sarcomere [*see illustration on opposite page*].

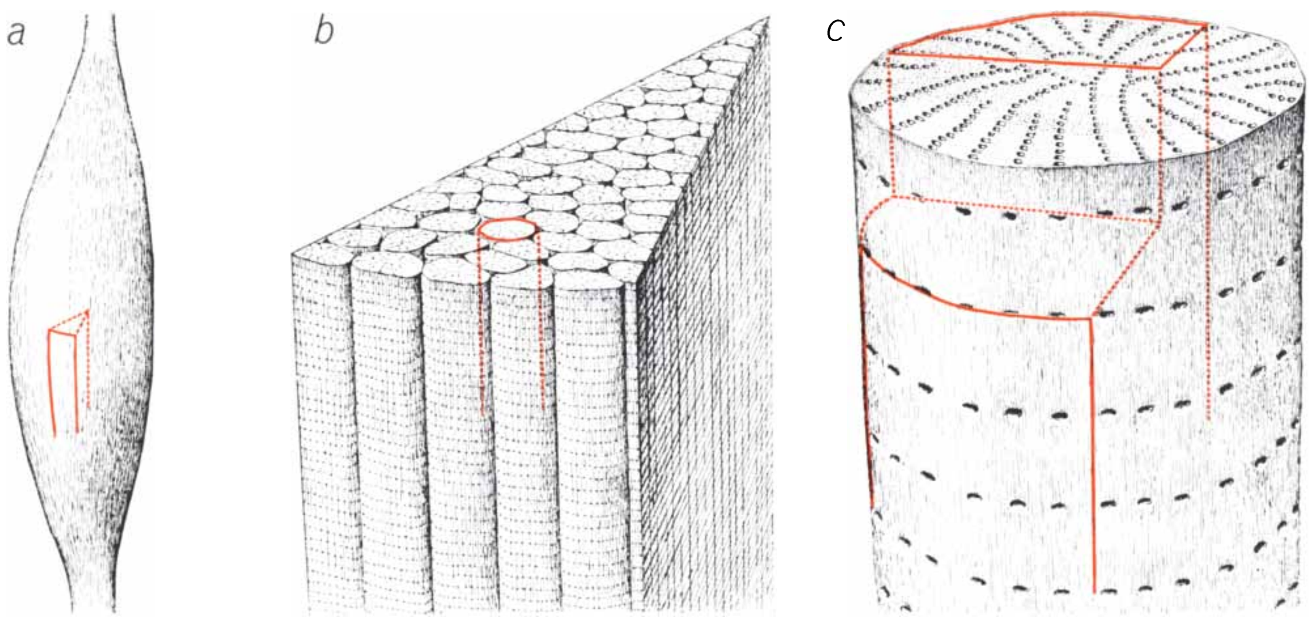
When this continuous system of tubules and sacs was discovered, it immediately suggested to investigators several interesting ideas. The tubes might provide just the kind of plumbing needed to distribute to the myofibrils the energy-rich substances required for contraction. The thin membranes limiting the tubules, in conjunction with enzymes that are active on such surfaces, could take in selected substances from the surrounding sarcoplasm to pass on the products of metabolism to the fibrils. Moreover, the membranes might transmit electrical signals along their surfaces and thus convey the action potential from the outside of the fiber to the inner myofibrils.

In short, the system seemed ideally suited for the communication and distribution functions required by a muscle cell. It remained to be demonstrated, however, that the network actually performed these functions. An encouraging step toward confirmation was soon forthcoming. A. F. Huxley and his coworkers at the University of Cambridge, testing the stimulation of muscle fibers by means of tiny electrodes, found that they could excite the fibrils to contract only when they applied the electrode at the fibrils' Z line, that is, exactly where certain transversely oriented structures of the sarcoplasmic reticulum are located.

This discovery stimulated a closer examination of these structures. Each of them contains three elements that together have been named the "triad" [*see top illustration on page* 77]. Two of the elements are vesicles, or sacs, belonging to the sarcoplasmic reticulum. The third is a smaller tubule between them. Curiously the tubule has no visible connection with the sarcoplasmic reticulum vessels next to it and seems to belong to a separate system that runs across the muscle fiber, linking up the myofibrils at the Z-line level. It has been given the name *T* system (for transverse).

The identification of the *T* system as an apparently independent network suggested that it, rather than the sarcoplasmic reticulum, was the telegraphic channel that transmitted electrical messages from the outer membrane of the muscle fiber to the inner fibrils. The difficulty with this hypothesis was that no clear connection could be found between the fiber membrane, or sarcolemma, and the *T* system. In virtually all the pictures of skeletal muscle fibers that had been made by the standard techniques the internal *T* channels seemed to be definitely separated from the outer fiber membrane.

Was it possible that connections actually existed but had somehow been obscured by the conditions of the experiments? In our laboratory at Harvard University we considered various ways to improve the chances of detecting the connections if they existed. For one thing, it seemed that they might be more likely to show up in constantly active muscles than in relatively inactive ones. Furthermore, it was possible that the connections were destroyed by osmium tetroxide, the agent customarily used to fix the muscle preparations for viewing in the electron microscope; perhaps a change to another fixative would preserve them more successfully. With these possibilities in mind, we chose for new experiments the segmental muscles of fishes, which are more or less constantly active,



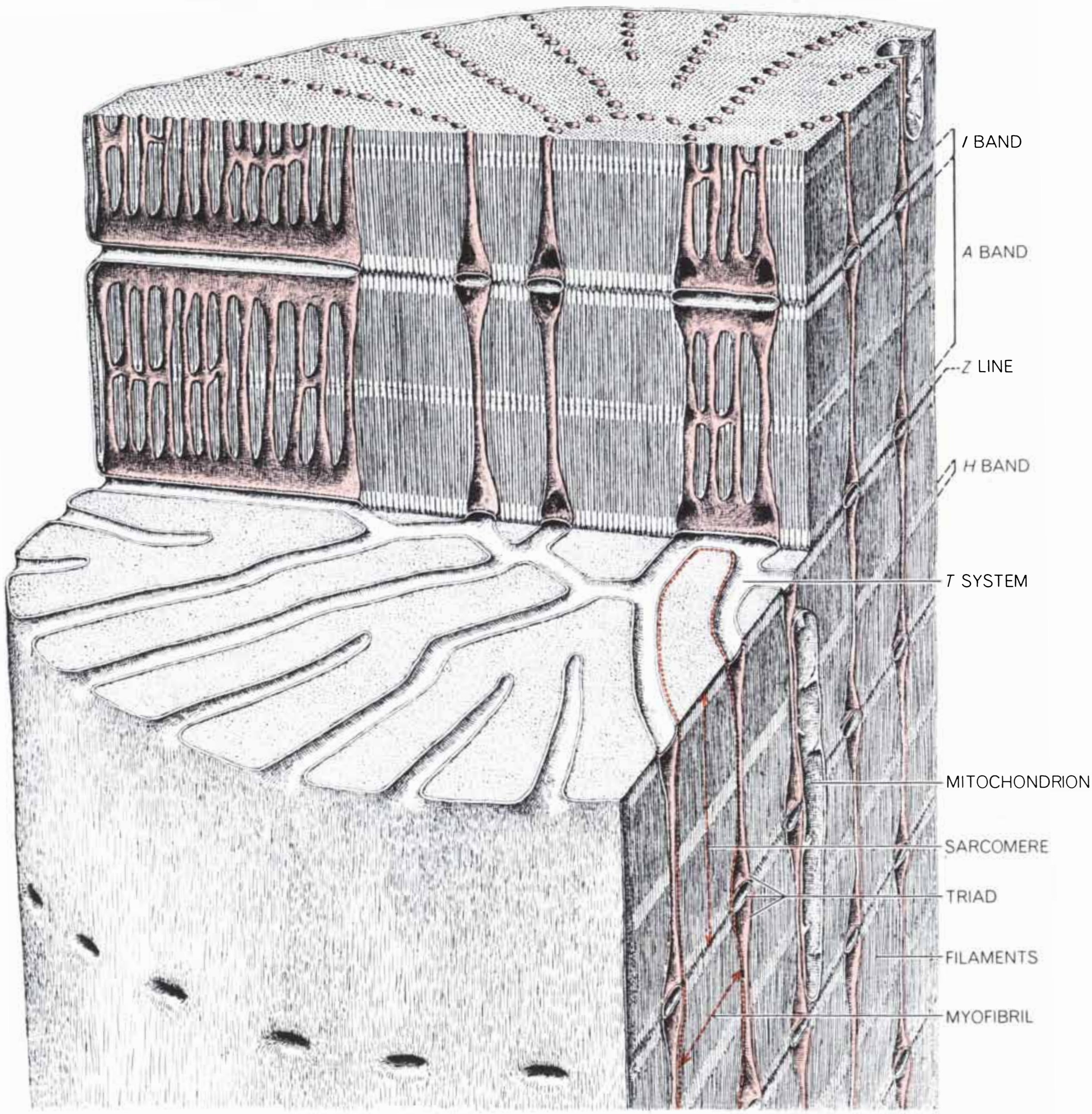
STRUCTURE of a typical striated muscle is depicted in the series of drawings on these two pages. A muscle (*a*) is made up of many individual muscle fibers (*b*), one of which is shown in *c*. The muscle fiber shown greatly enlarged in *d* is cut in several sections. The transverse section at the top is the same as that in the micrograph on page 72. The transverse section in the middle contains

and switched to glutaraldehyde instead of osmium tetroxide.

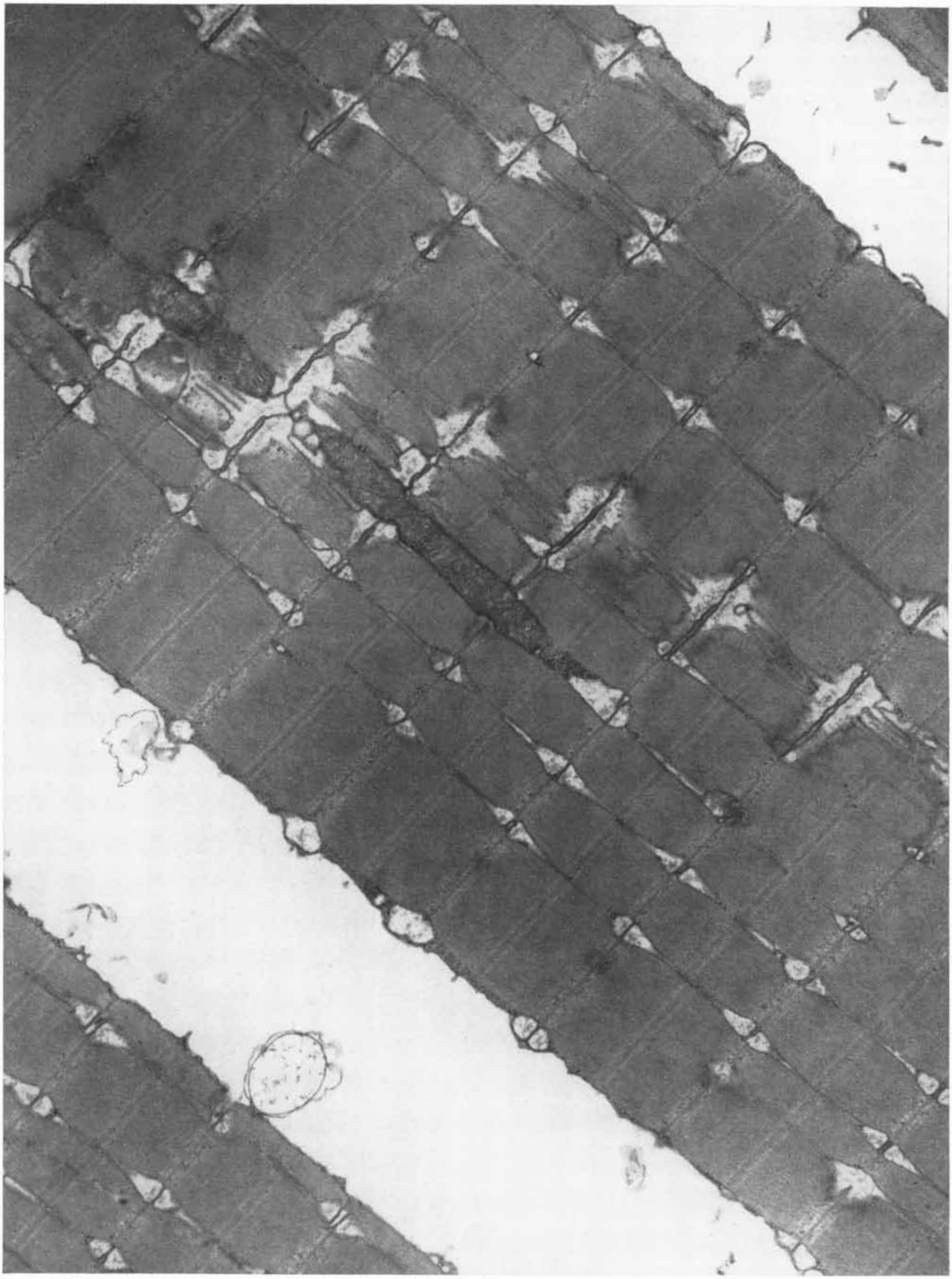
To our delight the new experimental conditions, particularly the use of glutaraldehyde, did indeed produce a different picture. The *T* channels, preserved intact, now showed themselves to be not only connected to the fiber sheath but also actually part of the membrane itself, infolded deep into the interior of the fiber at each Z line or, in some muscles, at each junction between *A* and *I* bands [*see bottom illustration on page* 77]. As inward extensions of the sarcolemma the *T* channels could, of course, conduct electrical messages into the cell's interior. Moreover, they would serve as inlets through which the fluid outside the cell, bearing various ions and other substances, could flow in among the myofibrils and come into close contact with them.

We must now ask: What relation does the *T* system have to the sarcoplasmic reticulum? Is there a continuity between the two systems or are they simply in contact? A closer look at the triads, where the sacs of the sarcoplasmic reticulum and the *T* system lie very near each other, showed that the thin spaces between them are marked at certain points by unusually dense concentrations of material that may well

d



the *T* system (for transverse), an independent network of tubules that transmits electrical messages, called "action potentials," from the sarcolemma, or outer membrane, of the muscle fiber to the inner fibrils. Other components of the fiber are indicated in the longitudinal section at right, which is identical with that in the micrograph on the next page. The sarcoplasmic reticulum is in color.



LONGITUDINAL SECTION of a striated muscle fiber from a black mollie is enlarged about 20,000 diameters in this electron micrograph. The great regularity of the elements that make up the sarcoplasmic reticulum in the skeletal muscle fibers of most vertebrate animals is evident. The long, cigar-shaped objects at center are mitochondria, which do not abound in this type of fiber.

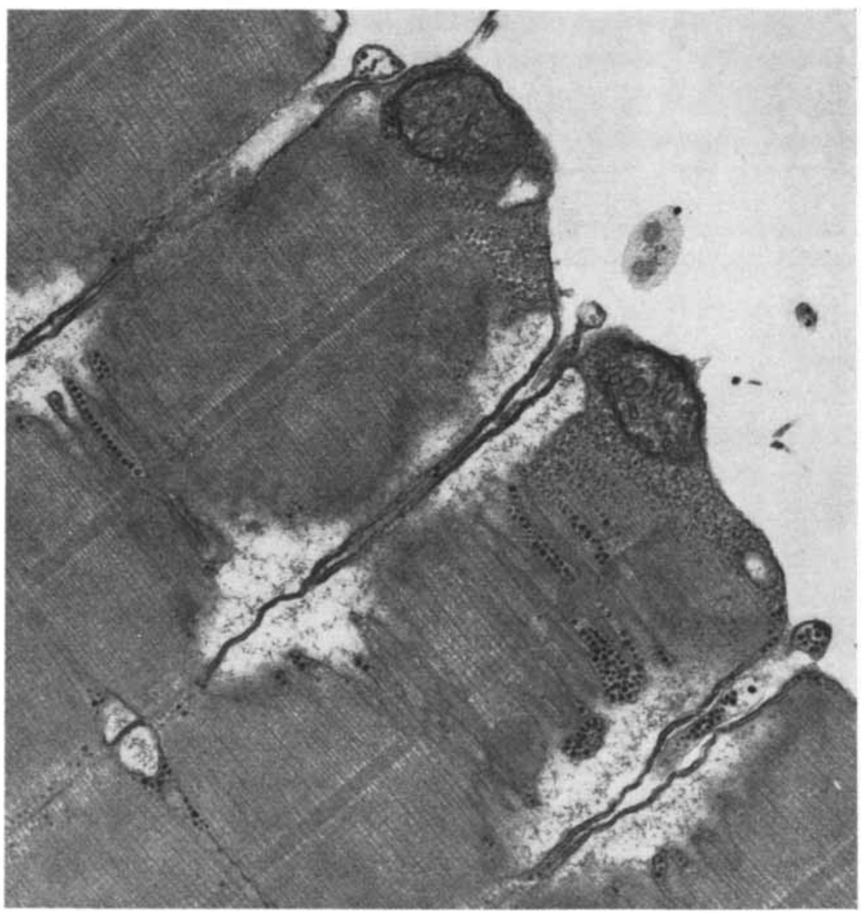
serve as bridges. Between the channels of the sarcoplasmic reticulum and the *T* system, however, there is no open continuity. The close association of the two systems in the triad structure is particularly extensive in muscles that can contract and relax very rapidly; in these muscles the triads are opposite the junctions of the *A* bands and *I* bands and so are twice as extensive as they are in slower muscles. This fact and other evidence suggest that the sarcoplasmic reticulum and the *T* system work together in triggering the contraction of myofibrils and thereafter assuring their prompt relaxation. It appears that the electrical excitation, arriving by way of the *T* system, may trigger a sudden release of calcium ions within the cell at the *Z* line of each myofibril segment, and that this in turn leads to the contraction of the segment. With equal rapidity the sarcoplasmic reticulum acts to pull calcium ions out of the myofibrils, thus inducing their relaxation.

We have discussed so far just one of the clues to the specific functions of the sarcoplasmic reticulum, namely its association with the triadic structure that is involved in triggering muscle contraction and controlling relaxation. Let us go on to other structural clues, providing further information on the roles of the sarcoplasmic reticulum.

There can be little doubt that the sarcoplasmic reticulum serves as a system for the distribution in the muscle cell of enzymes and other substances required for metabolism. Although it has its own unique features, the sarcoplasmic reticulum is similar to a system called the endoplasmic reticulum, which performs these functions in many other kinds of cell. A detailed examination of striated muscle cells not only confirms this role of the sarcoplasmic reticulum in a general way but also indicates some of the specific chemical activities in which it is involved. Definite clues to the sarcoplasmic reticulum's plumbing and supply functions emerge when one compares the structures of the various kinds of striated muscle cell.

The striated muscles can be divided into three categories according to the nature of their activity. One type, of which heart muscle is an outstanding example, works slowly but constantly. It requires a steady supply of oxygen. In contrast to this is the kind of muscle, typified by the skeletal muscles, that contracts and relaxes much more rapidly but must pause at frequent intervals to "catch its breath," that is, restore its energy and eliminate toxic

EARLY MICROGRAPH of a longitudinal section of muscle fiber reveals vessels running from the sarcolemma (*outer sheath*) to the *T* system in the middle of the triad (*sandwich-shaped structure within the fiber*). Resemblance of *T* system to the vessels suggested that they were connected in a continuous tubule but were disrupted when fixed for viewing.

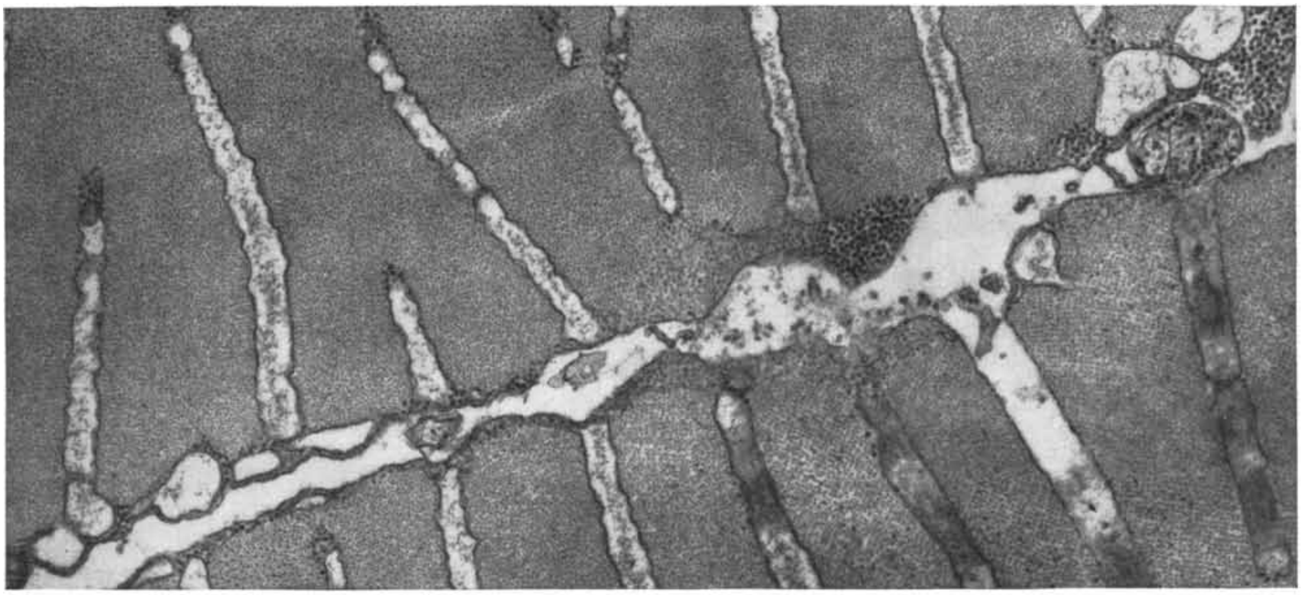


RECENT MICROGRAPH of a longitudinal section of muscle fiber shows the sarcolemma folding into the fiber. The folds are identical with the *T* channels. They form the mid-sections of the triads (*large white areas in the fiber*). Enlargement of 30,000 diameters is roughly three-quarters that of early micrograph (*above*). Improvement is in resolution.

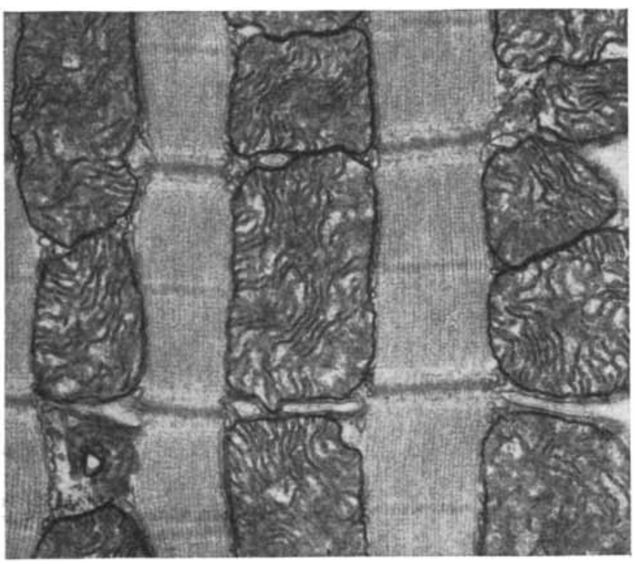
waste products, notably lactic acid. The third type of striated muscle combines the two attributes: it works rapidly and for long periods without pausing. An example is the cricothyroid muscle of the bat, which modulates the pitch of the sound used by the bat in its sonar echo-location system.

Now, a microscopic inspection of the three types of muscle cell brings forth the exciting finding that the development of the sarcoplasmic reticulum in each case is clearly correlated with the particular metabolic needs of the cell. In heart muscle, which does not require rapid and short-order replenishment of its energy, the sarcoplasmic reticulum is not very prominently developed. Instead the myofibrils are bordered by an abundant supply of large, well-developed mitochondria, the intracellular bodies sometimes called the "powerhouses" of the cell. On the other hand, rapidly acting skeletal muscles that work in bursts have a highly developed sarcoplasmic reticulum and few mitochondria. In the third muscle type, working rapidly and constantly, both the sarcoplasmic reticulum and the mitochondria are well developed.

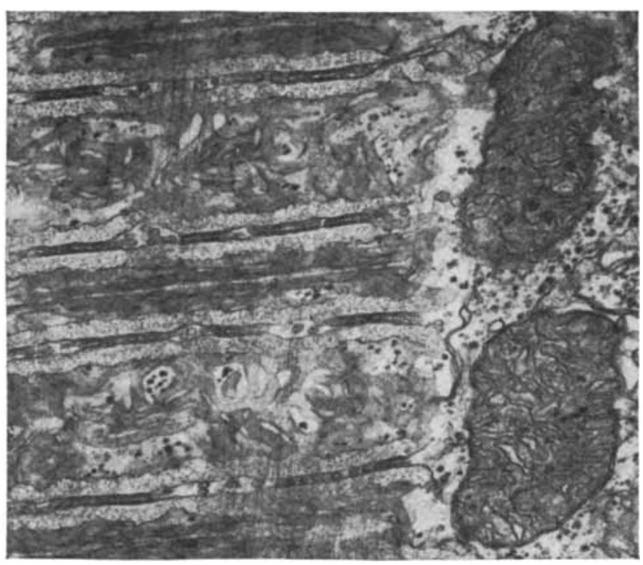
From these observations it seems reasonable to suggest that the sarcoplasmic reticulum serves as a source of quick energy for muscles that act rapidly. That is to say, it apparently is able to produce ATP and to do so very quickly; it is also only a short distance from where the ATP is needed. In most other cells the production of ATP is



TWO ADJACENT FIBERS from the tail of a black mollie are shown in transverse section. The light-colored channels that open outside of the cell membrane are components of the *T* system. The channels that do not open to the outside are tubular elements of the sarcoplasmic reticulum. Both types lie in spaces between myofibrils of the muscle fiber. The enlargement is 31,000 diameters.



SOLE ENERGY SOURCE in heart muscle, the mitochondria, lie astride myofibrils and appear rich in cristae (*strandlike folds*). The tiny invaginations between the mitochondria are parts of the *T* system. The sarcoplasmic reticulum is poorly developed in such slow but steadily working muscles. The enlargement is 19,000 diameters.



TWO ENERGY SOURCES, the mitochondria (*right*) and the sarcoplasmic reticulum (*broad gray bands at left*), give power to cells that must work rapidly for short periods of time. This micrograph is of muscle fiber from the swim bladder of a toadfish. Enlargement is 24,000 diameters. Thin bands are of *T* system.

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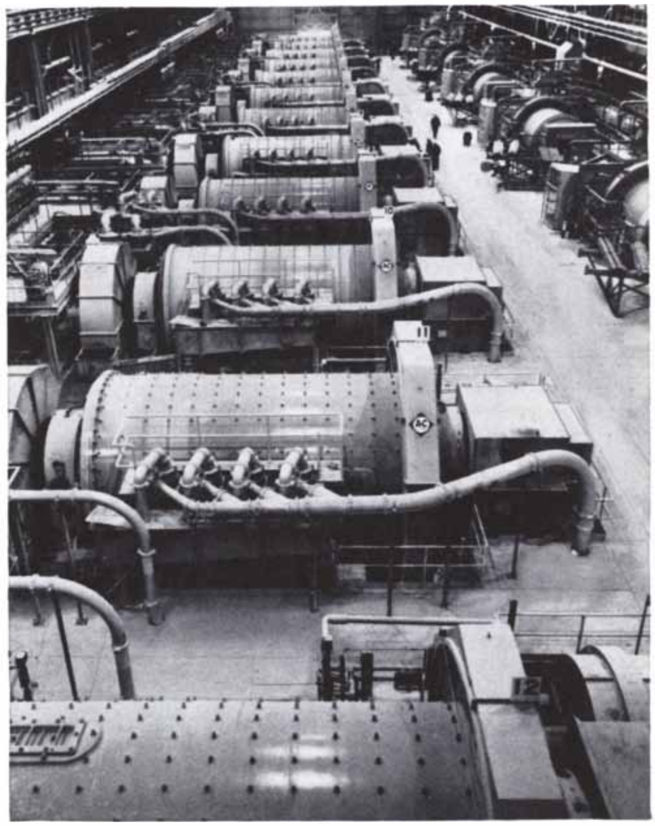

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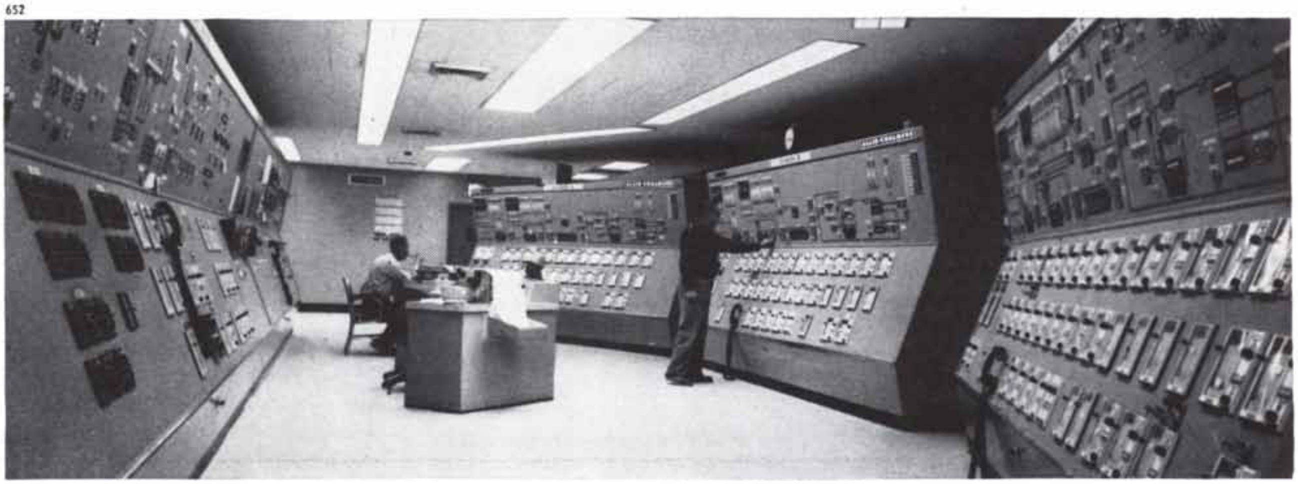
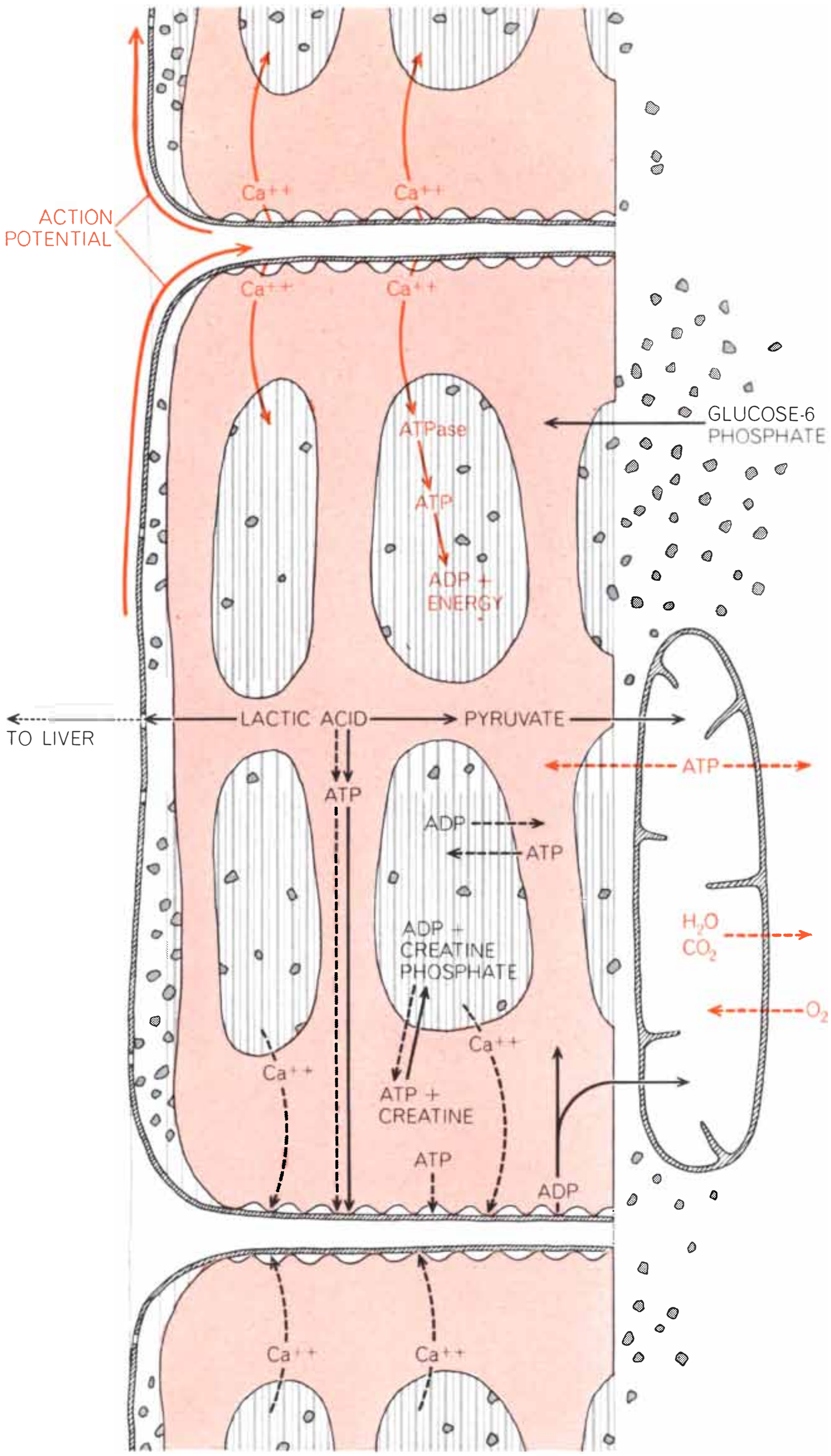


concentrated solely in the mitochondria, which synthesize ATP by means of a complex series of reactions that depends on the consumption of oxygen and on oxidative phosphorylation as the key reaction. This system evidently is too slow and the distances involved are too great for the needs of the muscle cells that consume energy at a high rate. For the myofibrils of the muscle cell the sarcoplasmic reticulum, closely intertwined with the fibrils, provides an energy reservoir that is directly at hand and also apparently is capable of generating energy in a simpler and faster way than the method of the mitochondrion. It seems altogether likely that the sarcoplasmic reticulum synthesizes ATP by means of anaerobic glycolysis, the process that uses energy already stored in glycogen, or animal starch.



DIFFUSION of metabolic materials during four stages of muscle action is mapped here. Four stages are contraction (*solid colored arrows*), relaxation (*broken black arrows*), recovery (*solid black arrows*) and recharge (*broken colored arrows*). Small gray particles are glycogen; oblong object at right is a mitochondrion. Sarcoplasmic reticulum is in color.

From what has been learned about the fine structure of the striated muscle cell we can deduce a plausible picture of the chemical dynamics of the system [*see illustration at left*]. It starts with the release of calcium ions by the sarcoplasmic reticulum and *T*-system tubules where they lie close together at the sensitive points of the myofibrils. The calcium ions trigger an enzyme action associated with myosin—the contractile protein of the fibrils—to bring about the hydrolysis of ATP, breaking it down to adenosine diphosphate (ADP) with the release of energy. This energy powers the shortening, or contraction, of the fibrils. The calcium ions are recaptured by the sarcoplasmic reticulum and the *T* system, and the fibrils then relax. Meanwhile the ADP has been quickly regenerated to ATP, which serves to energize the next contraction. All of this takes place within a few thousandths of a second.

Where does the energy to regenerate the ATP come from? Apparently it is provided by the dephosphorylation of creatine phosphate, which is present in the sarcoplasm. The creatine phosphate thus lost must, of course, be replaced; the cell apparently keeps up its stores of the compound by synthesizing it in a series of reactions that draws energy from its glycogen, granules of which lie close to the membranes of the sarcoplasmic reticulum. These reactions produce both ATP (through anaerobic glycolysis) and then creatine phosphate. They also generate the waste product lactic acid. Presumably the sarcoplasmic reticulum transports the lactic acid to the surface of the cell, where it is discharged outside the cell and borne off by the bloodstream to the liver. Some of it, however, may be converted within the cell itself into pyruvate, which can be used by the mitochondria for the synthesis of ATP.

It may seem a stretch to deduce all of this merely from electron micrographs of the cell's fine structure. Decades of close study of cells of all types, however, have given cytologists so intimate a knowledge of the machinery of the cell that it is now possible to relate function to form with a high degree of precision and with confidence that the clues are being read correctly.

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Acoustic Methods in Psychiatry

In which the speech of disturbed persons is analyzed not for content but for such attributes as loudness and timbre. The results indicate that this analysis can be useful in the description of mental state

by Peter F. Ostwald

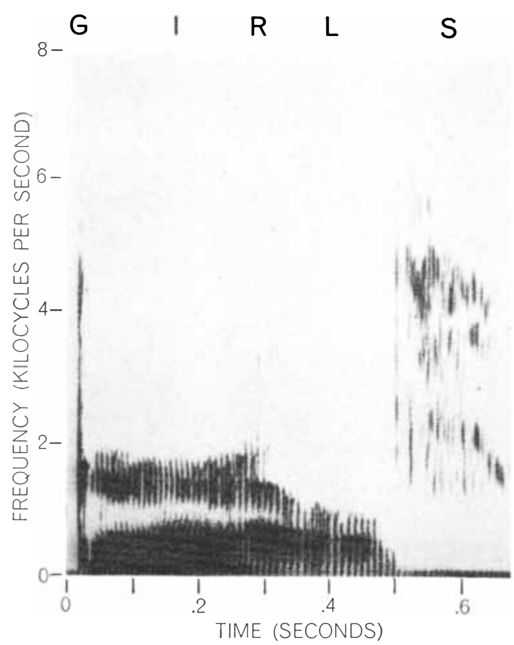
When someone calls on a physician, usually the first thing he does is talk about the symptoms that have led him to conclude he may be ill. The physician translates this description into a written history that, along with the results of a physical examination and any necessary X-ray or laboratory tests, helps to establish a working diagnosis and plan of treatment. The patient's oral testimony not only provides indirect clues about the illness but also on occasion offers direct acoustic evidence as to the pathological process that caused it. A tumor of the larynx or vocal cords, for example, imparts a hoarse quality to the voice. Brain damage due to a blood clot prevents the patient from thinking of certain words to describe his condition; hence his speech contains gaps, errors or peculiar word substitutions.

Clearly not all acoustic evidence of disease is obvious, and not all patients make an effort to reveal their problems. An emotionally disturbed patient may be unaware of his difficulties and inner conflicts, or he may try to hide them, fearing embarrassment, rejection or even punishment. Psychiatrists, who attach considerable diagnostic importance to the patient's history, must be particularly alert to acoustic manifestations of illness. When a patient begins to lose control over his emotions, he often betrays his distress by slips of the tongue, mispronounced words or changes in the quality of his voice. If the patient suffers from a disorganizing illness such as schizophrenia, he may alert the psychiatrist's "third ear" by rambling, repeating himself or using bizarre terminology or words he has coined himself. The speech of the schizophrenic patient may also have a peculiar blandness of expression called "flat affect."

The written history, even if it includes actual quotations or a letter in which the patient describes his disturbance, remains a soundless document. On occasion this is an advantage: some abnormalities in a patient's verbalized thoughts become clearer when they are set down on paper. But the written history also has a major shortcoming, apparent to anyone who has winced at a novelist's reproduction of a Southern drawl. Speech has nonlexical features that are almost impossible to capture on paper, such as intonation, tempo, loudness and timbre. Such features are affected by illness. A person suffering from multiple sclerosis, for example, develops a "scanning" type of speech that can only be recognized when it is heard. Psychoneurotic patients who stutter produce sounds that defy translation into words.

The inherent limitation of the written history has stimulated physicians to search for more precise methods of describing the sounds made by their patients. As long ago as 1827 James Rush of Philadelphia published a book entitled *The Philosophy of the Human Voice,* in which he used a kind of musical notation to depict the nonlexical aspects of speech. In recent years Paul J. Moses, an eminent laryngologist at the Stanford University School of Medicine, has developed a method of analyzing human vocalization in terms of the "five *R*'s": respiration, range, register, resonance and rhythm. My own search for ways to study the speech of psychiatric patients has led me to try a radically different method of describing voice patterns. My colleagues and I at the University of California School of Medicine in San Francisco have borrowed the techniques developed in acoustic laboratories for precise analysis of sounds and have put them to clinical use in analyzing speech.

With the help of George Wilson, an acoustical engineer at the University of California at Berkeley, we undertook to determine if one could characterize the sound produced by a psychiatric patient in purely physical terms. We set up a tape recorder in a room where a psychoneurotic woman with dangerous trends toward depression and overeating was to be interviewed. During a series of interviews we recorded her speech through a microphone 10 inches from her mouth and in full view. After selecting four-second segments of tape containing her most voluble utterances (which struck us as having a childish tone), we spliced the segments into loops of continuous tape and ran the loops



NORMAL SPEECH PICTURE, made by sound spectrograph from a healthy man's pronunciation of the word "girls," shows distinctive pattern associated with each letter.

through a sound analyzer. This device divided the constituent frequencies of the sound into bands either one octave wide or half an octave wide. The amount of energy in each band was then plotted against frequency to obtain a curve that represented a characteristic sound pattern of the speech being analyzed.

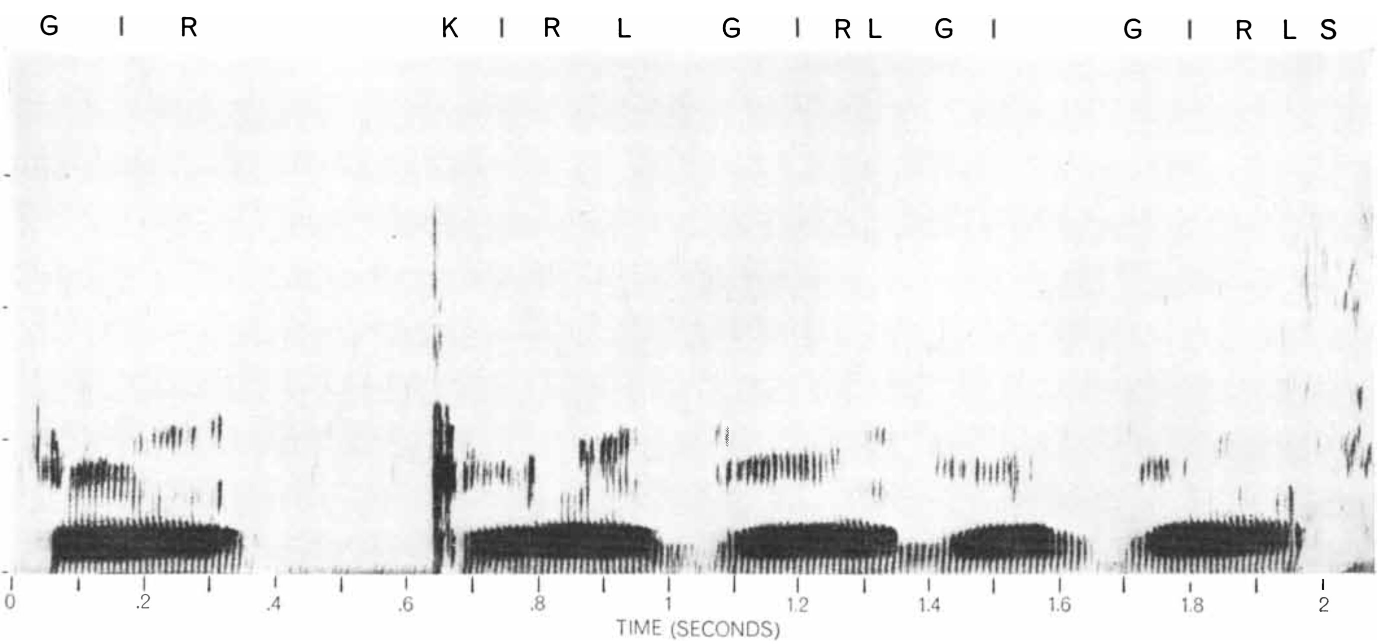
When human beings speak, most of the sound energy they produce lies at frequencies between 100 and 10,000 cycles per second, the pattern of frequencies varying with the age and sex of the speaker and the words spoken. The sound analyzer showed the speech of our first patient to have a fundamental focus of energy at 250 cycles per second (close to middle *C* on the musical scale) and a focus of resonance energy at 500 cycles per second—one octave higher. After repeatedly detecting the same distribution of frequencies in her voice and the voices of patients who sounded much the same, we dubbed this particular pattern the "sharp" voice. Later we obtained an almost identical acoustic pattern from the speech of a 10-year-old boy, which supported our impression that the sharp voice has a childish quality.

With our technique of sound analysis we have also developed quantitative definitions for such vocal stereotypes as "flat," "hollow" and "robust" [*see illustrations at bottom of next two pages*]. The flat voice—which can be equated with the monotonous, low-pitched delivery of patients in states of depression—yielded a pattern of sound energy spread quite evenly over a broad band of the frequency spectrum. The hollow voice—which is common to extremely retarded, inhibited or repressed patients and victims of certain types of brain disease—can be described as an exaggerated kind of flat voice; it has one prominent energy focus representing the fundamental tone of the voice and has little resonance energy. The robust voice—which is characteristic of patients who speak in an oratorical, overly emphatic way, often with some pomposity—yielded a striking pattern of relatively large amounts of sound energy concentrated at the center of the frequency spectrum in a symmetrical manner.

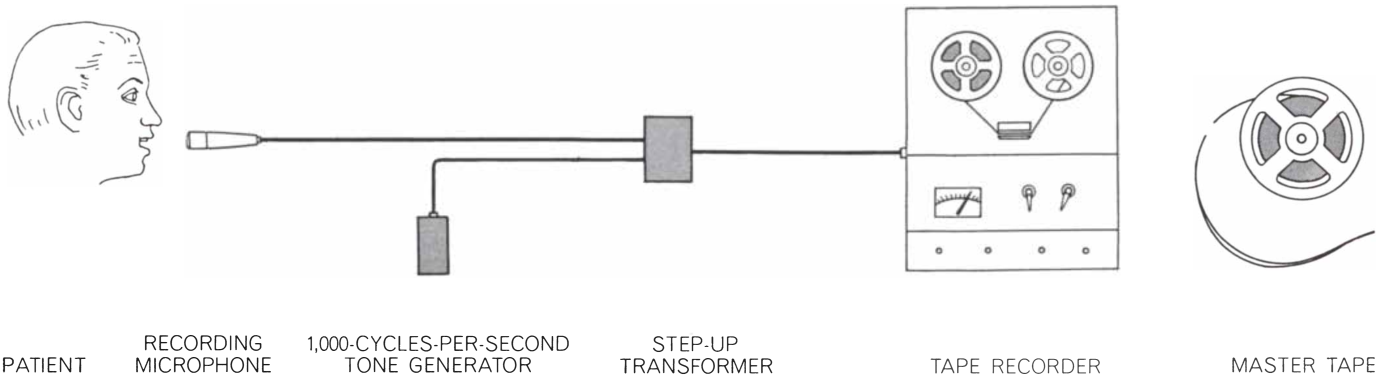
The use of acoustic methods to describe the overall quality of a patient's voice suggested that one might be able to use such methods to detect the detailed variations that emotional stress causes in the voice. Encouraging support came from some work done by Leonard Rubenstein of McGill University. He had asked experimental subjects to hum a certain tone during the day and then to hum what they thought was the same tone at night. He found that the frequency pattern of the hummed tone changed regularly from day to night, and that this diurnal fluctuation of the voice corresponded to measurable biochemical changes.

We decided to set up an experiment in which nonpatient volunteers would be subjected to a stress and their voices would then be recorded for comparison with their normal speech patterns. The stress was brought on by sudden exposure to an extremely bad smell. Each member of a group of subjects was asked to come into a room, sit down in front of a microphone and read "Joe took father's shoe bench out," a test sentence chosen for its variety of sounds. After the sentence had been repeated three times the subject was instructed to pick up a glass of what appeared to be water but in reality was a concentrated solution of ammonia. He was told to take a deep breath from the glass and repeat the test sentence into the microphone. Members of a second group of subjects were asked first to smell the ammonia and later on to record their normal voice; this was done to remove the possible effects of the sequence of procedures from the final results of the experiment. When we examined the half-octave-band analyses for the subjects, we found that the voices recorded after olfactory stress contained strikingly less energy than normal voices in the half-octave band centered at 500 cycles per second.

Having determined that the testing technique would work, we undertook a similar study of a group of psychiatric



ABNORMAL SPEECH PICTURE of the efforts of a stutterer to say the word "girls" was made by sound spectrograph. A weak opening "g" is followed by adequate vowel formants (*resonance energy rising in streaks*) but the final "ls" is missing. A second start results in a sound resembling a "k." After two more false starts the word is completed. A spectrogram charts frequency in kilocycles per second (*vertical axis*) against time in seconds (*horizontal axis*). The author added an alphabetized transcription.



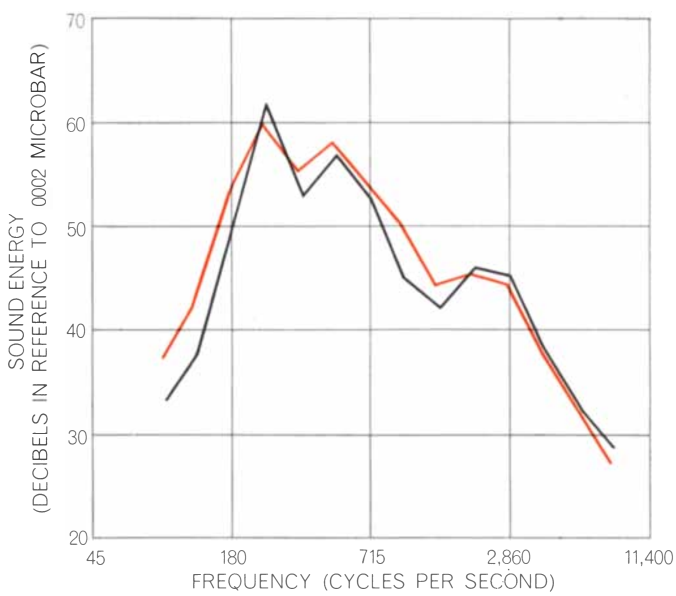
METHOD OF ANALYZING SPEECH used by the author in his earliest acoustic studies involved recording a patient's speech, splicing samples of it into continuous loops of tape and playing these loops backward through a tape recorder. A sound analyzer

patients. Because we did not want to expose the patients to any kind of additional stress we dispensed with the bad-smell stimulus and compared the sounds they produced before and after psychiatric treatment. Each patient was interviewed as soon as possible after being admitted to the treatment ward in an acute state of emotional disturbance. During the interview, which was tape-recorded, we asked the patient to read aloud "Joe took father's shoe bench out." After about three weeks of treatment by the ward physicians the patients were again interviewed and asked to repeat the test sentence.

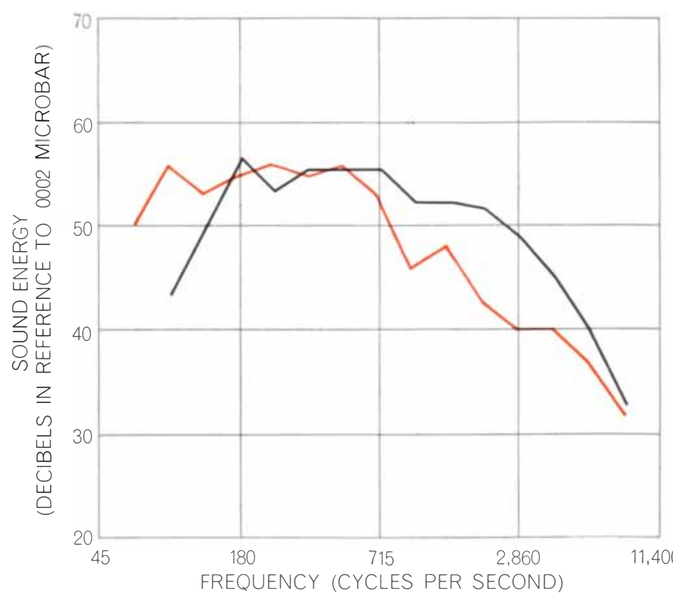
The "reading voice" adopted by a patient uttering a test sentence does not provide a sample of spontaneous speech. To compensate for this we compiled two other samples of a patient's voice during each recorded interview, one consisting of high-pitched segments of sound and the other of low-pitched segments. For purposes of analysis we then considered not the voice of a patient but his voices: the high voice, the low voice and the reading voice.

One man we studied in this way entered the hospital in a state of severe depression resulting from manic-depressive psychosis; his voices were uniformly flat. After a series of electroconvulsive treatments he spoke in such a way that his high voice assumed a robust pattern characteristic of exuberance and overconfidence. His reading voice also became more robust, but his low voice retained the basically flat configuration observed before treatment. Taking into account only this acoustic evidence, we surmised that the patient had undergone a profound clinical change, tending outwardly toward aggressive, extroverted behavior but inwardly toward a sense of sadness reflecting the depression that had necessitated his coming to the hospital. This surmise was verified by the physicians and nurses in the ward who had been following the patient's daily course in detail.

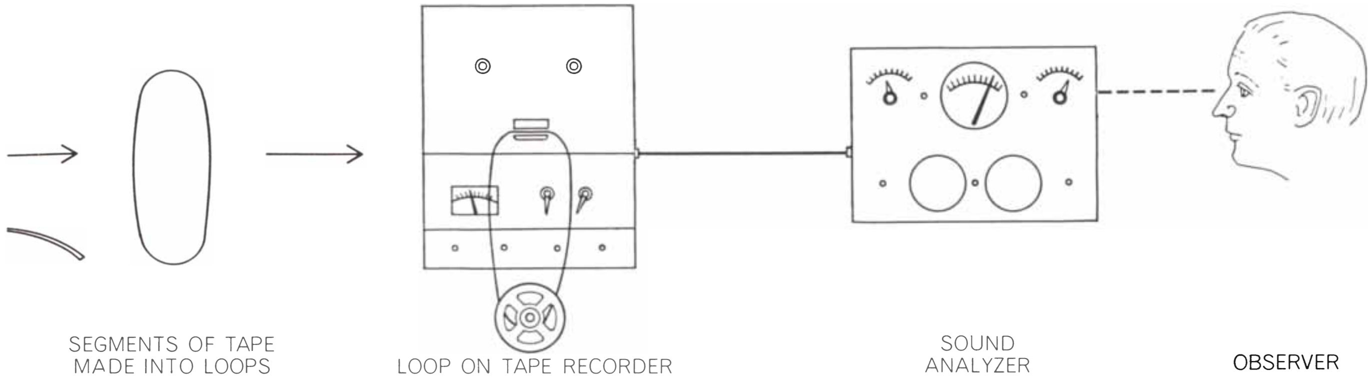
Another case we studied was that of a woman admitted for treatment of a type of schizophrenia that involved bizarre behavior and almost total social withdrawal. Before she had been treated her voice was audible but sounded subdued, a condition we traced acoustically to a sharp low voice, a sharp reading voice and a flat high voice. After she had been treated with a phenothiazine drug known to ease acute schizophrenic reactions, there was a greater difference between the voices, indicating greater variability in her behavior from moment to moment. Her



SHARP VOICE of a boy (*colored curve*) and that of a woman (*black curve*) are analyzed. Each has peaks a single octave apart. Level of sound energy (*vertical axis*) was measured along half-octave bands. Frequency (*horizontal axis*) is in cycles per second.



FLAT VOICE, subjectively associated with monotonous speech, is defined by acoustic analysis as a pattern of sound energy spread quite evenly over the frequency spectrum with few resonance peaks. Curves show the speech of a man (*color*) and a woman (*black*).



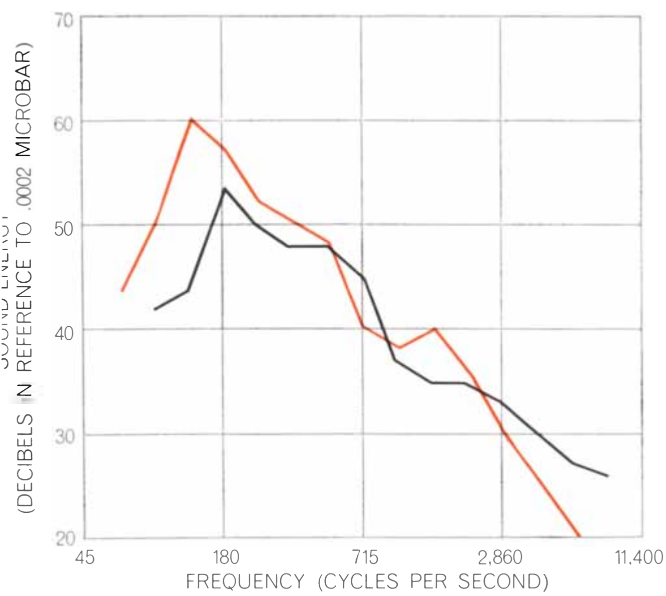
would then indicate the level of sound pressure (energy) existing within consecutive half-octave and octave bands on the frequency spectrum. The needle of the sound analyzer was observed as it fluctuated so that data for graphs could subsequently be compiled.

voices after treatment also showed an increase in the amount of total energy produced, suggesting that she had become more assertive and outgoing. There also appeared a tendency toward the flat-voice or hollow-voice pattern, implying that her feelings of depression had increased or that the drug had exerted some inhibiting effect on her vocal behavior.

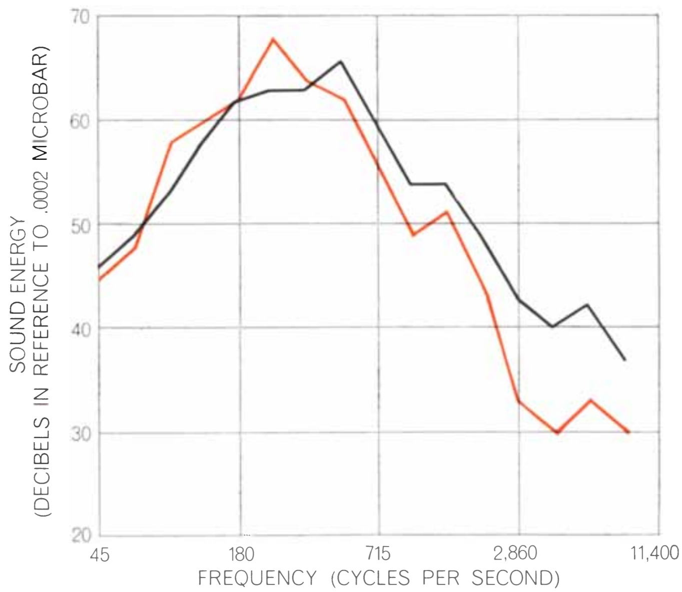
A third patient whose voices we analyzed was a woman admitted to the hospital in an acute state of agitation and excitement diagnosed as a hypochondriacal panic reaction. Both her high voice and her reading voice showed the robust pattern associated with an overly dramatic manner, whereas her low voice was flat, indicating depression. When the patient's voices were analyzed after treatment, they had become more alike; the robust high voice had come down and the formerly flat low voice was almost up to the robust reading voice. The regime of treatment in this case had consisted of careful ward management coupled with intensive group therapy and individual psychotherapy. Once the patient's attention was diverted from her physical condition she became a more controlled, easygoing individual, although she was still given to a theatrical manner, as indicated by her predominantly robust voice.

Since we had obtained identical test sentences from all the patients before and after treatment, it was possible for us to say something about how they changed as a group. We used the results of acoustic analyses of the reading voices to test for any statistically significant associations with such clinical elements as diagnosis and form of treatment. One association seemed readily apparent: the use of electroconvulsive treatment consistently led to increased sound-energy levels over the entire acoustic spectrum, particularly at 500 cycles per second.

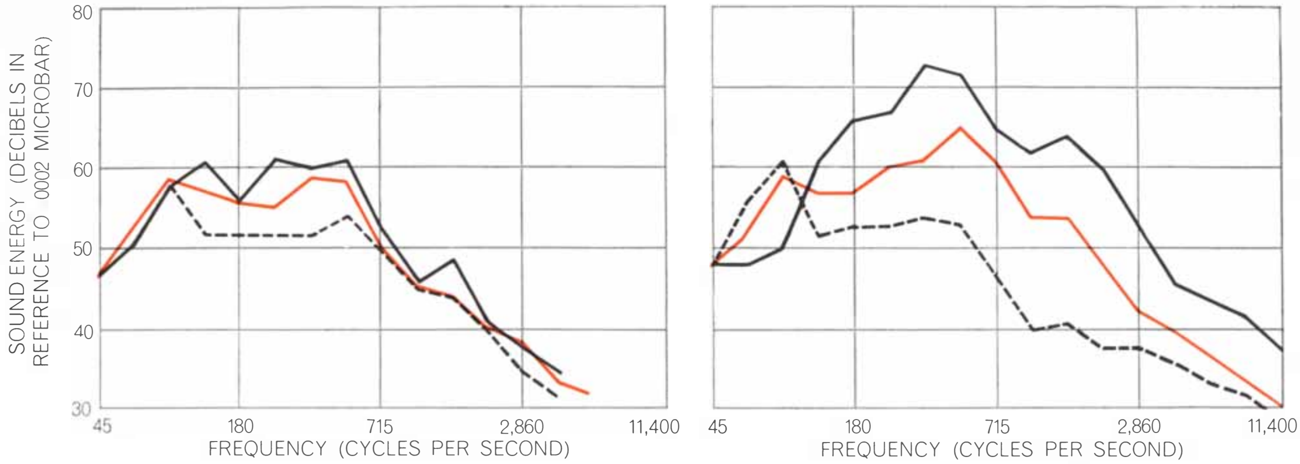
The persistent way in which energy changes centering at 500 cycles per second showed up in our studies turned out to have some biological significance. It is a fundamental fact of auditory perception that the human ear is most sensitive to tonal stimuli above 500 cycles per second. Almost all sounds calculated to arouse human beings—whistles, cries, sirens, screams—contain a large amount of sound energy above 500 cycles per second. On the other hand, the fundamental tone of the human voice, which is located at lower frequency levels, is so dispensable in



HOLLOW VOICE is a vocal category characterized by a single-peaked curve. The peak indicates that only the fundamental tone of the voice is carrying much sound energy. The level of energy, or sound pressure, is in decibels in reference to .0002 microbar.

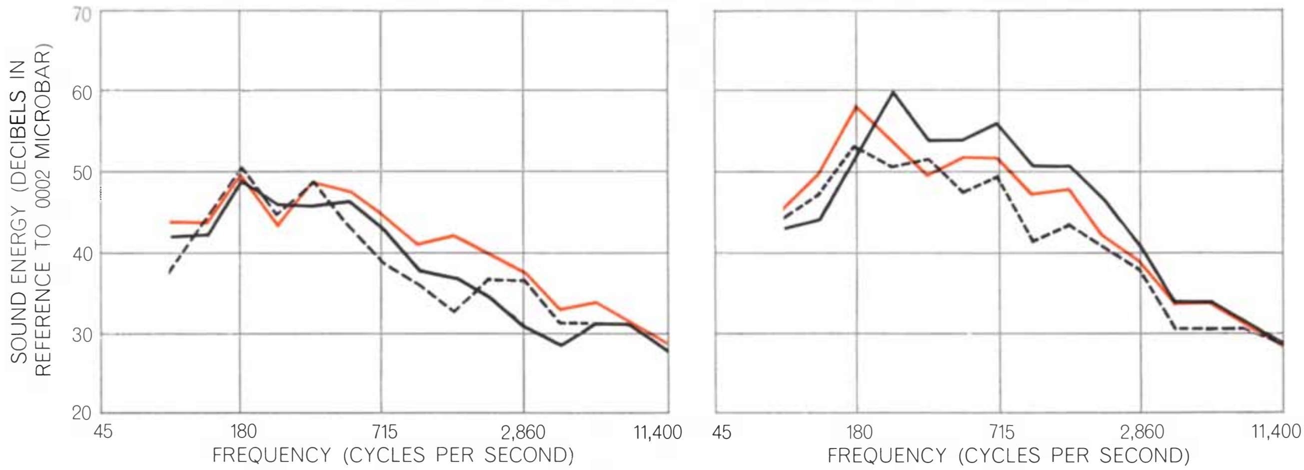


ROBUST VOICE, commonly identified with oratorical speech, makes use of more sound energy than other vocal categories. In samples from a man (*color*) and woman (*black*) sound energy is spread somewhat symmetrically over the frequency spectrum.



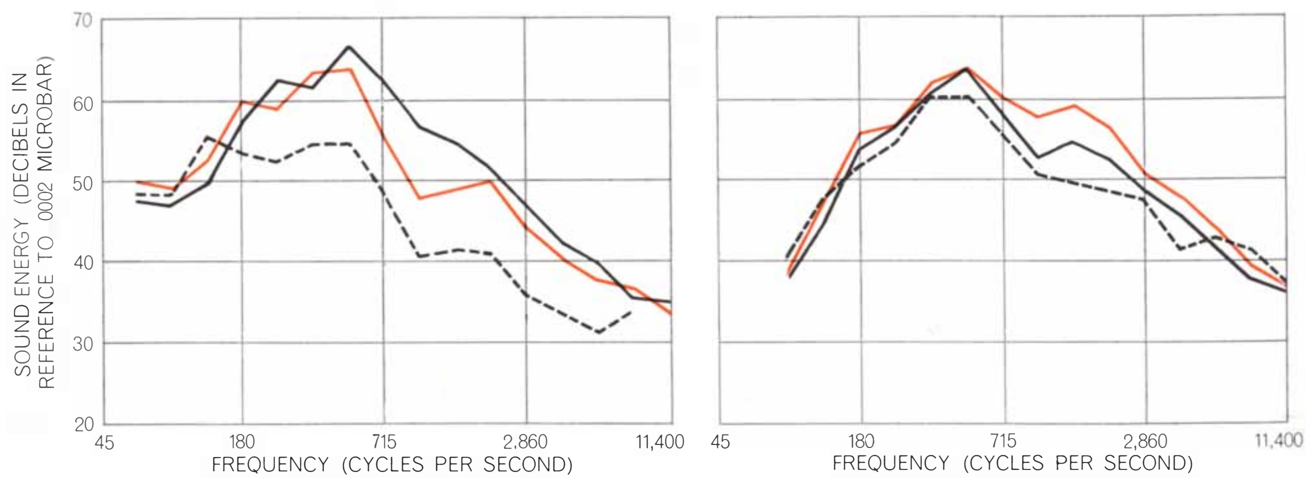
HIGH VOICE
LOW VOICE
READING

DEPRESSED PATIENT studied by author changed speech pattern in hospital. Before treatment his three voices seemed flat (*curves at left*). After therapy his high and reading voices took on a robust pattern, whereas his low voice remained flat (*curves at right*), implying slight recovery. Curves are keyed to voice types.



HIGH VOICE
LOW VOICE
READING

SCHIZOPHRENIC PATIENT sounded subdued when admitted to hospital. Her voices lacked energy and were uniform in pattern (*curves at left*). After treatment her voices acquired energy and variety (*curves at right*). Persistence of flat and hollow patterns, however, indicated that her vocal behavior was inhibited.



HIGH VOICE
LOW VOICE
READING

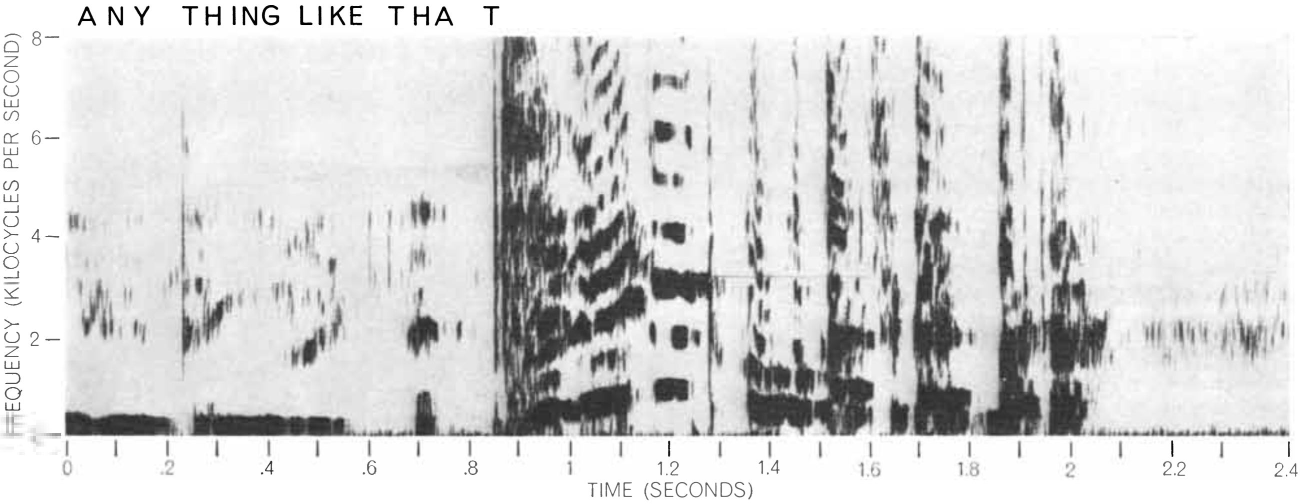
FRIGHTENED PATIENT entered hospital in a disorganized mental state. Her panic was reflected in robust high and reading voices; her feelings of depression were suggested by a flat low voice (*curves at left*). After therapy her voices gained similarity to each other (*curves at right*), implying better personal control.

ordinary conversation that telephone companies do not even bother to transmit it. We advance the hypothesis that speakers increase the amount of sound they emit at higher frequencies when they want to be listened to and reduce their high-frequency output when they prefer to be ignored.

We departed somewhat from our main line of study to examine in detail a human sound specifically designed to attract attention: the crying of a baby. Analysis showed that babies' cries invariably have a fundamental tone located around 500 cycles per second and resonance bands appearing at 1,000, 2,000 and 4,000 cycles per second. Nonetheless, the individuality that leads mothers to use such diverse characterizations as "lusty," "strong," "loud," "feeble," "weak" or "whiny" in describing a given baby's cry was not reflected by the half-octave-band method of acoustic analysis. Eventually our interest in such detail led us to abandon the sound-analyzer method for a more sophisticated technique: sound spectrography.

The sound spectrograph is a device that analyzes sound into bands of frequencies and converts it into electrical impulses that, when they are recorded on a special paper, provide a vivid picture of the particular sound under observation. Workers in acoustic phonetics describe consonant sounds as "noise" and vowel sounds as "formants": discrete bands of resonance energy that vary according to the vowel being uttered. A sound spectrogram—the picture made by the spectrograph—presents vowel formants as heavy, dark bands and consonant noise as unevenly scattered gray spots. Normal speech has characteristic formant and noise features; it is therefore easy to detect abnormalities in the speech of psychiatric patients by looking at their sound spectrograms. The spectrogram also makes it possible to analyze speech disturbances in considerable detail.

A disturbance that readily lends itself to analysis by spectrogram is stuttering. Regularly associated with other behavior disturbances, this condition occurs more frequently among males than among females. The voice of a young man who stuttered and was under treatment for a distressing emotional conflict was recorded by sound spectrograph as he attempted to pronounce the word "girls" [*see illustration on page 83*]. He began with a weakly articulated "g," and although he enunciated the following vowel and the consonant "r,"



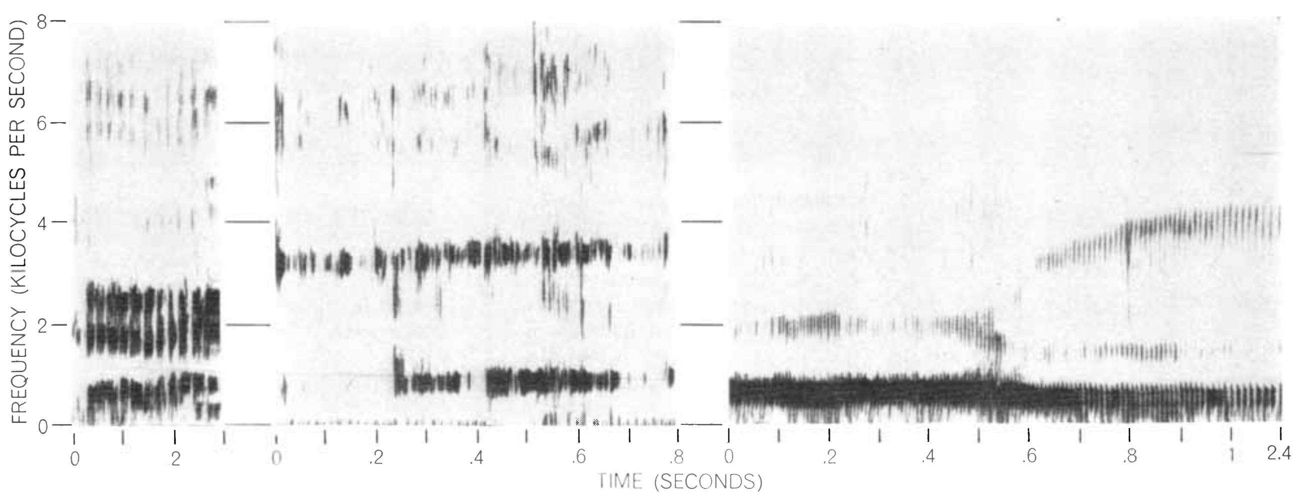
SPECTROGRAM OF GLOSSOLALIA, or "talking in tongues," shows normal speech ended by a burst of noise at .8 second on the horizontal axis. Ensuing is a series of rising formants with a resonance pattern exceeding 8,000 cycles per second (*vertical axis*). A break at 1.3 seconds is followed by a drop in pitch and some short bursts with formants and noise resembling true speech sounds.

he could not manage the terminal consonant cluster "ls" to complete the word. Instead the patient fell silent for about three-tenths of a second and started over again. He then made too forceful an attack on the "g," giving it more the properties of "k." Again the vowel followed, but as before he could not complete the word. He started twice more without success. Only on the fifth try was he able to produce the consonant noise needed to complete the word.

A speech disorder more elusive and difficult to record, and one that has interested theologians as well as psychiatrists, is glossolalia, or "talking in tongues." Victims of this disturbance are quite capable of producing normal speech, but in states of intense emotional excitement they make peculiar and incomprehensible sounds. Spectrograms of the sounds show that they have such properties of normal speech as formants, noises and brief separations due to the articulation of speechlike fragments. The sounds are uttered, however, without the logical structure necessary for intelligibility [*see illustration above*].

Schizophrenia is another disorder that can be studied in detail by means of the sound spectrograph, particularly when that disorder renders the speech of children and adolescents unintelligible for long periods of time. One schizophrenic patient whose speech we analyzed spectrographically kept his mouth open almost all the time he spoke, with the result that his speech sounds were devoid of distinctive features. There was almost no acoustic output above 1,000 cycles per second, his vowels lacked formant structure and his consonants produced little noise in the high-frequency part of the spectrum. Such a defect cannot be explained simply on the basis of inability to reproduce the required phonetic properties of speech. As we observed the patient during various emotional states it became apparent that he could in fact vocalize energetically, but in doing so he often made sounds that completely lost the character of human speech and turned into something more reminiscent of the screeches, rasps, squawks or growls made by animals [*see illustration below*].

Part of the problem that emotionally ill patients have is that they cannot perceive the effects of their own be-



SPECTROGRAMS OF ANIMAL-LIKE SOUNDS were made during the outbursts of a disturbed boy. The sound depicted at left was described by the author as a rasp; the one in center, as a froglike squeak-squawk; the one at right, as a growl sounding like "aw-er."

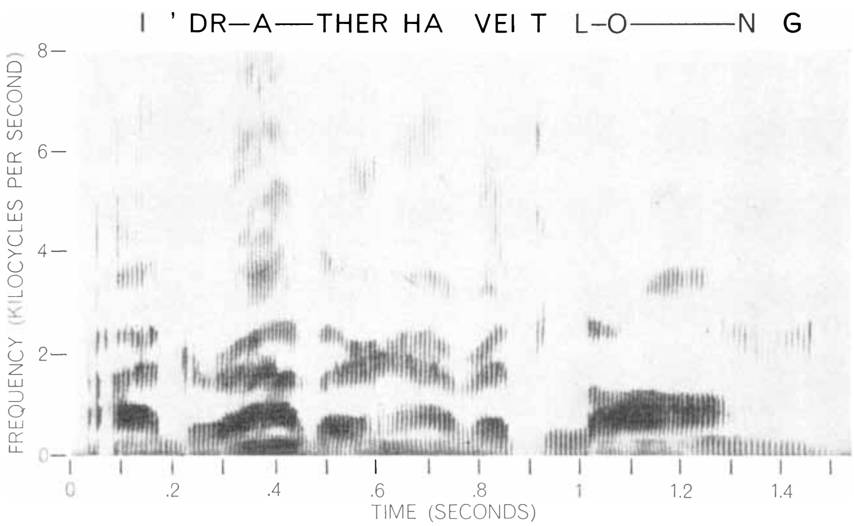
havior—including their speech—as well as healthy people perceive the effects of what they do and say. The emotionally sick person often has a long-standing sense of inferiority; his painful feelings of shame or guilt tend to isolate him from other people or cause him to deal with them as though they did not exist. As a result he gets little or no self-corrective feedback from the social environment and his behavior becomes increasingly bizarre, leading to the diagnosis of mental illness. For dealing with such emotionally sick people the new techniques of acoustic analysis can be combined with clinical and experimental methods to study behavior. John A. Starkweather and William A. Hargreaves of the Langley Porter Neuropsychiatric Institute in San Francisco have developed an ingenious way of studying voice changes during psychotherapeutic interviews. Using a digital computer they correlate the sounds made by the patient with variations in his mood from moment to moment.

In the summer of 1963 I witnessed a particularly imaginative combination of acoustic analysis and personal interaction in the treatment of a withdrawn, schizophrenic boy of eight. The treatment was undertaken by Mary O'Keeffe, a student at the University of California School of Medicine who was working on a summer research fellowship. As a psychiatrist at the School of Medicine I served as her consultant.

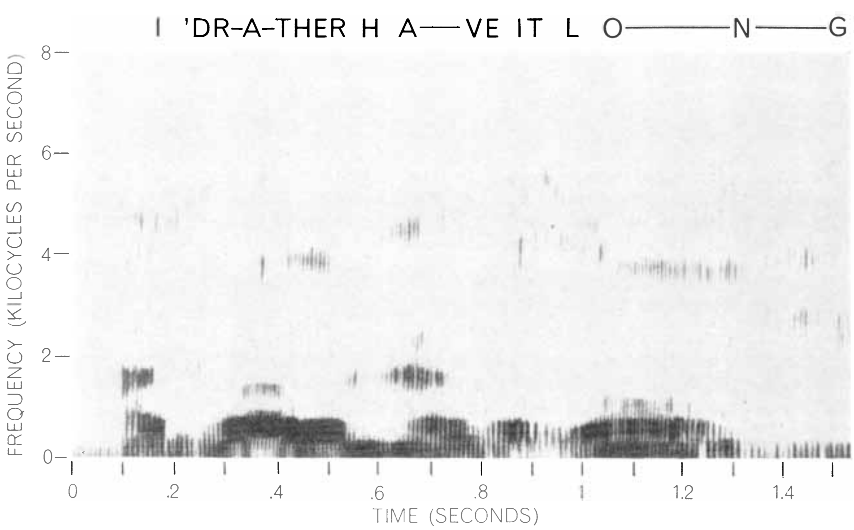
Miss O'Keeffe's patient was restless and frequently unmanageable. He would dart about the room or freeze into an immobile posture for no apparent reason. He grimaced and moved his hands in a strangely stereotyped manner. Often his speech seemed akin to the babblings and mouthings of babies. There were other times when the boy produced recognizable fragments of words and sentences, disconnected and without grammatical order but revealing an unusually large vocabulary. Much of this vocabulary consisted of words he had heard but could not use for meaningful communication. Miss O'Keeffe spent many hours observing the boy in the ward and in the playground. She also tried to speak with him, and she tape-recorded these sessions whenever possible.

Analysis of the tape recordings revealed that the content of the patient's speech fell into three distinct categories. The first category—message content—consisted of words and phrases that seemed relevant to the situation confronting the patient and conveyed information in a semantic sense, such as "I want to go out." The second category—slogan content—included words from songs, rhymes, television advertisements and other incidental verbal material that the patient would memorize and compulsively repeat. Slogan content seemed related to his internal problems, fears and concerns and never to the actual situation in which he found himself. The third category—nonsense content—contained sounds in which it was impossible to discern any words whatsoever, and it also included pseudowords superficially resembling speech.

When the patient's acoustic productions were separated in terms of content, the vocal characteristics of these productions were studied and three different voice types became distinguishable. In addition to the "normal" voice characteristic of a healthy child there was a "screech" of high, unvarying frequency and much noise, and a "chant" containing gliding sounds and imparting a singsong effect. An attempt to relate these three different voice types to the differences in speech content indicated that the screech almost exclusively accompanied message content [*see illustration on page 91*]. That is, at moments when the patient sounded most agitated, he produced meaningful statements almost exclusively. Miss O'Keeffe and I concluded that the patient reserved his verbally meaningful speech

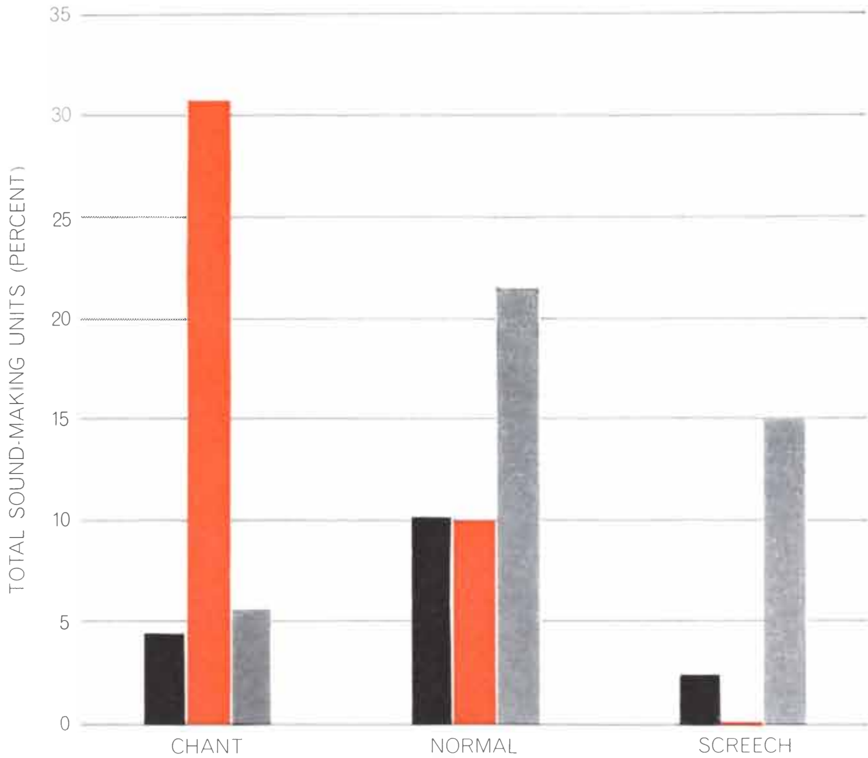


SPECTROGRAM OF INTELLIGIBLE SPEECH makes the vowel formants readily apparent as resonance energy bands rising throughout the frequency spectrum (*vertical axis*). The spectrogram also depicts a clearly articulated stop consonant (the "t" of the word "it").



SPECTROGRAM OF UNCLEAR SPEECH represents the attempt of a schizophrenic boy to say "I'd rather have it long." The spectrogram lacks distinctive vowel formants, precise consonants and significant output in the part of the spectrum above 1,700 cycles per second.

U.S.
MAIL

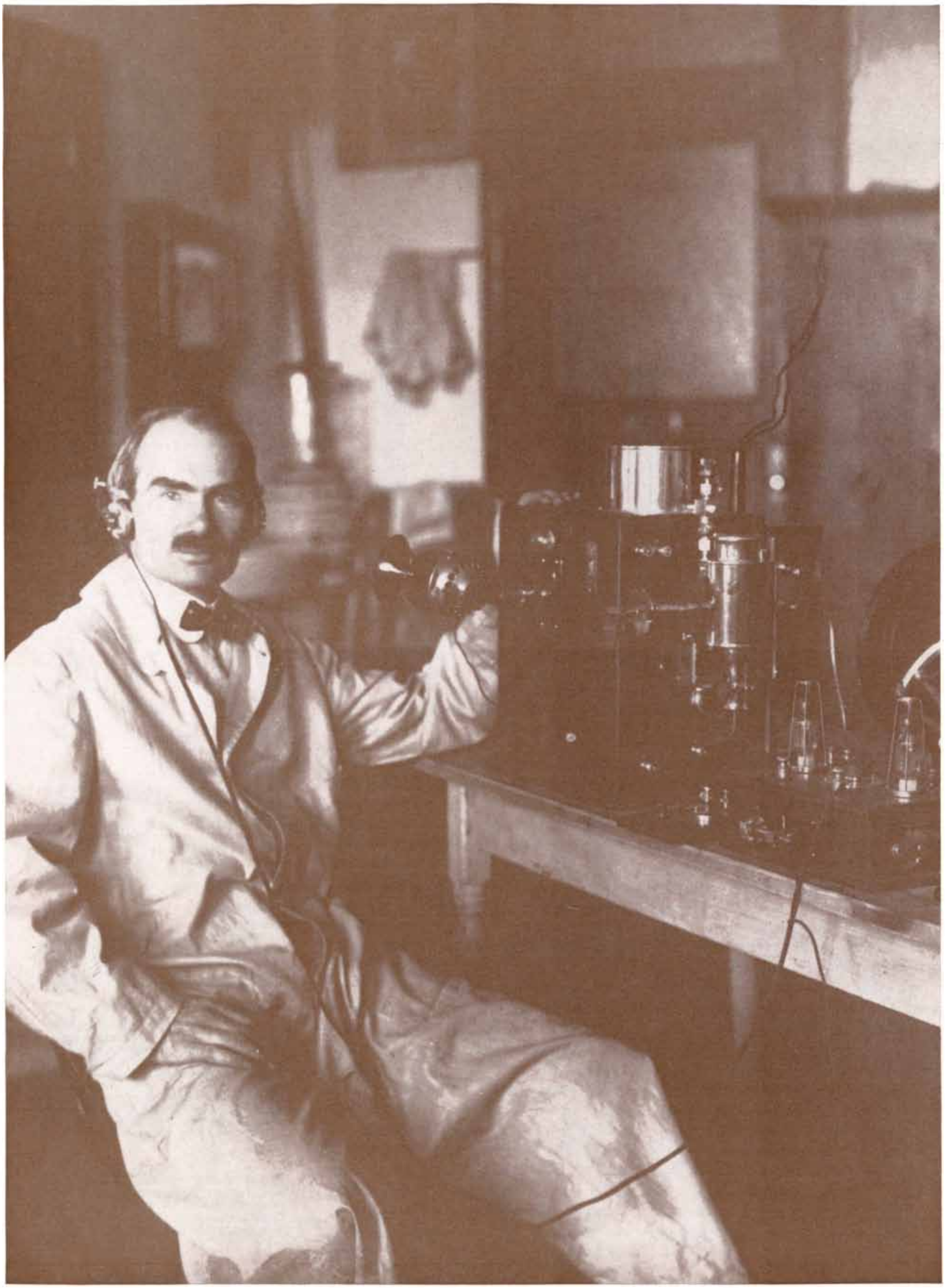


CONTENT AND STYLE of a patient's speech are correlated in this chart. The entire verbal output of a schizophrenic boy was divided into three categories with meaningful statements called "message," advertisements and other set expressions classed as "slogan," and meaningless statements called "nonsense." The child's vocal styles were then divided into three predominant types: a screech, a chant and a normal voice characteristic of healthy boys his age. By this technique it was shown that the boy spoke his most meaningful statements in the voice of high frequency that expressed the greatest desire to be heard.

for times when he indicated, by screeching, the urgency of being heard.

Had it happened that people had paid no attention to him when he spoke more normally? Such a question can only be answered by studying the developmental background and behavior pattern of a patient through extensive interviews and direct observation. From an acoustic study we were able to learn that while using his normal voice the patient spent as much time emitting nonsense or slogans as he spent producing message content. This almost "fifty-fifty" split between meaningful and meaningless speech in his normal voice represented a characteristically ambivalent quality in his behavior. Whenever the patient spoke in a normal voice, he in effect both gave the listener information and took it away. Furthermore, he spent as much time chanting as he did using his normal voice, and the chanting was almost completely devoid of message content.

The behavior of schizophrenic children can be explained in terms of a number of unfavorable factors—some genetic, some physiological and some environmental—combining to interfere with the child's ability to learn language and to use speech for social communication. We have studied patients who could not produce the distinctive features of vowels and consonants. From such studies of people with brain damage as have been conducted by the Soviet neurologist A. R. Luria it seems likely that the information needed for normal speech is stored in the temporal zone of the cerebral cortex. If a patient who has suffered brain damage cannot recall or reproduce the distinctive features of the speech sounds, his utterances remain incomprehensible to others. Something much like this seems to happen in certain schizophrenic patients. We have reason to believe that further application of acoustic techniques to clinical phenomena in psychiatry will make possible precise descriptions of the communication disturbances associated with mental illnesses. One hopes that the information gathered by acoustic techniques will also provide new leads to effective treatment.



DE FOREST POSED with his wireless telephone set in 1907 or 1908. The large cabinet on which his hand rests houses the carbon-arc transmitter. The low cabinet at right is the receiver. Two tubes, apparently early grid-triodes, are visible under wire guards.

De Forest and the Triode Detector

He invented the three-electrode vacuum tube without understanding how it worked. His grid-triode was no great success as a detector, but it did eventually make modern radio and electronics possible

by Robert A. Chipman

The history of inventions is almost always clouded by claims and counterclaims and embellished with legend; often the inventor himself is a major contributor to the confusion. So it is in the case of the thermionic triode, which Lee De Forest invented in 1906 as a detector of wireless-telegraph signals. The triode, a three-electrode vacuum tube, was a truly seminal creation. As a detector, amplifier and oscillator it became the foundation of modern radio, and with its derivatives it dominated electronic technology for 50 years.

Most of what has been known about the invention of the triode comes from De Forest himself. Until his death in 1961 he told and retold stories about his invention, but in his speeches and writings De Forest was more a poet than an engineer or a scientist; there is often only a superficial relation between his recollections and the actual sequence of events. Only by interpreting De Forest's lively accounts in the light of independent evidence can one hope to construct a realistic description of his experiences in the early days of radio and of his processes of technological creation. Those processes turn out to have involved much imitation and self-deception, along with large measures of ingenuity, persistence and good luck.

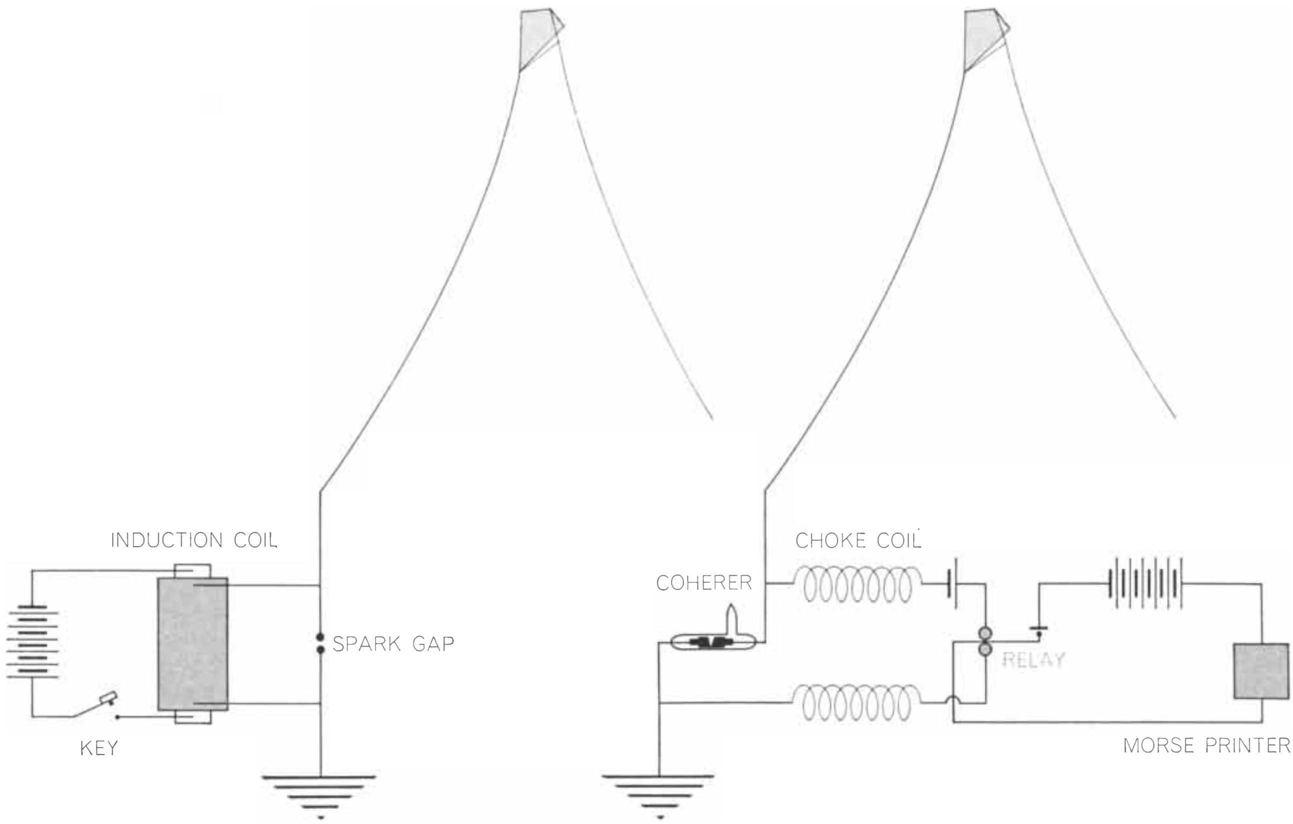
Lee De Forest was born in 1873 in Council Bluffs, Iowa, and grew up in Talladega, Ala., where his father was the principal of a school for Negroes. Before he was 16 the boy had gone on record as intending to be an inventor, and his pursuit of that ambition was facilitated by a remarkable circumstance: a wealthy ancestor had endowed a scholarship at Yale University for young men named De Forest. Lee received his bachelor's degree from Yale's Sheffield Scientific School in 1896, and in spite of an undistinguished undergraduate record he went on to a Ph.D. in 1899. His dissertation was on the reflection of Hertzian, or electromagnetic, waves traveling on wire transmission lines—possibly the first Ph.D. thesis in the U.S. on a topic closely related to wireless telegraphy.

His determination to achieve fame as an inventor was undaunted by his failure to sell any of the many "inventions" (including games and bicycle gears, but no wireless equipment) he conceived while at Yale. "I aim at Tesla," he wrote in his diary in 1896. And to the question (in a college questionnaire) "If you weren't yourself, who would you prefer to be?" he answered, "Tesla." Nikola Tesla, the brilliant but erratic worker in alternating-current technology who had invented the induction motor, refused him summer employment in 1897. Whether for that reason or not, De Forest shifted his sights; he wrote in his autobiography: "From the first I had the one aim in view, to make my name at least rank with that of Marconi." (Later, on the occasion of his being awarded the Edison Medal of the American Institute of Electrical Engineers in 1946, De Forest showed further flexibility: "From early boyhood, Thomas A. Edison was my ideal, my living inspiration, my idol.")

It was Guglielmo Marconi, at any rate, whom the young man chose to challenge. Emerging from Yale at the age of 26, De Forest took a job with the Western Electric Company in Chicago. He was not, however, enthusiastic about selling his services to any employer. Quick fame and riches were his goal, invention his chosen road; soon he decided that wireless telegraphy would be his vehicle. The young Italian engineer Marconi was then moving from success to success, attended by worldwide publicity on an unprecedented scale. From wireless transmission across the nine-mile Bristol Channel in England in 1897 Marconi had progressed to 20-mile communication while reporting a regatta in the Irish Sea in 1898; he conquered the 33-mile English Channel in 1899, linked two British warships across 75 miles of open water in 1900 and in early 1901 established communication over a 200-mile path in southern England. At the end of that year he climaxed his work by receiving a signal transmitted across the Atlantic Ocean.

Inventors in those days seldom issued patent licenses to competitors on a royalty basis; De Forest knew that he could challenge Marconi in the wireless-telegraph business only by owning the rights to a transmitter-receiver "system" sufficiently different from Marconi's to be reasonably safe from lawsuits for patent infringement. Marconi's transmitter was based on the induction coil and the spark gap, with which Heinrich Hertz had produced electromagnetic waves in his pioneering experiments of 1886. Marconi's receiver was based on the fact, discovered by the French physicist Édouard Branly in 1890, that an electric spark has the power to change the resistance of loose aggregations of metallic powders at a distance. Marconi's "coherer" was a tube containing nickel and silver filings; placed in series with a battery, it allowed a current to pass whenever an electromagnetic wave emitted by the transmitter arrived [*see top illustration on page 95*]. To both the transmitter and the receiver Marconi added a vital contribution: good electrical connections to the ground and long, high wires as antennas.

Reviewing his studies of Hertzian waves at Yale, where he had worked with similar apparatus, De Forest decided to start by finding a substitute



EARLY MARCONI APPARATUS is diagrammed. At the transmitter (*left*) trains of sparks generated by the induction coil set up electrical oscillations in the antenna, which is held aloft by a kite. The resulting electromagnetic waves excite high-frequency oscillations in the receiving antenna (*right*); these signals cause the coherer to operate the relay, closing the circuit of the local battery and the code printer. The two "choke coils" in the receiver serve to isolate the antenna circuit from the relay and printer.

for Marconi's coherer as a detector. (He was not alone: the magazine *Electrical World* carried 28 news items on various versions of the coherer in 1900.) The coherer was insensitive; it was sluggish, permitting code transmission at less than half the speed of wire transmission lines, and it required extensive auxiliary apparatus. Morever, since it was inherently an on-off device, it could never be adapted to wireless telephony, which was already being contemplated. Detector research had the virtue of being inexpensive and requiring little space—no small advantages to a would-be inventor working during off-hours in his bedroom while earning $10 a week at a full-time job.

Searching the technical journals for some new detector principle, De Forest learned that three different German experimenters had described new detectors in which a telephone receiver was connected in series with a battery and with two metal electrodes separated by a thin layer of a conducting liquid such as water; the operation of a spark coil nearby produced a scratchy sound in the receiver. With financial and technical help from a fellow employee, Edwin H. Smythe, De Forest experimented with such arrangements for nearly a year. On September 1, 1900, he and Smythe applied for a patent on what he called a "Responder": a sandwich of two flat metal strips separated by a thin layer of liquid or of liquid-soaked porous material. The device was obviously simple and quick-acting, and there is no reason to doubt that it could detect wireless waves. Nevertheless, it was probably very insensitive; there is no trace of evidence that it was ever put to use in a communication system.

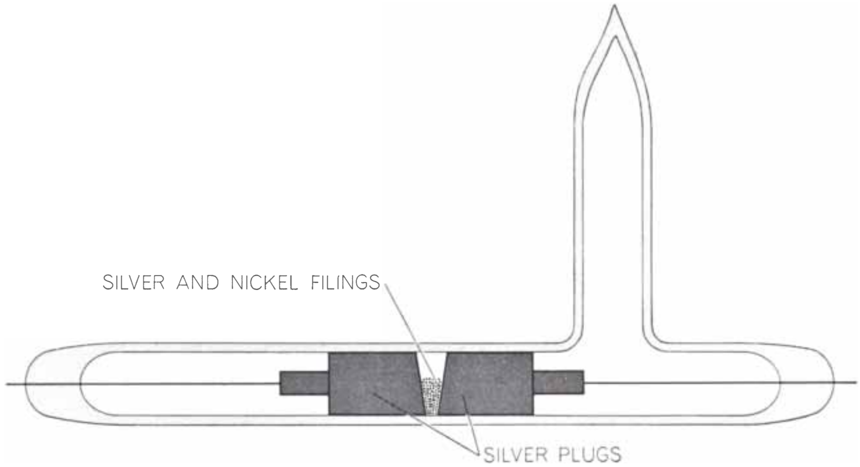
De Forest and Smythe next came on a report (perhaps in an article in *Electrical World* for May 18, 1901) of a paper presented to the French Academy of Sciences describing a "loud-speaking radio-phone," a detector capable of handling such strong signals that the dot-dash buzzing of a telephone was audible throughout a large room. The device resembled a Marconi coherer but the dry metal filings were replaced by a pasty mixture of silver filings and a powdered insulator such as sulfur in glycerine. Like the sandwich device, the French detector was actually an "anti-coherer": its resistance increased instead of decreasing in the presence of electric waves. After brief experimentation De Forest and Smythe applied in 1901 for a patent covering essentially the same device. Since De Forest applied the name "Responder" indiscriminately to this detector as well as to his first invention and even to similar inventions made later by other people, it is hard to tell from his writings how effective the various designs were. Apparently, however, the 1901 "goo" detector did work, if only sporadically.

Whatever its deficiencies, it was the beginning of a "system," and any system was better than none. The *Western Electrician* for July 27, 1901, carried an article announcing "A New System of Space Telegraphy." The transmitter was a distinctly new type invented by Clarence Freeman, a professor at the Armour Institute; it produced a high voltage when a number of condensers that had been charged in parallel were suddenly switched into series connection. The receiver was the new Responder. The maximum transmission distance was reported as four miles. In his autobiography De Forest characteristically referred to "this *first attempt* on the Great Lakes, indeed in all America, to send dots and dashes by wireless"—knowing full well that Marconi had demonstrated wireless over 35 miles to the U.S. Navy in New York in 1899 and that the U.S. Army Signal Corps and the Weather Bureau were communicating regularly over like distances!

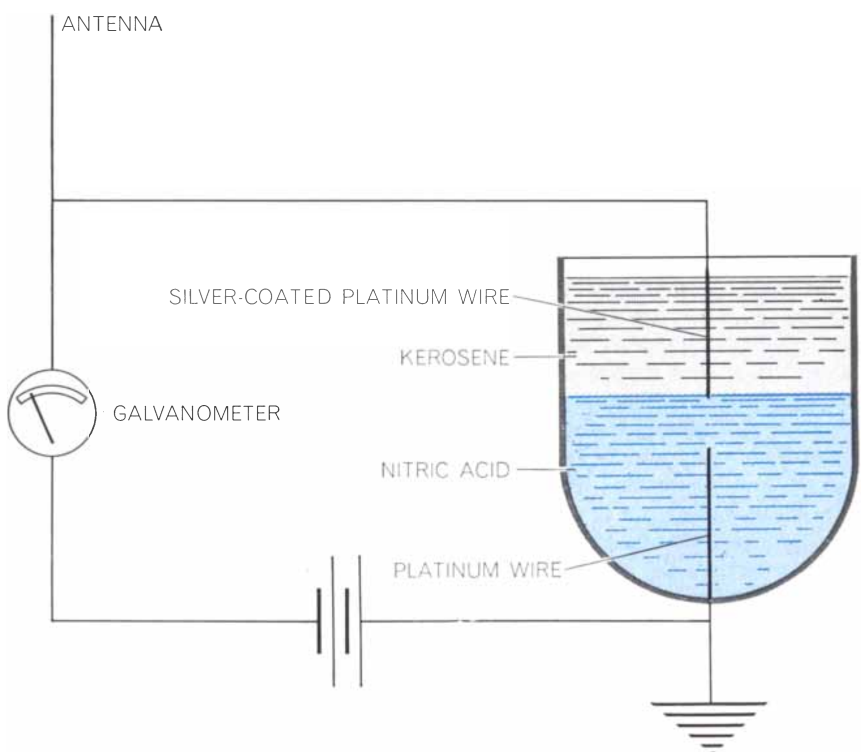
In less than three months there came an opportunity to test the system in direct competition with Marconi, who had contracted with the Associated Press to provide ship-to-shore reporting of the America's Cup races. De Forest made a deal to provide the same service for a rival news agency, the Publishers' Press. Fortunately for posterity the Navy detailed a lieutenant to check on the operation of the two systems; *Electrical World*'s account of the confrontation, apparently largely derived from his report, differs considerably from De Forest's later recollections.

Not having anticipated competition, Marconi had brought only his simplest equipment, with none of the elements he had recently developed to provide selective tuning of the receiver. Since De Forest's apparatus also lacked selectivity, both receiving stations responded equally well to both transmitters; when the transmitters were sending simultaneously, the signals received were unintelligible. When the De Forest and Marconi operators realized what was happening, they agreed to transmit alternately for five-minute intervals. That worked for a short time, until suddenly a third transmitter came on the air and created interference that prevented all further reporting of the races. De Forest never mentioned the intruder in his accounts of the event; he was probably unwilling to admit that anyone else in the U.S. knew enough about wireless telegraphy at the time to have attempted the feat. The third telegrapher later identified himself as G. P. Gehring, president of the American Wireless Telephone and Telegraph Company. His claims to have reported the races successfully were shown to be fictional, but the following year a subsidiary of his company did inaugurate the first daily wireless service in the U.S., between Catalina Island and the California mainland.

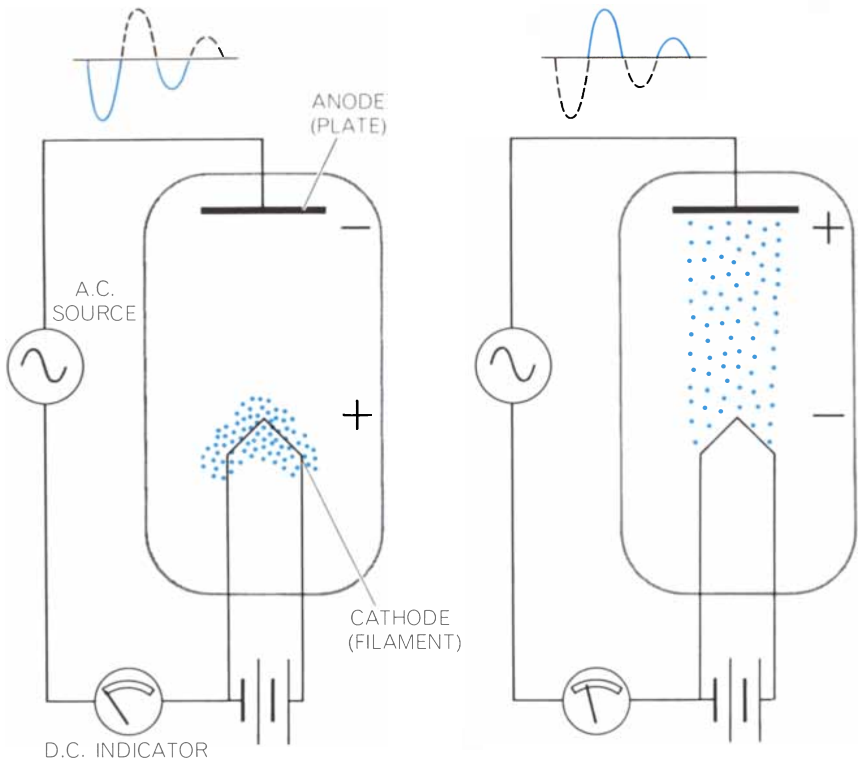
For his venture at the races De Forest had formed a small company with Freeman, Smythe and a former Yale classmate who provided most of the money. The idea of sharing with others his glory as an inventor, however, was intolerable to De Forest. During the races he had tossed Freeman's transmitter overboard (perhaps justifiably), and in the midst of his collaboration with Smythe on the Responder he had written in his diary: "Not for Smythe did I toil six years at Yale." Early in 1902 he interested a Wall Street promoter named Abraham White in financing his operations on a wider scale. De Forest became vice-president, scientific director and one-third owner of a new company capitalized at several million dollars, and his old associates were eased out. The company announced that it would construct coastal stations for communication with ships and inland stations to compete with Western Union and Postal Telegraph. Its tangible assets were the patents on the doubtful Responder and a record of wireless communication over seven miles at the races. Meanwhile Marconi had trans-



COHERER, as modified by Marconi, is here enlarged to twice its actual size. It detected signals because current flowed through the filings only when their resistance was lowered by a radio-frequency wave. The fragile glass vessel was lashed to a bone holder for convenience. An electric-bell mechanism vibrated the coherer to restore its sensitivity after each pulse.



ELECTROLYTIC DETECTOR patented by Reginald A. Fessenden in 1903 was a rectifier, although its mode of operation was not then understood. Electrochemical action converted high-frequency oscillations from the antenna into direct current that registered on the meter.



DIODE PRINCIPLE is shown schematically. The heated filament emits electrons (*colored dots*). The plate is connected to a source of alternating voltage. When that voltage acts in one direction, the plate is negative and the electrons are repelled (*left*). When the alternating voltage changes polarity, the plate is positive, electrons go to the plate and a current flows (*right*). An alternating-voltage input therefore can yield a direct-current output.

mitted thousands of words from England to a ship 1,200 miles at sea. *Electrical World* commented: "We continue to be regaled with newspaper accounts of experiments that are inferior to what Marconi achieved three years ago."

For the next five years De Forest enjoyed a great deal of publicity, far more than any other American engaged in wireless telegraphy. Yet his technical contributions during that period were minute and his commercial success was nil. His company did build more than 100 wireless stations in the East and Middle West, but they were primarily for the purpose of stock promotion; as *Scientific American* put it in 1907, they seemed to serve only to "educate the masses" and not to send messages. De Forest did obtain more than 25 patents during the period but not one proved to have contemporary commercial value. It is doubtful that any of the devices he patented were put to use in the company's stations.

The detector remained De Forest's big problem. The Responder could not be counted on even for a successful promotional demonstration; when De Forest exhibited his system to the Signal Corps in 1902, his detector was a sensitive anticoherer invented by an Italian naval officer and used by Marconi in his first transatlantic reception. In 1903 De Forest began installing in his company's stations an electrolytic detector similar to the one just patented by his American arch-rival Reginald A. Fessenden [*see bottom illustration on preceding page*]. Since the detector employed metal electrodes and a conducting liquid he referred to it as "our new Responder" until court injunctions and fines stopped him in 1905.

Without title to any adequate detector, the company dared not operate its stations commercially for fear of further punitive court action. His partners blamed De Forest and forced him out of the company. Again without funds and thrown back on his own resources, De Forest decided that a new and more brilliant future lay in wireless telephony rather than telegraphy. The Danish inventor Valdemar Poulsen was already successfully transmitting voice signals by wireless, generating with his patented electric arc the continuous oscillations required for telephony. De Forest modified the transmitter slightly, but he still needed a noninfringing detector.

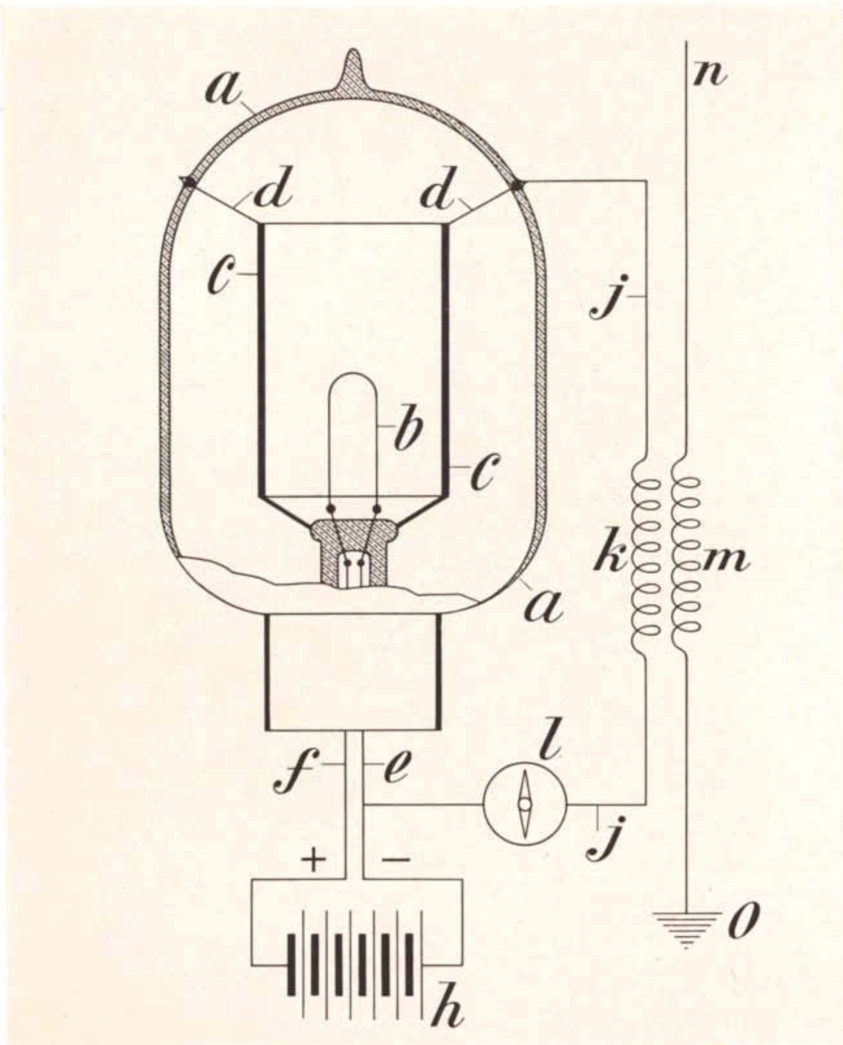
He found the detector clue he needed in a two-electrode vacuum tube for which John Ambrose Fleming, a professor at the University of London and a consultant to Marconi, had received British and U.S. patents in the fall of 1905. The principle on which Fleming's invention was based had been discovered, but not utilized, by Edison about 20 years earlier. Edison noticed that if he placed an extra metal-plate electrode near the filament inside an incandescent lamp, connected to the positive side of the filament, an electric current flowed across the space between filament and electrode. No such current flowed if the plate was connected to the negative side of the filament. The explanation, provided by the British physicist O. W. Richardson in 1903, was that negative electrons were being emitted by the heated filament and were attracted only to a positive electrode. Fleming, who had been a consultant to Edison's British firm and had published papers on the "Edison effect," was the first person to understand clearly that wireless signals could be detected by this "rectification." In 1904 he saw that his Edison-effect lamps could rectify signals by acting as "valves."

A dot or dash from any of the spark transmitters consisted of a sequence of damped high-frequency oscillations [*see "a" in illustration on pages 98 and 99*]. No indicating meter or telephone receiver could follow the rapid positive-to-negative reversals of the signal oscillations; nor could they respond to an average value, because the average value was zero. If, however, a distortion could be created by rectification so that responses to the portions of the oscillation patterns above and below the base line were not identical, then the average would no longer be zero. The lightly constrained current meter would accumulate impulses from successive trains of waves, being deflected more for a dash than for a dot; the diaphragm in the telephone receiver would vibrate once for each wave train, giving a long buzz for a dash and a short one for a dot. Fleming's valve produced a distorted response by "unilateral conduction," passing a current only during the positive portions of each incoming wave [*see "b" in illustration on pages 98 and 99*].

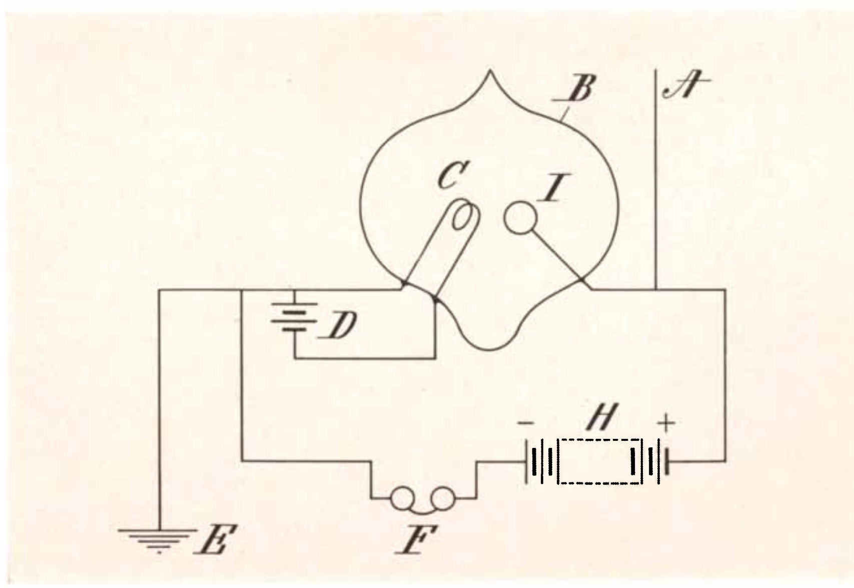
The Fleming valve was manufactured in small quantities beginning in 1905 and installed in many Marconi wireless stations during the next seven or eight years. As a detector it played an unimportant role in wireless communications, but it was certainly the first radio vacuum tube and it was of prime importance as an antecedent to the triode. As he read about Fleming's new detector De Forest immediately saw two ways in which its circuit differed from the one he had been using with other types of detectors. It had a galvanometer instead of a telephone receiver as an indicator and it had no battery in the indicator circuit. De Forest applied in January, 1906, for a patent covering these modifications and some other changes and in May for a patent on the telephone and battery only [*see bottom illustration at right*]; the patents were granted in June and November respectively.

Today De Forest's circuit would be classified as a "forward-biased thermionic diode rectifier"—"forward-biased" because the extra battery maintains a positive voltage on the plate electrode, "thermionic" because electrons are emitted from the filament electrode by heat, "diode" because there are two electrodes. On October 26, 1906, De Forest delivered a long paper to the New York section of the American Institute of Electrical Engineers in which he advanced for the first time the two broad claims about his diode that he was to reiterate for half a century as part of his legend of the invention of the triode. Both claims are technically unjustifiable; taken literally, they would be evidence of a scientific naïveté remarkable in an active inventor only seven years away from a Ph.D. in physics. It is more charitable to assume that the claims and their supporting narrative were developed as defenses against a potential suit for infringement of the Fleming patent. (The suit did come, nine years later, and was won by Marconi, who owned the patent.) Whatever its purpose, De Forest's oft-told tale must be reckoned with if one is to understand the reasoning and the experimentation that led to the triode.

De Forest contended first of all that his invention of the forward-biased diode did not stem from his knowledge of the Fleming valve but was a logical outcome of work he had begun in 1900. In that year he had seen the light of a gas lamp momentarily dimmed by the sparking of a nearby induction coil. He soon found that the dimming was caused by sound waves from the sparks, not by electric waves, but "there yet remained the firm conviction that in the heated gases surrounding incandescent electrodes there must nevertheless exist a response, in some electrical form, to high-frequency electrical oscillations." (De Forest had not mentioned this "conviction" in reporting the gas-lamp observation in *Electrical World* in 1902.)



FLEMING VALVE, or thermionic diode, is shown as illustrated in the patent of 1905. Electrons emitted by the filament (*b*) moved to the cylindrical plate (*c*) when the plate was positively charged by the signal from the antenna (*n*). The indicator was a meter (*l*).



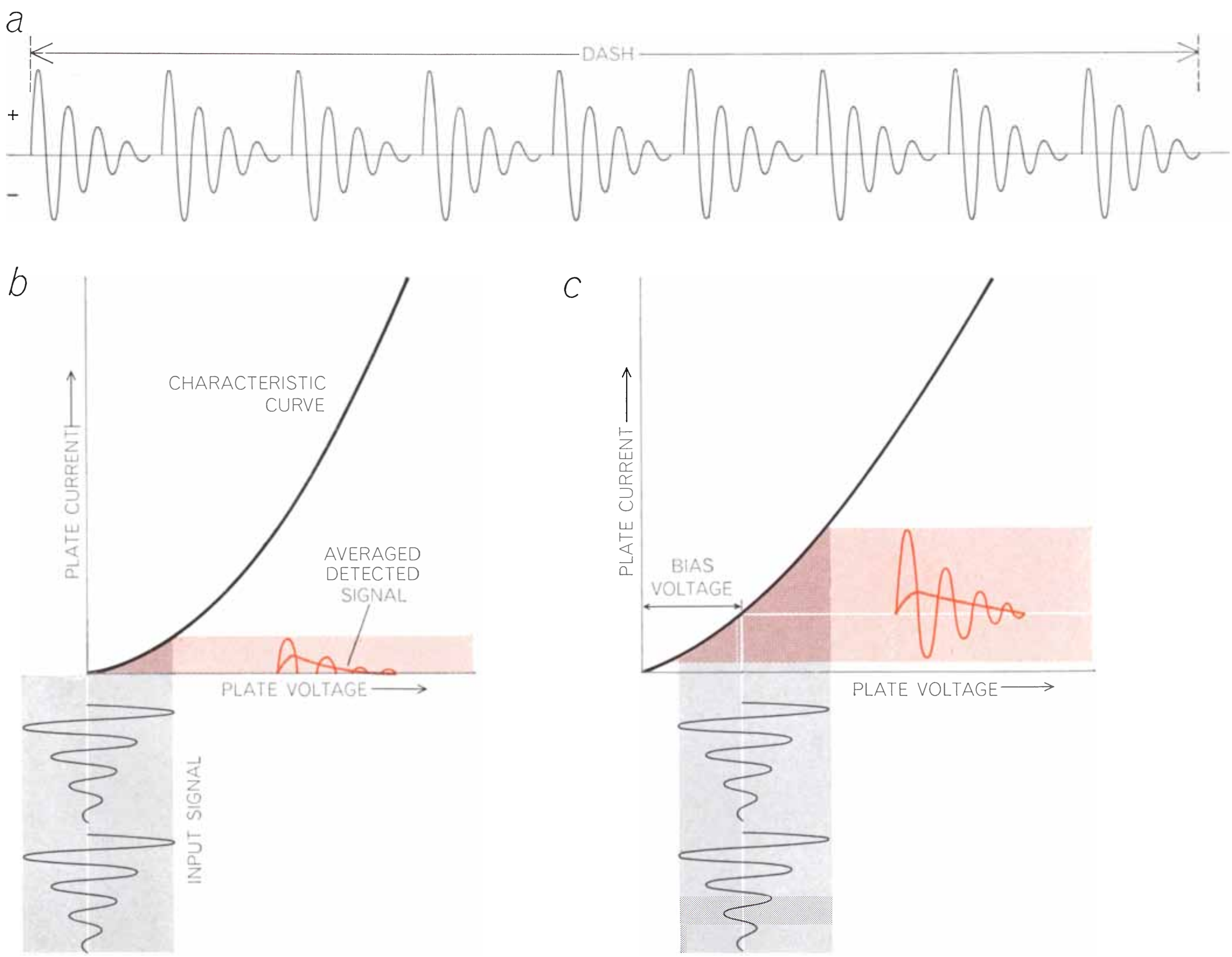
DE FOREST'S DIODE of 1906 had a telephone receiver for an indicator and added a battery (*H*) to the plate circuit. The battery served to maintain a positive "bias" on the plate.

He had followed up the idea by developing detectors in which the ends of platinum wires were placed in the flame of a Bunsen burner. The recurring theme in the patent applications for these devices in 1905 and 1906 was that the wireless signal oscillations were being applied to "a gas maintained in a state of molecular and ionic activity," "a sensitive gaseous conducting medium" or "a heated gas."

De Forest made the transition from gas flame to thermionic diode in these words: "Inasmuch as the gases ionize more readily at lower heats and are in their most mobile, delicate and sensitive conditions in vacuum, it seemed to me certain after experiments with the flame that the attenuated and ionized gases around an incandescent filament would undergo very considerable changes when subjected to hertzian oscillations." This is somewhat lyrical but it is illogical and technically meaningless. It epitomizes De Forest's lifelong aversion to the precision of technical language. His staunch loyalty to the mystical idea of a "sensitive gaseous conducting medium" kept him from appreciating the fundamental electronic basis of the thermionic diode and triode until long after it was generally accepted.

In his second claim De Forest insisted that the addition of a battery in the plate circuit, with the positive terminal to the plate, converted the detector to a mode of operation totally different from the rectifying action of the Fleming valve. It was now, he said, "a so-called 'trigger' or genuine relay." He had in mind the old coherer, which was in fact such a device: the low-power wireless signal "triggered" a change in the resistance of the metal filings and the local battery then supplied a much larger power to the indicator circuit.

It does seem plausible, as one looks at De Forest's patent drawing, that the antenna-to-ground wireless signal across the diode might change conditions inside the bulb and so trigger a sizable current from the battery through the diode and the telephone. Analysis makes it clear that this does not happen, and that the device is purely a rectifier. The battery does no more than maintain a bias voltage on the plate, shifting the diode's action from rectification by unilateral conduction to rectification by



RECTIFICATION changes an oscillating high-frequency signal into a detectable direct-current signal. In wireless telegraphy the signal from the antenna is in the form of sequences of damped oscillations (*a*). The detection process is shown graphically in the lower diagrams; the "characteristic curve" shows how input voltage is related to magnitude of output current. In the Fleming valve only the positive half of each wave applied to the plate produces an output current, which is then "averaged" by the mechanical inertia of the diaphragm or meter needle (*b*). In De Forest's diode a "forward bias voltage" keeps the plate always positive; the asymmetric relation between input voltage and output current distorts the output to yield a detectable averaged signal (*c*). In the triode detector the signal is impressed not on the plate but on a grid of closely spaced wires placed near the filament, between it and the

"curvature of the characteristic." The response to the positive portions of the signal is greater than with zero bias but is partly offset by a reverse response to the negative portions [*see "c" in illustration on these two pages*].

The fact is that a thermionic diode generally detects small signals best when it has no bias or even a small negative bias; Fleming had chosen the latter condition by connecting his plate electrode to the negative side of the filament. (Crystal or electrolytic detectors, which also work by rectifying, do often perform best with positive bias.) Moreover, in all simple rectifying detectors, whether they are supplied with forward or reverse bias or with no bias at all, all of the signal power that reaches the telephone or other indicator

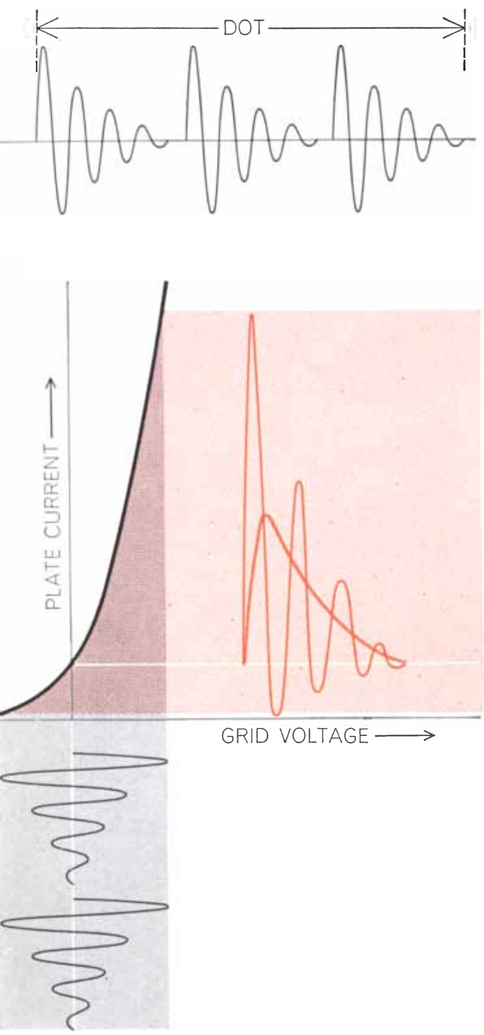


plate. If the grid is properly designed and located, the plate current is more responsive to signals on the grid than it would be to signals on the plate: the characteristic curve is steeper. For this and other reasons (*see illustration on next page*) output power can be greater than input power (*d*).

comes from the input signal at the antenna.

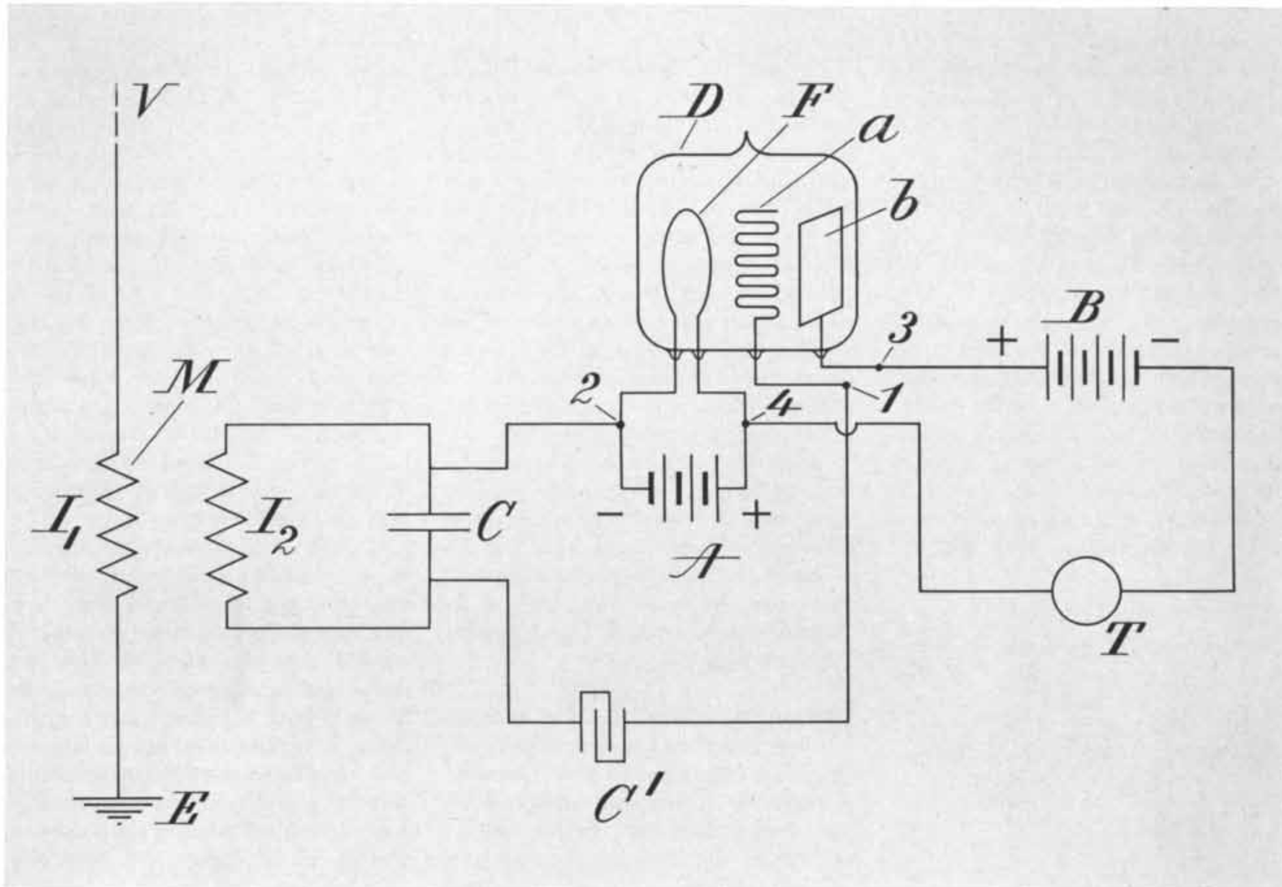
The forward-biased thermionic diode, then, had no practical value; it was never put to commercial use. It was of historical significance, however; in spite of the fallaciousness of De Forest's reasoning it seems clear that he was indeed pursuing the elusive "trigger action" when he created the triode late in 1906. He said later that he was also trying to overcome an apparent weakness of the diode circuit: a portion of the wireless signal from the antenna was able "to pass to earth through the telephone and battery circuit instead of concentrating . . . upon the ions between the plate and filament." Again the idea seems to make sense, but De Forest had described in his very first patent application how the detector could be isolated from the battery circuit by small choke coils as in Marconi's early receiver [*see top illustration on page 94*].

Driven by wishful thinking and the urge to solve a nonexistent problem, De Forest experimented with a number of different electrode configurations that would allow the wireless signals to "trigger" the "sensitive gaseous conducting medium" and would also keep them out of the telephone-battery circuit. He applied for patents on a variety of such designs during 1905 and 1906. All of them were "triodes": they each had a third electrode of some kind, to which the incoming signal was connected instead of being connected to the plate. All these models were highly inefficient, although they may have detected very strong signals. Finally De Forest decided he got the best results with an extra electrode in the form of an open grid of fine wire located between the filament and the plate. He filed a patent application for this grid-triode detector in January, 1907, and received his patent in 1908. The input was connected to the grid and the telephone receiver was actuated by variations of the current in the plate circuit [*see illustration on next page*].

De Forest's legend of the triode insists that each step in his experiments brought a marked improvement and that he immediately found the grid-triode to be the most sensitive device of all. The fact is that all the versions except the final grid-triode must have been extremely poor detectors. The impression, implicit in popular accounts and nurtured by De Forest, that the grid-triode was immediately recognized as a miraculous achievement is also contradicted by a number of facts. In 1908 one of De Forest's assistants wrote in a *Modern Electronics* article that "the audion [a name De Forest applied indiscriminately to all his diodes and triodes] in its present form is quite unreliable and entirely too complex to be properly handled by the usual wireless operator." In 1910 tests at the National Bureau of Standards gave a somewhat more favorable verdict: the triode was declared to be about 50 percent more sensitive than the electrolytic detector, with the crystal rectifier and other detector types only slightly behind. In practical communications a superiority of 50 percent is barely perceptible, but De Forest found the result pleasing enough to proclaim it in his advertising years later.

Modern measurements on some of the early triodes show that as detectors they were not much better than diode rectifiers. If De Forest had ever experimented with variations in the size, shape and spacing of the electrodes, he could have achieved great improvements in performance, but he seems to have considered the 1906 audion essentially a completed invention, and he made no contribution to the important changes in its design that eventually occurred. As late as 1916, when a would-be competitor marketed a triode of radically different but incredibly inefficient geometry, De Forest's uncritical response was to manufacture a duplicate of the inferior device, even though Western Electric and the General Electric Company had by that time developed greatly improved tubes based on better understanding of fundamental design principles.

There is ample evidence that the early triode was no great commercial success. During 1909 and 1910 De Forest manufactured and sold a variety of radio-equipment products, but in his advertising he mentioned the audion either not at all or only as one among many minor items. In 1912 he allowed his British patent to lapse for nonpayment of a $125 renewal fee. W. J. McCandless, who in his New York City plant manufactured all the triodes produced in the U.S. until 1913, reviewed his early records some years ago. It appears that he had turned out only about 200 to 300 triodes a year up to 1910, after which the annual output rose to about 600. These figures represent a very small percentage of the estimated number of commercial and amateur wireless stations in the country during those years, indicating that other devices, primarily the crystal and electrolytic detectors, were far more popu-



TRIODE-DETECTOR CIRCUIT, redrawn from De Forest's patent application of 1907, shows a grid (*a*) between the filament (*F*) and the plate (*b*). De Forest's grids did not provide much increase in power of the kind described on the preceding page. He did find, however, that connecting condenser *C′* in the circuit improved the tube's sensitivity. In 1914 Edwin H. Armstrong showed that this improvement was the result of a charge-storage effect that increased the variations in the voltage delivered to the grid.

lar than the expensive and short-lived triode.

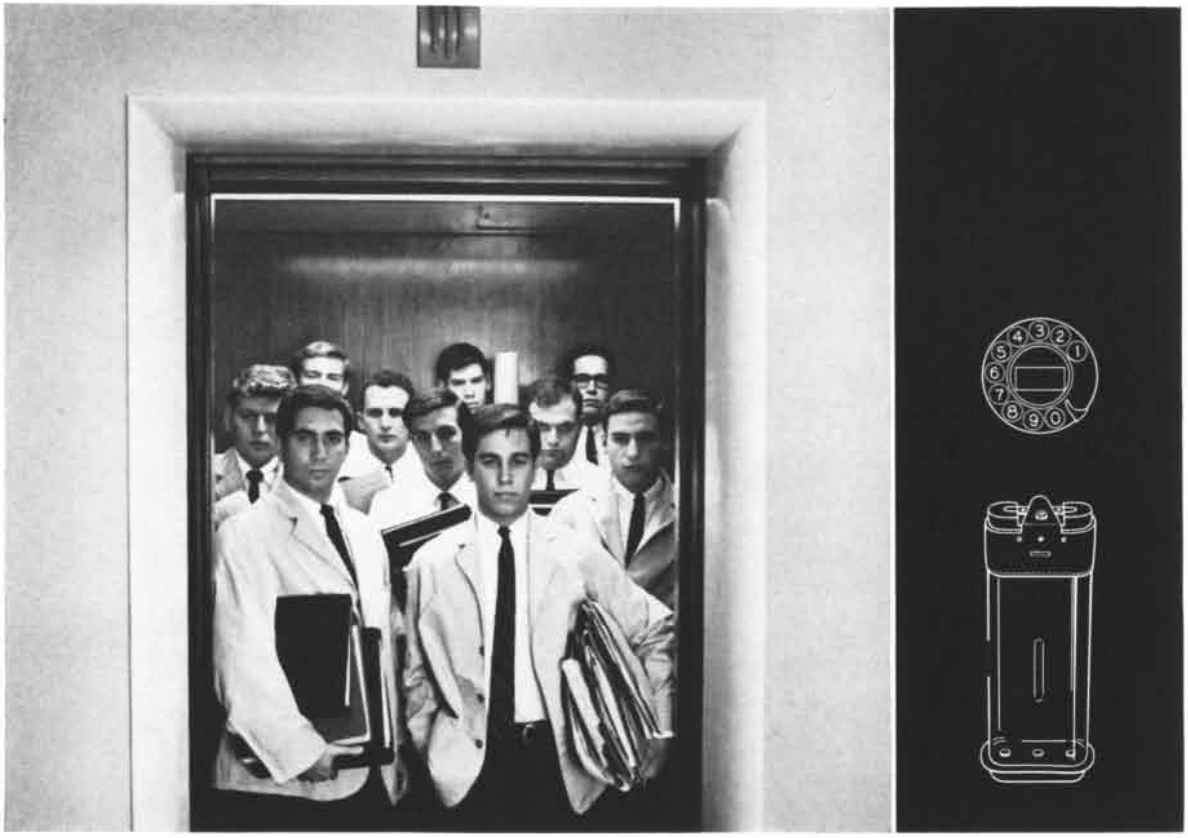
In summary, the first stage in the history of the triode vacuum tube, in which it was a detector of radio signals, is entirely De Forest's. He invented the device in the cut-and-try sense of the word and with no scientific understanding of what he was doing. All of the few thousand triodes produced in this country before 1913 were manufactured under his authority and to his designs. Yet to most of the wireless operators of the time the triode was just another detector, sometimes better but often worse than other detectors. The invention of the triode detector as such would never have brought De Forest the lasting fame or the riches he craved.

The second stage of triode history began in 1912. For years telephone engineers had been seeking a "repeater," or amplifier, for voice signals; without such a device it appeared that transcontinental telephone service might never be possible. Always quick to sense a commercial possibility, De Forest filed a patent application as early as June, 1907, for a "System for Amplifying Feeble Electric Currents." The circuit included triodes but they served only as detectors, and the device did not actually amplify.

The discovery that the triode could perform the function of amplifying voice-frequency signals was made independently by De Forest in 1912 and by a number of other scientists and inventors in at least three countries during 1912 and 1913. Several of these experimenters made two additional discoveries. The first was that triode circuits could amplify high-frequency radio signals as well as voice frequencies; the second was that if the output of an amplifier was fed back into its own input, the circuit could become a self-sustaining oscillator, or generator of electrical signals, and therefore a radio transmitter.

The U.S. courts took more than 20 years to decide who should be awarded patent priority for these valuable new triode circuit inventions. In 1934 they finally declared De Forest the winner, dating his inventions in the late summer of 1912. This decision established De Forest as the inventor not only of the triode as an assembly of parts but also of its principal applications; it is the justification for his eminent position among U.S. inventors.

The discovery of the amplification and oscillation functions of the triode marks the beginning of the modern age of electronics, but De Forest played no large part in the development of that age. Major industrial laboratories took over, and in less than three years De Forest's crude, erratic and gassy triode, which had changed little since 1906, was transformed into a variety of reliable, efficient and powerful forms so useful for communication that more than a million tubes were manufactured for military purposes in World War I. De Forest's patent position and his production facilities earned him a modest portion of the war contracts, but he made no further creative contributions to the development of his great invention.



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Computer Experiments in Fluid Dynamics

The fundamental behavior of fluids has traditionally been studied in tanks and wind tunnels. The capacities of the modern computer make it possible to do subtler experiments on the computer alone

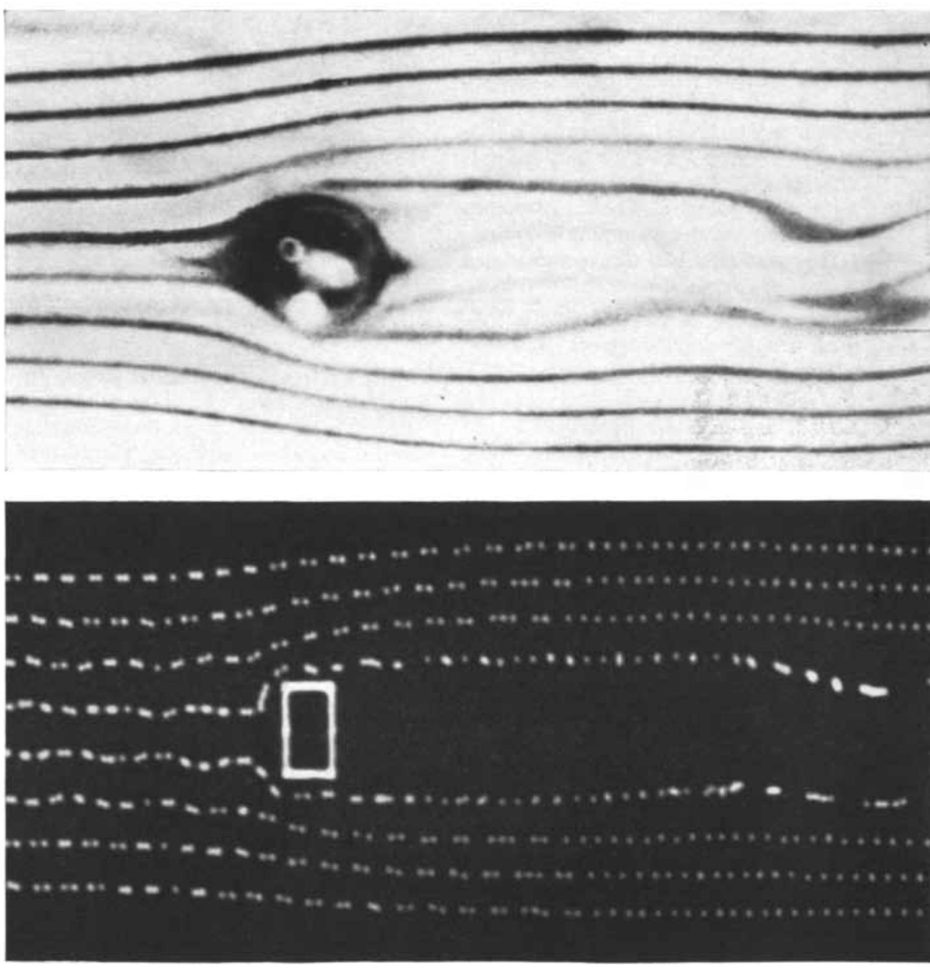
by Francis H. Harlow and Jacob E. Fromm

The natural philosophers of ancient Greece liked to do experiments in their heads. Centuries later Galileo developed the "thought" experiment into a fruitful method of inquiry and in our own time the method appealed strongly to such men as Albert Einstein and Enrico Fermi. Now the arrival of the modern electronic computer has made the method immensely more powerful and versatile. The computer makes it possible to simulate nature with numerical models and to investigate it in ways that have never been practicable before. Physical processes of enormous complexity are being examined minutely and with considerable realism. New hypotheses are being proved true or false. In physics, engineering, economics and even anthropology the computer has become a revolutionary tool.

One of the great attractions of experiment by computer is that it can avoid some of the uncertainties of measurement. Moreover, it provides a technique that can be classed as both theoretical and experimental. It is theoretical because it deals with abstract (that is, mathematical) statements of how things relate to one another. It is experimental because the computer is given only data specifying the initial state of a system and a set of rules for calculating its state at some time in the future. The computer worker has no more idea how this future state will unfold than has the traditional worker who conducts a comparable experiment in an actual laboratory. To demonstrate the power of computer experiments we have chosen a single example involving the dynamic behavior of fluids. The particular experiment is a study of the flow of air past a rectangular rod.

At first thought the use of a computer for calculating this flow may seem to be a needlessly roundabout procedure. Would it not be simpler and more enlightening to put the rod in a wind tunnel and observe how air containing filaments of smoke flows around it? Actually it would not. For many of the questions to be investigated the physical experiment would be more complicated and costly, and it would not provide as much information as the experiment by computer.

For an example one can point to the problem of redesigning the Tacoma Narrows Bridge after it had been shaken to pieces by wind-induced vibrations soon after it was built. For the rebuilding of the bridge many elaborate models



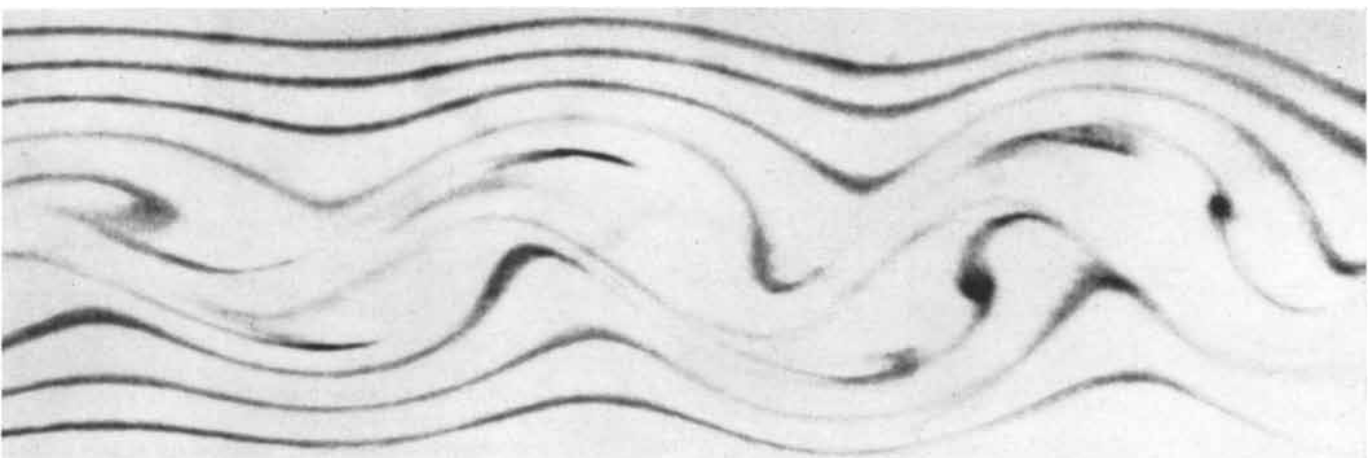
VORTEX EXPERIMENT with a fluid is compared with a similar computer experiment using a mathematical model. In a tank dark lines of dye within a moving body of water (*top*) flow past a cylindrical obstacle; the water's velocity is great enough to disrupt lamiwere made and tested again and again before a safe design was finally developed. Without doubt much of the cost and time spent on the problem could have been saved by computer calculations if the computers and appropriate numerical techniques had then been available. Experiments with numerical models can show the interaction of winds and a bridge in detail and produce answers in far less time than it takes to prepare a physical experiment. The Soviet physicist A. A. Dorodnitsyn has remarked about such problems that computer calculation "can give a solution that is not only more rapid and cheaper but also more accurate" than the physical experiment itself.

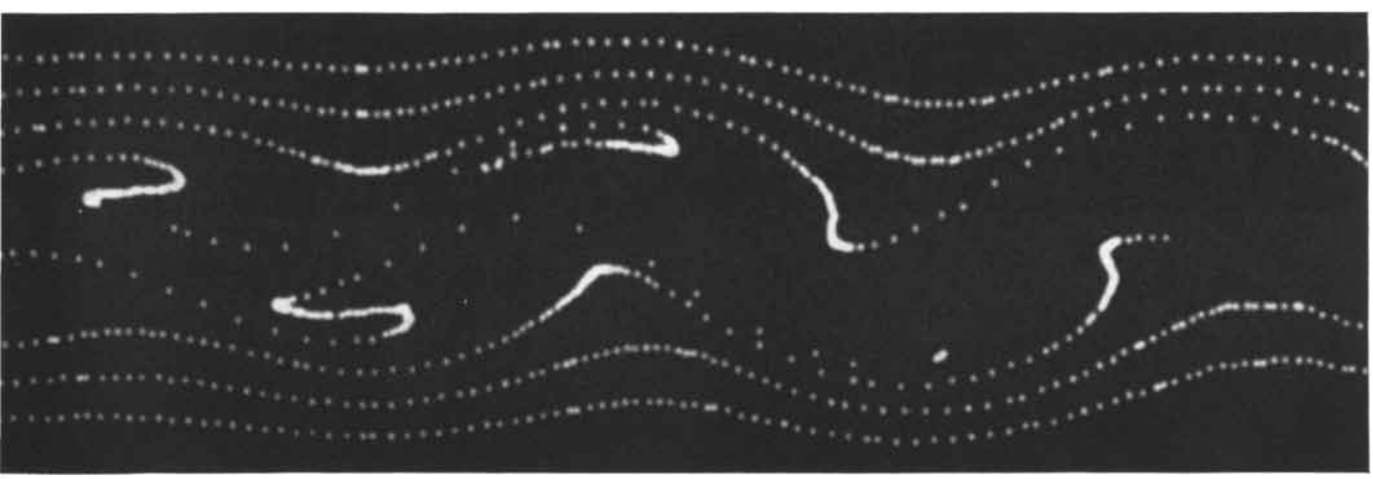
Experimentation by computer also allows the investigation of many phenomena that are either inaccessible to direct study or involve factors that cannot be measured accurately. In the flow problem that we shall discuss, for example, it is difficult to measure directly in a wind tunnel the temperature distribution in the complicated downstream wake. Computer experiments, however, can yield a reliable description of the temperature distribution.

Another benefit of a computer experiment is that it usually affords far better control of the experimental conditions than is possible in a physical experiment. In wind tunnel studies, for instance, the experimenter must modify his interpretations to include the consideration of such effects as those due to the compressibility of the working fluid, variations in fluid viscosity and uncertainties in flow velocity. In a computer experiment such properties often can be excluded or included at will. Moreover, the computer program can isolate crucial features for examination, can eliminate irrelevant factors and can often assess the experimental uncertainties.

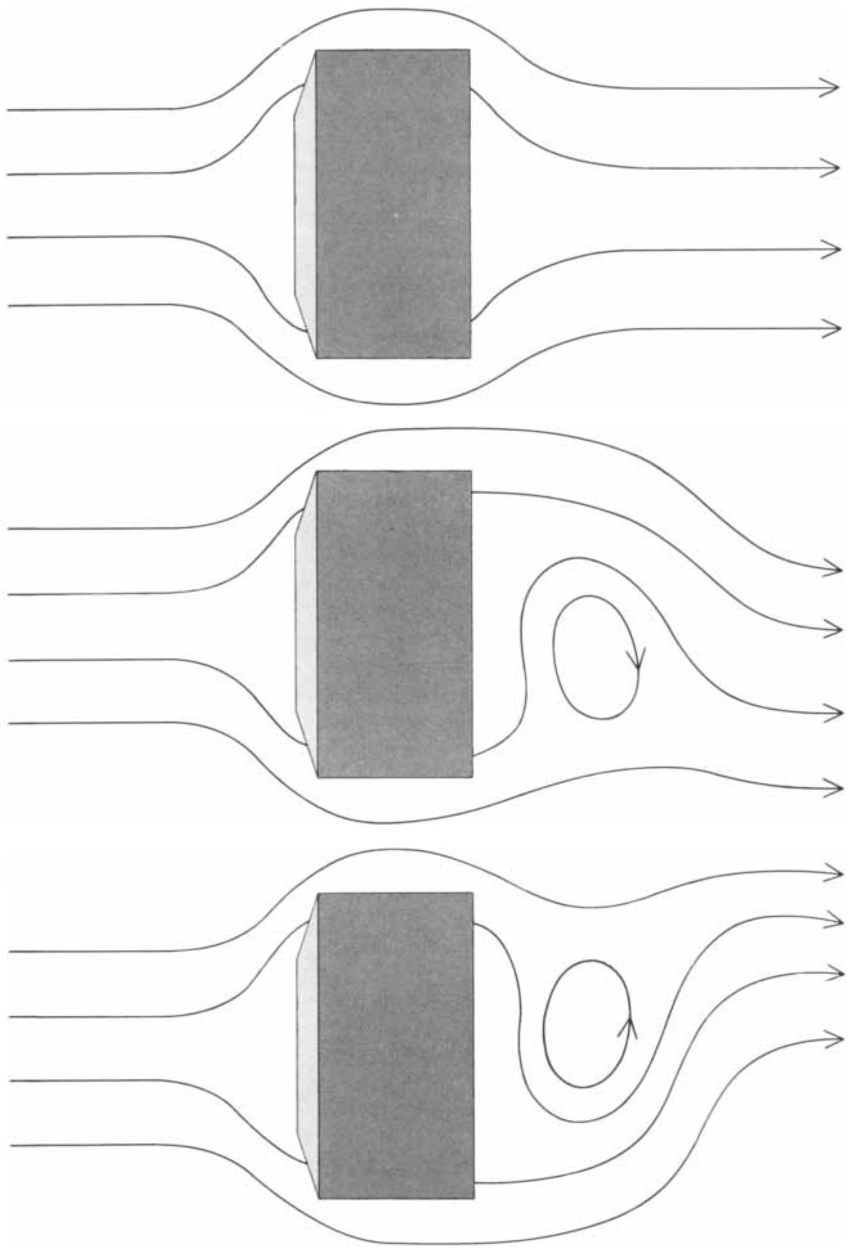
Finally, and most importantly, experiments by computer provide a test of the applicability of theory to the complicated phenomena under investigation. Do the equations of fluid dynamics really represent the correct theoretical description when applied to phenomena as complicated, say, as the oscillatory flow that develops in the wake of a rectangular rod? For such problems the mathematician would like to obtain what he calls an analytical solution—the kind of exact solution that can be obtained by the processes of mathematical analysis. For problems in fluid dynamics, however, the necessary mathematical techniques for obtaining the complete solution have not yet been developed. The detailed results provided by a computer can actually help in the development of analytical solutions to the basic equations of fluid dynamics. Usually in the mathematical model of a complex problem some of the factors can only be approximated, and obtaining a realistic solution depends on finding out which features are crucial for a reasonable representation. With the help of computer experiments one tries to discover workable approximations that will simplify the mathematics needed to solve complicated problems—in this case a problem in oscillatory fluid flow.

The reader will find the "computer





nar flow and generate a characteristic double row of vortices. In the computer experiment (*bottom*) comparable marker lines are simulated and their motions are recorded on microfilm; although the obstacle is a rectangle rather than a cylinder, the real and model patterns show close agreement. The dye-line experiment was performed by Alexander Thom of the University of Oxford.



CLASSIC PROBLEM in fluid dynamics is to predict the progression from orderly laminar flow past an obstacle at slow speed (*top illustration*) to total turbulence at high speed. A crucial midpoint in this progression is reached when vortices form alternately at opposite edges of the obstacle (*middle and bottom illustrations*) and then are shed downstream.

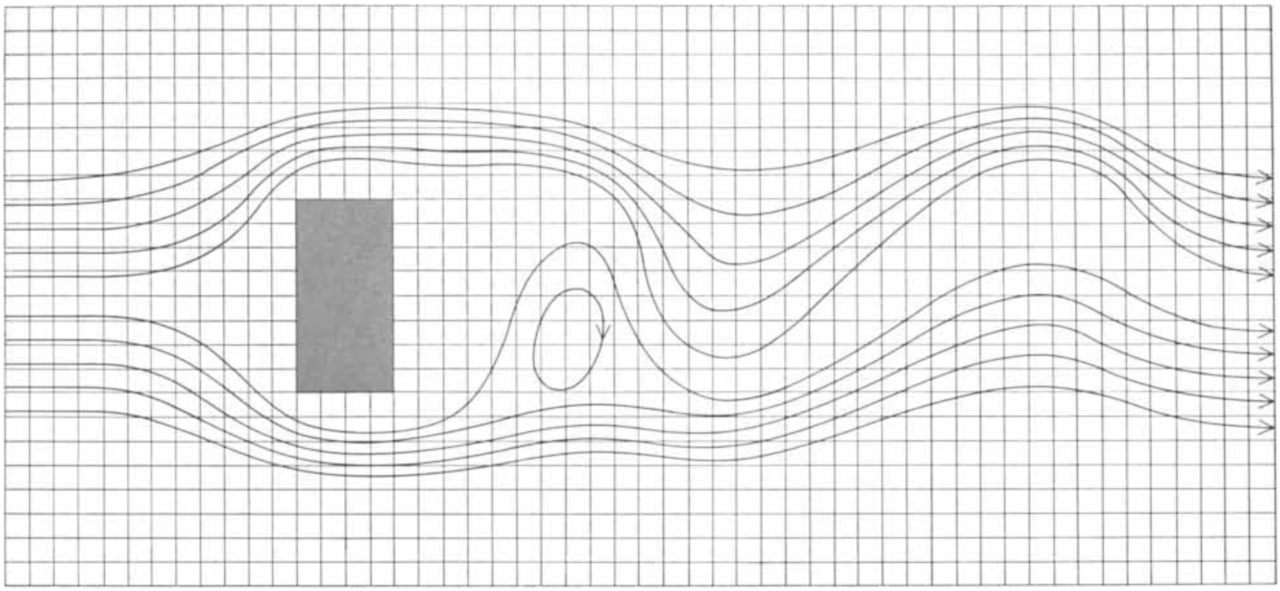
wind tunnel" experiment easier to follow if we consider briefly how a fluid behaves when it flows around a fixed object such as a rectangular rod. At low speed the airflow is smooth and steady, a condition described as laminar flow. At a certain critical speed, which depends on the size of the rod, the laminar flow breaks down. For a rod one inch in height the critical speed in air is about one inch per second; the smaller the rod, the higher the speed at which turbulence begins. If the fluid is more viscous than air, laminar flow is more easily maintained and the critical speed for turbulence becomes higher.

Above the critical speed the airstream breaks up into vortices that are similar to the small whirlpools seen when a cup of coffee is stirred. These vortices are shed alternately from the top and bottom of the object placed in the airstream. This oscillating wake was first extensively studied by the aerodynamicist Theodor von Kármán and is known as a "von Kármán vortex street." The oscillating wake sends out pulses that react back on the object itself. The vibration so produced is responsible for the sound made by a golf club swung rapidly through the air and for the whine of a ship's rigging in the wind. It was resonant vibration produced by the wind that caused the Tacoma Narrows Bridge to break and fall into the bay. As the air speed increases, the vortices in the vortex street become more and more ragged and eventually break up into tiny eddies whose motion is almost entirely random. At this stage fully developed turbulence has been reached.

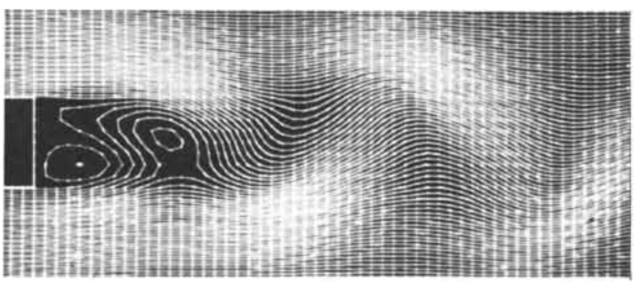
The known patterns of air motion past an object, then, give us certain definite phenomena to look for in the computer experiments. If the computer reproduces a vortex street and, at a later stage, turbulence, it will show that the theoretical understanding of fluid dynamics is accurate and therefore can be relied on to predict what will happen when a fluid flows past objects of various shapes and at various speeds.

To set up the calculational experiment we must first translate the physical situation into the language of numbers for the computer. For bookkeeping purposes the experimental area in the computer wind tunnel is divided into many square cells, which form the basic computing mesh. A typical mesh requires at least 49 cells in the direction of horizontal flow and 24 cells in the vertical dimension, for a total of 1,176 cells. Each cell must contain two numbers representing the components of average air velocity in two directions, together with other numbers representing such variable quantities as "vorticity," "stream function" and, if heat flow is desired, temperature as well. Finally, the computer must be supplied with a set of operating instructions, or "code," that spells out in detail exactly how the computer must manipulate every number in every cell in order to calculate how the flow configuration will change from instant to instant. It can require billions of mathematical operations and anywhere from a few minutes to a few hours of computing time to carry out the calculations needed to represent the flow of air for a time interval of several minutes. In our studies we have used either an IBM 7090 computer or the somewhat faster machine, also built by the International Business Machines Corporation, known as Stretch.

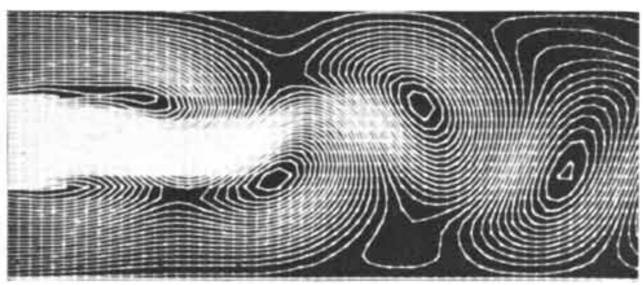
The actual development of a successful code is a time-consuming process and is carried out in three steps. The first involves the testing of detailed numerical methods and is strewn with pitfalls. It is no trick, for example, to invent methods that develop numerical instability: the computer results rapidly



BASIC COMPUTING MESH for a mathematical wind tunnel is a grid of 1,176 individual cells, arrayed in rows 49 cells long and 24 cells wide. The obstacle, twice as high as it is deep, is located 12 cells away from the input flow at the left margin of the mesh. At the start of an experiment each cell is programmed with a minimum of two numbers, which represent the horizontal and vertical components of the average air velocity at that point in space. The cells can also be programmed to contain numerical notations for additional variables such as heat flow, vorticity and stream function. During the run of a calculation the computer must carry out billions of mathematical operations in order to determine how the flow configuration varies. In this example the flow of air past the obstacle has reached the critical speed at which alternating vortices are formed (*see illustration on opposite page*).

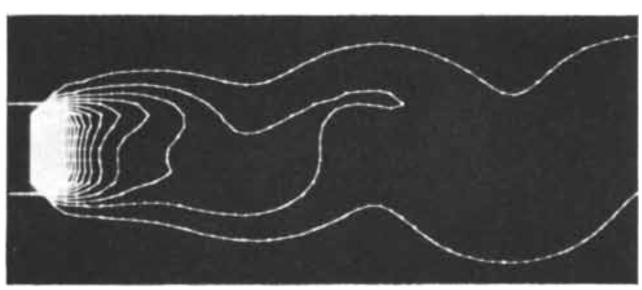


SIMULATED MOTION OF AIR past an obstacle (*extreme left*) that is stationary with respect to the observer produces a plot of swirling streamlines. The course of each line parallels the direction of the adjacent air current's flow; the narrower the spacing between lines, the higher the speed. This is one of four plots that show different data from the same instant in a single experiment.

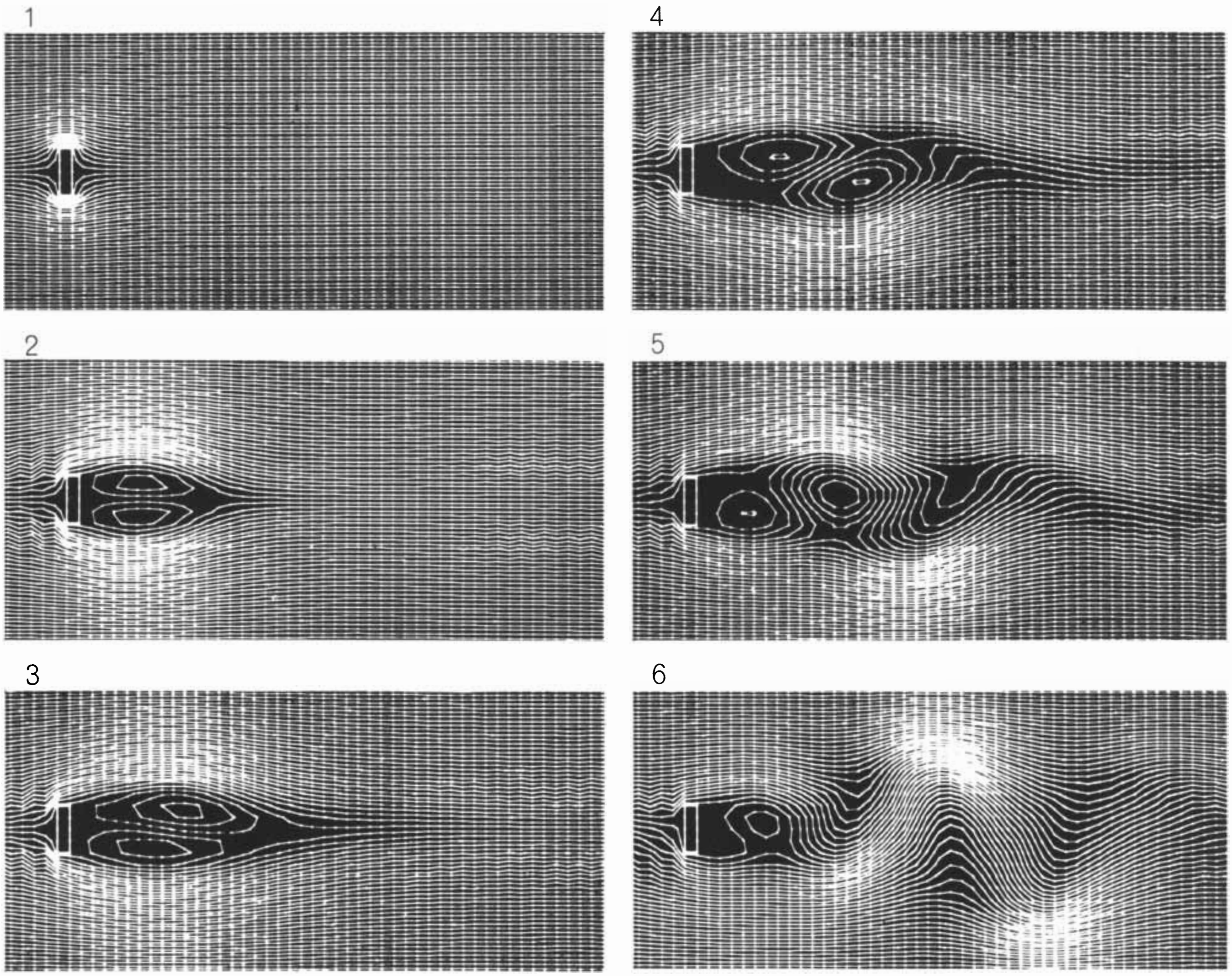


SIMULATED MOTION OF OBSTACLE through a body of still air, although mathematically identical with the situation illustrated at the left, produces a quite different streamline plot. In this instance the air mass rather than the obstacle is stationary with respect to the observer; the pattern of vortices traced by the streamlines resembles the turbulence in the wake of a passing ship.

STREAK-LINE PLOT is a third kind of configuration possible in computer experiments. In this case, indicator numbers that do not play any part in the flow calculations have been inserted in four cells of the computer mesh at the rear of the obstacle. These numbers become "computational particles" that trace out the downwind eddies in streaks, as do smoke filaments in a wind tunnel.



ISOTHERM PLOT provides a fourth example of the data that can be obtained by means of computer experiments. A set of temperature values simulating a heated body has been inserted in the eight cells along the rear of the obstacle. As the flow of air passes downwind the computer calculates the rate at which the heat is conducted; the lines connect points of equal reduction in temperature.

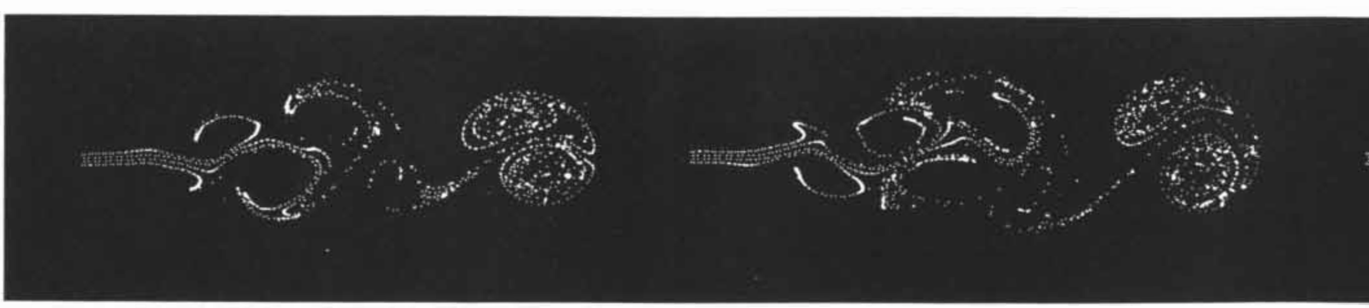


DEVELOPMENT OF A VORTEX STREET is documented in six consecutive streamline plots (*left and center illustrations, top to bottom*). The laminar flow at the outset (*1*) quickly changes to a stable pair of eddies behind the obstacle (*2*). The stability ends when one or another of the eddies begins to grow. The larger eddy shifts position both downstream and toward the center line, thus pushing the smaller, upstream eddy out of its normal position (*3 and 4*). The upstream eddy is now exposed to acceleration both by

run askew and lead to complete nonsense. Like physical experiments, computer experiments are also subject to interference by gremlins. Just as the vibration of a motor may produce extraneous turbulence in a wind tunnel, so the numerical approximations fed into a computer may lead to equally unwanted "truncation turbulence."

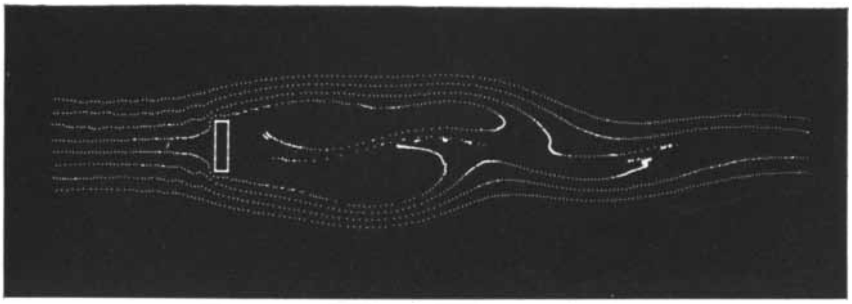
The second step is to prepare a full-scale code. For our problem in fluid dynamics this required many months, most of them consumed by "debugging," or ferreting out errors in, the step-by-step instructions. Such a code is written with sufficient generality so that it can be used to solve a wide variety of roughly similar problems. Thus a good code can be used for years and will often be a source of inspiration for workers in other laboratories.

The third step is to formulate the code in terms of a specific problem. In our oscillating-wake study an important part of the formulation was to determine the "initial" and "boundary" conditions. The initial condition describes the state



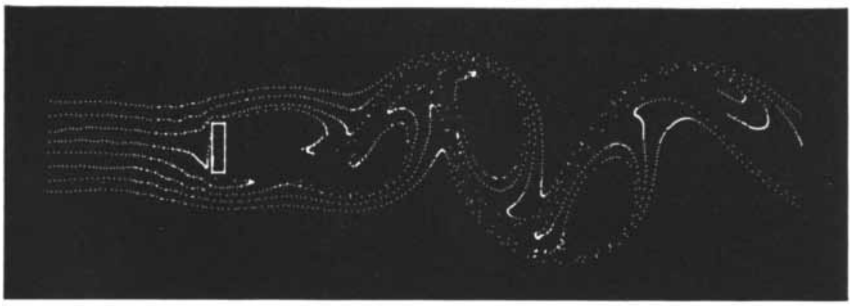
SEQUENCE OF STREAK LINES traces the transformation of a jet of air as turbulence progressively increases (*four steps from left to right*). In this experiment computational particles are introduced through a single cell (*horizontal streaks*), as though squirting

a



b

c



the main stream and by the reverse currents of the downstream eddy (*4*) and begins to grow in its turn. Soon the growing upstream eddy pinches off the downstream one, which is then shed as a vortex while a new eddy forms behind the obstacle (*5 and 6*). The streak-line plots ("*a*," "*b*" *and* "*c*" *at right*) outline the formation of the vortices during stages *4*, *5* and *6*.

of the air at the start of the computation. We could have assumed, for example, that the air was at rest, corresponding to the condition in a real wind tunnel before the fan is turned on. We found that it was simpler, however, to start with the fluid behaving as if it were flowing past the rod in a simple laminar manner without viscosity.

The boundary conditions refer to what is happening at the edges of the computational mesh. Our decision was to have the top and bottom edges represent the walls of the wind tunnel and to have the left edge represent an air input of uniform flow. The right edge gave us more trouble, but we finally arranged for the fluid to flow out and back into the computing region in a way that created a minimum of mathematical disturbance.

The computing process itself can be compared to the making of a motion picture. Starting with the initial conditions prescribed for each of the 1,176 cells in "frame" No. 1, the computer follows the coded instructions to determine the conditions in each cell a brief instant of time later, thereby producing frame No. 2 of the film. Each successive frame is similarly generated on the basis of numerical data computed for the preceding frame. The fastest computer available to us, Stretch, can generate about 10 frames a minute. When the calculation has proceeded far enough, the results are gathered up for study.

The computer's results can be presented in any of several different forms. One form of print-out consists of all the numbers describing the flow in each frame. Usually this form of print-out is restricted to samplings taken at selected intervals, because the complete data for every one of the hundreds or thousands of cycles in an experiment would be far too much for an analyst to digest, to say nothing of storing the reams of paper. Sometimes the computer is programmed to print certain calculations that supply particular points of information, such as the amount of air drag caused by the obstacle at specific wind speeds. The most useful and popular type of print-out, however, is the actual plotting of the flow in pictorial form.

The computer itself can generate plots of the flow configurations and put them on film by means of a microfilm recorder. Several selected frames from such recordings, exactly as they came from the computer, are among the illustrations on this page and preceding pages of this article. The sequence of all the frames of an experiment, combined in a film strip and run through a motion-

colored water into a clear tank. The jet of air is unstable and soon breaks into expanding, irregular vortices like those exhibited by a plume of smoke. Similar but far more complex experiments can be used to test theories about aircraft jet engine noise suppression.

picture projector, gives a very vivid picture of the development of vortices and other features as a fluid flows around an obstacle.

From the numbers describing the flow in each cell of the computing mesh, the computer generates streamlines that show both the direction and the speed of flow throughout the space. The speed is indicated by the spacing between the streamlines: where the lines are close together the flow is fast; where they are farther apart the flow is slower. The computer can show the streamline patterns in either of two ways: as if a camera were photographing a stream of air flowing past it or as if the camera were moving along with the stream. The latter view shows the pattern of vortices in clear detail.

The computer can even simulate the motion of markers often used to make flow visible, such as filaments of smoke in air or of dye in water. In the computer the markers consist of "computational particles." At certain desired points in the computation these particles are thrown in (the magic of the computer allows their creation anywhere at will) and thereafter they are carried along wherever the flow of air goes. Their paths of motion produce lines called streak lines. The streak lines generated by the computer give a remarkably faithful impression of the behavior of smoke or dye filaments. Perhaps the most striking of these computer constructions is the configuration of streak lines emerging from a jet: it looks like a filament of cigarette smoke.

Usually the computer is programmed to furnish several different configuration plots, showing features of the flow from various points of view. These are by no means merely an interesting album of pictures. They show the qualitative features of the development of the flow and provide precise quantitative information about the flow at every point. In many cases the computer reveals important details that would be extremely difficult to obtain from physical experiments.

The example we have described of a computer technique for investigating fluid flow is only one of many successful efforts that have been made to carry out complex experiments by computer. Other workers have used computers to tell in detail what is going on inside a nuclear reactor and to assess in an instant the progress of a rocket soaring into space. Tomorrow the computer may give accurate forecasts of the weather, of the future of the economy and of the state of man's health.

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MATHEMATICAL GAMES

A new group of short problems and answers to last month's questions

by Martin Gardner

The following short problems are on the whole less difficult than those of a similar nature that have appeared from time to time in this department. The minimum solution of the last problem—the sliding-block puzzle—is not yet known, but it is a problem on which even the nonmathematically inclined will enjoy working, and in May or June I shall report on the best results that have been received. All the other problems will be answered next month.

1.

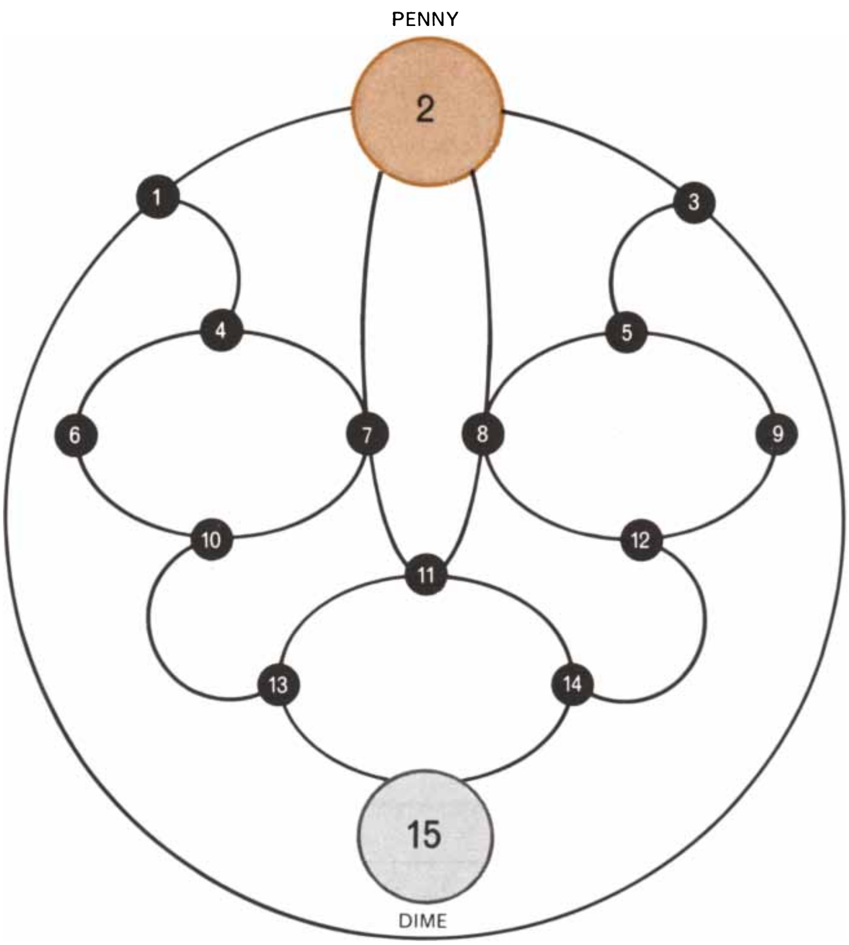
Who would have thought that the poet Samuel Taylor Coleridge would have been interested in recreational mathematics? Yet the first entry in the first volume of his private notebooks (published in 1957 by Pantheon Books) reads: "Think any number you like—double—add 12 to it—halve it—take away the original number—and there remains six." Several years later, in a newspaper article, Coleridge spoke of the value of this simple trick in teaching principles of arithmetic to the "very young."

The notebook's second entry is: "Go into an Orchard—in which there are three gates—thro' all of which you must pass—Take a certain number of apples—to the first man [presumably a man stands by each gate] I give half of that number & half an apple—to the 2nd [man I give] half of what remain & half an apple—to the third [man] half of what remain & half an apple—and yet I never cut one Apple."

How long will it take the reader to determine the smallest number of apples Coleridge could start with and fulfill all the stated conditions?

2.

Each end of a 10-foot length of rope is tied securely to a man's ankles. Without cutting or untying the rope, is it possible to remove his trousers, turn them inside out on the rope and put them back on correctly? Party guests should try to answer this confusing topological question before initiating any empirical tests.



Can the penny always trap the dime?

3.

The two-person game shown at the left has been designed to illustrate a principle that is often of decisive importance in the end games of checkers, chess and other mathematical board games. Place a penny on the spot numbered 2, a dime on spot 15. Players alternate turns, one moving the penny, the other the dime. Moves are made along a solid black line to an adjacent spot. The penny player always moves first. His object is to capture the dime by moving onto the spot occupied by the dime. To win he must do so before he makes his seventh move. If after six of his moves he has failed to catch the dime, he loses.

There is a simple strategy by which one player can always win. Can the reader discover it?

4.

Logic problems involving truth-tellers and liars are legion, but the following unusual variation—first called to my attention two years ago by Howard De Long of West Hartford, Conn.—has not to my knowledge yet been printed.

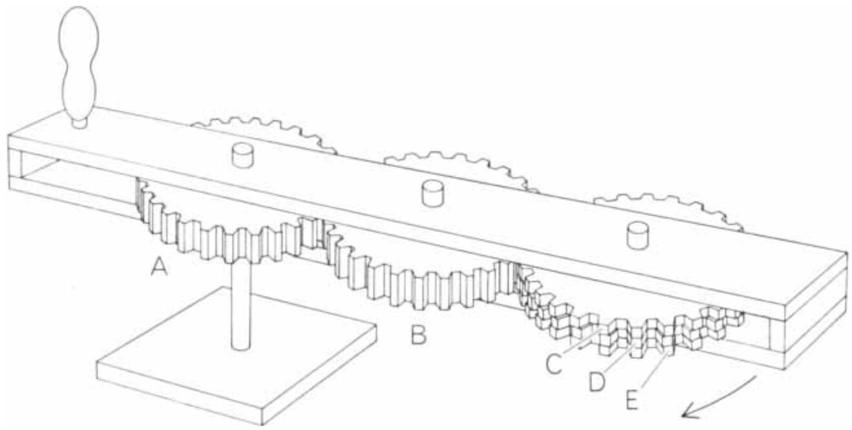
Three men stand before you. One always answers questions truthfully, one always responds with lies and one randomizes his answers, sometimes lying and sometimes not. You do not know which man does which, but the men themselves do. How can you identify all three men by asking three questions? Each question may be directed toward any man you choose, and each must be a question that is answered by "Yes" or "No."

5.

The mechanical device shown at the right was constructed by James Ferguson, an 18th-century Scottish astronomer well known in his time as a popular lecturer, author and inventor and for the remarkable fact that although he was a member of the Royal Society his formal schooling had consisted of no more than three months in grammar school. (One of his biographies is called *The Story of the Peasant-Boy Philosopher*.) His device is given here as a puzzle that, once solved, will be seen to be a most curious paradox.

Wheel *A* and its axis are firmly fixed so that wheel *A* cannot turn. When the device is rotated clockwise around wheel *A* by means of the handle, wheel *B* will of course rotate in the same direction. The teeth of *B* engage the teeth of three thinner wheels *C*, *D* and *E*, each of which turns independently. *A*, *B* and *E* each have 30 teeth. *C* has 29 teeth, *D* has 31. All wheels are of the same diameter.

As seen by someone looking down on the device as it is turned clockwise, each of the thin wheels *C*, *D* and *E* must turn on its axis (with respect to the observer) either clockwise, counterclockwise or not at all. Without constructing a model, describe the motion of each wheel. If the reader wishes to build a model eventually, it is not necessary that the wheels have the exact number of teeth given. It is only necessary that *A* and *E* have the same number of teeth, *C* at least one less and *D* at least one more.

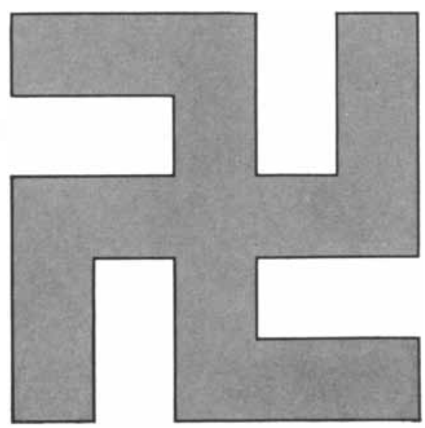


James Ferguson's gear paradox

6.

During World War II a gag problem that made the rounds was: How can you make a Nazi cross with five matches? One answer was "Push four of them in his ear and light them with the fifth." Here is a somewhat similar problem, although one that does not hinge on any kind of wordplay.

The reader is asked to take four cigarettes and eight sugar cubes, place them on a dark-surfaced table top and form the best possible replica of the Nazi swastika shown at the right. All 12 objects must be used and none must be damaged in any way.


Model for swastika

7.

According to a recent book by two prominent Soviet mathematicians, the following method of fortune-telling was once popular in certain rural areas of the U.S.S.R. A girl would hold in her fist six long blades of grass, the ends protruding above and below. Another girl would tie the six upper ends in pairs, choosing the pairs at random, and then tie the six lower ends in a like manner. If this produced one large ring, it indicated that the girl who did the tying would be married within a year.

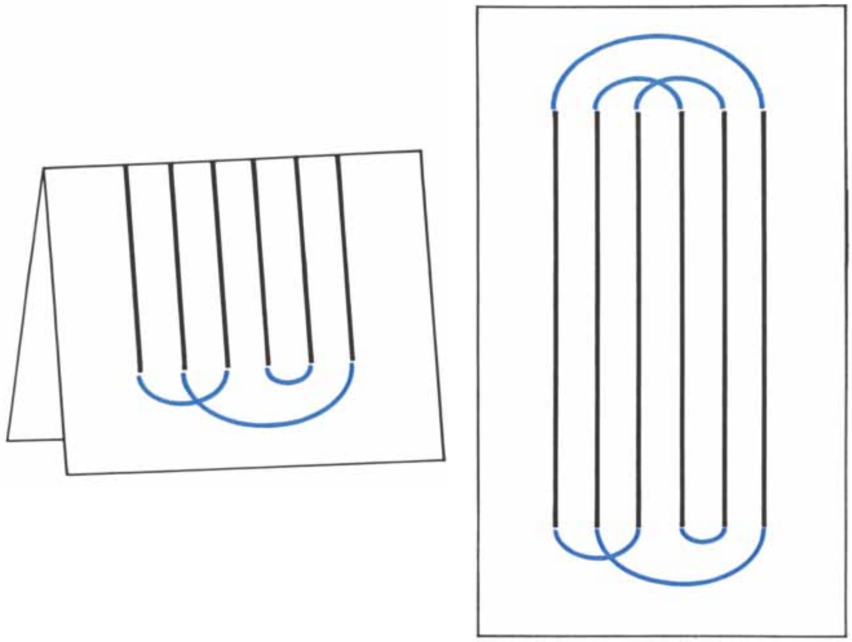
A pencil-and-paper betting game (a pleasant way to decide who pays for drinks) can be based on this procedure. Draw six vertical lines on a sheet of paper. The first player joins pairs of upper ends in any manner, then folds back the top of the paper to conceal the connecting lines from his opponent. The second player now joins pairs of bottom ends as shown at the left in the illustration at the top of the next page. The sheet is unfolded to see if the second player has won by forming one large closed loop. (The illustration at the right at the top of the next page shows such a win.) If even money is bet, whom does the game favor and what is his probability of winning?

8.

During a baseball game in Mudville, Casey was Mudville's lead-off batter. There were no substitutions or changes in the batting order of the nine Mudville men throughout the nine-inning game. It turned out that Casey came to bat in every inning. What is the least number of runs Mudville could have scored? Charles Vanden Eynden of the University of Arizona originated this amusing problem.

9.

Sam Loyd's well-known 14–15 Puzzle was last mentioned in this department in February, 1964, in a discussion of sliding-block puzzles. For all puzzles of this type, in which unit squares are shifted about inside a rectangle by virtue of a "hole" that is also a unit square, there is a quick parity check for determining if one pattern can be obtained from another. For example, on the simplest nontrivial square field shown at the bottom of the next page can the pattern at the left (with the blocks in descending order) be changed to the pattern at the right? To answer this we switch pairs of numbers (by removing and replacing blocks) until the desired pattern is achieved, counting the switches as we go along. This can be done in helter-skelter fashion, with no attempt at efficiency. If the number of switches is even (as it always will be



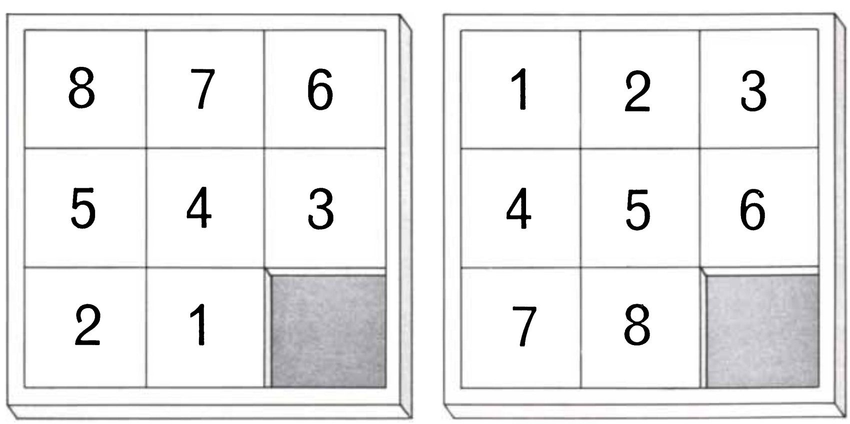
A pencil-and-paper betting game

in this case), the change by sliding is possible. Otherwise it is not.

But what is the *smallest* number of sliding moves sufficient to make this change? Surprisingly little work has been done on methods for minimizing such solutions. The problem given here —reversing the order of the digits—can be shown to require at least 26 moves. If each square takes the shortest path to its destination, 16 moves are used. But 4 and 5 are adjacent and cannot be exchanged in fewer than four moves, and the same reasoning applies to 3 and 6. This lifts the lower limit to 20. Two moves are lost by the opening move of 1 or 3 and two more by the last move of 8 or 6, since in each case a square must occupy a cell outside its shortest path. This raises the lower limit to 24. Finally, if one constructs a tree graph for opening lines of play, it is apparent that two more moves must be lost by the ninth move. The puzzle therefore cannot be solved in fewer than 26 moves. Because the hole returns to its original position, it can be shown that every solution will have an even number of moves.

The best solution on record (it is the solution to problem 253 in Henry Ernest Dudeney's posthumous collection, *Puzzles and Curious Problems*) requires 36 moves. Recorded as a chain of digits to show the order in which the pieces are moved, it is as follows: 12543 12376 12376 12375 48123 65765 84785 6. I have good reason to believe, however, that it can be done in fewer moves.

To work on the problem one can move small cardboard squares, numbered 1 through 8, on a field sketched



Change the pattern at the left to the one at the right on paper. I shall be grateful if readers who do better than Dudeney will send their solutions to me. I cannot reply to this mail, but I shall report on the best answers received.

Last month's problems having to do with tetrahedrons are answered as follows:

1. A regular tetrahedron cut by six planes, each passing through an edge and bisecting the opposite edge, will be sliced into 24 pieces. This is easily seen when one realizes that each face is dissected into six triangles, as in *a* in the illustration on page 117, each of which is the base of a tetrahedron with its apex at the model's center. (The problem was contributed by Harry Langman to *Scripta Mathematica* for March–June, 1951.)

2. Any paper triangle, if all its angles are acute, can be folded into a tetrahedron.

3. The bug's shortest path from A to B is 20 feet, as shown on the unfolded tetrahedron at b on page 117. This is shorter by .64+ feet than the shortest path that does not touch a third face.

4. Four is the largest number of spots that can be placed on a sphere so that every pair is the same distance apart. The spots mark the corners of an inscribed regular tetrahedron.

5. If one-inch regular tetrahedrons are sliced from the four corners of a two-inch regular tetrahedron, the remaining solid is a regular octahedron.

6. It is not possible to label the sides of a tetrahedron with four different numbers so that the sum of the three faces at each vertex is the same. Consider any two sides A and B. They meet side C at one vertex and side D at another. For the sums at both vertices to be constant the numbers on sides C and D would have to be the same, but this violates the condition that the four numbers must be different.

A proof (from Leo Moser) that the edges of a tetrahedron cannot be labeled with six different numbers to yield constant corner sums is a bit more involved. First label the edges as shown at c on page 117. Assume that the problem can be solved. Then $a + b + c = a + e + d$, therefore $b + c = e + d$. Similarly, $f + b + d = f + e + c$, therefore $b + d = e + c$. Add the two equations:

$$\begin{array}{c} b + c = e + d \\ b + d = e + c \\ \hline 2b + c + d = 2e + c + d\,. \end{array}$$

The sum reduces to $b = e$, which of

COMMUNI
TIONS

Massive radio transmitters to cut past the ''Bamboo Curtain'' with the message of freedom. ''Walkie-talkies'' to pierce the impenetrable jungle. ''Stand-still'' satellites to bring television from across the oceans. This is Hughes at work in communications.

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Groundstations are the vital earth-based "ears" of satellites. Plans are under way to build a satellite ground terminal in Arkansas. It can be used for research,






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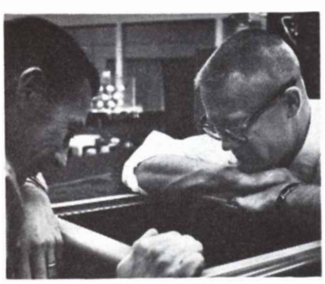

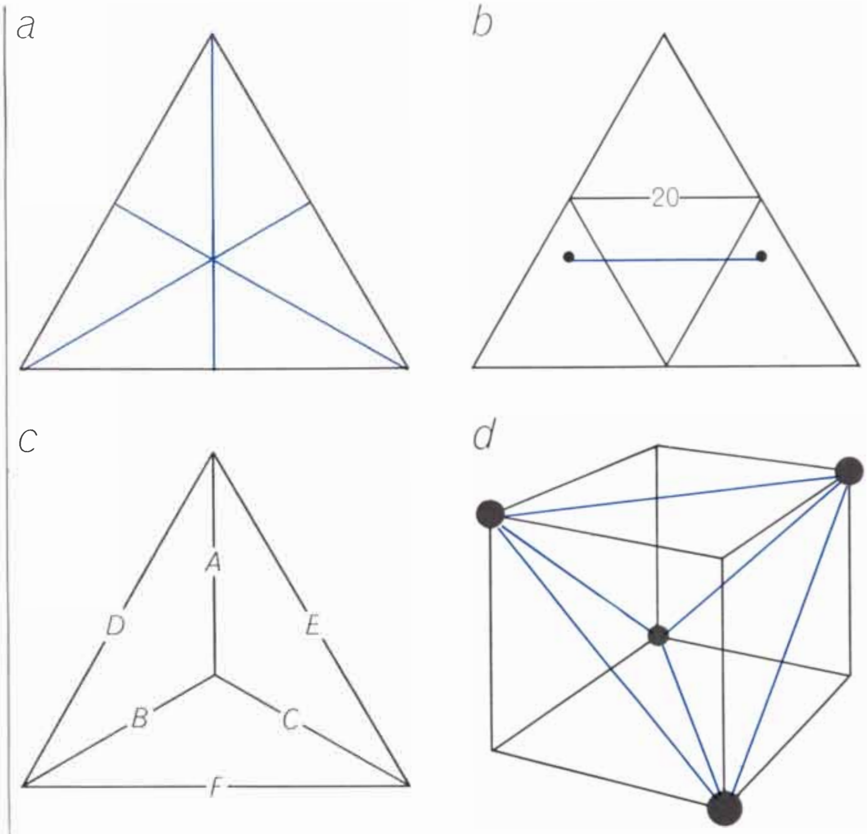

Answers to last month's problems

course violates the assumption that no two numbers are the same.

7. The largest regular tetrahedron that can be placed inside a unit cube has a side the length of which is the square root of 2 [*"d" in illustration above*].

8. Four equilateral cardboard triangles of four different colors will combine to make two different tetrahedrons, one a mirror image of the other.

9. If each side of a regular tetrahedron is painted red, white or blue, it is possible to paint 15 different models: three will be all one color, three will have red-blue faces, three will have red-white faces, three will have blue-white faces and three will have red-white-blue faces with two faces of the same color. The formula for the number of different tetrahedrons (counting mirror reflections but not rotations as being different) that can be made with n colors is

$$\frac{n^4 + 11n^2}{12}.$$

In December's department on hexiamonds it was said that there are 25 heptiamonds. Many readers caught the mistake: there are only 24. Daniel Dorritie of Endicott, N.Y., was the first to send a proof that the triplication problem for the butterfly is impossible. Similar proofs were found by Esther Blackburn of Montreal; Wade E. Philpott of Lima, Ohio, and Dennis C. Rarick, a student at Indiana University. Karl Schaffer, a ninth-grade student in Birmingham, Ala., was able to prove that the six-pointed star answer given in January is indeed the unique solution. All these proofs are of the exhaust-all-possibilities type and are too lengthy to give here.

The outstanding unsolved hexiamond problem—the 3-by-12 rhomboid—was solved at the Lawrence Radiation Laboratory of the University of California. A computer program written by John G. Fletcher had previously been set up for testing pentomino problems. A trivial modification by Fletcher converted this program to one capable of testing hexiamond patterns. The 3-by-12 rhomboid was found to be impossible, and the 3-by-11 rhomboid was shown to have 24 distinct solutions, all of which omit the bat. Running time for both problems, on an IBM 7094, totaled 20 seconds.

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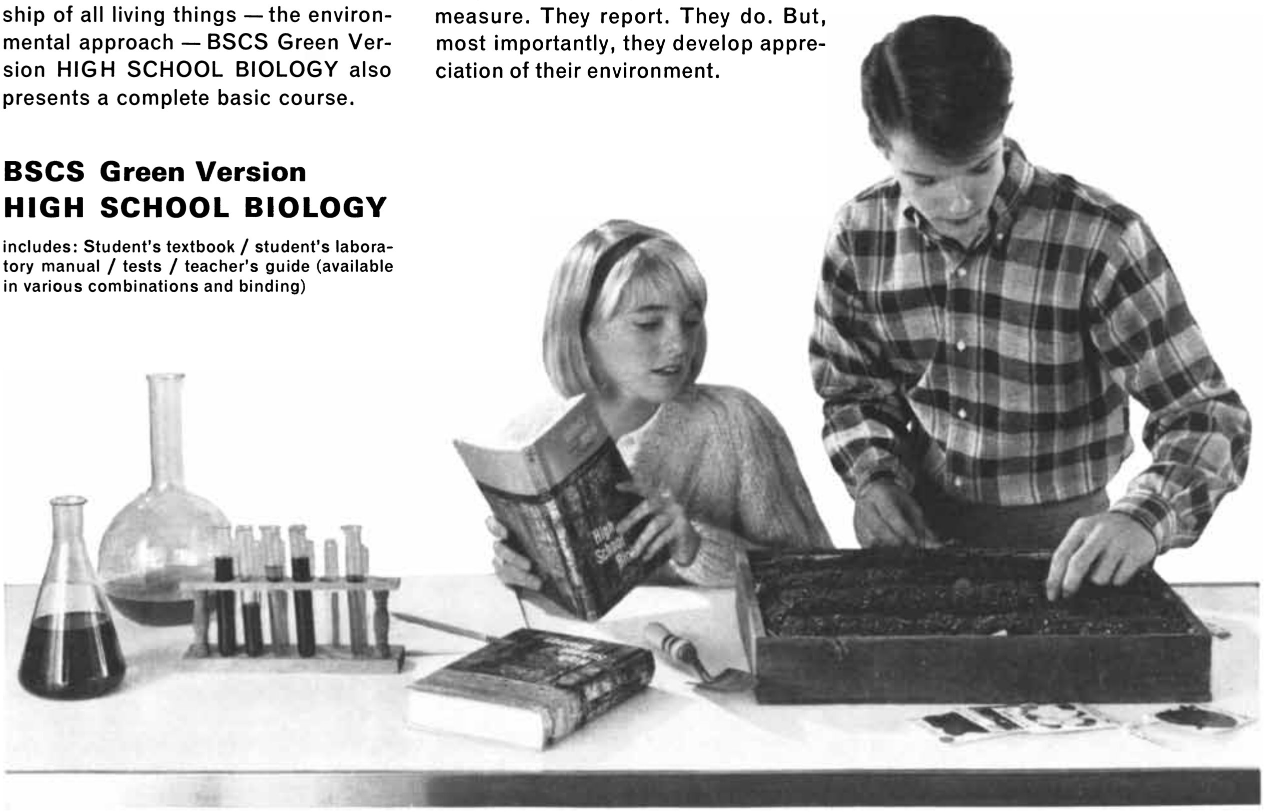

THE AMATEUR SCIENTIST

On collecting and preserving animals that live along the edge of the sea

Conducted by C. L. Stong

Although the edge of the sea is populated by a greater number and variety of animals than any comparable area, few amateurs can afford enough time at the beach to make a thorough study of even a single organism. For this reason some enthusiasts collect and preserve marine specimens. The animals are caught during occasional visits to the shore and studied elsewhere at leisure. Of course a preserved collection cannot show how an animal behaves. Having the animals in preserved form, however, can serve as an aid in recalling the behavior of the living creature and can also disclose far more anatomical detail than is provided by either drawings or photographs.

To find the animals the amateur must first become well acquainted with their various habitats: rocky shores, sandy beaches and marine eelgrass meadows. He must also know the proper methods of preservation. The techniques employed for preserving lifelike specimens are not necessarily easy to master. Some organisms, particularly the more fragile invertebrates, are easily damaged during capture and tend to assume grossly distorted forms when treated with harsh chemicals. Others, such as brittle stars, literally break into pieces when they are excited. According to Jack J. Rudloe, a former amateur collector who now operates the Gulf Specimen Company in Panacea, Fla., the collection and preservation of marine specimens is largely an art, based on an admixture of zoology, biology and biochemistry.

"The sand and surf," Rudloe writes, "tend to keep the secrets of their marine animals hidden from the casual vacationer at the seashore, but actually all one requires to find the teeming life at the edge of the sea is curiosity and observation. Every little ridge, hump, hole and trail in the sand points the way to a beach creature. The techniques of collecting tend to vary according to the nature of the habitat—rock, sand or grass.

"Rocky shores are home to animals that have the ability to cling tenaciously to their perches to keep from being dislodged by the battering surf. Rather than loosen their hold many rock-dwelling forms will allow themselves to be ripped to pieces. As a result they present certain problems to collectors. Typical examples include removing a polyclad flatworm or a nemertean worm from a rock without fragmenting the creature, and picking up a sea cucumber without having the specimen nervously expel its viscera. The acquisition of techniques for coping with such problems makes all the difference between catching and losing the animals.

"To dislodge rock-dwelling animals such as limpets, abalones and chitons without damaging them one must pry them off tediously with a flat-bladed knife. Barnacles can pose a particularly difficult problem: such forms as *Balanus balanoides, Chthamalus* and *Tetraclita* have only a membranous base, and one cannot remove them from rocks without breaking the shell or tearing the gonads. Even an experienced collector will crack more barnacles than he cares to. The best approach is to chip off a piece of rock with barnacles growing on it, using a geologist's hammer; alternatively one might seek the same species of barnacle on more manageable surfaces such as wood or shell.

"Often the type of rocky surface determines the method of collecting the particular animal. Sandstone, common in the Pacific, permits digging, and one can chip out an animal without too much trouble. On hard rock the nature of the surface regulates the collecting approach. For example, one can occasionally collect polyclad flatworms found on smooth, hard rock by letting them ooze onto the blade of a knife. The knife is useless, however, on rough surfaces because the flatworm hides in crevices and generally breaks, tatters and finally disintegrates if the collector persists.

"A technique I have found useful is to mold a plastic bag over the surface of the rock and gently chase the flatworm into the opening by splashing the creature lightly with water. The plastic bag method has worked well with other sensitive invertebrates. A squirt gun filled with weak isopropyl alcohol will drive out many of the shrimps, amphipods, polychaete worms and brittle stars that dwell in deep crevices.

"On the upper limits of the slippery rocks and cliffs are hundreds of scurrying isopods, or multilegged crustaceans, which can cause the inexperienced collector much difficulty. The novice may try to climb the dangerous rocks, slapping at the creatures. Even if he catches any, the delicate specimens may end up squashed. I have found insecticide spray effective in stopping these animals in their tracks. After it is applied they can be dropped directly into a vial of alcohol.

"When the tide recedes, undisturbed sea anemones hang flaccid. If a collector quickly jerks them, they generally come right off the rock. Speed is necessary or they will whip in their tentacles and contract immediately into a tough, fast-sticking bulb. Some species even burst their body walls. If the rocky surface cannot be broken away from the anemone's basal disk, pounding the rock next to the specimen with a geologist's hammer will do the trick: the vibration causes the anemone to fall off.

"Much collecting in rocky areas can be done by hand. Among the creatures thus obtainable are nudibranch mollusks, polychaetes, sponges, tunicates, hydroids, hermit crabs and snails. Sea anemones and sipunculid worms, however, prefer deep crevices and crannies and are often impossible to pull out. By turning over rocks with a crowbar (wearing heavy gloves to protect the hands from cutting shells and the calcareous spicules of sponges) one can obtain assorted varieties of sea cucumbers, echiuroid worms, mud shrimps and even small eels. Octopuses live in burrows in temperate zones and can be spotted by the heaps of crab shells they have discarded. Pinching crabs and cutting mantis shrimps should be cautiously handled or captured with a small dip net.

"The beautiful sabellid worms known as feather dusters pull in their tentacles at the slightest disturbance and withdraw into their tubes. Gently pry the tube from the underside of the rock. Always remember to return the rock to its natural position or entire animal and plant communities will die needlessly from exposure.

"Although collecting marine animals on rock piles is often easier than combing miles of sandy, muddy beach, the sandy habitats give rise to a diverse and complex community of animals that presents a challenge to the amateur collector. Almost every little creature is adapted to burrowing. Some, such as the translucent lancelet amphioxus, can move through hard-packed sand almost as quickly as a fish swims through water. Others that move slowly over sand, such as the frilled sea hare, *Bursatella leachi,* have protective coloration. There are many bivalves and worms that avoid sunlight and stay buried.

"To find the inhabitants of sandy areas one must do some sleuthing. The clues are peculiar slits and trails in the sand. These will vary, of course, with the animal and with the type of habitat. At low tide you can find numerous polychaetes, moon snails, little portunid crabs and an occasional sea cucumber. One must know not only how to recognize an animal but also where it hides and when it is most likely to show itself.

"On most outer beaches where the rolling waves wash up, large numbers of the small, multicolored coquinas (*Donax*) burrow rapidly into the drenched sand to escape their many predators. Every receding wave exposes the little clams and they busily begin burrowing again. The amateur collector soon learns to recognize their presence by the thousands of tiny pepper-shot holes. By screening or handpicking he can easily fill a bucket. The same surf tumbles mole crabs (*Emerita*) about in the water for a second and they burrow down again swiftly. With one sweep of the net you can build up a good series of specimens.

"Air and water temperatures influence the mobility of marine animals. It is often much easier to collect the rapidly burrowing forms at low tide in freezing winter weather than in the summer. The burrowing sea anemone (*Bunodactis stelloides*) rapidly draws in its tentacles and sucks down into the sand when lightly touched, but in winter it contracts only slightly while being spaded up. The cerianthid anemone known locally as 'sloppy guts' spins its own tough, leathery tube with mucus, sand and mud. The animal rides up and down this long tube as if it were an elevator. In warm weather, even at the slightest disturbance, the anemone will rocket down to the bottom. The collector must dig slowly. One impatient yank may leave him with an empty tube. In winter when the air temperature is below freezing, however, it is possible to sever the tube and block the anemone's descent with a shovel before the animal can respond to stimuli.

"The eelgrass in enclosed sandy bays and estuaries shelters an abundance and diversity of animal communities all year. At spring tides that are windblown, so that the ribbed sand is exposed far beyond the normal littoral, the flats are strewn with castings of polychaete worms, balanoglossid worms, callianassid mud shrimps and other animals adapted for burrowing. The huge, reddish-black lugworm (*Arenicola marina*) tunnels a foot or two below the surface, making its presence known by little heaps of digested mud. It takes two collectors digging toward each other from both ends of the long burrow to capture a single specimen.

"Often in the sandy shore habitats there are mysterious creatures, probably crustaceans of some kind, whose burrows are so deep that the most energetic, rapid shoveling will not expose them. From the Sakalava natives of Madagascar I learned one effective trick for removing the deep-burrowing sipunculid worms. The natives insert a long, flexible wire all the way down the hole until they feel the animal squirming. The holes are deceptive: they go straight down for about a foot and then level out horizontally before ending in another opening. After locating the worm with a wire the Sakalava, who use sipunculids for fish bait, speedily dig

Jack J. Rudloe digging among bryozoans for polychaete worms

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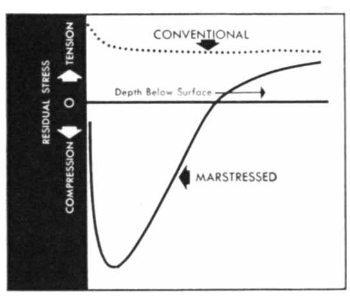


Comparison of subsurface stress patterns in conventionally hardened and *Marstressed* parts down to the exact location of the worm and yank it out.

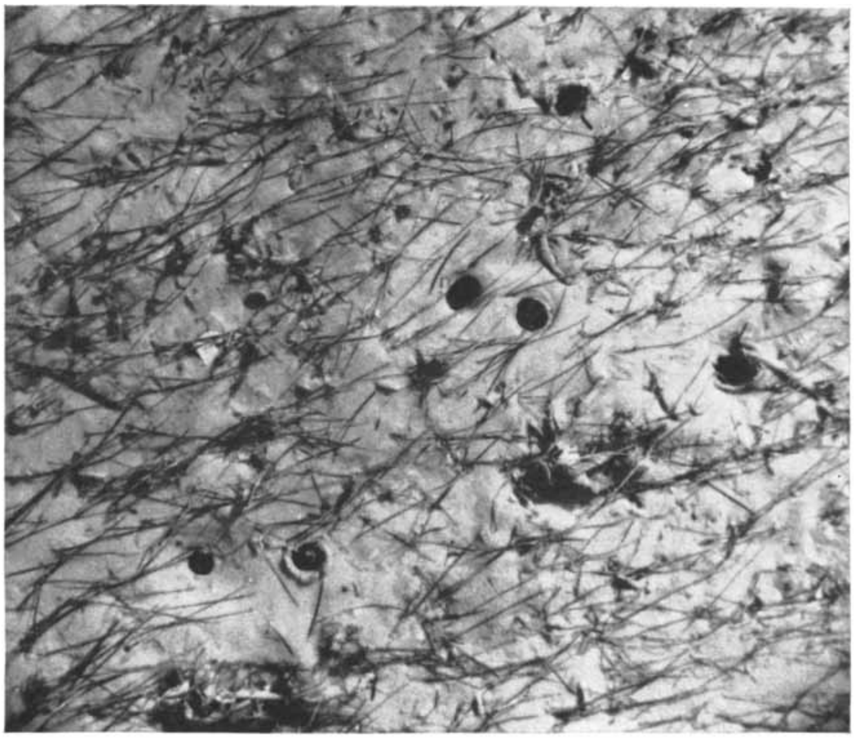
"Another clue to hidden creatures is the sudden spurt of water one may see or hear as one walks along the exposed beds of sandy or muddy shores. Such a spurt may lead you to clams, mussels, sea cucumbers or sea squirts (*Styela plicata*). Often the animals are so well camouflaged that one might overlook them if it were not for the spurts.

"In eelgrass I have been challenged by the task of finding the small, elusive brachiopods that are often known as lamp shells. When I first tried, I would occasionally bring one up in a shovelful of sand while I was digging over a large area. In time I came to recognize their knifelike slits in the sand among the eelgrass roots, and I learned that they live close to the surface. Since then I have been able to collect hundreds of these animals in just a few square yards by turning them out with a table fork.

"Along the mud flats of protected lagoons and bay shores of the southeastern U.S. one can collect hundreds of the common sea cucumbers (*Thyonella gemmata* and *Thyone briareus*) when they expand their floriated crowns up out of the mud at night to feed. Quickly clamp your fingers behind the expanded tentacles of the cucumber, strangling it so that it cannot draw its crown back into its body. Then tie a rubber band tightly behind the tentacles to keep them expanded and immerse the cucumber in 95 percent ethyl alcohol. Do not pull or tug too hard because the animal has the habit of bursting its body walls and ejecting its viscera.

"By sweeping a fine-meshed net along the bottom of the waving eelgrass at high tide one can find an abundance of shrimps, hermit crabs, snails, gobies, pipefish, flatworms and tunicates in an astonishing variety. Surprisingly, dipnetting in the eelgrass meadows is one of the least known but most productive methods of collecting.

"Collecting is absorbing work and can be exhausting. It is easy for a collector to work beyond his normal strength and endurance. He should guard against doing so, because collecting is only part of a day's work. It is also necessary to preserve specimens promptly in order to stabilize the tissues against drastic chemical change. Much material obtained at considerable effort has been ruined because the tired collector postponed caring for it until the next day. Some specimens can be carried alive for a time; a good way to do so is to put the animal in a plastic bag half-filled with



Sea cucumber dwellings in eelgrass

Sea cucumbers after capture

A nemertean worm

seawater, seal the bag and then carry it in a bucket containing some seawater for cushioning. Other specimens, such as sponges, must be preserved immediately or they will begin to undergo a process of deterioration that results in physical distortion and loss of the flagellate chambers. Although no animal will look the same after it has been preserved, it will look similar to its living self if the preserving is done with care. The collector has a responsibility: he knows how the animal looked when it was alive and must duplicate it as best he can.

"Sponges, starfish, sea urchins, crabs and shrimps may be placed directly in preservative. Brittle stars, sea spiders and certain crabs, however, often throw off their legs in their violent death struggle, so they are best killed by simply adding weak alcohol or fresh water to their seawater until they succumb. The feathery legs of barnacles can be extended in the same way. The trick is not to become impatient and pour in the killing agent too quickly.

"The highly sensitive sea anemones, hydroids, nudibranchs, tectibranchs, echiuroids, sipunculids and tunicates present real difficulty. Years ago, when I first began collecting, I had repeated failures in preserving such contractile invertebrates. I took my problem to Charles E. Cutress, a specialist in sea anemones at the U.S. National Museum in Washington, and he suggested some simple and inexpensive methods that are very effective. They involve anesthetizing the specimens before killing them.

"Three of the better anesthetics are Chloretone, menthol crystals and Epsom salts (magnesium sulfate). The first two are scarcely soluble in water and should be used in small amounts. A few crystals added to a dish of specimens will suffice. Magnesium sulfate is extremely soluble in water and is used in a saturated solution. To avoid disturbing the animals the Epsom salts should be tied in a piece of porous cloth, and only a corner of the bag should be allowed to touch the water. Diffusion will take place so slowly that the animals will not be agitated while going to sleep.

"Before adding an anesthetic to a dish of specimens make sure they are naturally expanded. Sea anemones, siphonophores, hydroids and gorgonians must have their tentacles or polyps distended, the gills of nudibranchs must be out and the introverts of sipunculids and echiuroids must be fully extended. Orifices of sea squirts should be open as they are when naturally siphoning the water; sometimes a glass rod can be used to support the openings.

"The time it takes to render specimens insensitive will vary widely. No two specimens will become insensitive at the same time. It is best to treat them individually. Never mix species of coelenterates because cross-contamination of their nematocysts, or stinging organs, makes the process of anesthetization twice as difficult. Some contractile creatures such as small anemones and hydroids may be rendered insensitive in an hour, certain species of polychaetes and sipunculids may take six hours and nudibranchs sometimes require 15 hours before they are ready for preservation. When the animal does not react to probing, it is ready for preservation. The animals should not be allowed to die in the narcotizing fluid; instead they should be preserved shortly after immobilization. When you have done a considerable amount of preserving, you will develop a sense of the right moment for fixing the specimen.

"Remove most of the water from the dish, leaving only enough to cover the organism. Then flood in full-strength formalin (37.9 percent) and the specimens will usually die in an expanded condition. There are always a few specimens, however, that gather up enough energy to contract at the last second. For this reason I prefer the old method of formalin poisoning I learned at the Marine Biological Laboratory in Woods Hole, Mass. The contractile specimens are first partially narcotized in a large volume of seawater and then a few drops of dilute formalin (three drops of 1 percent formalin per 100 cubic centimeters) are added at 15-minute intervals. In this process death results much more quickly and there is less chance of disintegration.

"With certain nemerteans and polychaetes, notably the sabellids, specimens are best narcotized by slowly adding alcohol at 15-minute intervals until they become insensitized. Otherwise nemerteans are apt to vomit their long proboscis and sabellids to throw off their feathery tentacles. Formalin poisoning will usually kill the animals in an expanded condition after the alcohol has immobilized them.

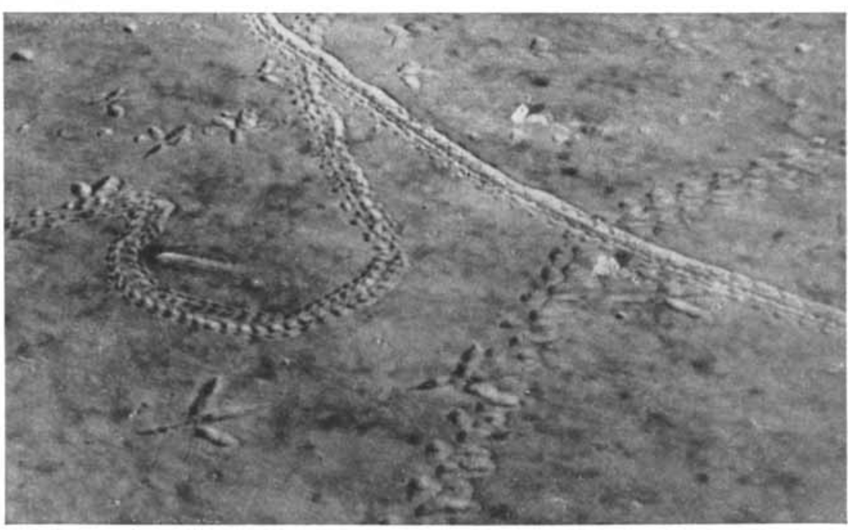
"Enthusiasts who go in for shell collecting face no problems. Simply boil the animal until the flesh is loosened, then scoop out the meat and allow the shell to dry. Those interested in preserving the whole animal will need the same patience as the collector of soft forms. I use a simple and inexpensive technique to get the best results. I boil a pan of seawater for a few minutes to drive off all the oxygen. When the water has cooled to room temperature, I place the mollusks in a flat, shallow pan for immersion in the cooled water. The specimens soon expand their meaty bodies far out of their shells in an effort to absorb the oxygen that is not there. When the soft parts have been extended to their natural feeding and moving positions, I place the pan in the freezer, along with a few jars of 70 percent ethyl alcohol. By the time the mollusks are frozen solid the alcohol is chilled to 25 degrees Fahrenheit or less. I remove the mollusks and place them in the prechilled alcohol, where they remain frozen solid, but the alcohol penetrates their tissues thoroughly and they die perfectly expanded. I learned from experience that if frozen snails are placed in alcohol at room temperature, they quickly thaw out and manage to withdraw completely into their shells before they die. Many corals and bryozoans can be killed in a similar manner. First they are narcotized until the polyps are expanded; then they are frozen and strong formalin is poured over the ice. As the ice thaws, the formalin mixes slowly with the water and penetrates and kills the specimens.

"There are more little tricks to learn. Polyclad flatworms generally explode no matter what preservative is used. I found that the tropical Indian Ocean forms could be fixed nicely if they were first relaxed with menthol and then dropped into hot nitric acid. Death is so instantaneous and the tissues are hardened so quickly that there is no time for the animals to contract. Nitric acid is also a good fixative for ctenophores, the comb jellyfish that are impossible to preserve otherwise. In both cases the specimens are washed in running seawater until all the fixative is washed out and are then preserved in 5 percent formalin.

"Denatured ethyl alcohol is a good general preservative for most of the invertebrates. Sponges, mollusks, crustaceans, echinoderms and tunicates can all be preserved directly in alcohol, but always make sure there is plenty of preserving fluid in the body cavity to prevent internal maceration. Sea anemones and jellyfish should never be put in alcohol because the solution will dehydrate and distort them. Therefore a 10 percent formalin solution (nine parts of seawater to one part of concentrated formalin) is recommended. Formalin, on the other hand, should never be used in preserving any starfish, sea urchin, sea cucumber, sponge or horny coral because the acid breaks down the calcareous spicules, rendering the specimen useless for identification. If, however, the specimens are preserved in neutralized formalin (one pound of hexamethylenetetramine added to one gallon of commercial formaldehyde), they will keep better and even retain some of their original color. Unfortunately no procedure has been developed for preserving intact the brilliant colors of marine fishes and invertebrates.

"After preserving a specimen be sure to include on an accompanying label data about the color, size before preservation and any other features that may seem diagnostic or liable to be lost in preserving. The label should also state where the specimen was collected, the date, the depth of the water and the collector's name. An unlabeled specimen floating in harsh preservative cannot supply this information.

"Preparing and preserving marine animals requires endless time and patience. A specimen can be well expanded and thoroughly preserved but still not be a good specimen. Specimens must be good before preservation. A squid with all its tentacles and no torn parts, a sea urchin with no broken spines or a starfish with all its arms is classed as a good specimen. If the animal does not look right before it is preserved, it certainly will not improve with age. The collector has approached perfection if his specimen is well extended and relaxed and retains at least some of its natural color."



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BOOKS

Lord Rutherford and the origins of nuclear physics at Manchester

by Martin J. Klein

The Collected Papers of Lord Rutherford of Nelson, Volume Two: Manchester, published under the scientific direction of Sir James Chadwick, F.R.S. Interscience Publishers, Inc. ($17.25). Rutherford at Manchester, edited by J. B. Birks. W. A. Benjamin, Inc. ($12.50). Rutherford and the Nature of the Atom, by E. N. da C. Andrade. Doubleday & Company, Inc.; Science Study Series of Anchor Books ($1.25).

In 1931 the Cavendish Professor of Experimental Physics at the University of Cambridge wrote to *The Times* of London; the occasion was the centenary of Michael Faraday's discovery of electromagnetic induction. The professor's remarks gave an apt description of Faraday, but they could have served almost as well to describe the professor, Ernest Rutherford. Among other relevant sentences we find these: "Faraday has often been called the prince of experimenters, and no one could deny his remarkable powers of penetration to the root of a subject by a number of well designed and well executed experiments.... It is a pleasure today to read his *Collected Researches.* ... There is everywhere such a freshness of thought and outlook, combined with a clarity of exposition, that it is difficult to recall that most of his work was written nearly a century ago.... Faraday was more than a great experimenter. He was a great Natural Philosopher. He sought by his experiments not only to accumulate new facts of nature and to show their relations, but also to understand the physical processes which underlie the phenomena under investigation." Rutherford actually shared each of the characteristics he properly attributed to his subject.

During that same year of 1931 Rutherford was a guest of honor at a dinner given by the University of Manchester, where he had served as professor from 1907 until 1919, a period that saw some of his greatest achievements. Rutherford was well aware of what he had accomplished; he commented in his after-dinner talk: "I owe a great debt to Manchester University for the opportunities it gave me for carrying on my studies. I do not know whether that University is really aware that during a few years from 1911 onwards the whole foundation of the modern physical movement came from the physical department of Manchester University." His statement was a bit strong, but only a little bit, since during those years the Manchester group produced some of the most brilliant experiments and boldest theories our century has yet seen—in the work of Hans Geiger, H. G. J. Moseley, C. G. Darwin, Niels Bohr and Rutherford himself, their unquestioned leader.

Two of the three books under review deal exclusively with just those Manchester years, and E. N. da C. Andrade also gives them a prominent place in his outstanding little biography of Rutherford. The primary work is, of course, Rutherford's *Collected Papers,* the second volume of which includes all his scientific articles written at Manchester. This suitably dignified volume is illustrated with contemporary photographs of Rutherford, his collaborators and several climactic pages from his research notebooks. There are also reminiscences of the Manchester period by some of his co-workers and an excellent critical survey of the period by Norman Feather that serves as an introduction.

The book entitled *Rutherford at Manchester* had its origins in the Rutherford Jubilee International Conference held at Manchester in 1961 to commemorate the 50th anniversary of "the discovery of the atomic nucleus." In addition to several of the retrospective talks given on that occasion, it includes a Rutherford bibliography and nine of the important papers published by the Manchester group between 1909 and 1919. (Only three of these are by Rutherford, and the others are therefore not included in the *Collected Papers.*) The book also contains four of the Rutherford Memorial Lectures, all of them interesting; one of them, Bohr's "Reminiscences of the Founder of Nuclear Science and of Some Developments Based on His Work," is an important document in the history of 20th-century physics.

In order to appraise Rutherford's Manchester work we must try to set it against the background of the physics of the time and Rutherford's own earlier accomplishments.

Rutherford began his scientific career in his native New Zealand, starting research as soon as he had taken his degree there in 1893 at Canterbury College in Christchurch. His earliest research was inspired by Heinrich Hertz's great work of a few years earlier: the experimental confirmation of James Clerk Maxwell's theory of electromagnetic waves. Rutherford studied the magnetic properties of iron at very high frequencies and used his results to develop a magnetic detector for Hertzian waves. Operating completely on his own, in what Andrade calls "intellectual solitude," Rutherford devised the kind of direct and ingenious experiments that were to become his trademark. He was actually on the road that Guglielmo Marconi would soon follow, and he could detect signals up to distances of about half a mile, but he put aside the chance to make a name in technology and turned to other matters. He had gone to England in 1895, having won a scholarship that enabled him to become a research student at Cambridge under J. J. Thomson, and it was Thomson who invited the talented young man to collaborate with him on the new problems that had seized the interest of the scientific world.

It would have been difficult for Rutherford to have timed his arrival in Cambridge any more appropriately for the serious start of his scientific career. In the fall of that same year Wilhelm Konrad Roentgen discovered X rays at Würzburg, and physicists everywhere took up the challenge of this startling phenomenon. Thomson and Rutherford worked on the ionizing effect of X rays on gases, and on explaining the electrical conductivity of the ionized gas. Rutherford continued this work on his own for another year or so, while Thomson investigated cathode rays and showed that they were composed of charged particles of a previously unknown kind, whose mass was far less than that of the lightest ions; they were the particles we have known ever since as electrons. By 1898 another recently discovered source of mysterious radiations had captured Rutherford's attention, and he set to work on a study of the radioactivity of uranium. He had found his own kingdom, and he was to spend the rest of his life exploring its absolutely unprecedented riches.

In 1898 Rutherford left Cambridge to accept the chair of physics at McGill University in Montreal, and that university became the world center for research in radioactivity. When Rutherford arrived at McGill, it was known that uranium, thorium and the two elements newly discovered by Pierre and Marie Curie—polonium and radium—were radioactive: they emitted rays of some kind that ionized the air. Rutherford had himself shown before leaving Cambridge that the radiation from uranium was complex, consisting of an easily absorbed component, which he named the alpha rays, and a second and more penetrating component, the beta rays. (Gamma radiation was discovered a year or two later.) And yet, as Rutherford wrote in the conclusion of his first paper on the subject: "The cause and origin of the radiation continuously emitted by uranium and its salts still remain a mystery." By the time Rutherford left McGill in 1907 the mystery had been transformed into a series of problems and the major ones had been solved.

The crux of the matter came in the work that Rutherford did with the young British chemist Frederick Soddy, extending the discoveries Rutherford had already made at McGill on the radioactive products of the decay of thorium. Rutherford and Soddy proposed, developed and justified the disintegration theory of radioactivity, which Rutherford described in 1908 in these words: "In its simplest form, the theory supposes that every second a certain fraction (usually very small) of the atoms present become unstable and explode with great violence, expelling in many cases a small portion of the disrupted atom at a high speed. The residue of the atom forms a new atomic system of less atomic weight, and possessing physical and chemical properties which markedly distinguish it from the parent atom. The atoms composing the new substance formed by the disintegration of the parent matter are also unstable, and break up in turn. The process of degradation of the atom, once started, proceeds through a number of distinct stages." The general nature and many of the specific details of these radioactive decay chains were worked out at McGill.

Essential to a full understanding of radioactivity was a knowledge of the nature of the alpha, beta and gamma radiation. The beta rays were early shown to be identical with the electrons discovered by J. J. Thomson and already assumed to be among the basic constituents of matter, but the nature of the alpha rays proved to be a much more challenging problem and one that Rutherford made peculiarly his own. Many of his colleagues and students have pointed out what Andrade phrases so neatly: "His favorite individual was, I think, the brisk little alpha-particle—and how he made it work!" Rutherford was the first to establish (in 1903) that the alpha was a positively charged particle by deflecting it in electric and magnetic fields, something not easily done in those days because of the great energy and momentum of the alphas. In the same year he correctly guessed that the helium always found in radioactive minerals was derived from the alpha particles. In a series of painstaking experiments Rutherford was able to show that alpha particles from all radioactive sources had the same ratio of electric charge to mass, although their velocities differed. This charge-to-mass ratio was consistent either with a unit charge and a mass twice that of the hydrogen atom or with a double charge and a mass equal to that of a helium atom. This was tempting, yet not really conclusive, evidence for his hypothesis that the alpha was a doubly charged helium atom, but it was as far as Rutherford had gone when he left Montreal for Manchester in 1907.

At Manchester he joined forces with his assistant Geiger and directly measured the charge on the alpha particle. This meant that they had to be able to count the alphas, for which purpose they invented the first particle counter, the predecessor of the Geiger counter. The counting process not only proved that the alpha particle had double the natural unit of charge; it also gave the best value then available for this basic constant and, as a glorious bonus, it exhibited the discreteness of matter in a way Democritus himself would have relished.

The last link was a simple and elegant experiment completing the proof that the alpha particles were charged helium atoms. Rutherford enclosed his radioactive source of alpha particles in a thin-walled glass tube, thin enough to allow the passage of the alpha particles but not the diffusion of a gas. This thin-walled tube was enclosed in another vessel whose walls were thick enough to stop the alphas. The outer vessel was initially evacuated, but after some days its contents were compressed into a fine tube through which an electric discharge was passed; the characteristic spectrum of helium was plainly visible. It grew stronger if one waited even longer for more alpha particles to be caught and neutralized as helium atoms. This work was done with the collaboration of T. Royds and Manchester's glassblower extraordinary, Otto Baumbach, and it was completed in time to be incorporated into Rutherford's Nobel lecture in 1908. Rutherford received the prize in chemistry, and so the lecture, in which he described "the long and arduous path trodden by the experimenter," was duly entitled "The Chemical Nature of the α-Particles from Radioactive Substances." He also remarked at the royal banquet in Stockholm that his own transformation from physicist to chemist was faster than any of the radioactive transformations he had studied!

Rutherford had recognized at least as early as 1902 that the investigation of radioactivity might well lead to results far transcending the explanation of the phenomenon itself. He wrote then that it was reasonable to hope that radioactivity "affords the means of obtaining information of processes occurring within the chemical atom." Rutherford's insight was prophetic but—perhaps for that reason—it was by no means universally shared; more than a decade later J. J. Thomson remarked at the Second Solvay Congress that one ought to rest a theory of atomic structure on a broader base than that offered by radioactivity. When Rutherford discovered in 1906 that even the enormously energetic alpha particles could be scattered slightly from their path when passing through matter, he immediately grasped the significance of his result: "the atoms of matter must be the seat of very intense electrical forces." The scattering had to be studied more closely to see what it would show.

At Manchester, Geiger carried out a series of scattering experiments with no startling results; he observed scattering through small angles, the slight deviations that were all one expected for the massive, energetic alphas. Then in 1909 Rutherford suggested that Ernest Marsden, an undergraduate who had been helping Geiger in his experiments, look for alpha particles scattered through large angles—reflected back, as it were, from the thin metal foils used as scattering targets. Years later Rutherford told an audience "in confidence" that he had expected no positive results from this experiment, and that the detection of back-scattered alpha particles "was quite the most incredible event" in his life. "It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

Geiger and Marsden obtained these results in the spring of 1909. It would appear that Rutherford recognized at once that this large-angle scattering was direct evidence for the intensity of the electrical forces within the atom, but he wrote nothing on the subject for close to two years. What was needed was a theoretical model of the internal structure of the atom that would describe these forces in detail and that could account for the measurements of the alpha particle scattering. A number of models of atomic structure had been proposed during the preceding few years in attempts to understand how the electrons were built into the atom. J. J. Thomson in particular had proposed an atom consisting of a sphere of positive electric charge, with the electrons placed at suitable positions within the sphere to make a stable structure. In 1910 Thomson calculated the scattering of charged particles by his model, assuming that individual deflections were small and that the observed deflections came from compound or multiple scattering. His calculations accounted for experimental results on small-angle alpha scattering and on beta scattering but were totally inadequate to explain even qualitatively the observations of Geiger and Marsden.

Rutherford seized on the idea that a large-angle scattering must be a single event and not the result of many small deflections and proposed a model of the atom in which the electrical forces would be intense enough to produce such large scattering. This was the nuclear model of the atom that appeared in print in the spring of 1911, almost two years after the report by Geiger and Marsden. All Rutherford's predictions about the variation of the scattering with angle, with alpha particle velocity and with target material and thickness were confirmed in detail by new experiments undertaken by Geiger and Marsden as soon as Rutherford told them that "he now knew what the atom looked like." Rutherford's vision of the atom is still basically unchanged: a very small central charge, carrying almost all of the atom's mass, surrounded by a sphere of opposite charge, very thinly spread. The small, massive nucleus was soon shown to be positively charged, so that the outer compensating charge distribution consisted of electrons.

Reading Rutherford's paper that introduced the nuclear atom, we are impressed almost as much by what he did not say as by what he did say. He made no attempt to face the question of the radical instability of his atom, nor to use it to account for any of the physical or chemical properties of matter. It would hardly be an exaggeration to say that he had no model at all in any sense that J. J. Thomson would recognize: Rutherford had written the prolegomena to any future model of the atom. Whatever went into the construction of an atomic model, it would have to exhibit the nuclear structure necessary to account for large-angle alpha scattering. Rutherford was no theorist, but he knew what a theory would have to do.

One of Rutherford's most striking characteristics is precisely the distance he kept between himself and the theoretical work of the day. He was able to do the most significant experimental work of his era, an era that saw the transformations of ideas demanded by relativity and the quantum theory, and yet to maintain the simplicity of his own classical approach. The stories of his pointed jibes at theorists abound. In 1934, for example, he wrote to Enrico Fermi, who had just sent him the report of the first neutron experiments done in Rome, and remarked: "I congratulate you on your successful escape from the sphere of theoretical physics!" Perhaps the most typical of his remarks in this vein was his comment on theorists: "They play games with their symbols, but we, in the Cavendish, turn out the real solid facts of Nature."

One must beware of exaggerating the simplicity of Rutherford's attitude toward theory, for one cannot overlook his relationship with Bohr. Bohr, who had come to Manchester in March, 1912, not only took up Rutherford's nuclear atom but also saw that a real atomic model would have to combine the key idea of the Planck-Einstein quantum theory with Rutherford's views. Bohr's theory of atomic structure, as presented in the three great papers of 1913, was as bold as a theory can be, but Rutherford quickly came to appreciate its power even if not all its subtleties. In an essay reprinted in *Rutherford at Manchester* Bohr describes the intellectual and moral support he received from Rutherford over the years, and particularly in the early days of the theory of atomic structure. (This essay nicely complements Bohr's more famous description of his extended dialogue with Einstein on the foundations of physical theory.) But even if we recognize that Rutherford's public and private remarks on theoretical physicists "with their tails up" did not express all the shadings of his attitudes, it remains true that he could and did work with an absolutely minimal contact with current theory, one sign of how far removed Rutherford's era now seems.

The other achievements of the Manchester period can be read in the volumes at hand: the identification of the gamma rays as very-high-frequency electromagnetic waves, the struggle to understand the relation between beta and gamma emission and X-ray emission (a struggle not resolved in the Manchester days), Moseley's work on the X-ray spectra of the elements and its confirmation of the Bohr-Rutherford atom, and more. The era ended, along with so much in European life, with the outbreak of war in 1914. Rutherford's young men went off to the trenches and he himself spent several years in war research, being particularly concerned with the problems of submarine detection. He was able to get back to his own research gradually in 1917 and proceeded to follow up some work on the collision of alpha particles with light atoms that had been begun by Marsden in 1914.

These experiments were reported in four papers published in 1919, the last of which, "An Anomalous Effect in Nitrogen," described an exciting result under its rather drab title. Rutherford had broken up the nucleus of the nitrogen atom by bombardment with alpha particles. The experiment had shown that energetic protons were produced by the bombardment, which means, as Rutherford wrote, "that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus." This first man-made nuclear reaction really marked the beginning of experimental nuclear physics, even as it marked the close of Rutherford's Manchester period.

Andrade, whose reminiscences of his Manchester days with Rutherford appear in both large volumes under discussion and at greater length in his book, makes a major point of the great gulf that separates us from the world of those days. The most obvious difference is, of course, the scale on which physics is done now. The size of the modern particle accelerators, the enormous cost of supporting them, the vast auxiliary staff they require—all of these are in sharp contrast to Rutherford's devoted little band of experimenters at Manchester, working on an annual equipment budget of a few hundred pounds and getting their results with table-top experiments. These contrasts do not lie on the surface alone; the whole character of current high-energy physics differs profoundly from what was practiced in Rutherford's laboratory. Many experiments now demand two or three or more senior physicists as well as several younger postdoctoral people to conceive and execute them, along with the resources of an accelerator group and the staff of a large computer to reduce the data to interpretable form. The effort that goes into acquiring new results is staggering compared with what was required half a century ago.

The differences appear in other ways. Rutherford's papers were written to be read; they were not addressed to the general public, but they were surely accessible to a wide scientific community. As E. V. Appleton remarks in the introduction to Volume One of the *Collected Papers,* Rutherford's writing is characterized by an "economic and masculine style." His descriptions of experiments are genuine descriptions, at times retaining a little of the flavor of a research notebook. It is clear that the object of the investigations is the understanding of the natural world. Unfortunately none of the statements in this paragraph can be applied to the overwhelming majority of articles reporting current research in physics, whose audience-to-author ratio often seems to be approaching unity.

Andrade remarks that "our universities have, inevitably and properly, become . . . factories for producing degrees and discoveries, which they do with great efficiency." Elsewhere he describes the goal of his little book as being "to try to present to the keen young generation of today a picture of what the

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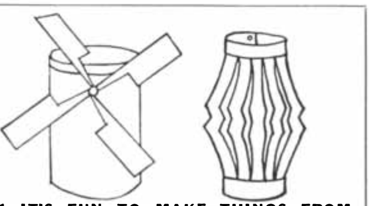

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pursuit of scientific discovery was like before it became a profession"—a goal he achieves most solidly. This too is part of the great gulf to which I have referred. One cannot educate the rapidly growing membership of a lucrative and attractive profession to have the attitudes and aims that once inspired the happy few.

Several questions kept obtruding themselves as I read Rutherford's works. Would such a man find the complete fulfillment of his enormous abilities in the physics of today? Has our science become so institutionalized and complex that a man like Rutherford, who liked to have all the strings in his own hands, would not be able to work in it? Has physics become so baroque that a mind like Rutherford's, with simplicity as its self-chosen description, would feel out of place?

No one anecdote characterizes a man, but one at least seems to have the real Rutherford flavor. When young Emilio Segrè and Edoardo Amaldi went to Cambridge in the summer of 1934 to discuss the Rome group's experiments on neutron-induced radioactivity, Lord Rutherford was most interested in their results. Segrè asked him if the paper describing this work would be published quickly by the Royal Society, to which the great man replied: "What did you think I was President of the Royal Society for?"

Short Reviews

Anaxagoras and the Birth of Physics and Anaxagoras and the Birth of Scientific Method, by Daniel E. Gershenson and Daniel A. Greenberg. Blaisdell Publishing Company ($10 and $1.45 respectively). Anaxagoras, who in these volumes is called the first experimental and theoretical scientist, was born about 500 B.C. in Ionia and came to Athens, the first city of Greece, when he was about 20 years old. He was at once accepted into the highest intellectual circles and after a time attracted many students, to whom he transmitted his teachings orally. He also prepared a written treatise but this was lost, so the only sources for the study of his work are partial accounts and fragments found in other writings of antiquity. Assuming the reliability of at least some of this material, it can be argued that Anaxagoras was indeed the first true natural philosopher. The case is well presented in these two volumes by Gershenson, a classical scholar, and Greenberg, a theoretical physicist—a happy collaboration. Their main thesis is that Anaxagoras not only propounded a comprehensive and in many ways brilliant theory of the nature of the physical world but also supported the theory with experimental demonstrations. The far-flung net of his theory enveloped the constitution of matter, dynamics, mind and the theory of perception, the creation of the world, optics, meteorology, astronomy, the earth sciences and biology. With respect to each of these he had remarkable insights—as well as, understandably, a host of prodigious misconceptions. Even his errors were not haphazard conjectures or mystical intuitions but rather the result of observation (however imperfect) and the logical development of hypotheses. In the larger volume the collaborators give a summary of his views, quote the sources from which they are derived, discuss ancient and modern views of Anaxagoras and survey modern interpretations of his work. There is also a bibliography of the ancient and modern sources. The smaller volume, a paperback, consists of the first portion of the major work: a sketch of Anaxagoras' contributions. Altogether a penetrating and often fascinating labor of analysis and scholarship that may well be a landmark in the history of science.

Cosmic Rays, by Bruno Rossi. McGraw-Hill Book Company ($5.95). The discovery of cosmic rays began in a mystery. The mystery was the rather wayward behavior of electroscopes, which, as 19th-century physicists had repeatedly observed, do not hold their charge indefinitely. The question was why. Many theories were advanced to explain this leakage of charge but none seemed wholly adequate. One thing became increasingly clear, namely that the molecules in the air surrounding the leaves of the electroscope were being ionized. It was suggested that the cause of the ionization was radioactivity of materials in the earth. This explanation was only partly true, and it fell far short of explaining the leakage phenomenon. Another notion was that unknown particles coming from the upper atmosphere were the ionizing culprits. Ionization experiments conducted in the first decade of this century on high places such as the Eiffel Tower were inconclusive. On August 7, 1912, the late Victor F. Hess made a balloon ascent from a field near the town of Aussig in Austria, carrying in the gondola three electroscopes of the kind being used to detect the radiation emitted by radium and other substances. Hess watched the electroscopes and recorded their fluctuations, and when the balloon finally landed some 125 miles from Aussig, he had a mass of data that for three months he submitted to intensive analysis. In *Physikalische Zeitschrift* for November, 1912, he presented a series of conclusions of profound scientific consequence. "The results of my observations," he wrote, "are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above." As Rossi rightly observes, this was the beginning of one of the most extraordinary adventures in the history of science. The story of this adventure, which opened up the intricate world of high-energy physics, is told in this book. Rossi, himself a foremost student of the subject, is always clear and sustains his narrative with a true appreciation of its excitement and drama. He stays away as much as possible from the mathematics and the highly technical aspects of the subject. His book is the best introduction to cosmic rays known to this reviewer and is comprehensible to any literate person. Illustrations.

THE WORLD OF BIRDS, by James Fisher and Roger Tory Peterson. Doubleday & Company, Inc. ($22.95). There are today more than 8,500 species of birds. This abundantly illustrated book by two established naturalists and ornithologists does not undertake to describe all of them systematically, but it does give a large amount of information about the world's bird families in a most palatable way. The alpine chough can fly as high as the top of Everest; the sociable weavers make coarse straw canopy nests that house up to 300 pairs of birds; the elephant bird, now extinct, laid eggs that were 14½ inches long and weighed about 27 pounds; the budgerigar can "learn nearly as many English words as some Englishmen, and can even associate some of them with objects, sounds or times in its environment"; the tethered baya weaver, when rewarded with millet, can learn to thread beads on a tasseled cord using a three-inch needle, held half an inch from the tip, in its beak; golden eagles trained by the Tadzhiks of the U.S.S.R. can take 30 to 50 valuable foxes a year; most of today's nest boxes and feeding stations are based on designs made by Baron von Verlepsch of Schloss Seebach in Germany, who in the 1880's became obsessed with the care of wild birds in the interest of insect control and aesthetics; the British now have "Old Bird Ties" in the tradition of old school ties. With the help of such out-of-the-way facts, oddments and anecdotes the authors describe the life and habits of birds, birds of the past, bird distribution, bird society, bird watching and, in a final chapter, the relation between birds and man. An entertaining and instructive all-around bird book.

PITTSBURGH, by Stefan Lorant. Doubleday & Company, Inc. ($12.50). At first glance there is no reason why this "Story of an American City" should be anything but a nonbook. Who except a resident of Pittsburgh would want to buy a huge 500-page picture gallery beginning with lithographs of Pittsburgh as a fort in the wilderness and running through an aerial photograph of the city in 1963, a courtship scene in Schenley Park and a photograph of a messy young married couple shopping downtown? Surprisingly enough, however, this overblown production by Lorant, who specializes in such things, attains something of the status of a book and is at times a gripping piece of literature. This is due in part to the photographs—some of which are very good, although there are far too many banal street scenes, meaningless to anyone but a Pittsburgher—and even more to a number of excellent essays on such topics as labor problems (Henry David), the entrepreneurs of that shockingly prosperous city (John Morton Blum), the muckraking era (Gerald W. Johnson) and the growth of the city (Oscar Handlin). These give the reader a remarkable, many-angled view of how a typical American industrial center came into being. Cruelly exploited Hunkies and Irish immigrants, hard-driving traders and businessmen, aristocrats and plutocrats together made a city of visible shape and distinctive character, neither the best nor the worst of American cities but the product alike of bitter conflict and common interests.

HISTORY OF CARTOGRAPHY, by Leo Bagrow, revised and enlarged by R. A. Skelton. Harvard University Press ($19.95). Published originally in German by a leading student of cartography and now issued in English as revised and enlarged by the Superintendent of the Map Room at the British Museum, this book examines the maps of various periods and cultures from early antiquity to the 18th century, delineated on materials ranging from stone, clay and leather to metal, cloth, silk, parchment and paper. Richly illustrated by more than 200 reproductions in black-and-white and color, it is not only a handsome volume but also one that affords an engrossing account of the evolution of man's ideas about different parts of the surface of the earth and his methods of recording his notions to guide and inspire him. One extraordinary item is worth specific mention: the Micronesian sailing charts of the Marshall Islands. They are made of lengths of palm fiber tied together by threads of coconut fiber so that they point in various directions; the threads represent the prevailing wave crests and the directions they take as they approach islands (which are represented by shells attached at the intersections) and meet other similar wave crests formed by the ebb and flow of breakers. It is these wave patterns, we learn, rather than the currents that play the most important role in navigation among the islands and channels.

THE FREUD JOURNAL OF LOU ANDREAS-SALOMÉ, translated and with an introduction by Stanley A. Leavy. Basic Books, Inc. ($4.95). Lou Andreas-Salomé, a Russian-born novelist, poet, essayist and psychoanalyst who died in Göttingen in 1937 at the age of 76, was, as Ernest Jones says in his *The Life and Work of Sigmund Freud*, "a woman with a remarkable flair for great men." Among these were Rainer Maria Rilke, Friedrich Nietzsche and Freud. She was almost 50 when she came in contact with the psychoanalytic movement in Vienna in the years 1912–1913. She attended the lectures of Freud, Alfred Adler and others and almost immediately impressed Freud as one who grasped the deeper meanings of his theories as surely as he did himself. This journal covers the two-year period; it reports her participation in psychoanalytic activities and also expresses her own ideas and reactions. Much of the writing is either terribly involved or impenetrably turgid, but parts of the book, particularly those in which she discusses problems of femininity, sexuality, infidelity and narcissism, are uncannily and exquisitely perceptive.

COLLECTED EXPERIMENTAL PAPERS OF P. W. BRIDGMAN. Harvard University Press (seven volumes, $100). A reprint of some 200 of the late Percy Bridgman's experimental papers, most of which deal with high-pressure phenomena, in which field he was the leading investigator of his time. Bridgman participated in the selection of the papers, added commentaries on many of them and prepared an introduction. It is scarcely necessary to say that this body of work represents a major contribution to physics and is a fitting memorial to so gifted a man, but it is important to add that Bridgman's skill as a writer graces almost every page of these highly technical volumes, and that even one who is not conversant with high-pressure physics will derive satisfaction from reading Bridgman's beautifully simple yet precise descriptions of his researches. Two excellent examples of Bridgman's literary abilities as a scientific explainer are a 1914 paper, "The Technique of High Pressure Experimenting," and his Nobel lecture, "General Survey of Certain Results in the Field of High Pressure Physics."

THE PEOPLES OF SIBERIA, edited by M. G. Levin and L. P. Potapov. The University of Chicago Press ($20). This book, first published in the U.S.S.R. in 1956, is an anthropological survey of 30 native Siberian peoples, from the Buryats, Yakuts and Altais of the south to the Chukchis, Eskimos and Koryaks of northern Siberia and the Far East. For each group information is provided about occupation, dwelling, dress, food, social organization, religion and contact with the Russians; there are also historical chapters on the ancient population of Siberia and its culture and physical anthropology.

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THE THUNDERSTORM, by Louis J. Battan. The New American Library (60 cents). A compact, informative and agreeable account of what is known about thunderstorms and of the many lines of research, including exciting and dangerous aircraft explorations, that are enlarging our understanding of this fascinating phenomenon. Paperback.

A HISTORY OF EGYPT, by James Henry Breasted. Bantam Books, Inc. ($1.25). In spite of the fact that this history was published more than half a century ago and great advances have since been made in Egyptology, it remains one of the finest and most attractive works on the subject. Paperback.

THE BOOK OF OLD CLOCKS AND WATCHES, by Ernst von Bassermann-Jordan. Crown Publishers, Inc. ($20). The fourth edition, fully revised by Hans von Bertele, of Bassermann-Jordan's noted handbook covering clocks, watches and other timekeeping instruments from ancient times through the 19th century. Hundreds of pictures and color plates; a delicious book.

MECHANISMS OF THE GENERATION OF PLANE CURVES, by I. I. Artobolevskii. The Macmillan Company ($12). A leading Soviet mathematician explains the different forms of kinematic linkages, much of the material being based on his original researches over many years.

THE FIRST ONE HUNDRED YEARS OF AMERICAN GEOLOGY, by George P. Merrill. Hafner Publishing Company ($15). A reprint of a work first published in 1924 and acknowledged to be the best history of American geology.

PHYSICS OF THE AIR, by W. J. Humphreys. Dover Publications, Inc. ($3). A paperback reprint of the third and final edition of a standard work of physical meteorology, the most enduring section of which deals with atmospheric optics. Many illustrations.

MYSTERIUM CONIUNCTIONIS, by C. G. Jung. Pantheon Books ($7.50). This 14th volume in the "Bollingen Series" collected works of Jung, originally published in German in 1955–1956, was his last major book and consists of a study of the relation between alchemy and psychology.

SCIENCE IN CZECHOSLOVAKIA, by Vladimir Slamecka. Columbia University Press ($6). A guide to the organization, topics and information sources of research in the natural and technical sciences in Czechoslovakia.

THE ARCHEOLOGY OF CAPE DENBIGH, by J. L. Giddings. Brown University Press ($12.50). A specialized, scholarly report and analysis of archaeological excavations conducted between 1948 and 1952 at Cape Denbigh in Alaska. Many illustrations.

GRAVITATION AND RELATIVITY, edited by Hong-Yee Chiu and William F. Hoffmann. W. A. Benjamin, Inc. ($15.75). The papers in this volume deal with the fundamental concepts and experimental foundations of gravitational theory in the light of present-day research.

THE PHYSIOLOGY OF INSECTA, VOLUME I, edited by Morris Rockstein. Academic Press ($22). The first volume of what is intended to be a multivolume treatise bringing together the known facts and the many questions and unsolved problems of insect physiology.

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