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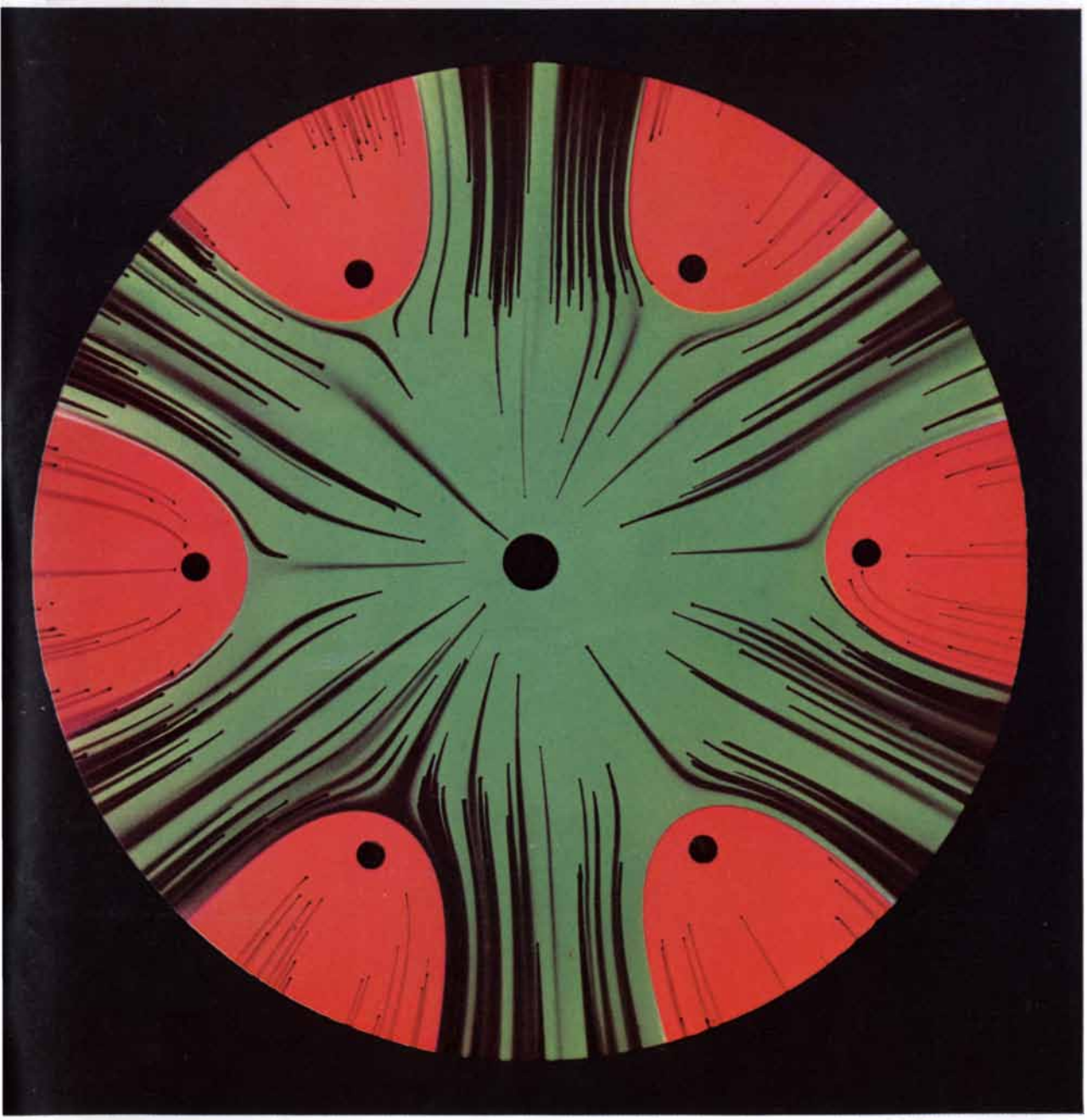

POTENTIAL-FIELD MAP

SIXTY CENTS

July 1967

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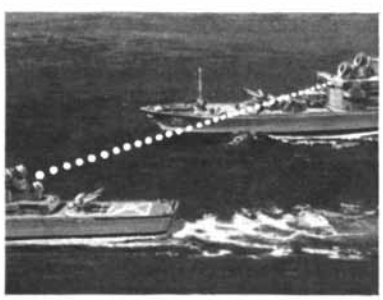

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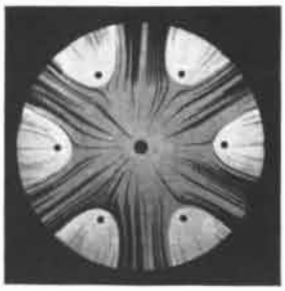
PUBLISHED MONTHLY BY SCIENTIFIC AMERICAN, INC., 415 MADISON AVENUE, NEW YORK, N.Y. 10017. SECOND-CLASS POSTAGE PAID AT NEW YORK, N.Y., AND AT ADDITIONAL MAILING OFFICES. AUTHORIZED AS SECOND-CLASS MAIL BY THE POST OFFICE DEPARTMENT, OTTAWA, CANADA, AND FOR PAYMENT OF POSTAGE IN CASH. SUBSCRIPTION RATE $7 PER YEAR.



THE COVER

The photograph on the cover shows a fluid model that simulates the interaction of electrostatic fields in an electronic tube. The simulation is taking place in a fluid mapper, a device in which a liquid is made to flow in a thin layer and the patterns of force are traced by dyes (see "The Amateur Scientist," page 118). The black spot in the center is a well representing the heated cathode of the tube; the six smaller black spots are wells representing the wires of a grid electrode. The black border represents the positive plate of the tube. Water dyed green flows from the central well and water dyed red comes from the smaller wells. The water flowing from each well meets particles of potassium permanganate, which give rise to the thin dark lines that show the direction of flow and so simulate the electrostatic forces of the tube.

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George Sarton
(1884-1956)

Woodcarving by William Ransom
Photographed by Max Yavno

"Pytheas was one of the greatest navigators of antiquity. It is possible that his voyages were undertaken by order and at the expense of the Massilian colony, which was competing bitterly with its Carthaginian rivals and was anxious to outdo them in foreign trade, especially the rich trade in amber and tin. It is equally possible that he was driven by his own eagerness and scientific curiosity. In the history of geographic discoveries, both motives, the personal and the social, are generally combined. Great deeds can be done only by great men, but however great, these men need help in order to accomplish their bold designs."[1]

[1]George Sarton, *A History of Science: Ancient Science Through the Golden Age of Greece* (Cambridge, Harvard University Press, 1959), p. 523.

INTERACTIONS OF DIVERSE DISCIPLINES

Man's bold designs for the exploration of this and other planets have pushed forward the frontiers of knowledge needed to help him succeed. Twenty-eight of the required areas of knowledge are resident in Planning Research Corporation. Mathematics, the physical, life, social, and computer-based sciences, and most branches of engineering are represented here. The Corporation's five hundred and fifty professionals work on multidisciplined teams–their disciplines interacting–for the solution of complex problems. The spectrum of problems ranges from those related to space exploration to those related to all kinds of commercial systems.

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LETTERS

Sirs:

The many shortcomings of the review of Professor Howard B. Adelmann's *Marcello Malpighi and the Evolution of Embryology* in the April *Scientific American* are too obvious to require comment. However, this is so out of line with the consensus of competent critics that unbiased readers will wish to consult what these critics have had to say before passing judgment. Also, since many of your readers may not have ready access to some of the other journals in which this work has been reviewed, I should like to direct their attention to the brief extracts quoted below from the reviews that have been published to date.

I should also mention the perceptive and highly commendatory review by the eminent historian of medicine Dr. Walter Pagel, which I have had an opportunity to read in proof and which will soon appear in *Clio Medica,* the organ of the International Academy of the History of Medicine.

"These volumes represent many years of patient and exacting toil by one who is both a competent classicist and an embryologist of unusual perception and erudition. [The] commentaries display amazing familiarity throughout a wide range of sources and subjects. The reader cannot escape being highly impressed with the pains taken, and the fairness extended to everyone, in reaching decisions.... The first volume ... is a triumph of meticulous biography.... Volumes 3 to 5 ... are given over to 28 excursuses. ... These essays are of the greatest importance to modern scientific scholars because they review, systematize, and correct observations and interpretations on developing parts from the beginnings with Aristotle to just before modern times. They make a fitting climax to a work that is destined to persist as a classic in its field" (Professor Leslie B. Arey in *Journal of Medical Education*).

"We now have a 'life' of Malpighi which is at last precise, complete, and free from the legendary superstructures and incrustations and errors which in the course of centuries had distorted the image of the Emilian anatomist.... The American embryologist has happily demonstrated the inconsistency of the 'preformist' position which has been habitually attributed to Malpighi even by illustrious medical historians who have placed him right in the midst of the founding fathers of scientific preformism. ... The entire important chapter on preformism, especially its treatment of the predecessors of Malpighi, is developed by Adelmann in an acutely critical spirit on the basis of an accurate and firsthand review of the texts.... The whole of this fundamentally important chapter in the history of embryology which had its beginnings in the seventeenth century and exercised an influence as late as the nineteenth has been rewritten from a new point of view. [The author's] method of work, which is really perfect ... in addition to permitting the author to make a precise and historically correct evaluation of Malpighi's contribution to the history of embryology ... leads to a stupendous history of embryology and a classic lesson in modern embryology.... The documents collected, examined, and assimilated ... are so imposing as to give the impression that the biography was written by a contemporary, ... who by a kindly turn of fate has been able to write about him with the detachment and knowledge of a man of today.... Whoever from now on wishes to concern himself with Malpighi, or more generally with the scientific life of the seventeenth century in Italy, will find it difficult to do without this monumental study" (Professor Carlo Castellani in *Castalia,* translated).

"Happy the student who sits down to this unhurried feast" (Professor Max Fisch in *The New York Times Book Review*).

"This monumental study is the fruition of a lifelong association with the great and beautiful books of the past.... The degree of its greatness ... can safely be assessed only with the passage of time, but it does make important contributions to knowledge and it elaborates a scholarly philosophy which is well worth our consideration" (Professor Charles M. Goss in *Anatomical Record*).

"A triumph of American scholarship, this massive study of Marcello Malpighi represents an achievement truly stupendous.... Realizing that no work can be understood apart from its environment, the author placed Malpighi in a historical context of tremendous scope and thereby contributes profoundly to our understanding of the 17th century.... The presentations furnish not only a definitive account of Malpighi but also a background indispensable for all serious students of 17th century biology or medicine.... The ... 'excursuses' ... represent systematic commentary, each a separate essay on a particular embryologic topic. These essays illuminate not only what Malpighi says but also the actual growth of our knowledge on the subject, for they cover the entire relevant embryological literature. [Adelmann] has provided a fabulous amount of source material, scrupulously accurate and splendidly translated, together with narrative material in great detail.... The entire work represents a monument which will endure for generations to come" (Lester S. King, M.D., book-review editor, *Journal of the American Medical Association*).

"Professor Adelmann has produced a truly superb contribution to his chosen subject.... The author has achieved his aim brilliantly. Only a scholar with his historical, linguistic, and scientific training and knowledge could have presented the work of Malpighi in a form which is readable and stimulating yet skillfully tuned to the overtones of a scientific text written in the 17th century.... Professor Adelmann's study ... will rank among the distinguished works of scholarship of this generation" (Anon. in *The Lancet*).

"In Rome, as in Florence and Messina, Malpighi made new friends and met many interesting people. Those friends enliven this remarkable account of Malpighi's life and make it of great value to any student of the period.... Professor Adelmann ... has been engaged on this study of Malpighi for the past twenty years.... This does not, however, seem too long for a work of this character and stature" (Anon. in the *Times Literary Supplement*).

"Although focusing upon Malpighi, Adelmann has ranged far and wide in this impressive work and has provided a many-faceted analysis of the history of embryology. [He] has put all those with an interest in the history of biology in his debt" (Everett Mendelsohn in *Science*).

"*Marcello Malpighi and the Evolution of Embryology* is an extraordinary contribution to knowledge and to literature, to science and to history. Each portion of it is unique, and its *ensemble,* which is a true synthesis of all the parts, is peerless among monographs in the history of science.... The central focus of the five volumes is, of course, the *Embryological Dissertations* themselves, and the light that reflects from it has been generated by the clarity and vitality of Adelmann's mind.... The biography alone, which is well written, as well as authoritative and exhaustive ... would have stood as a major landmark in the history of biology and medicine even had it not been incorporated into the larger set of volumes.... Adelmann has provided [in the first section of Part III], not a mere reader's guide, but a penetrating analysis of Malpighi's ideas as well as of his

observations. This, too, like each of the other sections and parts of the whole, would have represented a distinguished contribution to embryological history had it been a book in its own right. [Adelmann's] method of translation has been to remain literal in order to avoid the danger of making meanings obscure. ... Nonetheless his translations are freely readable and lucid.... The [excursuses] are...28 brilliant essays in the history of embryology.... These will be indispensable to students of embryology and of its history. They have no counterpart elsewhere in the literature.... The books as they are could only have been written by an embryologist; the meaningfulness of the interpretations of the development of embryological concepts results from the fact that Adelmann is a professional embryologist of distinction. ... Embryologists today and their successors are and will be eternally in his debt for what he has done for them" (Professor Jane Oppenheimer in *BioScience*).

In view of the high attainments of the scholars here cited it is hardly likely that your readers will conclude that they are all out of step but your reviewer.

WILLIAM MONTAGNA

Director
Oregon Regional Primate
Research Center
Beaverton, Ore.

Scientific American, July, 1967; Vol. 217, No. 1. Published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Gerard Piel, president; Dennis Flanagan, vice-president; Donald H. Miller, Jr., vice-president and treasurer.

Editorial correspondence should be addressed to The Editors, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017. Manuscripts are submitted at the author's risk and will not be returned unless accompanied by postage.

Advertising correspondence should be addressed to Martin M. Davidson, Advertising Manager, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017.

Subscription correspondence should be addressed to Jerome L. Feldman, Circulation Manager, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017.

Offprint correspondence and orders should be addressed to W. H. Freeman and Company, 660 Market Street, San Francisco, Calif. 94104. For each offprint ordered please enclose 20 cents.

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

JULY, 1917: "Events have moved rapidly in Greece. King Constantine is in exile in Switzerland after an exhibition of duplicity and blunders seldom equaled by any ruler. The Greek government has broken off diplomatic relations with the Central powers so that a practical alliance with the Entente and a condition of war with the Teutonic powers now exist. Greece can be of little practical assistance to her allies for some time to come, as enormous stores of her artillery, rifles and ammunition were surrendered by King Constantine to the Bulgars. But present conditions remove all fears of an attack from the rear on the troops operating in Macedonia, and in many other ways that country can be of value to the strategic plans of the Entente."

"We have noticed that in certain quarters there is a growing demand for what is called a more aggressive policy on the part of the British navy. There is an evident attempt to create the impression that Great Britain's naval policy has proved to be ineffective because it has failed to suppress the U-boat piracy. It is urged that the time has come for the British fleet to make a grand assault on the German bases at Kiel, Heligoland, Wilhelmshaven, etc. Well, 'twould be a thrilling spectacle, and to no one would it bring such unadulterated delight as to Admiral von Capelle and the German Admiralty. Nothing would give these gentlemen greater joy than to see the British fleet foundering in the uncharted channels and mine fields of the Bight of Heligoland and exposed to the terrific fire of the Heligoland and Cuxhaven 16-inch gun batteries. Equally absurd is the suggestion that the way could be cleared by mine-sweeping and countermining; a channel would have to be opened through 20 miles of mine fields, during which operations the trawlers and destroyers would be exposed to the combined fire of the sea coast batteries and the German fleet. But Churchill says it should be done. Well, if Churchill wants to add to the fiasco of Antwerp and the tragedy of the Dardanelles a third disaster, compared with which the Dardanelles would be child's play, he is certainly going the way to get it."

"A few days ago a correspondent of the *Daily Mail* resuscitated a well-known quotation from George Gissing's *Private Papers of Henry Ryecroft* in order to associate science with the horrors of the present war. We have on several occasions pointed out that it is merely pandering to popular prejudice to make science responsible for German barbarity or for the use of its discoveries in destructive warfare. Chlorine was used as a bleaching agent for much more than a century before the Germans first employed it as a poison gas, and so it is with other scientific knowledge—it can be made a blessing or a means of debasement. The terrible sacrifice of human life we are now witnessing is a consequence of the fact that the teaching of moral responsibility has not kept pace with the progress of science. As in medieval times all new knowledge was regarded as of diabolic origin, so even now the popular mind is ever ready to accept such views of the influence of science as are expressed in Gissing's work. The pity of it is that the public press does nothing to dispel illusions of this kind by urging that what is wanted is not less scientific knowledge but a higher sense of human responsibility in the use of the forces discovered."

SCIENTIFIC AMERICAN

JULY, 1867: "The subject of type writing is one of the interesting aspects of the near future. Its manifest feasibility and advantage indicate that the laborious and unsatisfactory performance of the pen must sooner or later become obsolete for general purposes. 'Printed copy' will become the rule, not the exception, for compositors, even on original papers such as SCIENTIFIC AMERICAN. Legal copying and the writing and delivery of sermons and lectures, not to speak of letters and editorials, will undergo a revolution as remarkable as that effected in books by the invention of printing, and the weary process of learning penmanship in schools will be reduced to the acquisition of the art of writing one's own signature and playing on the 'literary piano' recently invented, or rather on its improved successors."

"We respectfully call the attention of the President to the deplorable condition of the business of the Patent Office, asking that he will inquire into the mismanagement of the present Commissioner and do something to relieve the genius of the country from the oppressive delays occasioned by official stupidity. We understand that there are between 3,000 and 4,000 models of new applications now waiting examination at the Patent Office. The examinations in many of the most important classes of inventions are half a year, more or less, in arrears, and the interests of thousands of inventors are allowed to suffer without any steps being taken for their relief. The Patent Office was established expressly for the encouragement of inventors, but it is at present so mismanaged as greatly to discourage them."

"M. Tresca's paper on the flow of solids, read at the Paris meeting of the Institute of Mechanical Engineers, was interesting, and it was the opinion of many of those who heard it that it foreshadowed important improvements in the working of metals. Thus far we believe no direction in which M. Tresca's researches will have a practical bearing has been indicated, yet it does not follow that their ultimate results can at once be foreseen. That the particles of solids of which the form is altered must move upon each other, and in the direction of least resistance, is of course a physical law, long known to many. Cold rolling, cold tube-drawing, etc., are all examples of the flow of solids, and so indeed is all forging and working in heated but not liquefied metals, since they are then solids of but moderate cohesion. The most beautiful example in the arts, however, is the latest—the accurate pressing out of a thin tin tube within a lead one, from an ingot of tin placed within one of lead."

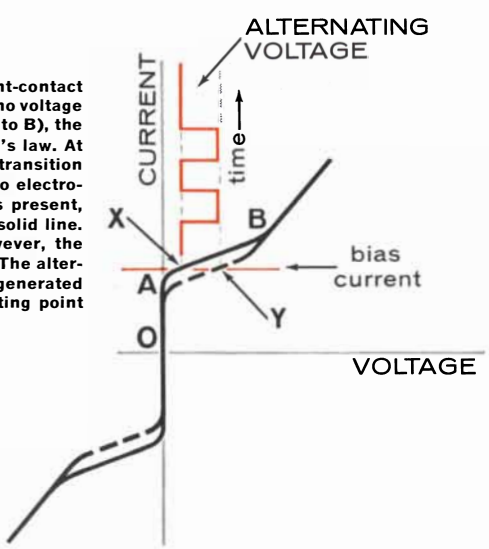
"A French engineer has made a plan for a bridge across the English Channel, which is greatly praised by the Paris *Moniteur*, broad enough to hold a double line of railway, a carriage road and a path for foot passengers. There would also be space for a row of shops along this Dover and Calais road, and half way across there would be a restaurant. The bridge would rest on a series of 32 vertical, rectangular iron piles, each pile to be about 670 feet high and 335 feet broad. The depth of the channel between the two points named is found to be not over 135 feet, so that the bridge would be about 535 feet above sea level. The body of the bridge would be formed of cables of plaited iron wire stretched from pile to pile. The cost of the bridge is estimated at $80,000,000."

Report from

BELL LABORATORIES

A fast-acting detector of infrared light

Bell Laboratories research physicist C. C. Grimes adjusts contact pressure in cryogenic apparatus in which infrared radiation is detected by a superconductor point-contact junction. Oscilloscope shows the junction's voltage/current characteristic (graph below) derived by passing a low-frequency sinusoidal current through the junction. The junction, submerged in a dewar of liquid helium, exhibits a sharp increase in voltage in the presence of electromagnetic radiation. Infrared signals enter from left through the horizontal light pipe (above left hand) and are reflected down toward the junction.



Behavior of a superconductor point-contact junction. A direct current flows at no voltage (origin O to A). After transition (A to B), the curve approximately follows Ohm's law. At a constant bias current within the transition region, the junction is sensitive to electromagnetic fields. When no field is present, the junction characteristic is the solid line. In the presence of infrared, however, the characteristic is the dashed line. The alternating voltage (square wave) is generated as the radiation shifts the operating point of the junction from X to Y.

If two sharp points of superconductor are lightly pressed together, a small direct current can be made to flow between them at zero voltage . . . much as if they were a single piece of superconductor. But, if the current (controlled by external circuitry) is increased beyond a certain critical value, the contact changes electrically and a voltage appears across it.

The critical current value (A on graph) is highly sensitive to external electromagnetic fields. Such fields cause the voltage to appear at a lower current. In this instance, then, the contact is analogous to a "Josephson junction" (after Brian Josephson of Cambridge University who predicted properties of superconductor contacts), and can act as a detector of electromagnetic radiation. Some time ago, a junction composed of thin films of superconductor separated by an oxide layer was shown to work at frequencies up to 25 GHz.

Now, at Bell Telephone Laboratories, researchers Charles C. Grimes, Paul L. Richards, and Sidney Shapiro have devised and demonstrated a superconductor point-contact junction that detects infrared signals . . . up to 1500 GHz. The present experimental form responds to infrared pulses as short as 0.1 microsecond and promises to operate at 1-nanosecond intervals. This has practical importance because heretofore there have been few devices that react as rapidly and as sensitively to submillimeter or far-infrared radiation (wavelengths from 100 to 1000 microns).

The range of peak sensitivity varies with different superconductors. Indium is most sensitive at wavelengths near 2000 microns; niobium shows several peaks—at approximately 333, 500 and 1250 microns.

Bell Telephone Laboratories
Research and Development Unit of the Bell System

THE AUTHORS

CARROLL M. WILLIAMS ("Third-Generation Pesticides") is Bussey Professor of Biology at Harvard University. After his graduation from the University of Richmond in 1937 he went to Harvard and successively obtained master's and doctor's degrees in biology and, in 1946, an M.D. He joined the Harvard faculty in 1946 and became full professor in 1953. From 1959 to 1961 he was chairman of the biology department. He has been a member of the National Academy of Sciences since 1961. Williams' studies of insects have won a number of awards; two months ago he received the George Ledlie Prize of $1,500, which is given every two years to the member of the Harvard faculty who has made "the most valuable contribution to science, or in any way for the benefit of mankind."

JAN A. RAJCHMAN ("Integrated Computer Memories") is director of the Computer Research Laboratory of the Radio Corporation of America Laboratories at Princeton, N.J. He has been with RCA since 1935, when he began work as a student engineer, and has been at the Princeton laboratories since 1942. There he developed the magnetic-core memory system that is standard equipment in modern computers. Rajchman has obtained more than 100 U.S. patents. He holds degrees, including a doctorate in technical sciences, from the Federal Institute of Technology in Zurich. His first field was electron optics; during World War II he was one of the first to apply electronics to computers. Work that he did later on the betatron won for him the Levy Medal of the Franklin Institute. At the RCA Laboratories he is in charge of research on electronic digital computers and data processing.

BILLY P. GLASS and BRUCE C. HEEZEN ("Tektites and Geomagnetic Reversals") are at the Lamont Geological Observatory of Columbia University; Glass is a graduate research assistant and Heezen associate professor of geology. Glass received a bachelor's degree in geology from the University of Tennessee in 1963 and was granted a Ford fellowship in oceanography at Columbia, where he is working on his Ph.D. He is writing his thesis on the use of paleomagnetism for dating deep-sea sediments. Heezen, who was graduated from the University of Iowa in 1948 and received a Ph.D. from Columbia in 1957, has been at the Lamont Observatory since its founding. He writes that his work is "largely concerned with the form, structure and history of the ocean floor, with emphasis on the tectonic and sedimentary processes responsible for the creation of submarine topography."

ANATOL RAPOPORT ("Escape from Paradox") is professor of mathematical biology at the Mental Health Research Institute of the University of Michigan. Born in Russia and educated in the public schools of Chicago, he began a career as a musician. He received degrees in composition, piano and conducting from the Vienna State Academy of Music and for four years gave concerts in the U.S., Europe and Mexico. In 1937 he enrolled as a 26-year-old freshman at the University of Chicago, and in 1941 he obtained a Ph.D. in mathematics from that university. After service in the Air Force during World War II he taught mathematics for a year at the Illinois Institute of Technology, was research associate and later assistant professor of mathematical biophysics at the University of Chicago for seven years and spent a year at the Center for Advanced Study in the Behavioral Sciences before going to Michigan in 1955.

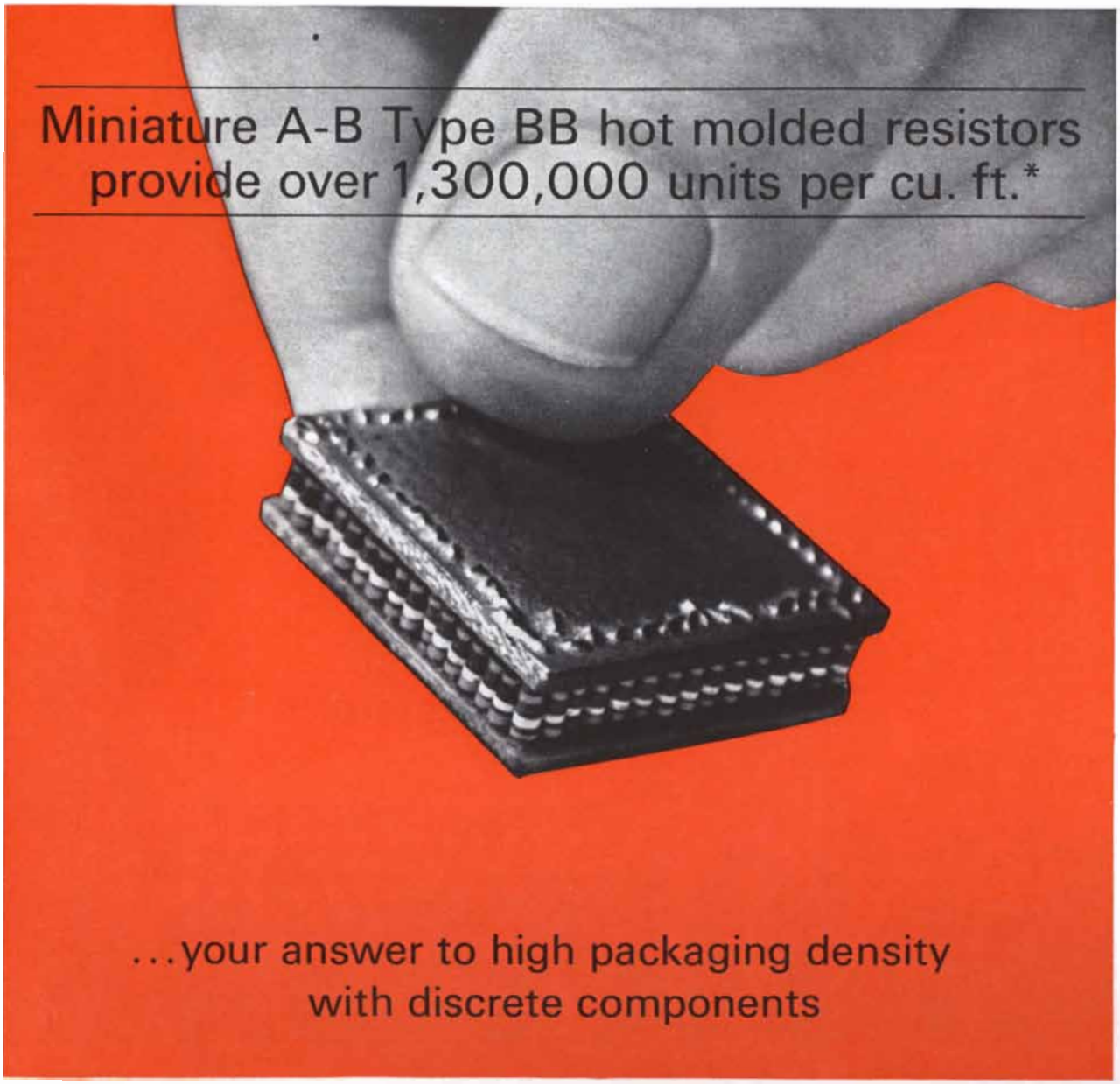
WILLIAM B. WOOD and R. S. EDGAR ("Building a Bacterial Virus") are in the division of biology of the California Institute of Technology; Wood is assistant professor and Edgar is professor. Wood, who did his undergraduate work at Harvard College, received a doctorate in biochemistry from Stanford University in 1963 and spent a year and a half as a postdoctoral fellow in Switzerland before joining the Cal Tech faculty. Edgar, a graduate of McGill University, obtained his Ph.D. from the University of Rochester. Wood writes that they began discussing the experiments described in their article in 1963 and started work in 1965. "I suspect," he adds, "that either of us alone might never have initiated these experiments."

FRANCIS F. CHEN ("The Leakage Problem in Fusion Reactors") is research physicist at the Plasma Physics Laboratory of Princeton University. Obtaining a bachelor's degree in astronomy at Harvard College in 1950, he stayed on at Harvard for graduate work in physics, receiving a Ph.D. in 1954. He has been at Princeton most of the time since 1954. In 1958 he was a U.S. delegate to the Geneva Conference on Peaceful Uses of Atomic Energy. Returning to Princeton, he built the university's L-2 machine for experimental studies of plasma. He writes that in 1965 "I converted L-2 into a large potassium-plasma machine and am currently studying the effect of magnetic shear on plasma fluctuations and confinement." In addition to his work at Princeton, Chen is visiting professor at the City College of the City of New York.

JAMES J. PARSONS and WILLIAM M. DENEVAN ("Pre-Columbian Ridged Fields") are respectively professor of geography at the University of California at Berkeley and assistant professor of geography at the University of Wisconsin. Parsons began his long association with his university as an undergraduate, receiving a bachelor's degree in economics in 1937 and master's and doctor's degrees in geography in 1939 and 1948 respectively. Among the books he has written is *The Green Turtle and Man.* He writes that he is currently concerned "with the introduction and spread of African pasture grasses to the New World tropics." His interest is in the history of the introduction and in its implications for land-use practices. Denevan, who took all his degrees at Berkeley, beginning with a baccalaureate in 1953 and ending with a doctorate in 1963, has been particularly concerned with the origin and character of tropical savannas in the New World.

VICTOR A. McKUSICK and DAVID L. RIMOIN ("General Tom Thumb and Other Midgets") are geneticists serving respectively as professor of medicine at the Johns Hopkins University School of Medicine and assistant professor of medicine at Washington University in St. Louis. McKusick, who is chief of the division of medical genetics at his institution, has been associated with the Johns Hopkins medical school since 1943, when he arrived as a student after doing undergraduate work at Tufts College. He is the author of six books, five on genetics and one on heart sounds. Rimoin, who received a medical degree from McGill University, has just completed the work for a Ph.D. in human genetics at Johns Hopkins University, where he has been serving as a fellow in medicine, and is beginning at Washington University this month.

ROBERT M. ADAMS, who in this issue reviews *H. G. Wells,* by Richard Hauer Costa, is professor of English at Cornell University.



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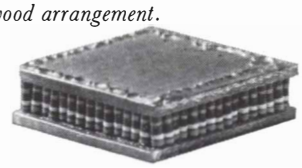

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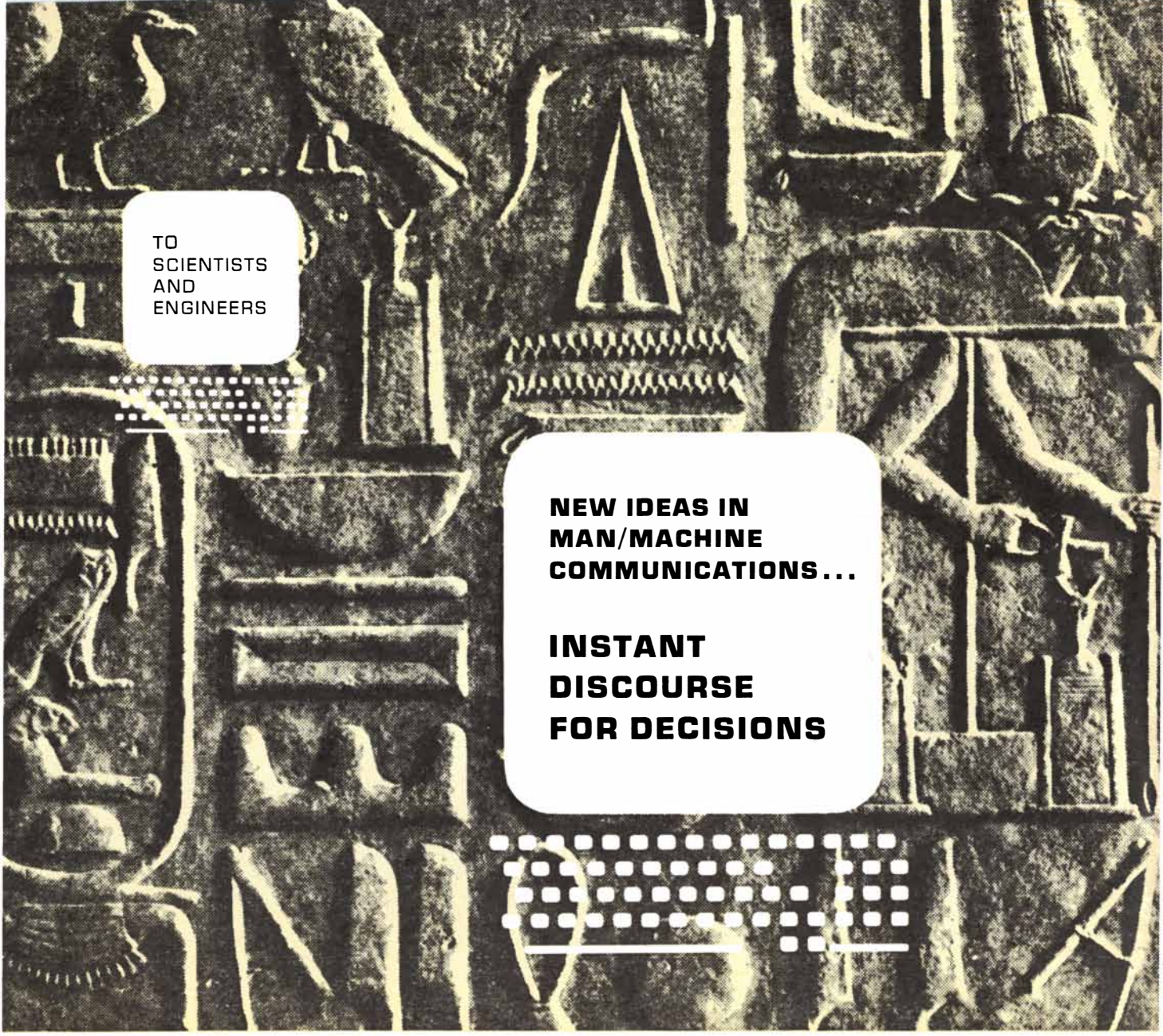

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Third-Generation Pesticides

The first generation is exemplified by arsenate of lead; the second, by DDT. Now insect hormones promise to provide insecticides that are not only more specific but also proof against the evolution of resistance

by Carroll M. Williams

Man's efforts to control harmful insects with pesticides have encountered two intractable difficulties. The first is that the pesticides developed up to now have been too broad in their effect. They have been toxic not only to the pests at which they were aimed but also to other insects. Moreover, by persisting in the environment—and sometimes even increasing in concentration as they are passed along the food chain—they have presented a hazard to other organisms, including man. The second difficulty is that insects have shown a remarkable ability to develop resistance to pesticides.

Plainly the ideal approach would be to find agents that are highly specific in their effect, attacking only insects that are regarded as pests, and that remain effective because the insects cannot acquire resistance to them. Recent findings indicate that the possibility of achieving success along these lines is much more likely than it seemed a few years ago. The central idea embodied in these findings is that a harmful species of insect can be attacked with its own hormones.

Insects, according to the latest estimates, comprise about three million species—far more than all other animal and plant species combined. The number of individual insects alive at any one time is thought to be about a billion billion (10^{18}). Of this vast multitude 99.9 percent are from the human point of view either innocuous or downright helpful. A few are indispensable; one need think only of the role of bees in pollination.

The troublemakers are the other .1 percent, amounting to about 3,000 species. They are the agricultural pests and the vectors of human and animal disease. Those that transmit human disease are the most troublesome; they have joined with the bacteria, viruses and protozoa in what has sometimes seemed like a grand conspiracy to exterminate man, or at least to keep him in a state of perpetual ill health.

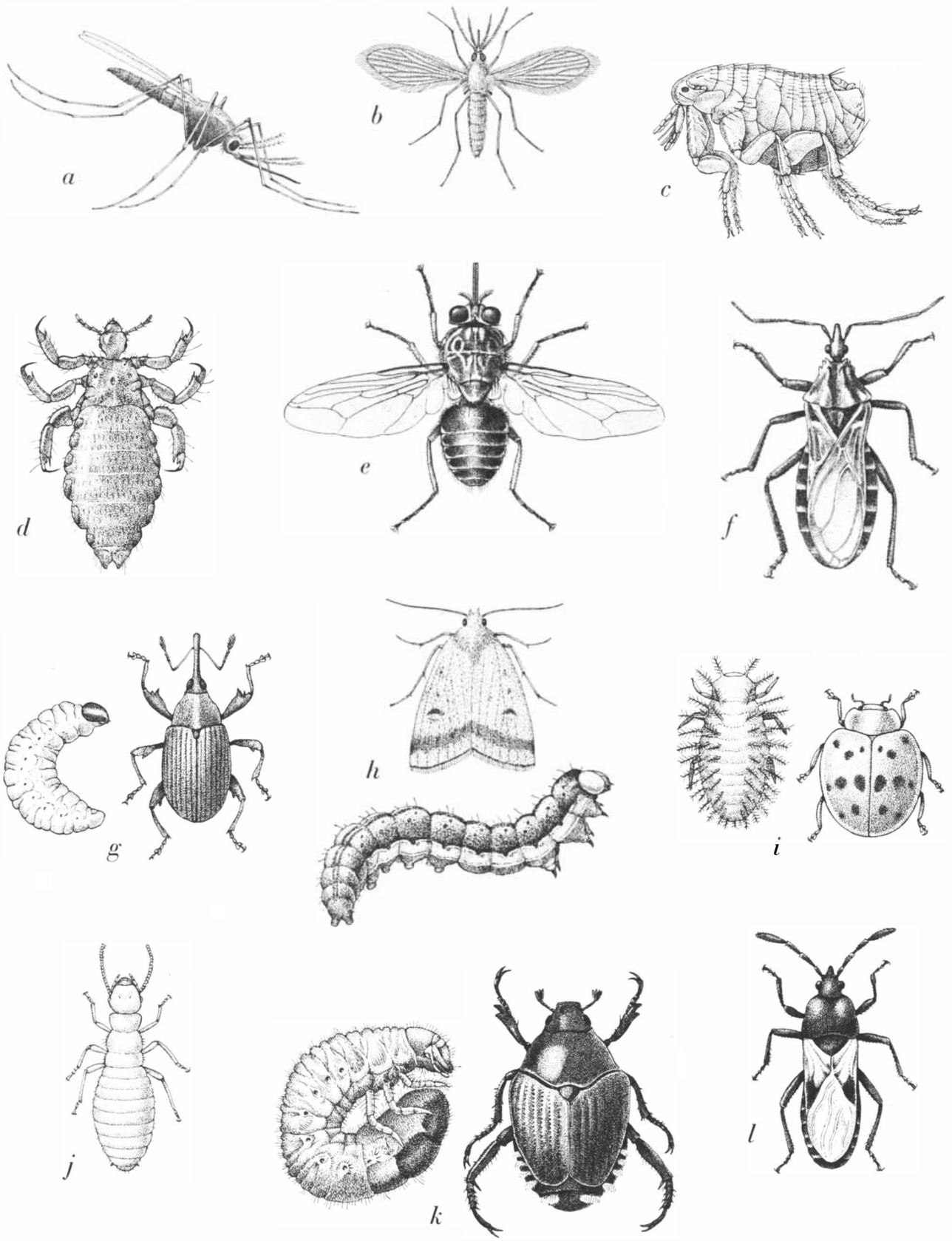
The fact that the human species is still here is an abiding mystery. Presumably the answer lies in changes in the genetic makeup of man. The example of sickle-cell anemia is instructive. The presence of sickle-shaped red blood cells in a person's blood can give rise to a serious form of anemia, but it also confers resistance to malaria. The sickle-cell trait (which does not necessarily lead to sickle-cell anemia) is appreciably more common in Negroes than in members of other populations. Investigations have suggested that the sickle cell is a genetic mutation that occurred long ago in malarial regions of Africa. Apparently attrition by malaria-carrying mosquitoes provoked countermeasures deep within the genes of primitive men.

The evolution of a genetic defense, however, takes many generations and entails many deaths. It was only in comparatively recent times that man found an alternative answer by learning to combat the insects with chemistry. He did so by inventing what can be called the first-generation pesticides: kerosene to coat the ponds, arsenate of lead to poison the pests that chew, nicotine and rotenone for the pests that suck.

Only 25 years ago did man devise the far more potent weapon that was the first of the second-generation pesticides. The weapon was dichlorodiphenyltrichloroethane, or DDT. It descended on the noxious insects like an avenging angel. On contact with it mosquitoes, flies, beetles—almost all the insects—were stricken with what might be called the "DDT's." They went into a tailspin, buzzed around upside down for an hour or so and then dropped dead.

The age-old battle with the insects appeared to have been won. We had the stuff to do them in—or so we thought. A few wise men warned that we were living in a fool's paradise and that the insects would soon become resistant to DDT, just as the bacteria had managed to develop a resistance to the challenge of sulfanilamide. That is just what happened. Within a few years the mosquitoes, lice, houseflies and other noxious insects were taking DDT in their stride. Soon they were metabolizing it, then they became addicted to it and were therefore in a position to try harder.

Fortunately the breach was plugged by the chemical industry, which had come to realize that killing insects was —in more ways than one—a formula for



INSECT PESTS that might be controlled by third-generation pesticides include some 3,000 species, of which 12 important examples are shown here. Six (*a–f*) transmit diseases to human beings; the other six are agricultural pests. The disease-carriers, together with the major disease each transmits, are (*a*) the *Anopheles* mosquito, malaria; (*b*) the sand fly, leishmaniasis; (*c*) the rat flea, plague; (*d*) the body louse, typhus; (*e*) the tsetse fly, sleeping sickness, and (*f*) the kissing bug, Chagas' disease. The agricultural pests, four of which are depicted in both larval and adult form, are (*g*) the boll weevil; (*h*) the corn earworm; (*i*) the Mexican bean beetle; (*j*) the termite; (*k*) the Japanese beetle, and (*l*) the chinch bug. The species in the illustration are not drawn to the same scale.

getting along in the world. Organic chemists began a race with the insects. In most cases it was not a very long race, because the insects soon evolved an insensitivity to whatever the chemists had produced. The chemists, redoubling their efforts, synthesized a steady stream of second-generation pesticides. By 1966 the sales of such pesticides had risen to a level of $500 million a year in the U.S. alone.

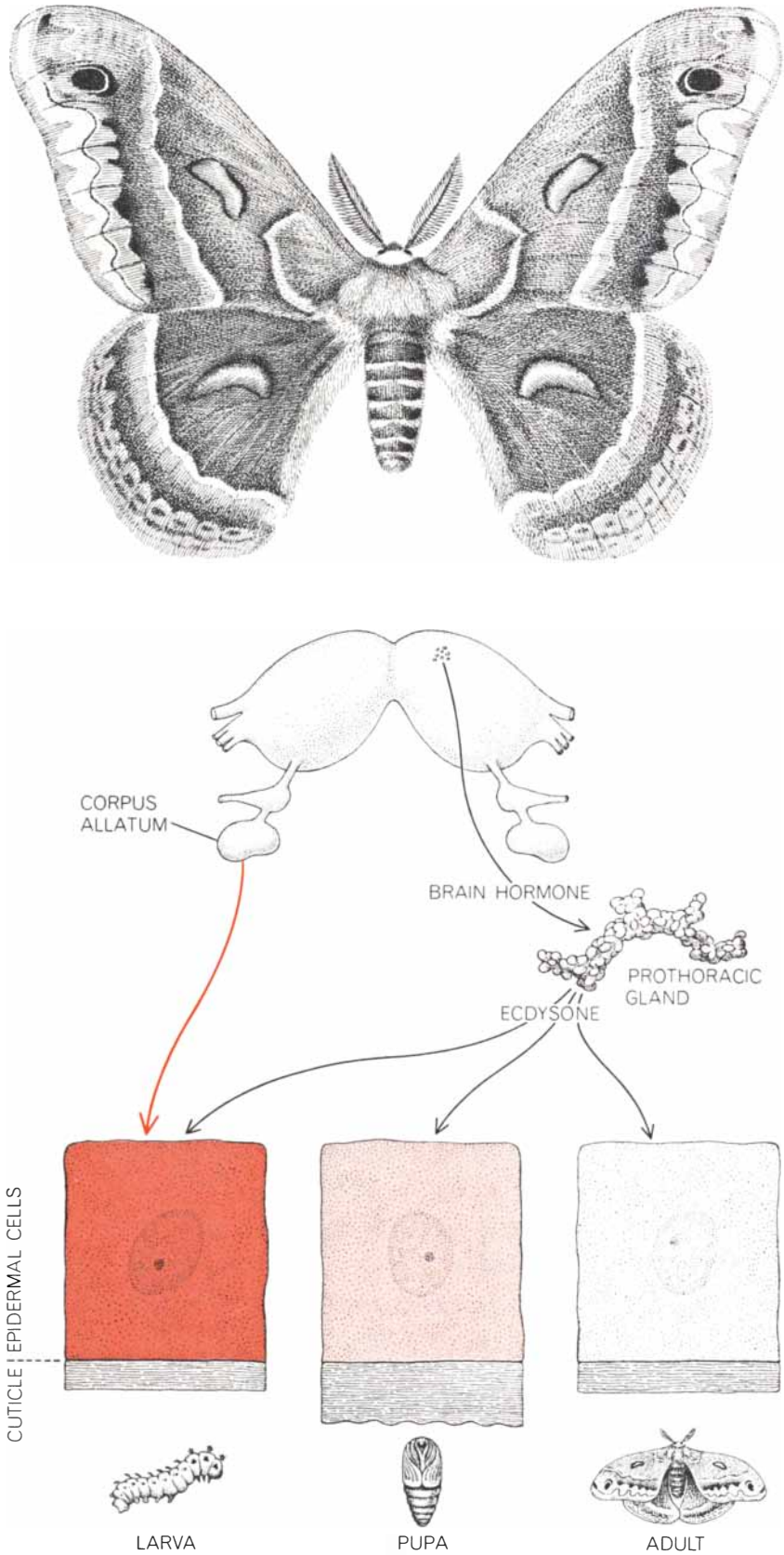
Coincident with the steady rise in the output of pesticides has come a growing realization that their blunderbuss toxicity can be dangerous. The problem has attracted widespread public attention since the late Rachel Carson fervently described in *The Silent Spring* some actual and potential consequences of this toxicity. Although the attention thus aroused has resulted in a few attempts to exercise care in the application of pesticides, the problem cannot really be solved with the substances now in use.

The rapid evolution of resistance to pesticides is perhaps more critical. For example, the world's most serious disease in terms of the number of people afflicted continues to be malaria, which is transmitted by the *Anopheles* mosquito—an insect that has become completely resistant to DDT. (Meanwhile the protozoon that actually causes the disease is itself evolving strains resistant to antimalaria drugs.)

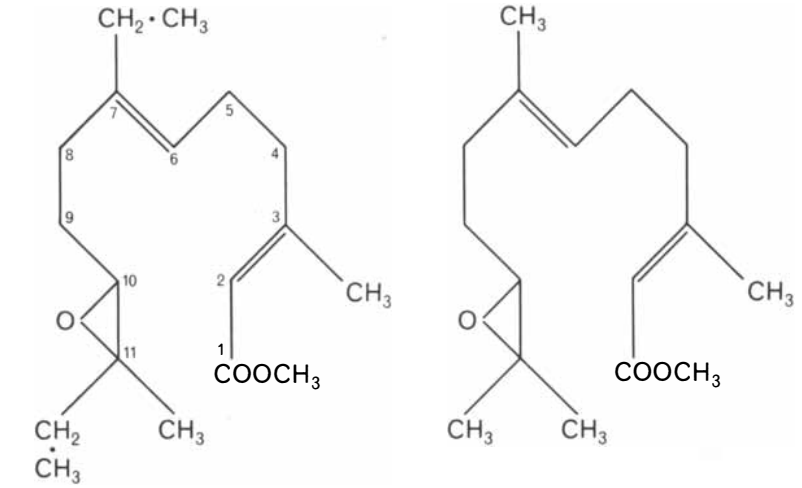
A second instance has been presented recently in Vietnam by an outbreak of plague, the dreaded disease that is conveyed from rat to man by fleas. In this case the fleas have become resistant to pesticides. Other resistant insects that are agricultural pests continue to take a heavy toll of the world's dwindling food supply from the moment the seed is planted until long after the crop is harvested. Here again we are confronted by an emergency situation that the old technology can scarcely handle.

The new approach that promises a way out of these difficulties has emerged during the past decade from basic studies of insect physiology. The prime candidate for developing third-generation pesticides is the juvenile hormone that all insects secrete at certain stages in their lives. It is one of the three internal secretions used by insects to regulate growth and metamorphosis from larva to pupa to adult. In the living insect the juvenile hormone is synthesized by the corpora allata, two tiny glands in the head. The corpora allata are also responsible for regulating the flow of the hormone into the blood.

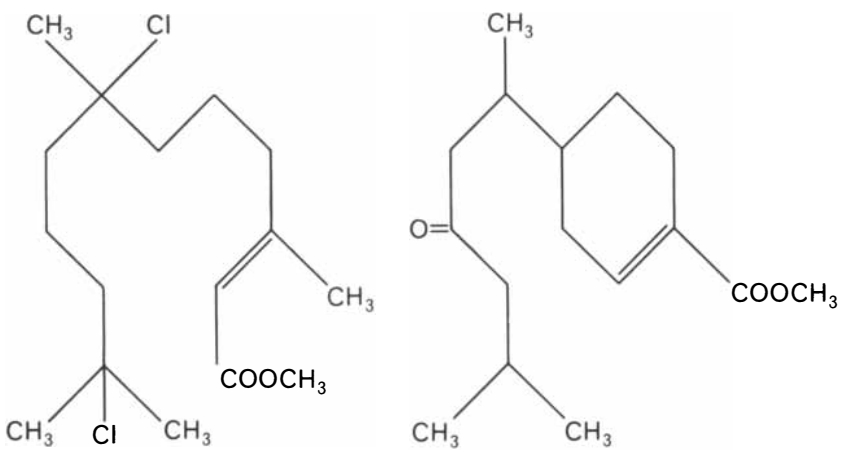
At certain stages the hormone must be



HORMONAL ACTIVITY in a Cecropia moth is outlined. Juvenile hormone (*color*) comes from the corpora allata, two small glands in the head; a second substance, brain hormone, stimulates the prothoracic glands to secrete ecdysone, which initiates the molts through which a larva passes. Juvenile hormone controls the larval forms and at later stages must be in low concentration or absent; if applied then, it deranges insect's normal development. The illustration is partly based on one by Howard A. Schneiderman and Lawrence I. Gilbert.



CHEMICAL STRUCTURES of the Cecropia juvenile hormone (*left*), isolated this year by Herbert Röller and his colleagues at the University of Wisconsin, and of a synthetic analogue (*right*) made in 1965 by W. S. Bowers and others in the U.S. Department of Agriculture show close similarity. Carbon atoms, joined to one or two hydrogen atoms, occupy each angle in the backbone of the molecules; letters show the structure at terminals and branches.



JUVENILE HORMONE ACTIVITY has been found in various substances not secreted by insects. One (*left*) is a material synthesized by M. Romaňuk and his associates in Czechoslovakia. The other (*right*), isolated and identified by Bowers and his colleagues, is the "paper factor" found in the balsam fir. The paper factor has a strong juvenile hormone effect on only one family of insects, exemplified by the European bug *Pyrrhocoris apterus*.

secreted; at certain other stages it must be absent or the insect will develop abnormally [*see illustration on preceding page*]. For example, an immature larva has an absolute requirement for juvenile hormone if it is to progress through the usual larval stages. Then, in order for a mature larva to metamorphose into a sexually mature adult, the flow of hormone must stop. Still later, after the adult is fully formed, juvenile hormone must again be secreted.

The role of juvenile hormone in larval development has been established for several years. Recent studies at Harvard University by Lynn M. Riddiford and the Czechoslovakian biologist Karel Sláma have resulted in a surprising additional finding. It is that juvenile hormone must be absent from insect eggs for the eggs to undergo normal embryonic development.

The periods when the hormone must be absent are the Achilles' heel of insects. If the eggs or the insects come into contact with the hormone at these times, the hormone readily enters them and provokes a lethal derangement of further development. The result is that the eggs fail to hatch or the immature insects die without reproducing.

Juvenile hormone is an insect invention that, according to present knowledge, has no effect on other forms of life. Therefore the promise is that third-generation pesticides can zero in on insects to the exclusion of other plants and animals. (Even for the insects juvenile hormone is not a toxic material in the usual sense of the word. Instead of killing, it derails the normal mechanisms of development and causes the insects to kill themselves.) A further advantage is self-evident: insects will not find it easy to evolve a resistance or an insensitivity to their own hormone without automatically committing suicide.

The potentialities of juvenile hormone as an insecticide were recognized 12 years ago in experiments performed on the first active preparation of the hormone: a golden oil extracted with ether from male Cecropia moths. Strange to say, the male Cecropia and the male of its close relative the Cynthia moth remain to this day the only insects from which one can extract the hormone. Therefore tens of thousands of the moths have been required for the experimental work with juvenile hormone; the need has been met by a small but thriving industry that rears the silkworms.

No one expected Cecropia moths to supply the tons of hormone that would be required for use as an insecticide. Obviously the hormone would have to be synthesized. That could not be done, however, until the hormone had been isolated from the golden oil and identified.

Within the past few months the difficult goals of isolating and identifying the hormone have at last been attained by a team of workers headed by Herbert Röller of the University of Wisconsin. The juvenile hormone has the empirical formula $C_{18}H_{36}O_2$, corresponding to a molecular weight of 284. It proves to be the methyl ester of the epoxide of a previously unknown fatty-acid derivative [*see upper illustration on this page*]. The apparent simplicity of the molecule is deceptive. It has two double bonds and an oxirane ring (the small triangle at lower left in the molecular diagram), and it can exist in 16 different molecular configurations. Only one of these can be the authentic hormone. With two ethyl groups ($CH_2 \cdot CH_3$) attached to carbons No. 7 and 11, the synthesis of the hormone from any known terpenoid is impossible.

The pure hormone is extraordinarily active. Tests the Wisconsin investigators have carried out with mealworms suggest that one gram of the hormone would result in the death of about a billion of these insects.

A few years before Röller and his colleagues worked out the structure of the authentic hormone, investigators at sev-

eral laboratories had synthesized a number of substances with impressive juvenile hormone activity. The most potent of the materials appears to be a crude mixture that John H. Law, now at the University of Chicago, prepared by a simple one-step process in which hydrogen chloride gas was bubbled through an alcoholic solution of farnesenic acid. Without any purification this mixture was 1,000 times more active than crude Cecropia oil and fully effective in killing all kinds of insects.

One of the six active components of Law's mixture has recently been identified and synthesized by a group of workers headed by M. Romaňuk of the Czechoslovak Academy of Sciences. Romaňuk and his associates estimate that from 10 to 100 grams of the material would clear all the insects from 2½ acres. Law's original mixture is of course even more potent, and so there is much interest in its other five components.

Another interesting development that preceded the isolation and identification of true juvenile hormone involved a team of investigators under W. S. Bowers of the U.S. Department of Agriculture's laboratory at Beltsville, Md. Bowers and his colleagues prepared an analogue of juvenile hormone that, as can be seen in the accompanying illustration [*top of opposite page*], differed by only two carbon atoms from the authentic Cecropia hormone (whose structure was then, of course, unknown). In terms of the dosage required it appears that the Beltsville compound is about 2 percent as active as Law's mixture and about .02 percent as active as the pure Cecropia hormone.

All the materials I have mentioned are selective in the sense of killing only insects. They leave unsolved, however, the problem of discriminating between the .1 percent of insects that qualify as pests and the 99.9 percent that are helpful or innocuous. Therefore any reckless use of the materials on a large scale could constitute an ecological disaster of the first rank.

The real need is for third-generation pesticides that are tailor-made to attack only certain predetermined pests. Can such pesticides be devised? Recent work that Sláma and I have carried out at Harvard suggests that this objective is by no means unattainable. The possibility arose rather fortuitously after Sláma arrived from Czechoslovakia, bringing with him some specimens of the European bug *Pyrrhocoris apterus*—a species that had been reared in his laboratory in Prague for 10 years.

To our considerable mystification the bugs invariably died without reaching sexual maturity when we attempted to rear them at Harvard. Instead of metamorphosing into normal adults they continued to grow as larvae or molted into adult-like forms retaining many larval characteristics. It was evident that the bugs had access to some unknown source of juvenile hormone.

Eventually we traced the source to the paper toweling that had been placed in the rearing jars. Then we discovered that almost any paper of American origin—including the paper on which *Scientific American* is printed—had the same effect. Paper of European or Japanese manufacture had no effect on the bugs. On further investigation we found that the juvenile hormone activity originated in the balsam fir, which is the principal source of pulp for paper in Canada and the northern U.S. The tree synthesizes what we named the "paper factor," and this substance accompanies the pulp all the way to the printed page.

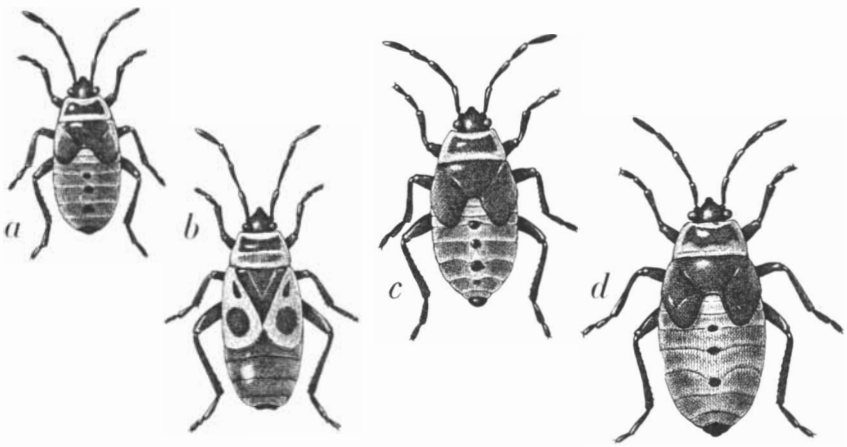
Thanks again to Bowers and his associates at Beltsville, the active material of the paper factor has been isolated and characterized [*see lower illustration on opposite page*]. It proves to be the methyl ester of a certain unsaturated fatty-acid derivative. The factor's kinship with the other juvenile hormone analogues is evident from the illustrations.

Here, then, is an extractable juvenile hormone analogue with selective action against only one kind of insect. As it happens, the family Pyrrhocoridae includes some of the most destructive pests of the cotton plant. Why the balsam fir should have evolved a substance against only one family of insects is unexplained. The most intriguing possibility is that the paper factor is a biochemical memento of the juvenile hormone of a former natural enemy of the tree—a pyrrhocorid predator that, for obvious reasons, is either extinct or has learned to avoid the balsam fir.

In any event, the fact that the tree synthesizes the substance argues strongly that the juvenile hormone of other species of insects can be mimicked, and perhaps has been by trees or plants on which the insects preyed. Evidently during the 250 million years of insect evolution the detailed chemistry of juvenile hormone has evolved and diversified. The process would of necessity have gone hand in hand with a retuning of the hormonal receptor mechanisms in the cells and tissues of the insect, so that the use as pesticides of any analogues that are discovered seems certain to be effective.

The evergreen trees are an ancient lot. They were here before the insects; they are pollinated by the wind and thus, unlike many other plants, do not depend on the insects for anything. The paper factor is only one of thousands of terpenoid materials these trees synthesize for no apparent reason. What about the rest?

It seems altogether likely that many of these materials will also turn out to be analogues of the juvenile hormones of specific insect pests. Obviously this is the place to look for a whole battery of third-generation pesticides. Then man may be able to emulate the evergreen trees in their incredibly sophisticated self-defense against the insects.



EFFECT OF PAPER FACTOR on *Pyrrhocoris apterus* is depicted. A larva of the fifth and normally final stage (*a*) turns into a winged adult (*b*). Contact with the paper factor causes the insect to turn into a sixth-stage larva (*c*) and sometimes into a giant seventh-stage larva (*d*). The abnormal larvae usually cannot shed their skin and die before reaching maturity.

INTEGRATED COMPUTER MEMORIES

The standard computer memory consists of ring-shaped ferrite "cores" threaded on wires. In the search for bigger, faster and less costly memories a number of microelectronic devices are being investigated

by Jan A. Rajchman

The computer has pervaded most fields of human activity and may well be the most important innovation of our age. Born out of the technology of communication, it is capable of handling enormous amounts of information at tremendous speeds. What makes it so potent and pervasive is the fact that a single mechanism, given the proper program, can perform any information-processing task capable of being specified. The same mechanism can calculate taxes and other items on thousands of paychecks, solve complex equations, control industrial processes, write music, form and compose characters for printing, guide space vehicles or help to teach children. This diversity of tasks —which often surprises even the designers of the machines—is made possible by the simple idea of the stored program.

The trick is to control electronically the nature and sequence of arithmetical and logical processes that are themselves electronic. In other words, what determines whether an addition, a multiplication, a simple juxtaposition or some other operation is executed, what determines the inputs of the operation and what determines the disposition of the result are not built into the machine but are part of the electronic process itself. A program is the enumeration of these determining commands; it specifies the method used for the solution of a problem in detail. It is a demonstrable fact that any determinate information-processing task can be performed by a sufficient number of minute steps, and therefore with a sufficiently fast computer can be solved in a reasonable time. When the machine is in operation, both the commands and the numbers or symbols being processed are constantly being taken out of and put into a depository of information known as a memory. This anthropomorphic name was coined by early computer workers; more restrained people, particularly in Britain, use the term "store."

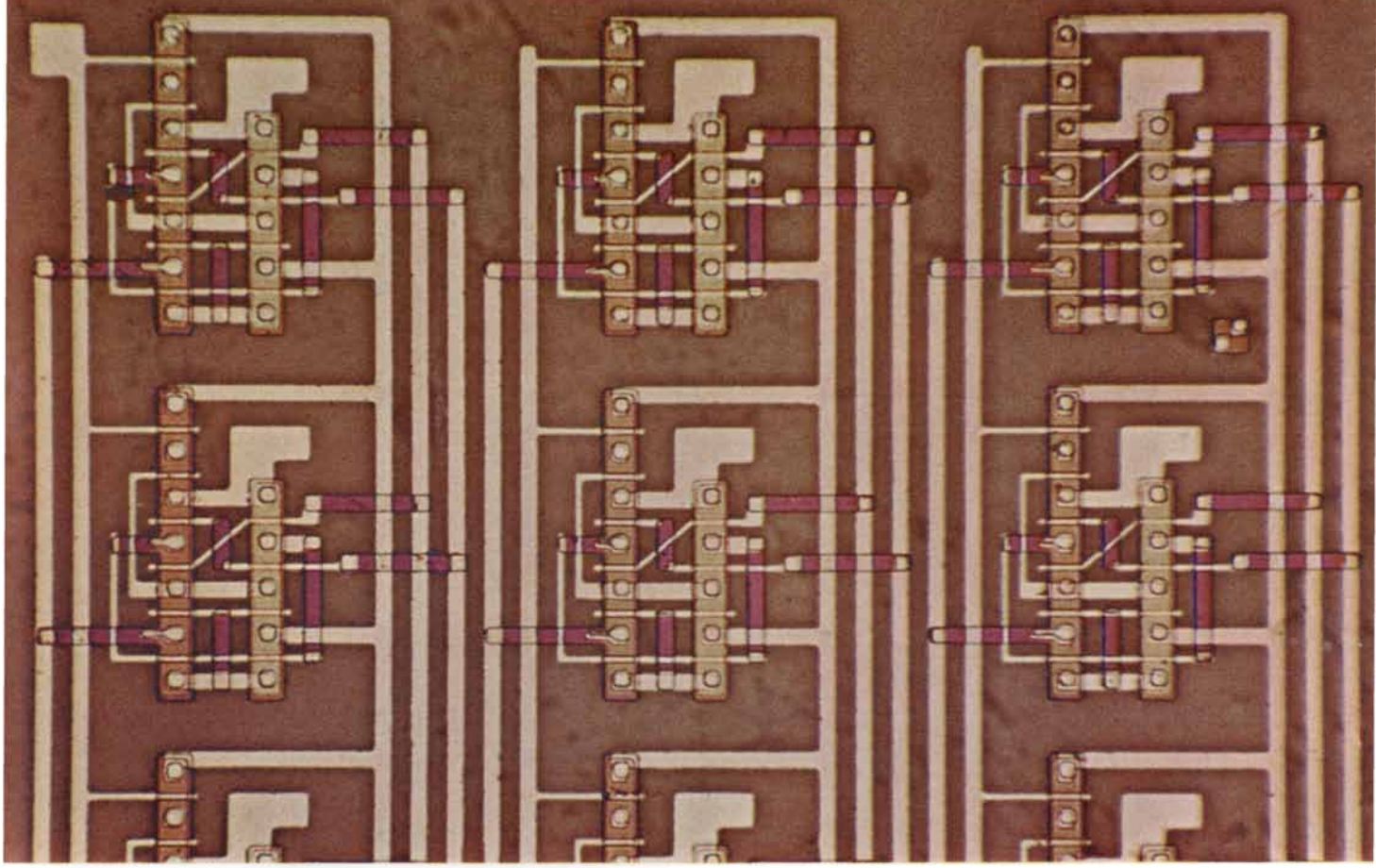
The commands, numbers or symbols needed in a processing task—known collectively as words—are stored in the memory, each with a certain "address." The address identifies the stored word and determines a definite physical location within the memory device. The power and universality of programming arises from the capacity to address the memory selectively, that is, to direct a word into any address and to retrieve it in a very short time, regardless of how the address was previously used. Such selective access is described as "random" to emphasize the programmer's total freedom to dispose of any information under any desired label and to retrieve it at any time, in contrast with "serial" memories, in which information was stored in queues and had to be retrieved in definite sequences. This made it necessary to wait for the desired information while irrelevant material was flowing by, and in general to wait longer with longer queues of information.

Perhaps the most important attribute of random access to a memory is the ease with which it is possible to choose one or another command according to the process being executed, thus allowing branching into one of two or more possible programming sequences. For example, a summation of terms is made by executing whatever operations are prescribed in each term, adding the term to the growing partial sum, and then comparing the number of terms to the total number of terms prescribed. If the prescribed limit is not reached, a new calculation loop proceeds and another term is added. If the number of terms has reached the limit, a new procedure is started: the sum can be printed out, stored for future use or become itself the input of a new process. Such "conditional transfer" and looping are the cornerstones of universal programming and are easy to execute with a random-access memory, since the number of steps in the loop can be readily programmed and conditional transfer merely amounts to the indication of another address to be selected. Clearly a high-speed random-access memory is the essential component that makes possible a modern electronic computer. Let us consider how such a memory can be implemented.

The reader will recall that digital information in a computer is expressed in "bits," each bit being the statement of a single alternative: yes or no, 0 or 1. A group of n bits can code a^n alternatives, which can express 2^n binary numbers. Accordingly all combinations of four 0's or 1's (0000 to 1111) can express 2^4, or 16, numbers, for example the numbers from 0 to 15. A sequence of bits can equally well represent a collection of arbitrary symbols, English words or artificial words.

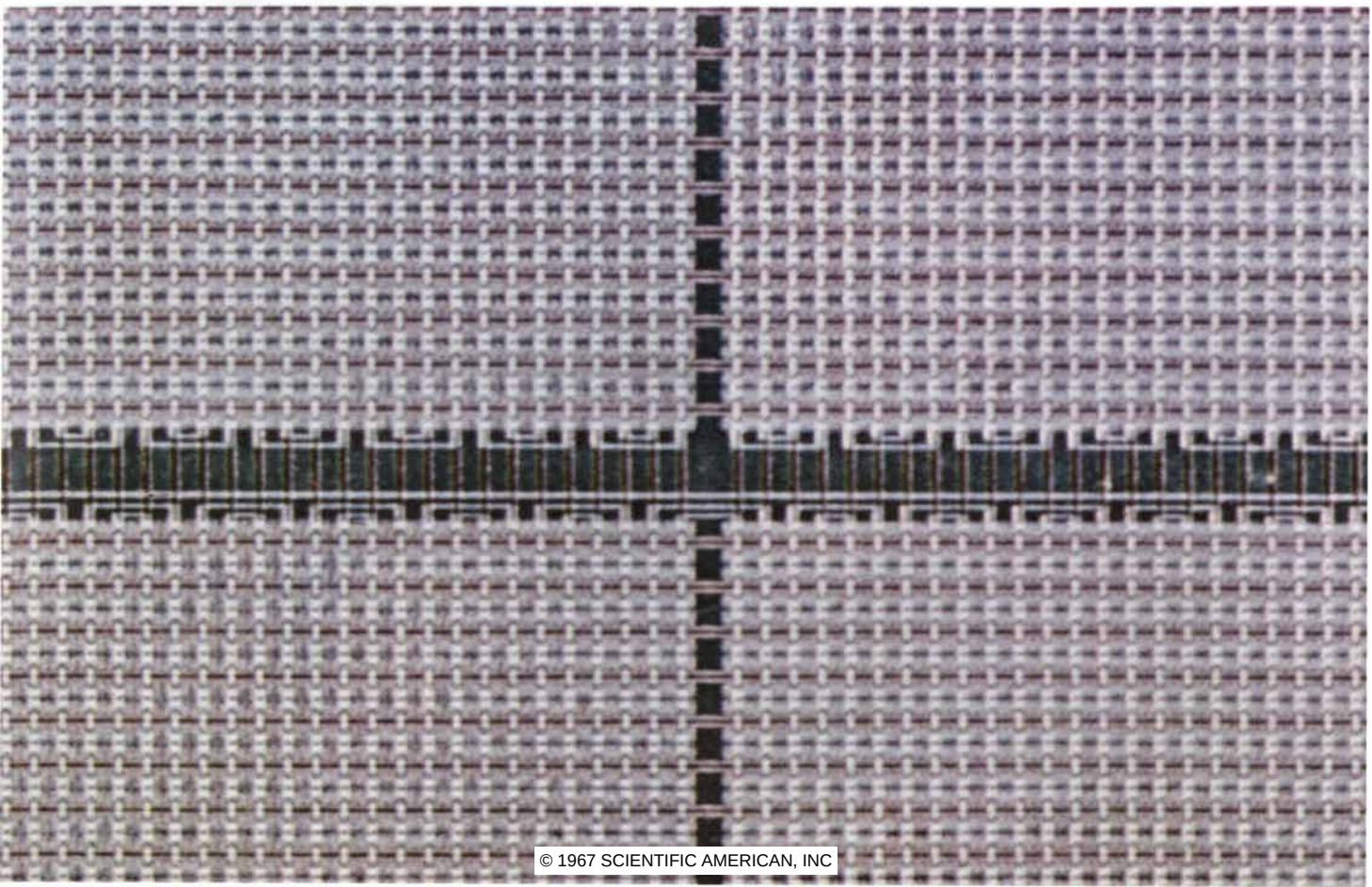
Most computers handle a fixed number of bits as a word. The function of a random-access memory is to store the m bits of a word on being supplied with an address specified in n bits. Subsequently the memory will furnish on demand, usually in less than a microsecond, the stored m bits on being supplied with the same n address bits. Such a memory has a storage capacity of 2^n words, corresponding to all possible addresses. Since each word is m bits long, the total capacity of the memory is $m2^n$ bits. In a typical "16 K" word memory n equals 14, so that the actual word capacity is 2^{14}, or 16,384 words; if m equals 40 bits, the total capacity is 655,360 bits.

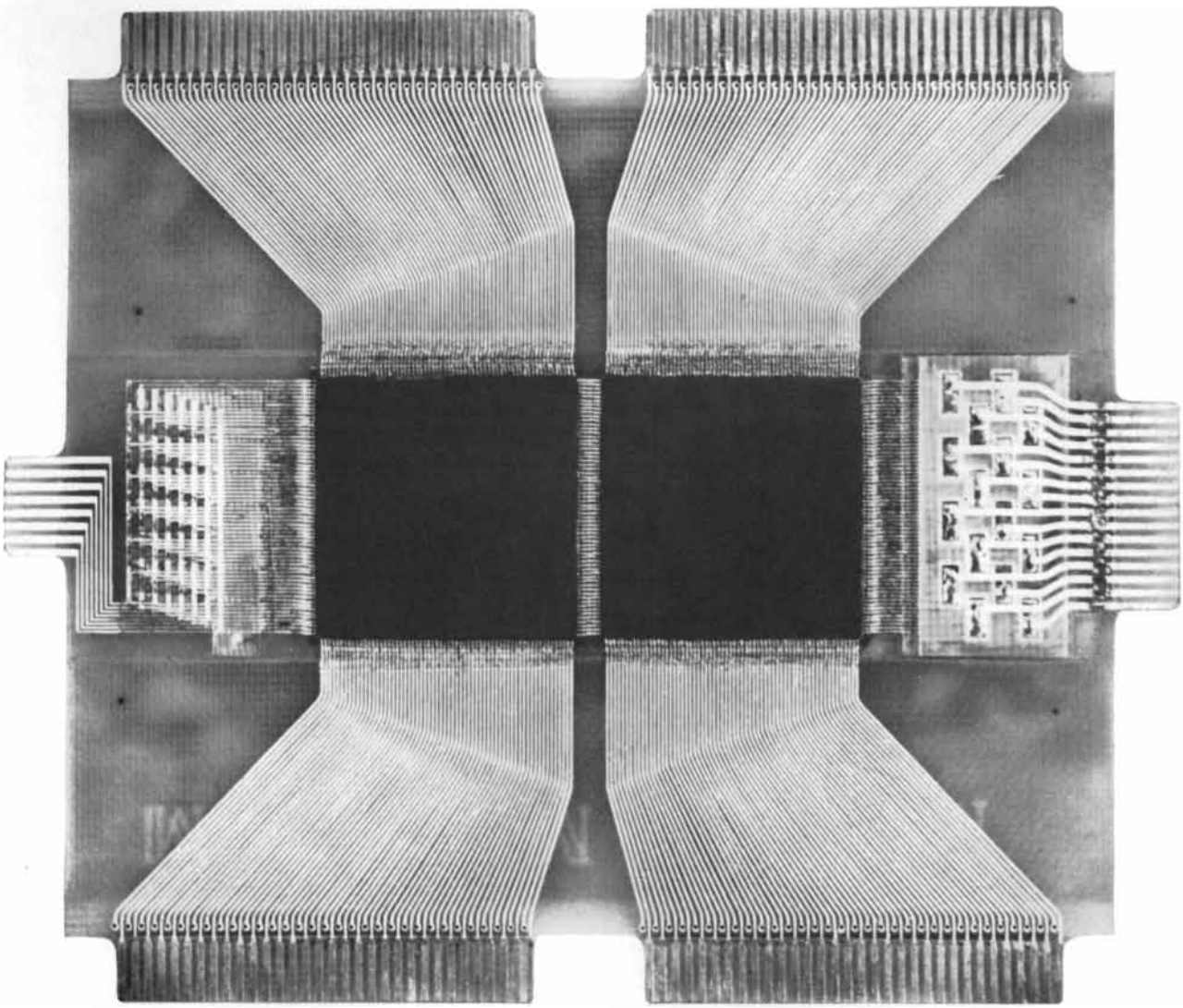
Since the early 1950's the standard random-access memory has been provided by an array of tiny ring-shaped



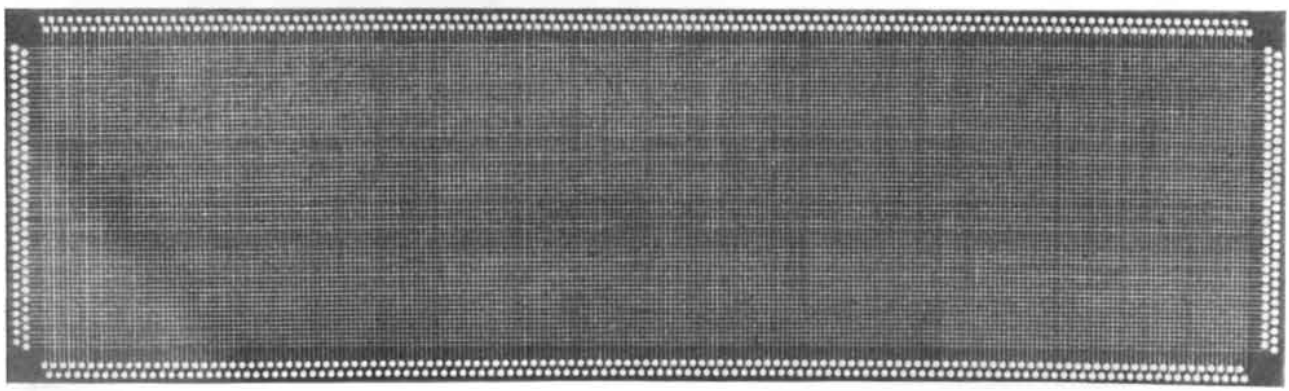
INTEGRATED SEMICONDUCTING MEMORY (*above*) is one of several new types of information-storage elements that are expected to supplant standard magnetic-core memories for certain purposes. The particular network shown here consists of nine one-bit cells, each of which contains 12 metal-oxide-semiconductor (MOS) field-effect transistors (*rows of squares*). Each cell is .015 inch on a side.

INTEGRATED SUPERCONDUCTING MEMORY (*below*) contains more than 13,000 memory cells per square inch. This enlargement shows a small section of a larger experimental memory plane. The circuit patterns were etched photographically in thin films of superconductive metals. Superconducting memories are particularly promising for large capacity, high reliability and great speed.





MONOLITHIC FERRITE MEMORY consists of three sheets of ferrite, an easily magnetized ceramic material. Two of the sheets contain conducting lines set at right angles to each other; these are separated by a third sheet of ferrite to form a sandwich. The intersections of the two sets of lines constitute the memory elements. This type of integrated magnetic memory is a contender by virtue of its high speed, compactness and low cost. The two dark squares at the center contain the memory elements; the fanlike arrays are connections to the digit lines; the staggered arrays are connections to the word lines. The entire structure is about four inches across.



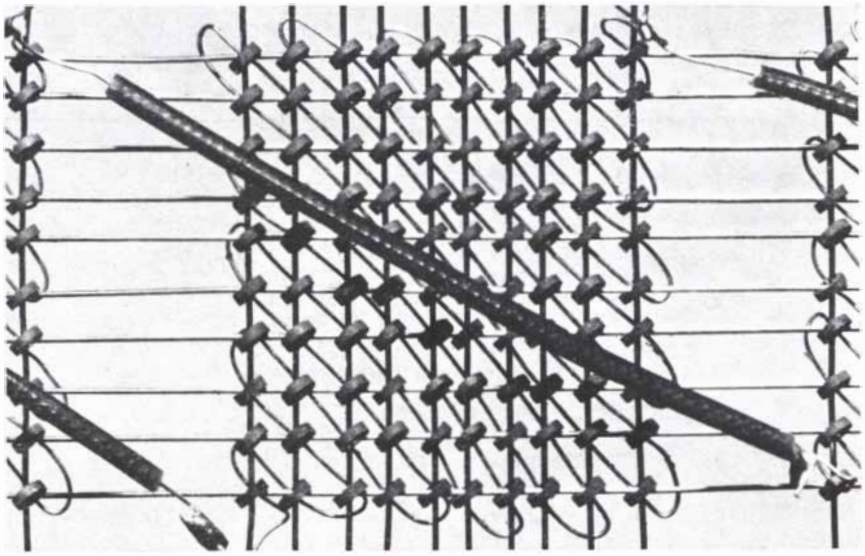
X-RAY PHOTOGRAPH of an experimental monolithic ferrite laminate reveals the 256 digit lines and 64 word lines that give this structure a total of 16,384 intersections, or individual memory elements. The laminate plane is 2.6 inches long and .84 inch wide.

cores made of a ferrite, an easily magnetized material. In its simplest form the array of cores is threaded by 2^n "word" conductors in one direction and by m "digit" conductors in the other [*see bottom illustration at right*]. Each core can hold one bit of information, which is stored in terms of the direction of imposed magnetization; in other words, the core "remembers" the direction of the effective magnetizing current sent through it last.

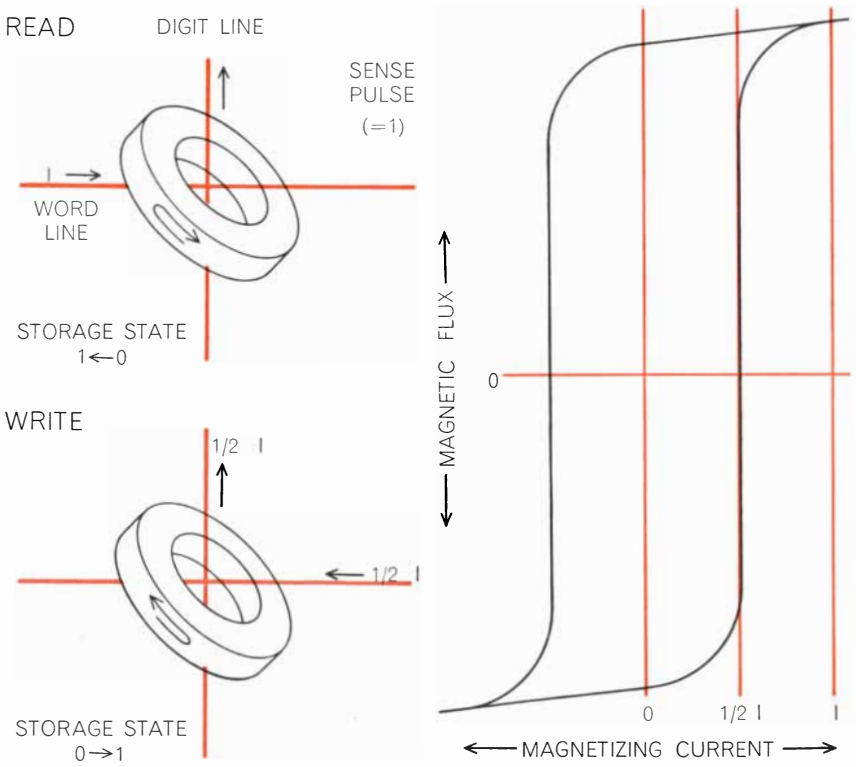
When the memory is in operation, there is a cycle of two steps: "read" and "write." In the read step a current in a given direction is sent through the selected word line and brings all the cores on it to the same state of magnetization. The magnetic flux of the cores that were in the opposite state is reversed, and this reversal induces voltages on the corresponding digit lines, which in this way sense "destructively" the word information. In a succeeding write step the current in the word line is reversed and also reduced, and simultaneously pulses of current are sent through certain digit lines. The amplitude of the word and digit currents is adjusted to be insufficient to switch a core by themselves but sufficient to switch it when they act together. As a result only the cores on the selected word threaded by energized digit lines will switch; all others will remain unaffected. In the write step the read information can be rewritten, thereby conserving the information within the memory system in spite of the destructive read-out. Until the information is rewritten it is momentarily in the circuits rather than in the cores. Alternatively, new information can be entered in the selected word address that was "cleared" in the read step.

Each of the word lines has to be energized by an active device such as a vacuum tube, a transistor or a diode. Hence a typical 16-*K* memory would require 16,384 devices, one for each address in the memory. In addition, circuits are needed to decipher the address code, whose function is to select one of the devices for every combination of n input bits. These circuits usually double the required number of devices. In the early days of the computer, when the only suitable devices were vacuum tubes, such a large number of devices would have made core memories impractical if they had had to be organized in the manner I have just described. For that reason this simple organization, called "word-organized," or "2*D*," was not the first one used.

The concept of coincident addressing,



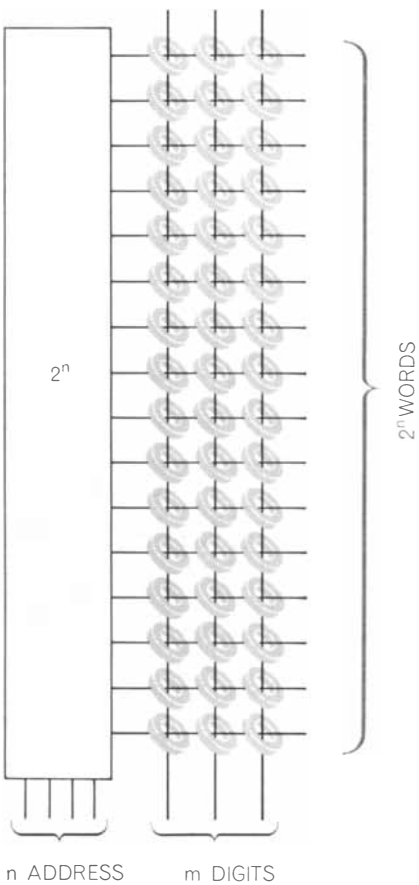
MAGNETIC-CORE MEMORY has been the standard random-access memory in computers since the early 1950's. The memory plane consists of an array of tiny ring-shaped ferrite cores, each of which can store one "bit" of information. The cores are threaded on a network of fine wires that provide the means for changing the magnetic polarity of the cores. This photograph shows one of the first core memories, made by the author in 1950.



SIMPLEST TYPE of magnetic-core memory (*left*) is threaded by "word" conductors in one direction and by "digit" conductors in the other direction. In the "read" step a current (I) in a given direction is sent through the selected word line and brings all the cores on it to the same state of magnetization. The magnetic flux of a core that was in the opposite state is reversed, and this reversal induces a voltage on the corresponding digit line, which in this way senses "destructively" the word information. In a succeeding "write" step the current in the word line is reversed and also reduced (to $\frac{1}{2}I$), and simultaneously a pulse of current (also $\frac{1}{2}I$) is sent through the digit line. The amplitude of the word and digit currents is adjusted to be insufficient to switch a core by themselves but sufficient to switch it when they act together. A memory organized in this way is said to be "word-organized," or "2*D*." A typical rectangular hysteresis loop for a magnetic-core memory (*right*) relates the magnetic flux around the core to the magnetizing current that is passed through it.

or "3*D*," made it possible to have a much smaller number of addressing circuits. In the most widely used form of coincident addressing the cores belonging to the bits of the word are distributed among as many square two-dimensional arrays as there are bits in a word. Thus a memory containing 40-bit words requires 40 arrays. A 16-*K* memory then calls for 16,384 cores (128×128) per array. Four wires are threaded through each core: a digit (*X*) wire and a word (*Y*) wire are connected in series through all the planes; two more wires, one to "sense" and one to "inhibit," are separately threaded through all cores in each plane [*see top illustration on opposite page*].

In the read step, pulses of equal strength are sent simultaneously through selected *X* and *Y* lines. Here again the amplitude of any one pulse is insufficient to switch any core by itself but sufficient to do so when acting in coincidence with another pulse. As a result, in each plane the core at the intersection of an *X* line and a *Y* line will switch or not, depending on its magnetic state; no other core will be affected. The voltages induced by the switching of the selected cores appear simultaneously on the corresponding sense lines. In the write step, *X* and *Y* currents of the same amplitude but reverse direction are applied, and they tend to switch all 40 selected cores to the opposite direction. This tendency is canceled on selected planes by simultaneous application of inhibit currents of the same amplitude but opposite direction, which travel through the inhibit wire. As before, the write step is used to rewrite information. Addressing in a coincident memory requires two sets of $2^{n/2}$ driving devices. In our example, where $n = 14$, $2^{n/2} = 2^7$, or 128, driving devices per set; this is far less than one set of 2^{14}, or 16,384, driving devices. The gain results from the participation in the decoding function of the core itself, which responds to two signals but not to one, and thus acts as an "and" gate. (In the binary logic of computers an "and" gate is a circuit whose output is 1 if, and only if, all input variables to the circuit have the value 1.)



WORD-ORGANIZED MEMORY stores *m* bits of a word on being supplied with an address specified in *n* bits. Such a memory has a word-storage capacity of 2^n words and, since each word is *m* bits long, a total capacity of $m2^n$ bits. In this example *n* equals four, so that the actual word capacity is 2^4, or 16 words; *m* equals three, so that the total storage capacity is 48 bits.

Coincident addressing is best achieved if all cores have identical magnetic characteristics known as rectangular hysteresis loops [*see bottom illustration on preceding page*]. It is then possible to choose a magnetizing current that will bring the cores on the selected lines just below the "knee" of the loop without causing any switching whatsoever, and yet that will cause complete switching of the selected core on which they act in coincidence.

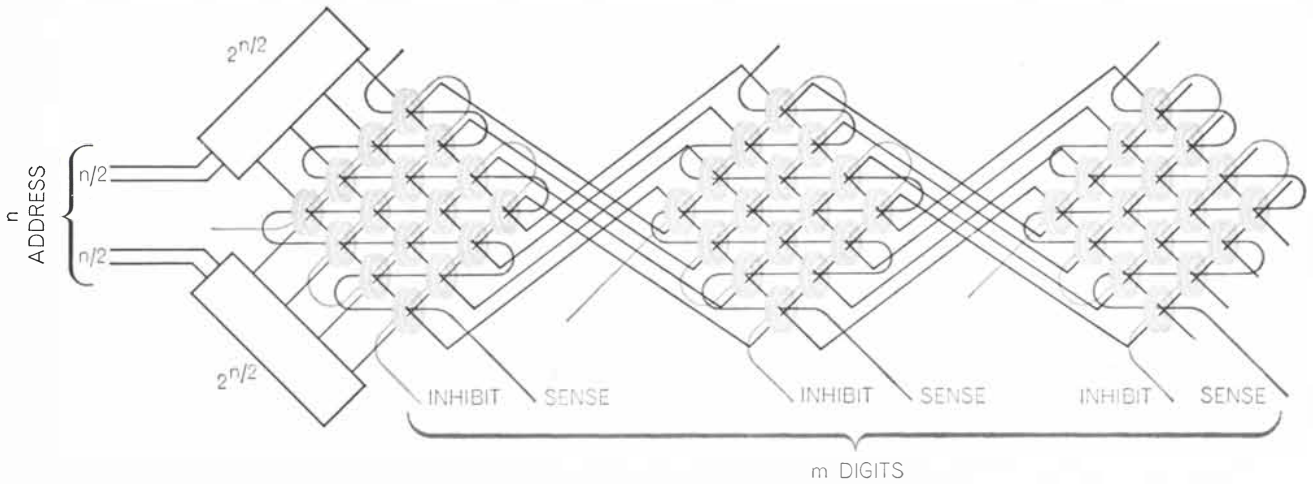
In practice it is fairly easy to approach these ideal characteristics, so that the cores will not "forget" their magnetic state even when they are subjected to millions of half-selecting pulses that tend to change that state. This is the only requirement in a 2*D* word-organized memory. In a 3*D* memory it is necessary to prevent small voltages induced in the sense winding of half-selected cores from "masking" the voltage of the selected cores. These numerous voltages (2×127, or 254, in our example) can usually be made to cancel each other by proper threading of the sense winding, but because the cores are not perfectly uniform and the hysteresis loop has not only a slope but a curvature, the cancellation is not perfect. This is one of the factors limiting the size of such current-coincident memory planes.

In addition to having a rectangular hysteresis loop the core should be capable of fast switching. Cores of nickel-iron alloy in the form of ultrathin ribbon, made during World War II for high-frequency magnetic amplifiers, had the adequate properties and made it possible to demonstrate the operation of the first memories. Such cores were delicate and expensive. Fortunately ferrites—fast switching magnetic materials made of oxides of iron, manganese, magnesium, zinc or lithium—had been developed during the 1920's and had been perfected for transformers and the electron-beam-guiding yokes of television picture tubes. Minimum hysteresis was sought for these applications. The maximum-hysteresis square loop needed for memories was achieved by ingenious modifications of composition and processing, and today many excellent core materials are available.

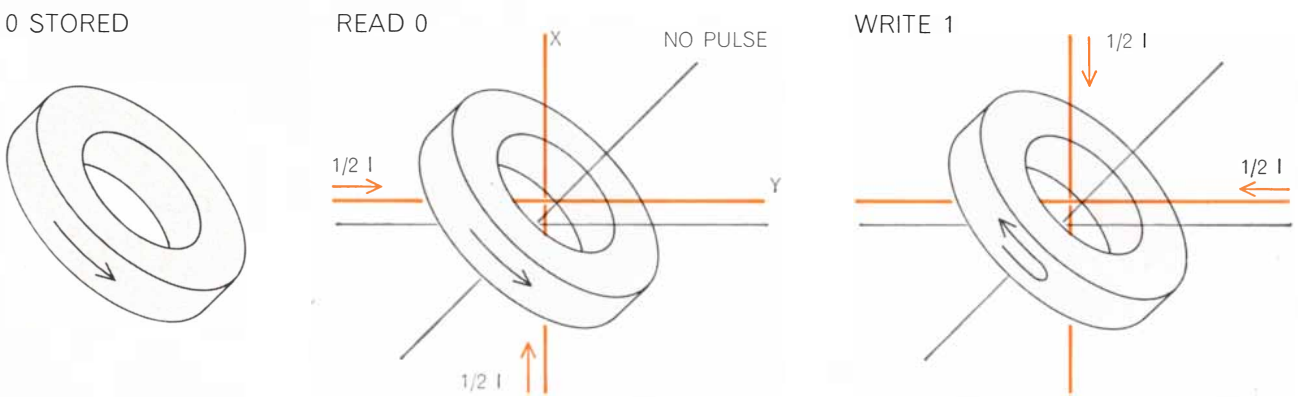
Fine powders of these materials, suspended in a binder as a slurry, are pressed into the shape of cores on automatic machines and baked. The cores are then tested and sorted automatically. The result is a low-cost, high-quality, ceramic-like element with a uniformity not surpassed by any other electronic component. The smaller the core, the less driving current it requires, the faster it switches for a given current, the tighter it can be packed to minimize delays along windings and the more difficult it is to handle and thread. As the art has progressed over the years, standard core sizes have gradually decreased from .080 inch outside diameter and .050 inch inside diameter, known in the trade as an 80/50 core, to 50/30, 30/18, 20/12 and recently even to 12/7. Typical arrays of 20/12 cores contain 16,384 of them in a square plane that measures only 6.4 inches on a side.

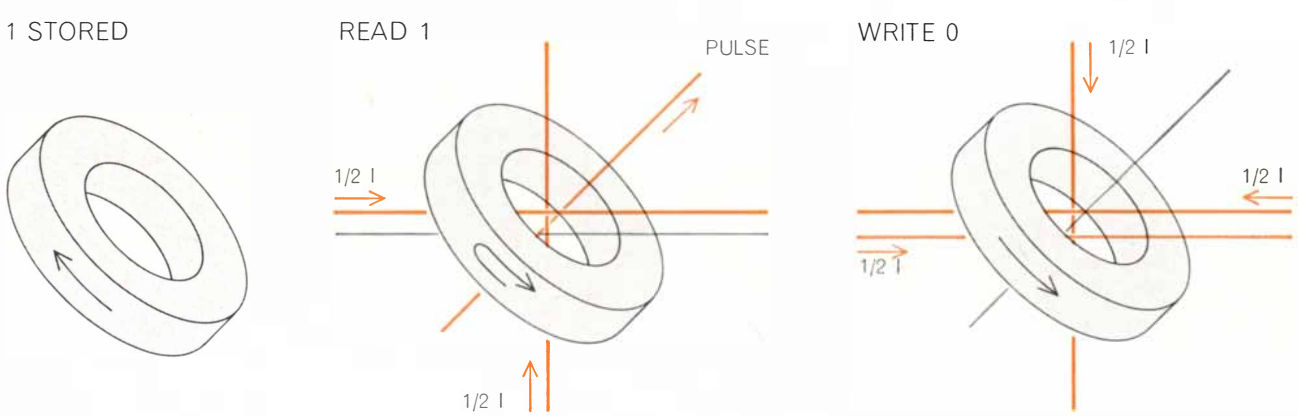
The cores are wired into arrays by painstaking handwork with only rudimentary mechanical aids. The operation is delicate and expensive, but mechanizing it is economical only for larger cores used in very large quantities. Much of the industry finds it more advantageous to use artisan labor, and some seek it at low wages in Hong Kong, Taiwan and Mexico. The situation is somewhat ironic: the heart of the computer, which itself is the symbol of mechanization, is made by the age-old kind of labor that produced brocades and carpets. The objective of this labor is not to turn out a few exquisite art objects but rather to mass-produce uniform core arrays. The annual production of core arrays in the U.S. alone involves the threading of an estimated 25 billion cores.

Made as they are, the core arrays have

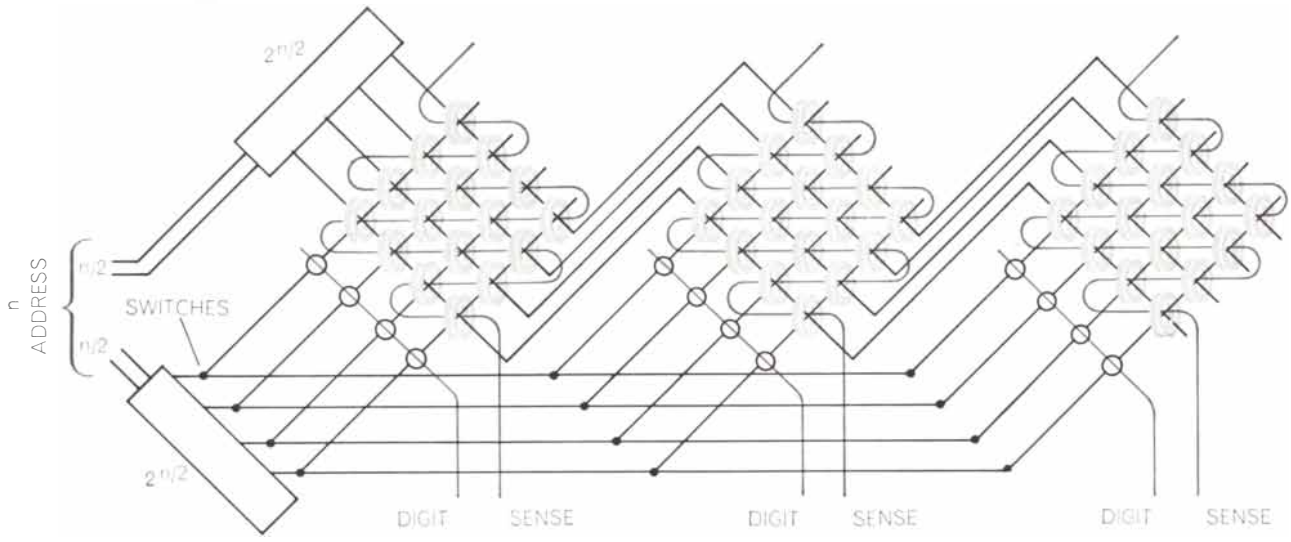


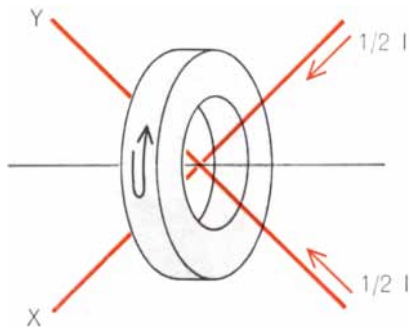
COINCIDENT ADDRESSING, a feature of "3*D*" magnetic-core memories, has made it possible to have a much smaller number of addressing circuits by distributing the cores belonging to the bits of the word along as many square two-dimensional arrays as there are bits in a word. Four wires are threaded through each core: an *X* wire and a *Y* wire (*black*) are connected in series through all the planes; two other wires, one to "sense" and one to "inhibit" (*gray*), are separately threaded through all the cores in each plane.





READING AND WRITING in a 3*D* core memory are carried out in the following way. In the read step, pulses of equal strength (½*I*) are sent simultaneously through selected *X* and *Y* lines. Here again the amplitude of any one pulse is insufficient to switch any core by itself but sufficient to do so if acting in coincidence with another pulse. As a result the core at the intersection of an *X* line and a *Y* line will switch or not, depending on its magnetic state. The voltages induced by the switching of the selected cores appear simultaneously on the corresponding sense lines. In the write step *X* and *Y* currents of the same amplitude but reverse direction are applied, and they tend to switch the selected cores to the opposite direction of magnetization. This tendency is canceled on selected planes by simultaneous application of currents of the same amplitude (½*I*) but opposite direction through the inhibit wires.



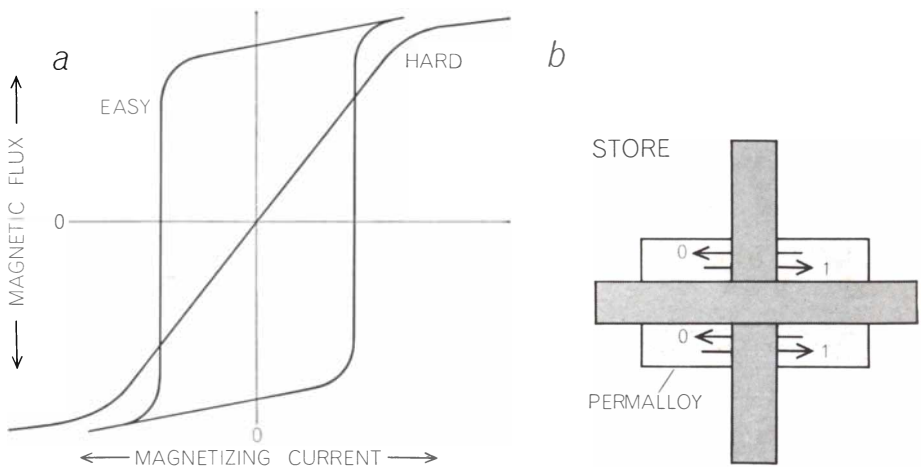


2½*D* CORE MEMORY, an organization intermediate between 2*D* and 3*D*, drastically reduces the write noise and makes the core technology faster and even more competitive with integrated technologies. The read step is the same as it is in 3*D*, but for the write step an inhibit winding is replaced by one set of selecting lines, in this case the *Y* line. The selected *Y* line in each plane is either energized or not according to the digit to be written in each plane. In the enlargement at left a 1 is written by simultaneously sending a signal through the *X* and *Y* lines; to write a 0 the signal would simply be omitted from the *Y* line.

provided reliable, fast random-access memories for practically all computers in use today. At the same time the possibility of avoiding both the manufacture of cores and the threading of them by hand has fascinated many inventors from the beginning. The stimulus has been not only to lower costs but also to increase speed of operation. The principal goal has been to produce "integrated" memories—memories in which the active elements and their connections are mechanically fabricated in a unitary process.

The problems have turned out to be difficult, and for years the constantly improving core technology has prevailed. It was found nearly impossible to obtain any magnetic element in integrated form that had a sufficiently square hysteresis loop or a switching threshold sharp enough and uniform enough from element to element to allow current-coincident operation. For the large decoder required in word-organized memories, nonintegrated arrays of cores were first used and were found rather expensive and inefficient. Today comparatively inexpensive semiconductor diodes permit a matrix arrangement of word lines for the first level of decoding, which makes a combination of cores and diodes equivalent to a coincident-addressed core array and about as economical. It was found that integrated technologies are subtle and not necessarily inexpensive. Nevertheless, a great deal of progress was made; some integrated memories have been introduced commercially, and the initial hopes are still valid, particularly for high speed. There are three significant contenders: the monolithic ferrite, the flat film and the plated wire.

The monolithic ferrite memory is made from the same type of material as the cores. The slurry is spread by a blade onto sheets. During this operation conducting parallel lines of a refractory



THIN PERMALLOY FILMS can be made to exhibit strong differences in magnetic properties along different directions of magnetization. In a "hard" direction there is practically no hysteresis but in an "easy" direction at right angles to it there is an almost perfect hysteresis loop (*a*). This property leads to two possible approaches to integrated mem-

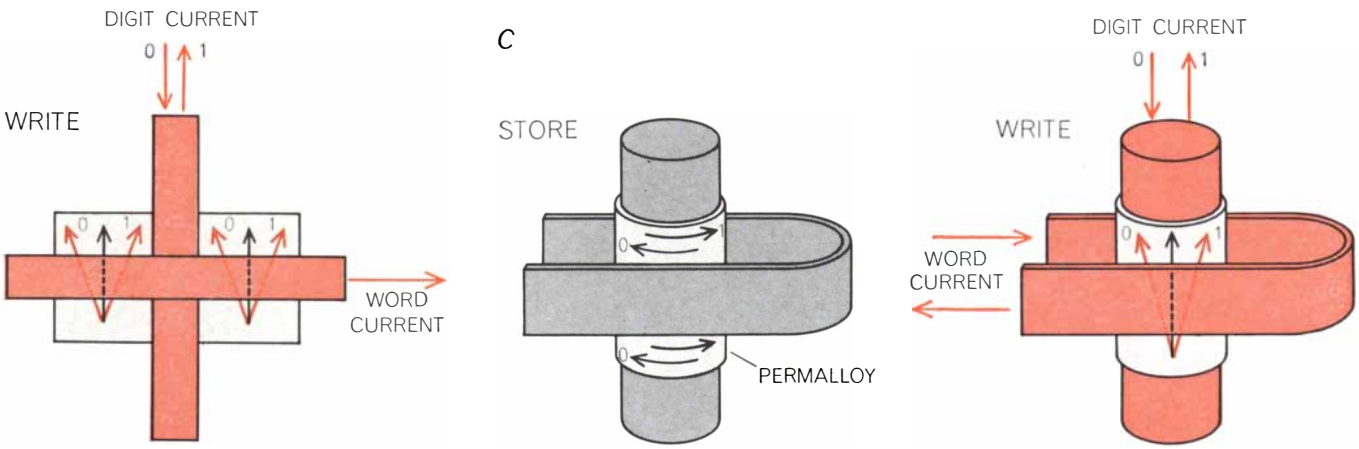
metal are also formed within the sheets. Two such sheets, with their conducting lines at right angles, face each other and are separated by a third sheet of ferrite to form a sandwich. The sandwich is then heated, pressed and sintered to produce a monolithic structure [*see illustrations on page 20*]. The conducting lines define the memory elements at their crossings. One set of lines are word windings, the other digit windings. Because the lines are at right angles to each other, a current applied to a selected word conductor switches magnetic flux along a path that does not link the digit conductor. If coincident digit pulses are applied, however, there will be flux common to the word lines and the digit lines at the corresponding crossings. The application of a word pulse in the opposite direction switches the mutual flux and induces sense voltages in the digit lines.

The monolithic integrated structure not only is easy to fabricate but also makes it possible to have very small elements. Experimental laminates about .005 inch thick have elements with an effective diameter of .003 inch. The close spacing of the lines (100 to the inch) corresponds to what can be achieved with an integrated row of diodes; indeed, fully integrated combinations of laminated ferrite and diodes have been made. One of these had a capacity of 65,416 bits and operated on a cycle of 400 nanoseconds. (A nanosecond is a billionth of a second.) The most delicate step in the construction is the actual connection between the laminate and the diodes.

The other two approaches to integrated memories involve the use of nickel-iron alloys called permalloys rather than ferrites. One difficulty with metals is that eddy currents develop and slow down the switching speed. If the thickness of permalloy sheets is held to about .00025 inch, the slowing is negligible. If the thickness is further reduced until it is comparable to the wavelength of ultraviolet radiation—say less than 3,000 angstrom units—entirely new properties appear. Switching can then be achieved by the rotation of magnetization, which is inherently a much faster process than the one that takes place in magnetic cores. In cores switching involves a movement of the walls of magnetic "domains." Thin permalloy films can be made to exhibit strong differences in magnetic properties along different directions of magnetization. In a "hard" direction there is practically no hysteresis but in an "easy" direction at right angles to it there is an almost perfect hysteresis loop. Furthermore, thin films are readily deposited by evaporation or electroplating, which lend themselves nicely to integrated fabrication. These advantages became apparent in the middle 1950's and spurred much activity.

In one approach permalloy is evaporated in a vacuum onto glass or metal to a thickness of between 1,000 and 2,000 angstroms in the presence of a direct-current magnetic field, which produces the desired direction of magnetization. Separate spots of permalloy are obtained either by doing the evaporation through a mask or by etching a continuous film. Mylar sheets with photographically formed copper lines are laid on the film and provide the word and digit lines [*see upper illustration on next page*]. The word lines run in the easy direction of magnetization. When a spot is storing a pulse, it is in one or another of the easy states of magnetization. In the read cycle a current pulse is applied to the selected word line; the corresponding spots are forcibly magnetized in the hard direction and thereby induce sense voltages on the digit lines in a direction corresponding to their state. In the write cycle or in rewrite currents are applied to the digit lines while the word current is still on; the combined currents tilt the magnetization one way or another from the hard direction and thereby establish the easy direction at the termination of the pulses.

This arrangement is attractive in that a small digit current suffices to trigger the spot into the desired state. In practice the directions of magnetization are not perfectly aligned and vary from element to element, so that a larger digit current is required to flip the flux in the desired direction in spite of irregularities haphazardly favoring one direction or another. When these imperfections are severe, the minimum digit current can be so large that it can cause elements of unselected word lines to "creep" from one magnetic state to the other. This state of affairs is particularly troublesome in lines near the selected one, which are subjected to its stray word field. The field strays because lines of magnetic flux can extend between storage elements through the air adjacent to the sheet. Still a worse result of having the elements open in this way is a stray field that can demagnetize the elements altogether. In order to keep such fields from diluting the desired sharp magnetic characteristics too much, it is necessary that the length of the storage



ories: flat-film memories (*b*) and plated-wire memories (*c*). In the storing condition the permalloy element is magnetized in one or the other of the easy directions, which are parallel to the long dimension of the flat film and around the circumference of the plated film. In the writing step the word current brings the direction of magnetization nearly to the hard direction (*black arrows*). The digit current tilts this direction one way or the other and thereby establishes the easy direction at the end of the pulses.

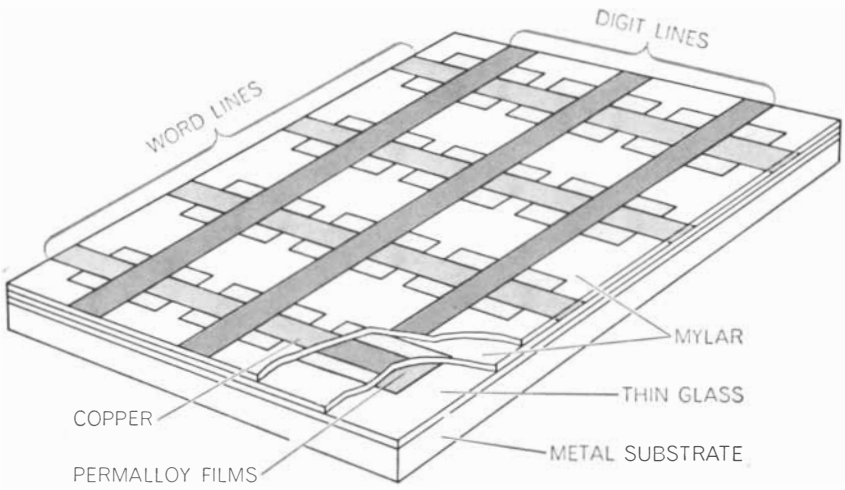
element in the easy direction be about 10,000 times its thickness, that is, more than a millimeter, and this sets a limit on compactness. The elements can be smaller, however, in the hard direction. To minimize creep and demagnetization some memories have a flat ferrite "keeper" plate on top of the sheet of storage elements.

Such inherent obstacles to thin-film integrated memories were at first something of a surprise, but they have been largely overcome. Typical flat thin-film memories have capacities of from 2,500 to 200,000 bits and cycle times as brief as from 100 to 500 nanoseconds. They began appearing in commercial computers early in 1966.

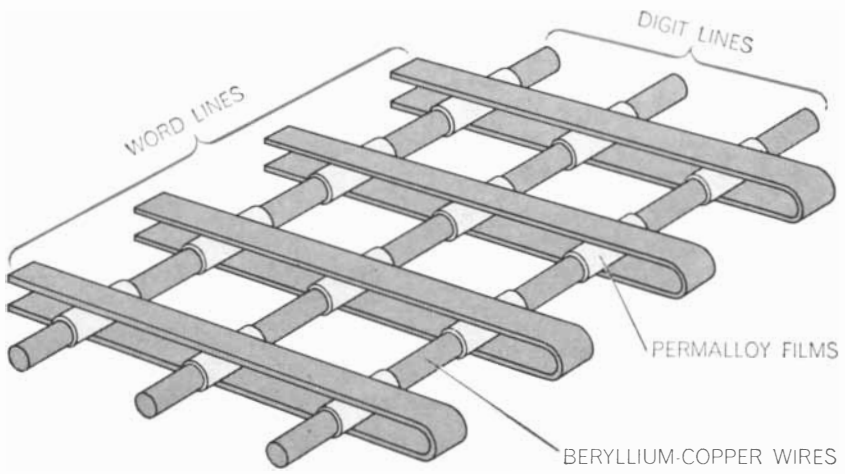
The third kind of integrated memory is the plated wire. A beryllium-copper wire is electroplated with permalloy. Straight parallel lengths of this wire are digit lines; conductive ribbons strapped on at right angles are word lines [*see lower illustration below*]. Storage is accomplished by magnetization around the circumference of the plated film, which is in the easy direction. That direction is established during plating by passing a direct current through the wire. The word current flips the fields toward the axis of the wire, which is the hard direction. This induces sense voltages in the digit lines, and small digit currents flip the fields to the selected easy directions as they do in the flat-film memory.

The plated-wire memory represents several fortunate compromises. Plating can be regarded as a one-dimensional integration. It is amenable to a continuous process, which should be more economical than the hand-threading of individual cores, and it is simpler to control than the lamination of ferrites or the deposition of flat films. Moreover, the plated-wire storage element has magnetic flux lines that are closed within the magnetic material in one direction, again a compromise between cores and flat films. The resulting reduction of demagnetizing effects makes it possible for the film to be comparatively thick: from 15,000 to 20,000 angstroms. This thickness of permalloy provides just the right amount of flux—more flux than the necessarily thin flat films and less flux than the difficult-to-miniaturize ferrite cores.

In spite of these attractions, it took years to develop plating techniques that avoided unfavorable magnetic effects. In addition, the wire on which the permalloy is plated is susceptible to strains that tend to distort the magnetic characteristics of the films. Such effects can be minimized by careful choice of materials, and today plated-wire memories are a technical success. Prototypes with a capacity of some 80,000 bits have operated on a cycle time of 150 nanoseconds. A memory system operating at 600 nanoseconds was announced for a line of commercial computers in 1966. The economy of such systems is still an open question.



FLAT-FILM MEMORY is fabricated by evaporating permalloy in a vacuum onto glass or metal to a thickness of between 1,000 and 2,000 angstrom units in the presence of a direct-current magnetic field, which produces the desired direction of magnetization. Mylar sheets with photographically formed copper lines provide the word and digit lines.



PLATED-WIRE MEMORY is fabricated by electroplating a beryllium-copper wire with permalloy. Straight parallel lengths of this wire are digit lines; conductive ribbons strapped on at right angles are word lines. The direction of magnetization around the plated film is established during the plating by passing a direct current through the wire.

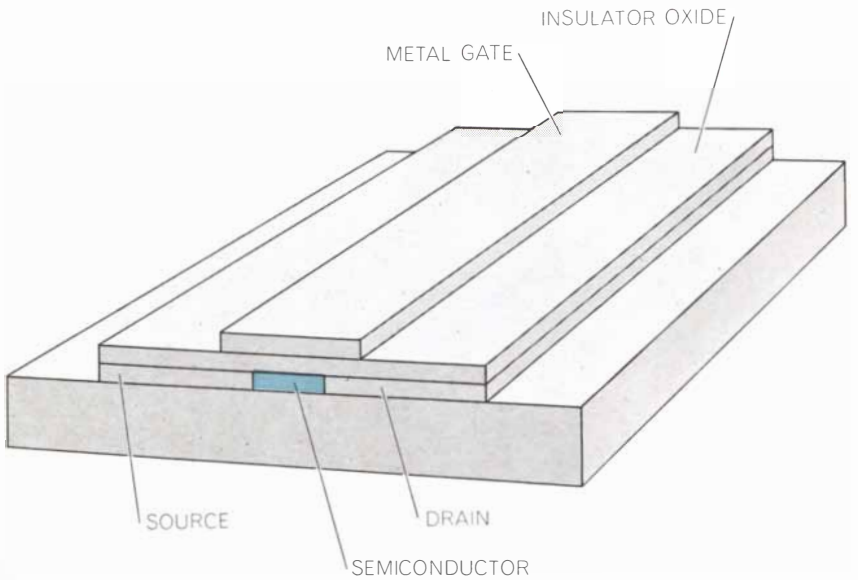
All magnetic memories have common characteristics. Access to an element in an array is achieved not by some kind of sharply selective pointer but by the somewhat imperfect means of coincident pulses on electrical lines. I have described the kind of imperfections one encounters in the storage elements; there are also unfavorable interactions between the driving lines and the sense lines. Because the driving currents are a considerable fraction of an ampere, spurious signals can be induced in the sense lines that can easily exceed the desired values (measured in millivolts) of sense signals. Such masking is not difficult to minimize in the read cycle of current-coincident memories. In the write cycle of 2*D* and 3*D* types, however, a large voltage can be induced in the sense line, since that line is itself the digit drive line or couples with it in every element of the digit plane. The induced voltage paralyzes the sense amplifier for a period that is often the most significant part of the memory's cycle time.

To minimize write noise in word-organized 2*D* memories, the two halves of the digit lines are often driven so as

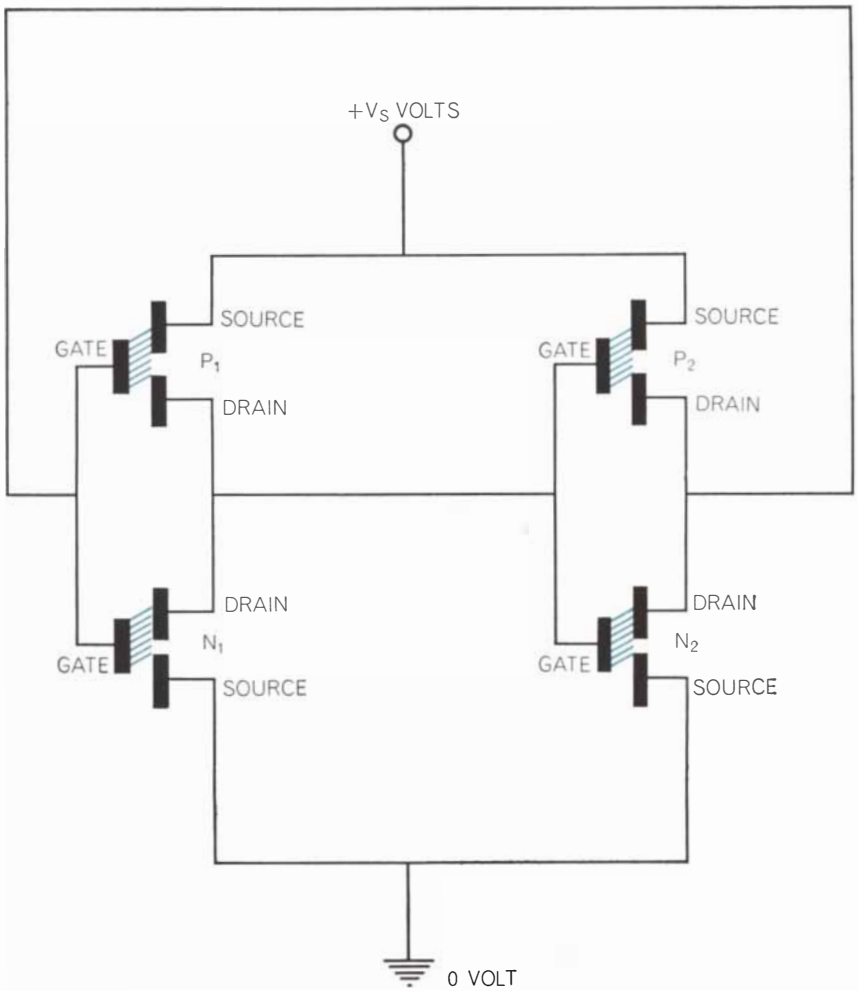
to induce opposing voltages in the sense amplifier and yet not attenuate the sense voltage. Such a circuit also serves to cancel the coupling by capacitance. In current-coincident 3*D* memories the inhibit and sense lines are wound in different patterns designed to minimize magnetic and capacitative coupling, but this cannot be done perfectly for both. Recently an organization intermediate between 2*D* and 3*D*, called 2½*D*, has become popular [*see top illustration on page 24*]. It drastically reduces the write noise and makes the core technology faster and even more competitive with technologies based on integrated laminates or films. The read step is the same as it is in 3*D*, but for the write step an inhibit winding is replaced by one set of selecting lines, say the *X* lines. The selected *X* line in each plane is either energized or not according to the digit to be written in the plane. Clearly write noise is greatly reduced, since the noise now originates from one line rather than from the entire plane. The price for this advantage is more circuitry.

Noise-cancellation techniques and 2½*D* are examples of stratagems to minimize the imperfections inherent in coincident-line addressing of arrays of magnetic elements. These stratagems can help only up to a point. In general the faster one wishes to operate the memory system, the smaller is the number of elements permissible in the sense and drive lines. This is so not only because of the write noise but also because of the time it takes signals to travel through the system and the power required by long drive lines. When detailed designs are worked out for memories of various capacities and speeds based on cores, laminates, flat film and plated wire, it rather surprisingly turns out that about the same speed, within a factor less than two, is obtained for a given ratio of storage elements to switching elements (transistors or diodes) required in the memory system.

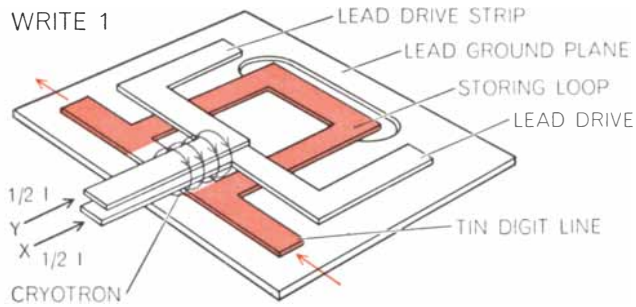
For fast systems with a cycle time of from 100 to 200 nanoseconds this bits-to-switches ratio may be as low as 30 to one; for the widely used 3*D* core systems operating at about one microsecond the ratio is about 300 to one, and for very large, slow systems it may be as high as 700 to one. Although the bits-to-switches ratio is not a complete criterion for choosing between various memory technologies, it determines the relative cost of the associated electronic circuitry. The ratio is most significant, however, in considering whether any magnetic technology can be extended to very high speeds or very large storage capacities.

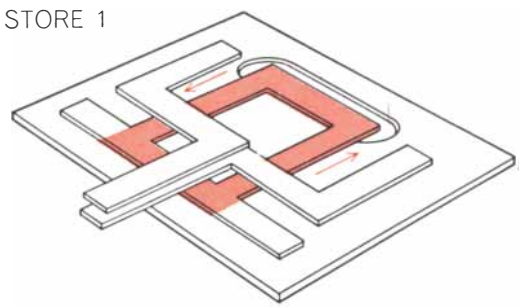


MOS FIELD-EFFECT TRANSISTOR is an almost perfect switch. The conduction between the "source" and "drain" electrodes is controlled by the potential of an insulated metal gate. There are two types of MOS (metal-oxide-semiconductor) transistor: the *n* type, which conducts by means of electrons, and the *p* type, which conducts by electron "holes."



"FLIP-FLOP" CIRCUIT is formed when two pairs of *n*- and *p*-type MOS transistors are connected in series and symmetrically cross-connected. Large arrays of such circuits are the basis of a particularly promising class of integrated semiconductor memory systems.





SUPERCONDUCTING MEMORY ELEMENT contains a cryotron switch, which operates by creating a local magnetic field that destroys superconductivity in part of a loop of superconducting tin. The memory depends on the principle of current coincidence in the selecting *X* and *Y* lines, which carry currents that are insufficient to activate the switch singly but are sufficient when they

These questions should be considered separately.

In a computer the time required to put commands and numbers into the memory and to retrieve them should be comparable to the time required to perform logic operations on them before they are again returned to the memory. Electronic logic has become far faster as technology has progressed from vacuum tubes to transistors and integrated circuits. Progress in memories was difficult, and a comparable evolution could be obtained only in memories of small capacity. Accordingly computer designers resorted to a hierarchy of memories: a small, fast "scratch pad" memory and a slower large main memory. In magnetic memories the cycle time—read followed by write—consists of (1) address-decoding time, (2) the time required for signals to travel along lines, (3) the time needed to switch elements twice, (4) delay in amplifiers and (5) delays due to write-in noise and timing imperfections. The fastest magnetic scratch pads use fast decoders, short lines, fast film memory elements and are cleverly designed to minimize delays. They call for much electronic circuitry, and at cycle times less than 100 nanoseconds the bits-to-switches ratio becomes very small. With the advent of integrated circuits the question arises of whether magnetic storage should be eliminated altogether. The economy in circuits achieved by the use of magnetic elements is no longer significant, and the necessity of amplifying the weak magnetic sense signals wastes cycle time.

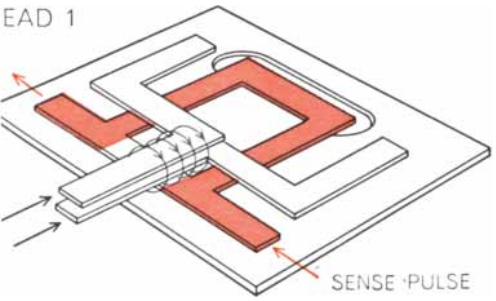
As a matter of fact nonmagnetic memories have been used for years in all computers. Semiconductor registers, which consist of a row of "flip-flops" each storing one bit, can be regarded as one-word memories. A genuine memory calls for selection among many words. Such selection does not differ from the type of function carried out in the computer by organs responsible for logic control and arithmetic. This type of function is accomplished by "and," "or" and "nor" gates. (The output of an "or" gate is 1 if at least one of the inputs is 1. "Nor" stands for "not or.") For each bit a flip-flop and selecting gates are needed, so that a complete circuit calls for perhaps 10 transistors. Together with peripheral circuitry this yields a bit-to-switches ratio of only about one to 10. Furthermore, direct-current power is continuously required to hold the state of the flip-flops. With the transistors available a few years ago, the high component count and holding power made all-transistor memories impractical. The situation is changed today by the large strides that have been made in integrated circuits and by the advent of the metal-oxide-semiconductor (MOS) field-effect transistor.

The MOS field-effect transistor is an almost perfect switch [*see top illustration on preceding page*]. The conduction between the "source" and "drain" electrodes of the transistor is controlled by the potential of a perfectly insulated metal gate. There are two types of MOS transistor: the *n*-type, which conducts by means of electrons, and the *p*-type, which conducts by means of "holes," or regions deficient in electrons. It is possible to fabricate *n*- and *p*-type transistors that have practically no conduction between the source and the drain when the gate is at the same potential as the source. However, when the gate potential is a few volts positive with respect to the source of an *n*-type MOS transistor, or a few volts negative with respect to the source of a *p*-type MOS transistor, there is good conduction between the source and the drain. Accordingly these devices behave somewhat like relays, and logic networks consisting of MOS transistors resemble relay networks.

When two pairs of *n*- and *p*-type MOS transistors are connected in series and symmetrically cross-connected, they form an almost perfect flip-flop circuit [*see bottom illustration on preceding page*]. Both states of the flip-flop are stable, and practically no current flows through either branch of the circuit except for small currents due to slight leaks in MOS transistors. To make it possible to set the flip-flop in one state to another, six more transistors are ordinarily added. Many words can be connected to the same digit line, and sensing is extremely fast (a few nanoseconds).

The switching speed is limited by the degree to which the transistor can amplify and by the capacitance of the electrodes and windings. Almost no holding power is required (.10 microwatt per cell). The total switching power of the entire memory, no matter how large, can be much less than one watt. There is no write noise and no sense-amplifier delay, since the sense signal is quite strong. The system is nearly ideal, but is any system that contains thousands of transistors practical?

The electronics industry is investing large sums on the assumption that the answer will be yes. The industry bases its hopes on the phenomenal success of integrated circuits for other purposes. This success is due to a mastery of silicon technology: the ability to produce silicon crystals of high purity, to "dope" them precisely with impurities and to create thin insulating layers. Of equal importance is the development of photographic techniques to form conductive, insulating or specifically doped semiconductor areas on a microscopic scale. Over the years the performance of transistors improved, and it became practical to integrate two, four and then eight transistors with all their connections and coupling elements. "Chips" consisting of 20 to 30 transistors have been commercially available for the past year or two. Today the large-scale integration of hundreds or even thousands of transistors is the object of an industry-wide effort.



act together. The current path in the superconducting tin digit strip for the write, store and read operations is indicated in color.

Last year MOS memory arrays of *p*-type elements were made that had a capacity of 256 bits. The future belongs, however, to MOS arrays of both *n*- and *p*-type elements. With such elements one can put a one-bit cell, complete with a flip-flop and logic gates, on an area .015 inch square. A memory with a capacity of hundreds of bits can then be made on a chip 1/4 inch on a side. An access time of 30 nanoseconds or less is expected.

Integrated semiconductor memories are inherently more promising than any magnetic memory. After all, the comparison is between an active electronic logic circuit with explicitly designed performance and a passive magnetic element of the same size that depends more or less on the properties of materials provided by nature. The question comes down to one of practicality: Can these intricate microelectronic elements be made in large arrays with adequate perfection and economy? The answer is definitely yes for small, ultrahigh-speed scratch-pad memories with a capacity of a few thousand bits. Concerning larger memories the prophets differ. Some think it is only a matter of time; others believe magnetic memories will retain their position because their associated circuits can also be made faster, cheaper and more reliable by the new microelectronic technology.

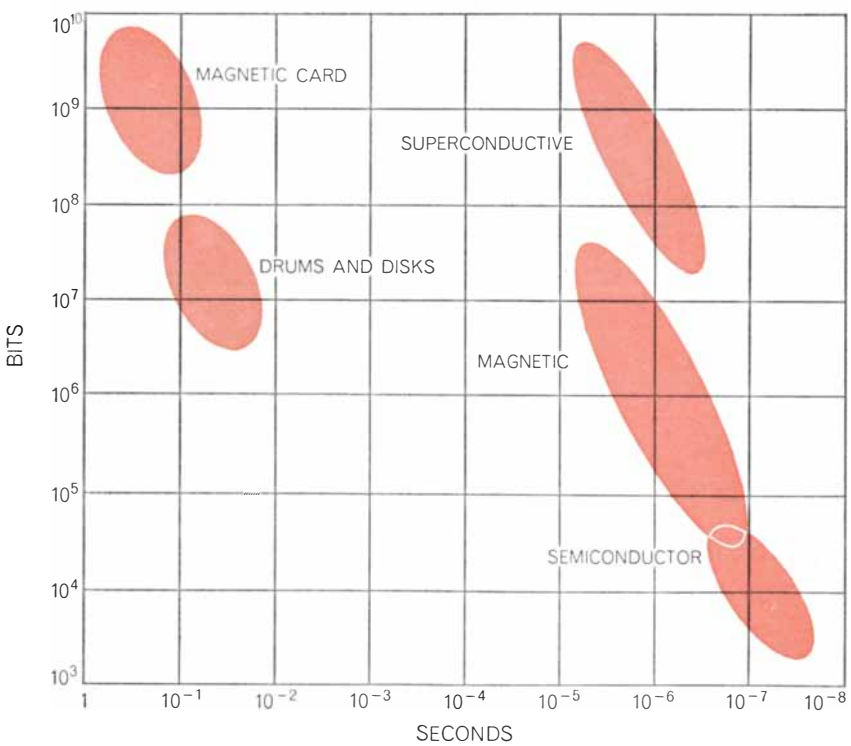
What of memories with very large capacities? Over the years the demand for larger computer memories has grown steadily as more ambitious problems with longer programs and more data were attacked, and as higher computer languages called for longer programs. Core memories were too expensive to provide the 100 million to one billion bits required for many uses, and this led to the development of memories based on spinning magnetic drums and disks. These electromechanical devices operate with a cycle time measured not in nanoseconds or microseconds but in milliseconds. When a computer is specially programmed, they seem to the user to be a simple extension of the core memory. This is a tolerable but undesirable state of affairs. Much effort is required to produce such programs (which also consume memory space), and much computer time is lost because of slow access time and the necessity of exchanging information between the cores and the drum or disk. Furthermore, the reliability of drum and disk memories leaves much to be desired.

The challenge is to produce electronic random-access memories with a capacity of billions of bits. Clearly integration on a grand scale is the only solution. Magnetic-integration techniques have yet to achieve anything like such a capacity, and even if they could millions of transistors would be needed. A more promising approach lies in the realm of superconductivity.

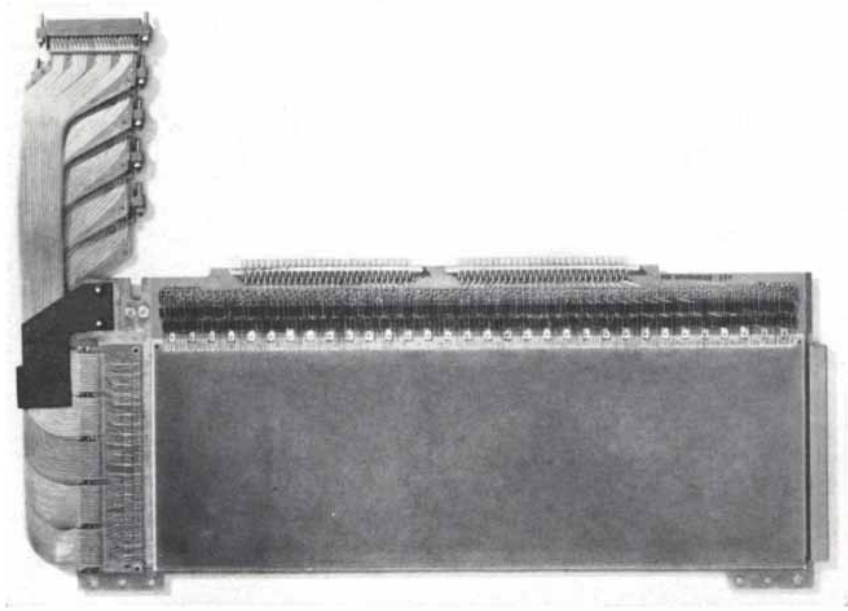
Superconductive materials, when cooled below a certain critical temperature, lose all electrical resistance. If current is started in a loop of such material, it will flow forever and therefore "remember" that it was started. The loop is in effect a one-bit memory register. Furthermore, superconductivity is destroyed by a sufficiently strong magnetic field. This effect is the basis of the cryotron switch. In the "on" state the switch has no resistance; an "off" state of finite resistance is created by passage of a current in a nearby controlling conductor that places the switch in a magnetic field. Tin, which is a "soft" superconductor, is a good material for the switch itself, because it can be changed from the superconductive to the resistant state by a weak magnetic field. A "harder" superconductor, which resists the weak field, can be used for circuit wiring. Most experimental cryotrons employ films several thousand angstroms thick. They can be switched in nanoseconds and are amenable to integrated fabrication techniques.

In a recently announced superconducting memory, storage loops made of tin are connected in series along a digit conductor and are on top of a lead sheet from which they are separated by a thin insulating film [*see illustration at left*]. The lead sheet has holes at locations corresponding to one side of each loop. The selecting *X* and *Y* conductors, made of lead and properly insulated, lie atop the other side of each loop and thus form a doubly controlled switch. The switch operates by creating a local magnetic field that destroys superconductivity in part of the loop.

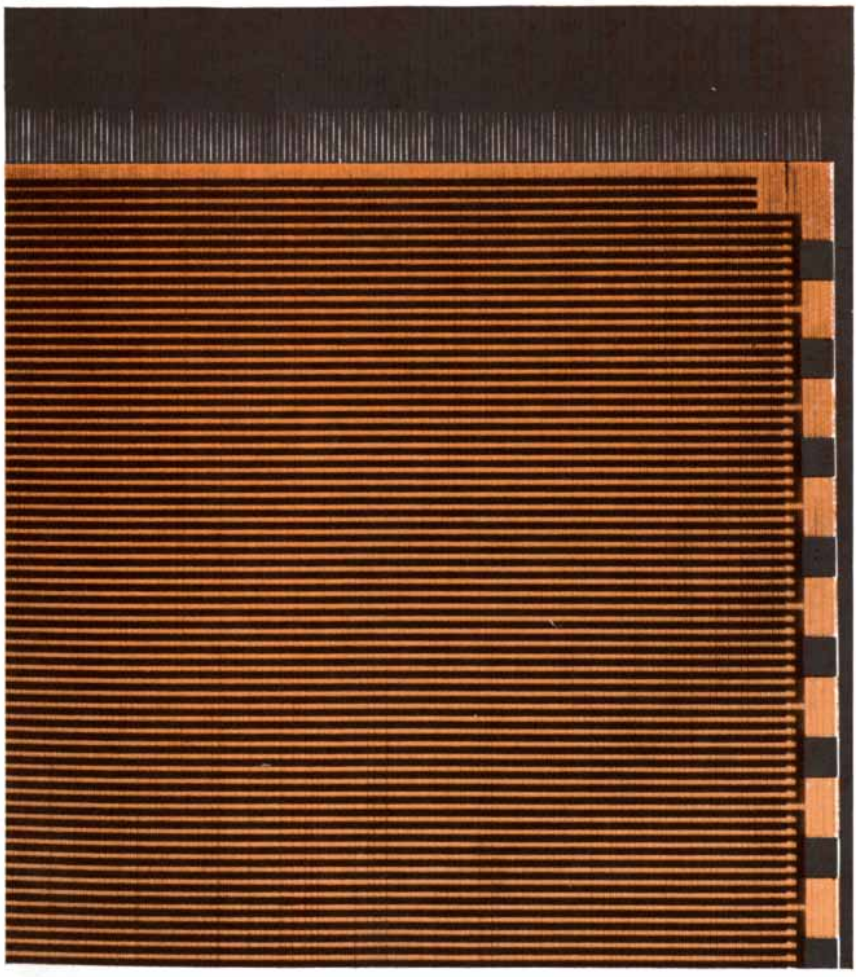
The memory system operates by current coincidence in the following manner. The selecting *X* and *Y* currents are



PERFORMANCE CHART shows the storage capacities and access times for various memories. Magnetic techniques include cores, monolithic ferrites, flat films and plated wires.



PLATED-WIRE MEMORY ARRAY was built by the Univac Division of Sperry Rand Corporation. Each side of the array holds 40,960 bits, representing the intersections of 256 word straps and 160 plated wires. The wires run in the long direction of the piece; the word straps run in the short direction. The entire assembly is approximately 18 inches long. The active area of the array is covered by a protective layer and is not visible in this photograph.



CLOSEUP VIEW of the memory array at the top of the page reveals the word straps (*black*) and the plated wires (*white*). Straps are .04 inch wide, wires .005 inch in diameter.

insufficient to activate the switch singly but are sufficient when acting together. In write-in the selecting currents are applied and then a current is sent through the digit line. The increased resistivity in the loop below the switch steers the current to the side of the loop over the hole in the lead sheet. Next the selecting currents are turned off and the magnetic field disappears, leaving the switchable side of the loop superconductive. Current does not flow through that side, however, until the digit current is turned off. When this happens, the current circulates as a persistent storing current around the complete loop. In the read cycle the selecting currents are applied and again increase the resistivity of the loop below the switch, thereby causing the persistent loop current to dissipate. As the current dissipates, it generates a sense voltage in the tin digit line. This voltage depends on the loop's magnetic flux, which is made as large as possible by allowing it to extend through the hole in the lead sheet.

Several properties of this superconducting memory are outstanding. In the first place, the loop is a more perfect memory element than any magnetic element, integrated or otherwise. There is absolutely no contribution to the sense signal from half-selected elements, there is no creep and the uniformity of the threshold of switching can be closely controlled. The selecting currents can vary from 80 to 120 percent of their standard value. There is, however, some write noise. Fortunately such noise can be eliminated by the cancellation techniques mentioned earlier. The result of these ideal properties of the loop and the low inductance of the connecting lines is that many loops can be driven and sensed by a single circuit. The bits-to-switches ratio can probably be 100,000 to one or more, which is two or three orders of magnitude better than for any magnetic memory. Furthermore, integration on the grand scale is eminently possible. Thin films of superconductive materials and other metals are easily evaporated over large areas. Photographic techniques are well suited for creating the desired patterns. The degree to which these techniques have been perfected is indicated by an experimental memory plane 4½ by five inches in size that contains 262,144 storage cells. This is a density of more than 13,000 cells per square inch [*see illustrations on opposite page*].

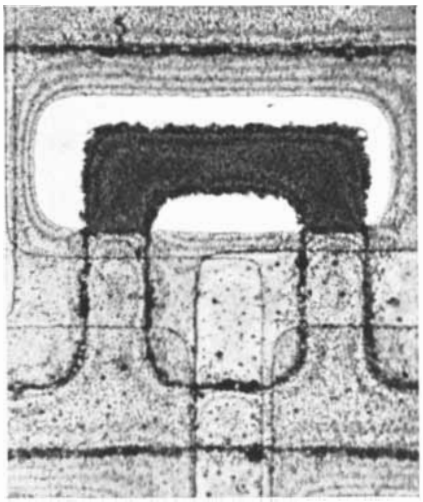
The price to be paid for these ideal properties is the necessity of providing low temperatures: for the lead-tin memory 3.5 degrees Kelvin (degrees centi-

grade above absolute zero). Such temperatures are no longer confined to the cryogenic laboratory; providing them would not add much to the cost of large-capacity superconducting memories. Memories of this kind may therefore offer capacities comparable to those of electromechanical devices at comparable cost, but with three orders of magnitude higher speed and also greater reliability.

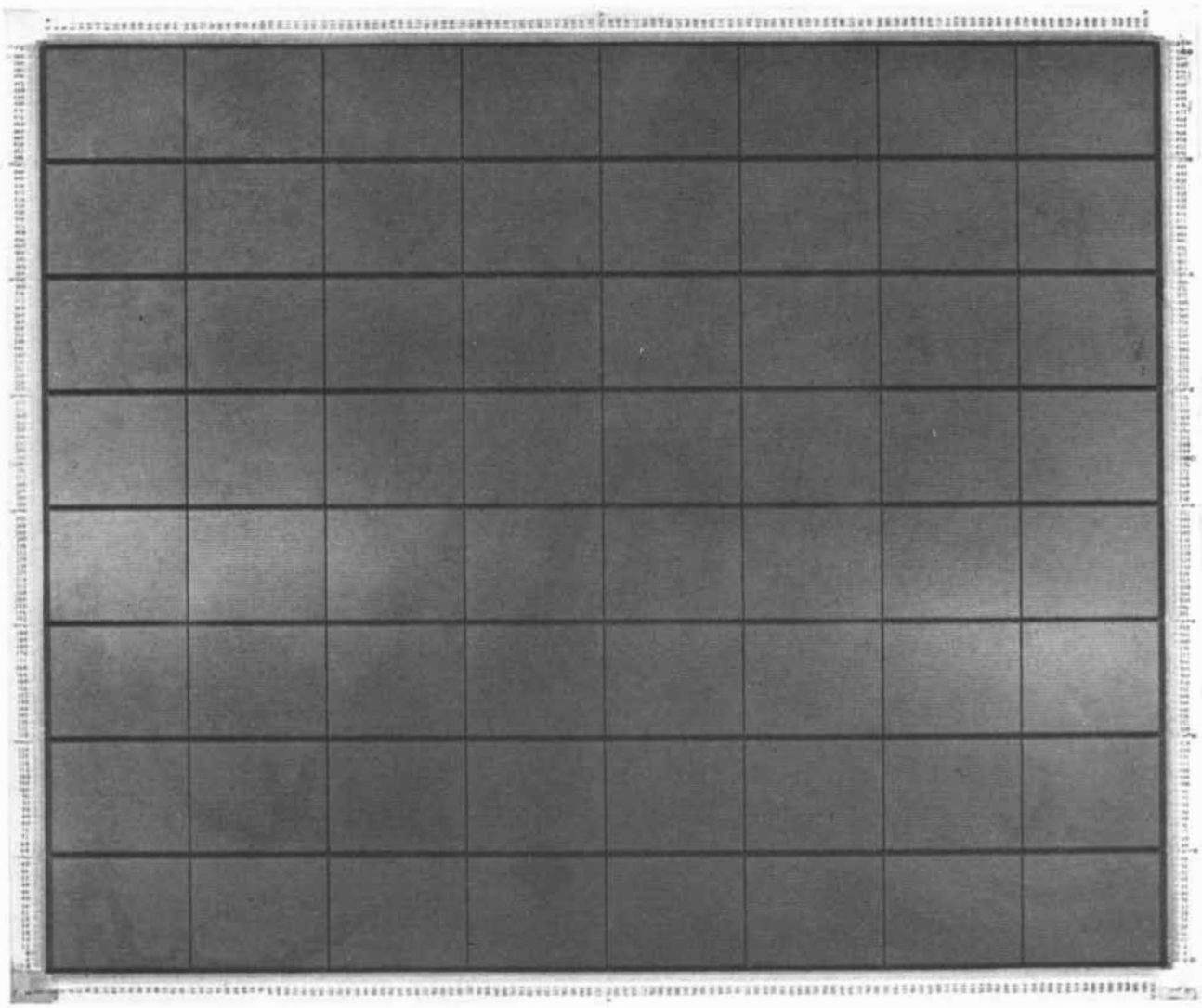
To sum up, the memory gives universal powers to the computer. For more than a decade it was based on separate cores and transistors. The arrival of integrated magnetic, semiconductor and superconductive structures may extend speeds and capacities and make computers still more powerful.

It seems that no one technology will sweep all before it. Rather, one can expect that magnetic techniques (cores, monolithic ferrites, flat films or plated wire) will provide capacities of from 10,000 to 10 million bits at speeds of a fraction of a microsecond. Integrated semiconductor techniques will provide memories of smaller capacity with speeds measured in tens of nanoseconds. Finally, superconductive mass memories with capacities of from 10 million to a billion bits will have speeds of about a microsecond.

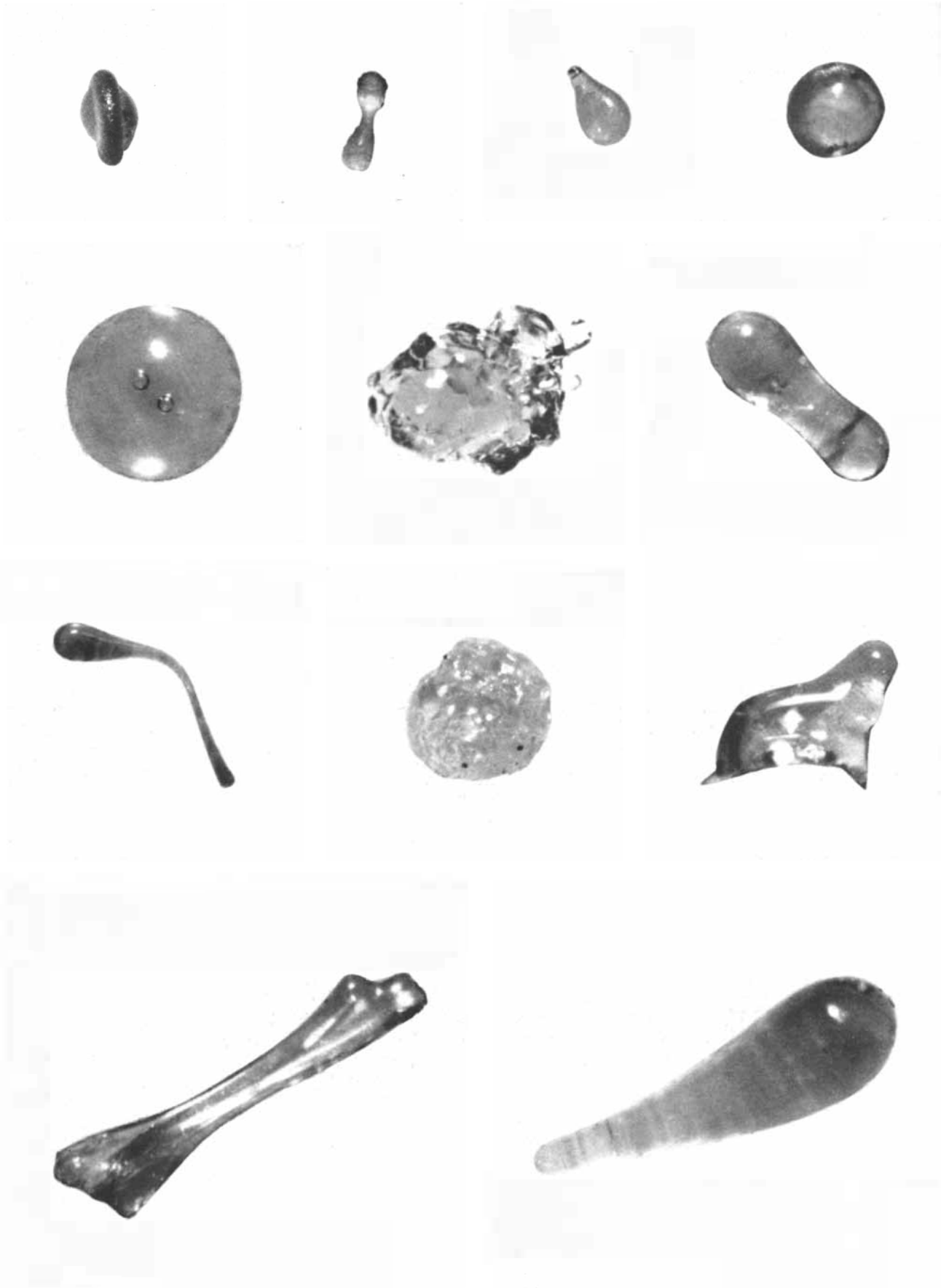
This is not the end. Already under study are various ways to avoid the making of physically distinct cells for each bit without losing the essence of digital addressing. One approach uses sound waves traveling in magnetic materials. Other approaches make use of electro-optical devices such as the laser. As long as the demand for better memory systems continues there will be no shortage of ingenious proposals.



SINGLE STORAGE LOOP, part of the large superconducting memory plane shown in the photograph below, is enlarged approximately 180 diameters in this photomicrograph.



COMPLETE MEMORY PLANE of an experimental superconducting memory built by the Radio Corporation of America measures 4½ by five inches and contains 262,144 individual storage loops. A portion of the plane is shown in the color photograph at the bottom of page 19. Superconducting memories operate at a temperature of 3.5 degrees Kelvin (degrees centigrade above absolute zero).



MICROTEKTITES were obtained from cores brought up from the bottom of the Indian Ocean. They were found at levels of the same age in various cores, indicating that they were deposited on the bottom at the same time. These specimens are at the same scale.

Tektites and Geomagnetic Reversals

The glassy stones strewn from the Indian Ocean to the South Pacific have an age that is coincident with the last reversal of the earth's magnetic field. Can both be attributed to the fall of a cosmic body?

by Billy P. Glass and Bruce C. Heezen

In 1908, shortly after seven o'clock in the morning of June 30, an enormous fireball flashed in the earth's atmosphere and exploded above a forest in the Tunguska Valley of Siberia. The explosion uprooted trees and flattened the forest over an area 25 miles in diameter. The only human beings near the scene were two families of nomads sleeping in tents at the edge of the area; the blast shook and deafened them, blew away their tents and killed or frightened off their reindeer. They were not, however, the only witnesses. It was so tremendous an explosion that people 250 miles away heard the noise, and barographs and seismographs all over the world recorded the shock. During the next few nights the sky throughout Europe and northern Asia was bright with silvery clouds.

It is estimated that the explosion released 10^{21} ergs of energy—a blast as great as the volcanic explosion that blew up the island of Krakatoa in 1883. Astronomers suspected that the explosion in Siberia had been caused by a large meteorite striking the earth. A diligent search of the ground failed, however, to disclose any impact craters or recognizable meteorites. The only significant clues were microscopic spherules, some composed of glass and others of metal, that were found strewn all over the devastated forest. Russian and American astronomers concluded that the blast was probably caused by a small comet entering the earth's atmosphere. The glassy spherules were believed to be remnants of the comet's exploded nucleus, and the brightening of the night sky that followed the blast was assumed to be due to the passage of the comet's tail through the atmosphere. Some investigators now speculate that an encounter with a small meteorite of antimatter, resulting in mutual annihilation with matter in the earth's atmosphere, might account for the explosion. It is still generally accepted, however, that in all likelihood the explosion resulted from a larger cosmic body plunging into the atmosphere.

Encounters with extraterrestrial matter—intrusions on our planet of particles and bodies from outer space—have provided food for thought in many branches of science, not to speak of literature and philosophy. There are the cosmic ray particles that continuously bombard us, the great craters in the earth that tell of the fall of large meteorites in the past and the spectacular falls that man has witnessed in our own century, such as the fireball of 1908 and the large meteorite that also fell in Siberia in 1947. We shall relate here some recent findings that may further illuminate the history of the earth's encounters with cosmic bodies. The writers of this article are not astronomers or physicists; we are marine geologists, and our evidence comes from exploration of the ocean bottom. This evidence suggests, among other things, that the earth has been subject to massive cosmic collisions at fairly frequent intervals, and that it may be due for another major encounter.

A number of investigations have shown that the poles of the earth's magnetic field have reversed many times. Indeed, in recent geologic periods they have reversed every few hundred thousand years [see "Reversals of the Earth's Magnetic Field," by Allan Cox, A. Brent Dalrymple and Richard R. Doell; SCIENTIFIC AMERICAN, February]. Such studies are based largely on magnetism "frozen" into certain rocks and sediments.

The investigation of fossil magnetism in deep-sea sediments began barely a year ago. A new apparatus for such purposes had been built by John Foster, working in the paleomagnetic laboratory of Neil Opdyke at the Lamont Geological Observatory of Columbia University, and within the first few days of its use on deep-sea sediments it had served to demonstrate that geomagnetic reversals are recorded in many of them. Then the observation was made that the layers of sediment that recorded the reversals were correlated with layers that indicated an abrupt change in populations of tiny marine animals.

These results were not totally unexpected; other investigators had detected magnetic reversals in deep-sea sediments. Brian Funnel and Christopher Harrison of the Scripps Institution of Oceanography had reported a correlation between a similar biological boundary in mid-Pacific sediments and the last geomagnetic reversal, which occurred 700,000 years ago. In fact, Robert Uffen, chairman of the Defence Research Board of Canada, had predicted on purely theoretical grounds that a correlation must exist between magnetic reversals and biological evolution. He reasoned that an abrupt decline in the strength of the earth's magnetic field, which normally tends to deflect the electrically charged particles of cosmic radiation, would allow more of the particles to reach the earth's surface; there they would exert a powerful effect on evolution by causing mutations, lethal and otherwise.

Critics of Uffen's proposal observed that the flux of cosmic rays at sea level would be only doubled and that, although land organisms might be affected, marine life would be largely shielded by seawater. Be this as it may, the correlation between evolutionary crises and magnetic reversals was first detected in fossil marine organisms. The correlation seems to be standing up, but it should be

said that there are unexplained gaps in it; more work on the fossil plankton must be done before a firm conclusion can be drawn.

The possibility that magnetic reversals and changes in fossil plankton were associated with an extraterrestrial intrusion was unexpectedly suggested to us as we were studying sediments from the sea bottom off Australia. In these sediments we found tiny spherules, teardrops, dumbbells and other shapes characteristic of the class of glassy meteorites known as tektites. These microtektites, none larger than a millimeter across, closely resemble larger tektites found on land in that part of the world. They were obtained from a layer starting at the bottom with sediments laid down at the time of the last geomagnetic reversal and ending between 30 and 50 centimeters higher. Spurred by this discovery, we found microtektites in core samples of the bottom taken off Australia and Tasmania, in the Philippines area, near Japan and across the Indian Ocean almost all the way to Capetown. The litter of tektites turned out to cover an area 6,000 by 4,000 miles in extent, from Tasmania to well north of the Philippines and from the East Indies to the east coast of Africa.

The fact that the microtektites were all laid down in sediments dated to the time of the last geomagnetic reversal immediately points to a common cause, possibly an encounter between the earth and some massive cosmic body. Naturally one is struck by the fact that the microtektites are similar to the microscopic glassy spherules that fell in the Tunguska Valley forest in the explosion of 1908. Our samplings from the ocean bottom indicate that at least a quarter-billion tons of glassy material was strewn over nearly a tenth of the earth's surface. Undoubtedly a cosmic collision that deposited this amount of material would have caused fantastic destruction of animal and plant life in the area, and it could have raised tidal waves that swept over shores throughout the world.

Harold C. Urey of the University of

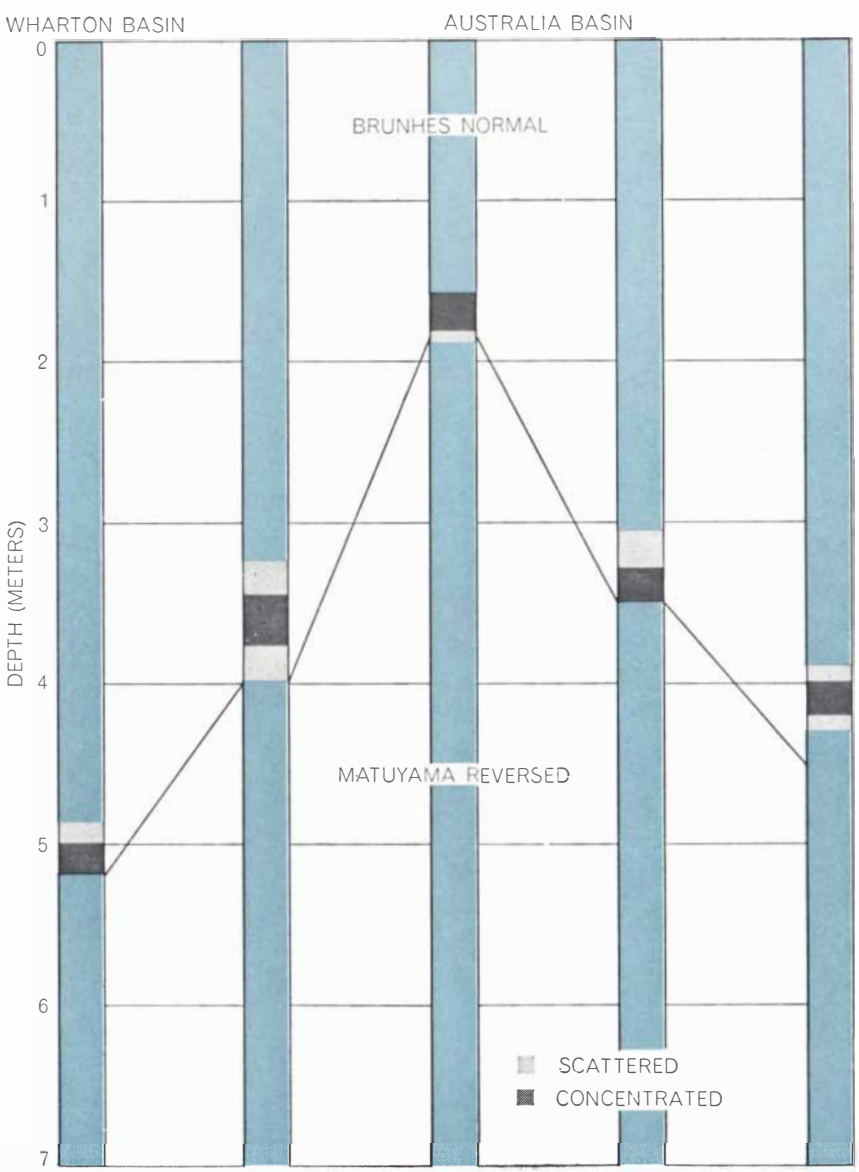
FAR EASTERN TEKTITES, all 700,000 years old, have been found on land from China on the north to Tasmania on the south. The microtektites found in deep-sea cores (*black dots*) taken in waters from Australia to the east coast of Africa are the same age, indicat-

California at San Diego and others have proposed that tektites are melted terrestrial materials such as soil or sandstone, but the fact that the exploding Tunguska object, although it did not reach the ground, sprayed glassy objects apparently identical with the microtektites over the flattened forest at least suggests that the tektites of the Far East, both large and small, are also extraterrestrial. The tektites might have been formed by the explosion and melting of extraterrestrial bodies within the earth's atmosphere. Their glassy character and their shapes suggest that they are bits of cosmic material that melted as it plunged at high speed into the earth's atmosphere.

The remains of Java man, now known as *Homo erectus* and considered the direct precursor of *Homo sapiens*, together with the bones of elephant, hippopotamus, rhinoceros, boar, tapir, buffalo, deer, porcupine, cats, hyena and otter are found mixed with nut-sized tektites in sediments deposited in Java 700,000 years ago. Similar tektites have been found in Australia, Indonesia, the Philippines and Indochina. They were thought to represent separate falls until it was determined by radioisotope dating that all the tektites analyzed from each of these areas had last been molten 700,000 years ago. Other studies showed that tektites lacked certain isotopes produced by the bombardment of cosmic rays, which indicated that the tektites had reached the earth and its protecting atmospheric and magnetic field within less than 100,000 years of the time they had last melted.

What kind of cosmic body might have produced a catastrophic explosion 700,000 years ago? Was it a comet, a giant meteorite, a small planet, a piece that had been chipped out of the moon by some cosmic collision? We can only speculate about the identity of the visitor, but certain items of information give us some idea of what may have happened to the body after it had entered the earth's atmosphere.

The Far Eastern tektites occur in at least three forms. Those in one group, found mainly in Australia, have the



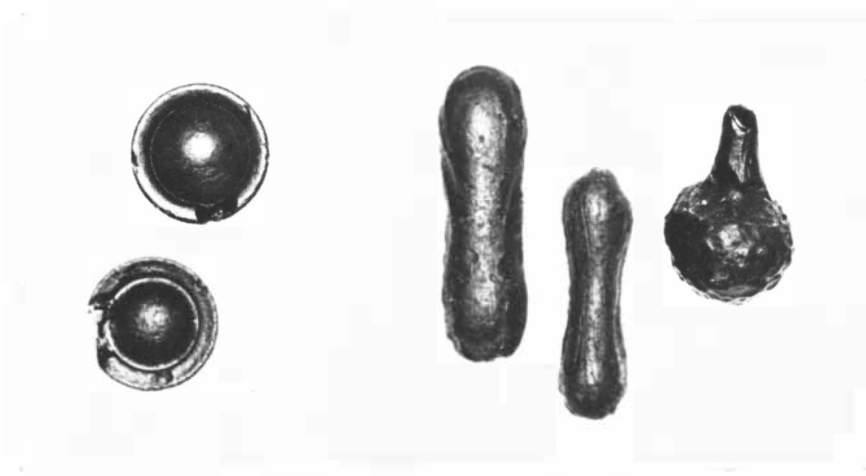
ing that both the land tektites and the microtektites were deposited by the same event.

LAYERS OF MICROTEKTITES (*two shades of gray*) in five cores taken off Australia are correlated with layers marking the reversal between Matuyama magnetic epoch and Brunhes.

shape of buttons; they look as if they had been originally molten, then had cooled and finally were partly remelted and eroded by the air as they fell through the atmosphere. Those in a second group, found all over Southeast Asia, are streamlined forms—teardrops, rods, dumbbells, ellipsoids and saucers—that apparently were not aerodynamically eroded after they had cooled. Those in a third group, found in Thailand, are irregular pieces of broken glass that show little sign of remelting.

From these facts it has been deduced that when the original body entered the atmosphere it was heated to an immense fireball and may have broken up into two or three (or more) separate bodies. One of these fragments may have exploded in the outer reaches of the atmosphere, so that its glassy debris was first cooled and then was reheated in its passage through the lower atmosphere, producing aerodynamically eroded tektites of the kind found in Australia. If a second major fragment had exploded closer to the ground, that might account for the uneroded shapes of the tektites that were not remelted (presumably because this debris traveled only a short distance through the atmosphere). The broken pieces found in Thailand may be the debris of a fragment that exploded so close to the ground that its pieces were not melted smooth by friction with the air. On the slopes of Mount Darwin in Tasmania there are bits of glass, resembling tektites, that may have been scattered over the ground by a small segment of the cosmic body that hit the ground.

The larger tektites are widely dispersed and are difficult to find in outcrops of stratified rocks. The discovery of microtektites in ocean sediments therefore opens a new avenue of research. Now that one knows that microtektites exist, one can look for them not only in ocean sediments but also in outcrops of rock on land and in core samples obtained by drilling in sedimentary rocks and salt deposits. The microtektites on land may have much to tell us about tektites in general and the event or events that gave rise to them.



TEKTITES of the kind that are widely strewn on land in the Far East are 35 to 100 millimeters across and may take the form of buttons (*left*) or dumbbells and teardrops (*right*).

MICROTEKTITES, none larger than a millimeter in diameter, closely resemble full-size tektites. At the right are two dumbbells and two teardrops; at the left are five small spheres.

It seems entirely possible, then, that the tektites of the Far East resulted from the fall of a cosmic body, and that the body fell at the time of the last reversal of the earth's dipole magnetic field. Here it is necessary to consider the reversals themselves. The main magnetic dipole field of the earth is usually attributed to the magnetohydrodynamic effects of slow convection currents in the earth's liquid core. The theory of this natural dynamo is well worked out, but nothing is yet known about the mechanism by which the magnetic fields are reversed. The sun has a very weak dipole field that apparently reverses at the beginning of each 11-year sunspot cycle. This regular reversal, which seems to be related to convection currents in the sun's interior, has led some workers to speculate that the reversals of the earth's field are due to a similar but slower oscillation in the earth's core. The reversals of the earth's field, however, do not have a regular cycle. In fact, there is no generally accepted theory that explains why the earth's magnetic polarity should be unstable at all.

If it can be assumed that the reversal of 700,000 years ago took place during a cosmic encounter, the encounter may have somehow disturbed the earth's magnetohydrodynamic dynamo. We cannot look into the nature of the disturbance or how it was brought about until we know more about the circumstances of the encounter and the operation of the earth's dynamo. In any event, we have good reason to continue with an intensive search for tektites on the ocean bottom. Thus far we have correlated only one magnetic reversal with one cosmic encounter. One might mention, however, that tektites fell on the Ivory Coast of Africa about a million years ago, and that the earth's magnetic field reversed at the same time. If we can find tektite falls associated with still other reversals

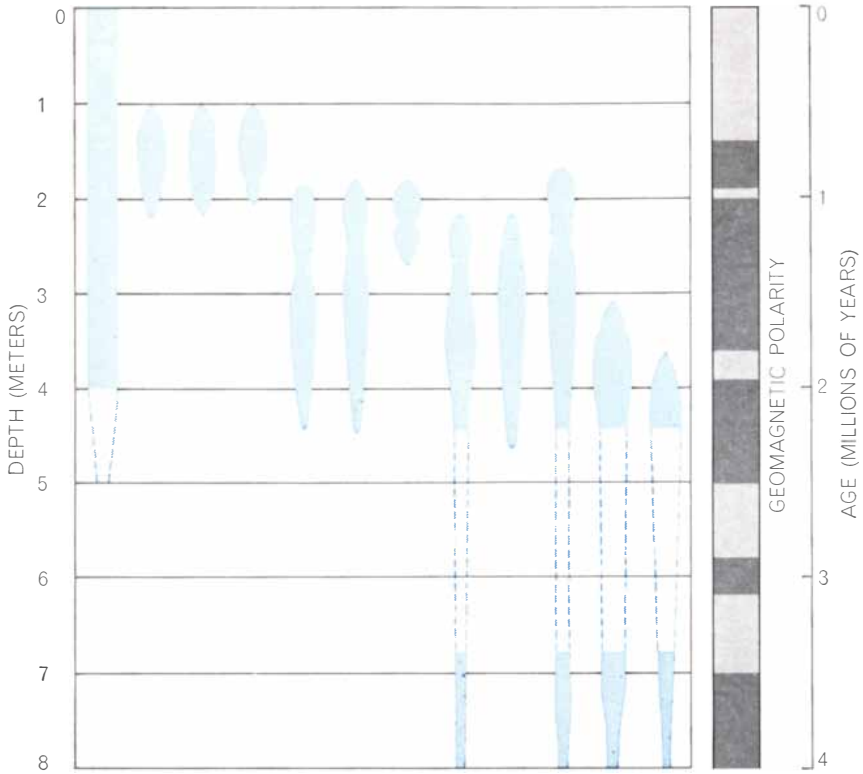
of the earth's field, we shall have stronger grounds for believing that the connection is more than a coincidence.

There are remarkably few craters on the earth showing the impact of foreign bodies. The moon, however, is copiously pitted with such craters. It seems logical to suppose that the earth is hit at least as often as the moon. The comparative absence of large impact craters on the earth may be due to two main factors: (1) bodies approaching the earth generally burn up or explode in its atmosphere and (2) the processes of erosion and sedimentation on the earth tend to wipe out most of the craters produced by the occasional impacts.

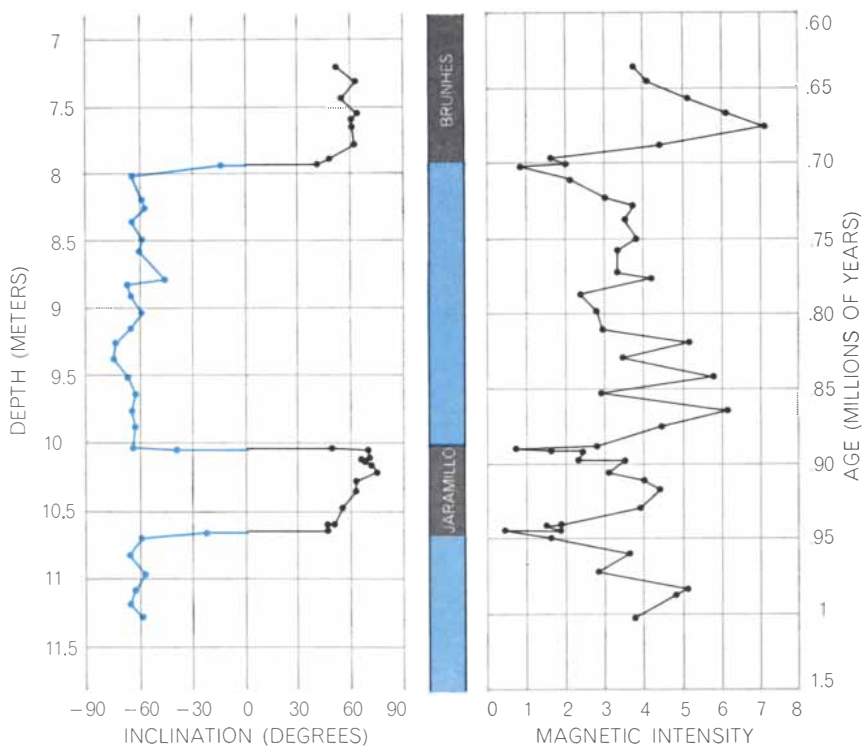
Three dates can be given for each tektite fall: the rubidium-strontium date indicating when the chemical mixture of the tektites was created, the potassium-argon date indicating when the tektites were last liquid, and the age of the strata indicating when the tektites were deposited. Tektites were melted and deposited 700,000 years ago in the Far East, 15 million years ago in Czechoslovakia and 35 million years ago in North America and Libya. All these tektites apparently come from an original mass that was chemically differentiated, possibly in some straying minor planet, some 400 million years ago. The Ivory Coast tektites were melted a million years ago, but the original mass seems to have differentiated two billion years ago.

It is of course hazardous to speculate on facts so few and so uncertain. If, however, tektite-producing encounters are responsible for most geomagnetic reversals, and if we can take the three-to-one ratio of tektite parent material 400 million years old to that two billion years old as a measure of their relative abundance in space, then we would expect to see an increase in the rate of reversal sometime subsequent to 400 million years ago. It must have been shortly after this time that the catastrophe took place that separated the parent bodies of the younger tektites. In this connection it is interesting that Russian workers have concluded that geomagnetic reversals occurred much less frequently in the lower Paleozoic era (perhaps 450 million years ago) than in the Mesozoic and Cenozoic eras (from 230 million years ago to the present). Their observations for the interval between 400 million and 500 million years ago indicate one reversal every five to 10 million years, compared with an average of one reversal per million years for the past 70 million years.

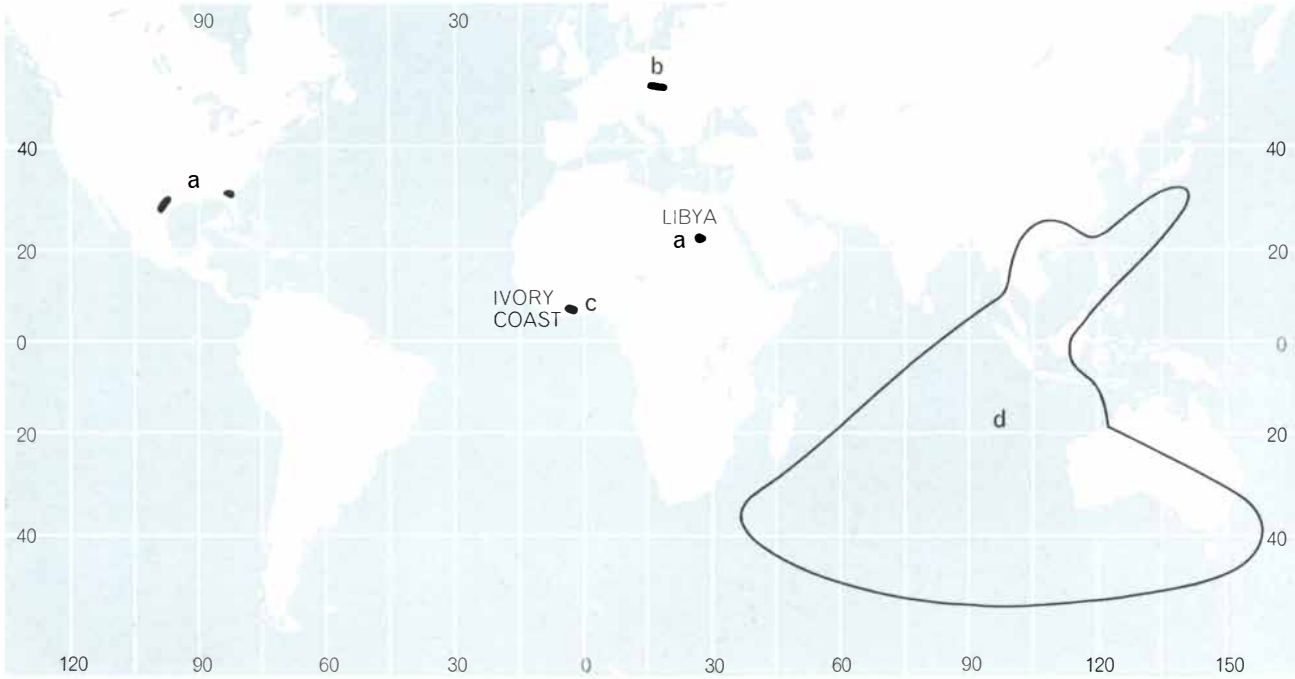
As one of the authors of this article



RISE AND DECLINE of 12 marine invertebrate species that inhabited antarctic waters in the past 3.5 million years (*color*) is measured by the number of their fossils found in deep-sea sediments. The appearance or disappearance of some species corresponds closely with times when the earth's magnetic field (*column at right*) underwent a reversal of polarity.



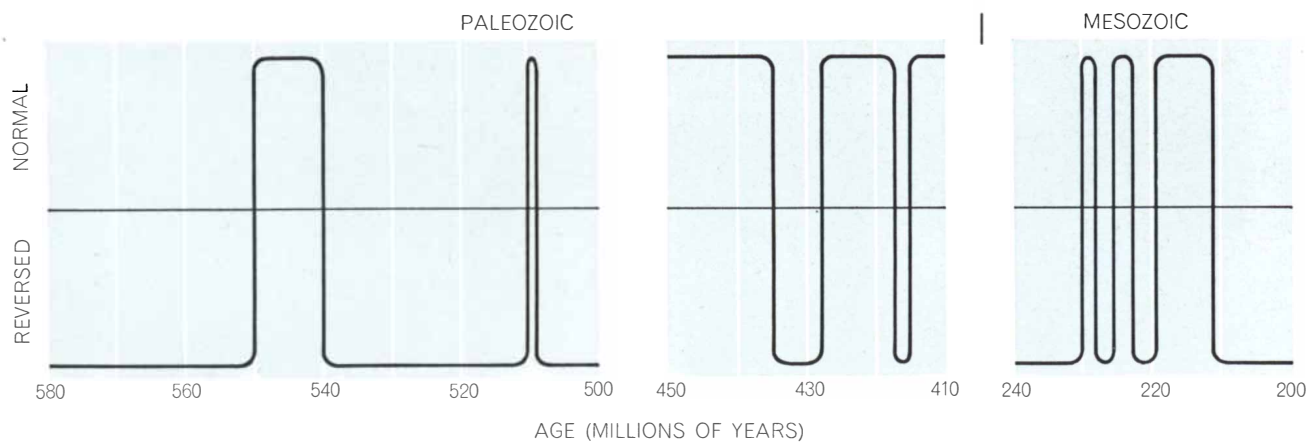
RECENT REVERSALS of the earth's magnetic field (*left*) were accompanied by declines in the intensity of the field (*right*) that may have persisted for a millennium. The resulting collapse of the earth's shield against cosmic ray bombardment, allowing such radiation to play a greater biological role than usual, may account for the rise and decline of species.



KNOWN TEKTITE FALLS, from oldest to youngest, are (*a*) in North America and Libya, 35 million years ago; (*b*) in Czechoslovakia, 15 million years ago; (*c*) on the Ivory Coast of Africa, one million years ago, and (*d*) in the Far Eastern strewn field 700,000 years ago. The most recent and the two oldest falls evidently originated with the same parent body, formed some 400 million years ago. The body responsible for the Ivory Coast tektites, however, is much older, having been formed some two billion years ago.

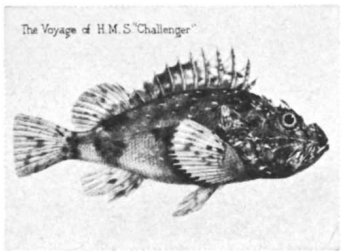
observed several years ago, the Mid-Oceanic Ridge, the undersea mountain system that runs down the middle of all the oceans, has gradually become wider as fluid rock has periodically risen through the rift that marks the center line of the ridge [see "The Rift in the Ocean Floor," by Bruce C. Heezen; SCIENTIFIC AMERICAN, October, 1960]. In the successive bands of outward-flowing rock the magnetic material exhibits changes in north-south polarity, as distinct as zebra stripes, that reflect the reversals of the earth's magnetic field. By examining these bands and dating them Walter C. Pitman III and James R. Heirtzler of the Lamont Geological Observatory were able to estimate that over the past 75 million years the earth's field has on the average reversed about once every million years. One may note that for the past 20 million years the average interval between reversals has been about 250,000 years, that the largest interval has been 800,000 years and that occasionally the interval was no more than 10,000 years. The next reversal would therefore seem to be due.

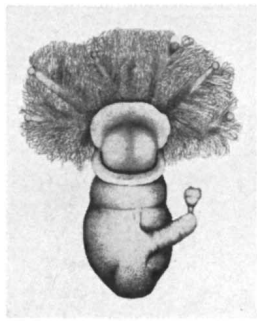
Many cosmic bodies of microscopic size fall on the earth each thousandth of a second. Meteors enter the atmosphere every second. Small meteorites hit the solid surface of the earth every day. A meteorite large enough to produce a small impact crater falls every few thousand years. A cosmic body sufficiently large to cause a reversal of the geomagnetic field may arrive every few hundred thousand years. It seems plausible that the geological clock may strike new periods when even larger bodies hit the earth every few tens of millions of years.

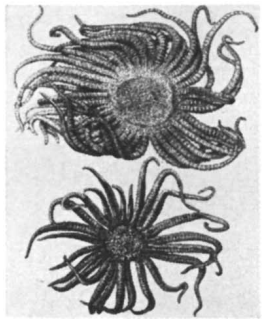


REVERSALS of the earth's magnetic field during the Paleozoic and Mesozoic eras, plotted by Russian workers, imply that there has been a gradual acceleration in the rate of reversals. The reversals of the past 200 million years are not shown in this presentation.

The hope of doing each other some good prompts these advertisements







Toward a better photo technology for ocean science

H.M.S. "Challenger," slightly over 2,000 tons displacement, left England in December of 1872, sailed and steamed 69,000 miles in the Atlantic, Antarctic, and Pacific under the scientific direction of Professors Wyville Thomson and John Murray, and returned to England in May, 1876. The Challenger Expedition Commission then put in 15 years of hard labor in Edinburgh preparing the findings for publication. Fifty large quarto volumes resulted. This brought oceanography into existence as a branch of organized science. Now it is said to be on the brink of a boom.

Now, among other advantages of our times, photography can make itself more useful to oceanographers. It can be made to work at abyssal depths, and it can release men from duty at the sketch pads on deck, and their sketches need no longer be redrawn on the lithographer's stone. Photographic recording materials yield visual analog representations of the output of sensing devices that Sir Wyville and Sir John would covet. Their successors—no longer universal oceanographers but biologists, engineers, physicists, geologists, and chemists pursuing separate leads that have been opened to them and tracing the interconnections—have enough to think about in their specialties without involving themselves in the intricacies of finding the right photographic materials for their special environment.

This is an invitation to turn such questions over to us. A Kodak man has been put under orders to listen to oceanographers and either help them or put them in touch with someone else who can. His name is Sheldon Phillips; his phone number is 716-325-2000, extension 3221; and his address is simply Eastman Kodak Company, Rochester, N. Y. 14650.

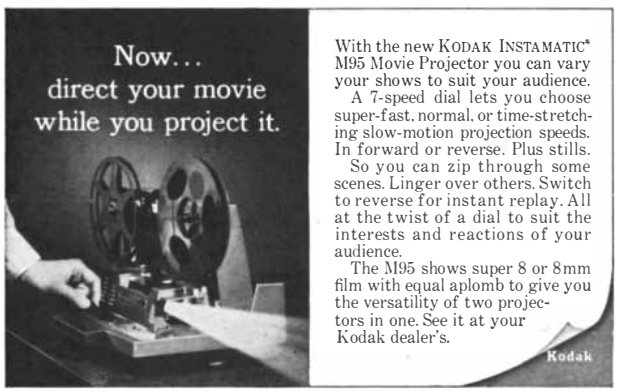
The substitute even works better

Benzidine ($H_2NC_6H_4-C_6H_4NH_2$) is a most useful reagent in both inorganic and organic analysis. It is valued for its ability through direct or induced redox reactions in acetic acid to form a blue quinoidic product. The well known Sieverts-Hermsdorf test for HCN depends on it.

That is all very well, but don't look for benzidine among the 5,000 EASTMAN Organic Chemicals. We won't make it, sell it, or allow it on the premises. A person ought to be able to earn his living without handling a potent carcinogen. What we can now do is to offer a replacement for benzidine in the detection of hydrogen cyanide and cyanogen: Bis(ethyl Acetoacetato) Copper as EASTMAN 10057.†

We will even supply a procedural abstract from The Analyst (91: 282) *on request to Distillation Products Industries, Rochester, N. Y. 14603 (Division of Eastman Kodak Company). When writing, please indicate whether you can use a copy of* EASTMAN *Organic Chemicals List No. 44 and its supplement of recent additions.*

†25 g., $9.60; 100 g., $35.10 plus shipping charges. Subject to change without notice.



Merchandise like this in well run camera shops fairly leaps off the shelves into the hands of customers who know value when they see it. Hurrah for our engineers who figure out new ways to manufacture new highs in performance into new products at new lows in cost!

What manner of man dedicates his career to such goals? In the case of this projector we cite for illustration a certain smart apple who is so eager for reinforcements that he is willing to forego some privacy of his own if he can thus convince smart newcomers* that Kodak leaves your soul alone (as he phrases the idea).

This engineer's non-Kodak identity has been nourished as follows after Kodak working hours (which for him most weeks come to considerably more than 40):

1. For 16 of his 17 Kodak years has been serving as general manager (and bass chorister) of 7 or 8 concerts per year of oratorio music sung and played by professional musicians and a chorus of 300. Twelve successive annual Bach festivals included.

2. Committee service with half a dozen Rochester musical organizations that vie for audiences with the one he runs.

3. Music, theater, and movie critic for a pure-highbrow FM radio station.

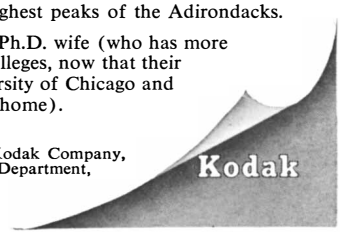
4. Owner and operator of a one-man cottage industry that manufactures neckties which sell well to the visual arts crowd.

5. Secretary for 15 years of Dartmouth's Class of 1949.

6. Scaler of 45 of the 46 highest peaks of the Adirondacks.

7. Non-Ph.D. husband to a Ph.D. wife (who has more time to teach history at two colleges, now that their eldest daughter is at the University of Chicago and only the two younger boys are home).

*Who should apply to Eastman Kodak Company, Technical and Business Personnel Department, Rochester, N. Y. 14650.



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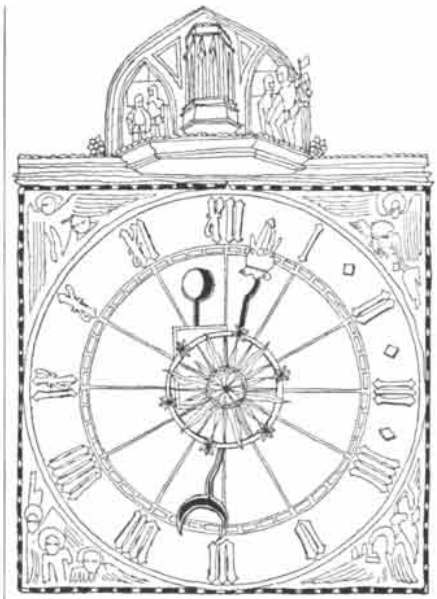


Moment of Decision

In the 22 years of the nuclear age the U.S. has been faced with several grave decisions in the arena that lies between technology and politics. The first was whether or not to make an atomic bomb. Among the others were whether or not to make a thermonuclear bomb and whether or not to build an extensive system of shelters against nuclear attack. The latest is whether or not to qualitatively expand the nation's defense against long-range missiles.

Some of the decisions have been made in private, such as those to build the bomb and then to use it in Japan. Antimissile defense is being partly debated in public, presumably because certain groups in the Government strenuously disagree and are seeking public support. Among the protagonists in the debate are the Joint Chiefs of Staff, who have urged President Johnson to proceed with the Nike-X antimissile system, and Secretary of Defense Robert S. McNamara. At a news conference in May, McNamara said: "In my opinion we are not capable of designing, producing and deploying systems to protect populations against heavy attacks."

The principal argument that has been advanced in favor of an antimissile system is that the U.S.S.R. is building antimissile defenses and increasing the number and capability of its offensive missiles; therefore the U.S. must enlarge its defense system or its nuclear forces will lose their effectiveness as a deterrent to nuclear attack. The principal argument that has been put forward against such a system is that any missile defense takes years to deploy, during which time the offense can more quickly devise countermeasures; therefore one might better invest in offense than in defense.

Various technical matters have been ventilated in the course of the debate. John S. Foster, Jr., Director of Defense Research and Engineering, has called attention to the fact that if a nuclear-armed antimissile missile were exploded in the near vacuum at altitudes above 60 miles, X rays from the explosion could knock out an incoming missile at some distance. The rocket being developed for this purpose in the Nike-X system is the three-stage, 35,000-pound Spartan. The defense against missiles that had penetrated to an altitude of some 20 miles would be the much lighter Sprint rocket.

Writing in *Scientist and Citizen*, the journal of the Scientists' Institute for Public Information, an anonymous group of scientists observes that an incoming missile set off at an altitude higher than 20 miles could cause catastrophic damage on the ground. Moreover, the group states, nuclear explosions, either offensive or defensive, in the atmosphere would drastically interfere with the defensive radar system, so that it would be ineffective against a second wave of offensive missiles.

Secretary McNamara also said at his news conference: "I think it is fair to say that we are capable of designing, producing and deploying a system to protect populations against light attacks." This view has suggested the possibility that, even if the U.S. could not install a defense system that would protect it against nuclear attack by the U.S.S.R., it could deploy one that would protect it against attack by a minor nuclear power. In this regard the Scientists' Institute for Public Information group comments: "During a probably short transition period beginning a few years from now, China will be in the category of a minor nuclear power.... While in this category, China would, however, be inviting its own destruction as a nation by attacking the U.S., whatever the state of U.S. defenses. After this period of a few years the situation of the U.S. would be the same vis-à-vis China that it now is vis-à-vis the Soviet Union. The *political* question then is whether or not the expenditure of billions of dollars... is

worth transient protection against an unlikely attack by a minor nuclear power."

The Protein Gap

Specific measures to cope with the critical protein deficiency in the developing countries of the world have been recommended to the United Nations Economic and Social Council by its Advisory Committee on the Application of Science and Technology to Development. Its report is based on a working paper prepared by Nevin S. Scrimshaw of the Massachusetts Institute of Technology. Many countries are "losing the capacity to feed themselves" as food production lags behind population growth, the committee finds. The problem of quality of diet is even more serious than that of quantity: there is not enough protein available, particularly animal protein, which alone contains certain essential amino acids. The gap between nutritional requirements and protein consumption in these countries is widening and threatens to halt their development completely, and conventional agriculture and animal husbandry cannot cope with the situation.

The committee urges a massive effort to close the protein gap. It recommends, first of all, that production from conventional sources be increased by improving agricultural methods, materials, incentives and credit facilities in the developing countries. The efficiency of fisheries can be improved by new fishing and distribution methods and by an emphasis on conservation and pollution control. Since more than 25 percent of the food supply in some countries is consumed by animal pests, spoilage and processing losses, improved methods of pest control, storage and distribution need to be introduced.

Turning to novel sources of protein, the committee suggests that new plant varieties can be developed through genetic research. Large amounts of protein are available in the form of oilseeds in many developing countries but remain unused; "no other single source of unconventional protein could contribute so greatly and promptly towards closing the protein gap." Methods have been developed for preparing palatable foods from oilseed concentrates. The same thing is true of various fish concentrates,

which can be processed to make palatable foods or food additives. The committee notes that "single cell" protein sources can provide more protein regardless of the availability of agricultural land. Such sources include yeasts and algae that derive their energy from petroleum and from photosynthesis respectively. Synthetic amino acids, particularly lysine, tryptophan and methionine, can be added to cereals and other plant products to improve their nutritive value. All these steps require research and training, and the committee proposes new UN-supported programs in these areas.

Brain Signals and Learning

A reduction of electrical activity in the cortex of the brain has been measured that apparently accompanies the completion of a learning task and suggests a change from "deliberate" to "automatic" behavior. This change is familiar to a person learning to drive a car or to type, for example; once the technique has been learned, actions that at first had to be thought out seem no longer to require conscious attention. Until now this kind of change had not been measured. The major reason has been that the avoidance behavior most suitable for operant-conditioning experiments involves movements by the experimental animal that give rise to extraneous electrical activity in the brain and so obscure signals directly related to the task under study. Such signals have now been measured, however, by a group at Princeton University's Auditory Research Laboratory headed by a graduate student, James C. Saunders.

The Princeton investigators implant electrodes in the auditory cortex of a cat and measure the electrical impulses evoked there in response to a series of clicking sounds. The animal is trained to react to the clicks in order to avoid a mild shock; it responds by tipping its cage slightly. The potential evoked by the clicks is very weak at first. As the animal "attends" to the clicks and learns how to avoid a shock by responding to the sound, the potential increases steadily. Then, quite suddenly and just as the animal attains maximum efficiency in avoiding the shock, the potential drops sharply to the level at which it was when the training began. Apparently the auditory cortex "shuts down."

Because the cat continues to respond successfully, quietly shifting its weight to avoid shocks, Saunders assumes that some other area of the brain may take over the work of the cortex, and he is now trying to locate such a site or sites. Further experiments should indicate to what extent the cortex, which is considered to be the seat of conscious behavior, can deal with different kinds of incoming sensory information at once. Does it divide its time among several tasks? Or does it deal only with new information, passing on to "subordinate" centers learned techniques for dealing with each new situation?

End of the "Monkey Law"

Tennessee's "monkey law" prohibiting the teaching of evolution in the state's public schools has been repealed. The law was adopted in 1925 and led later that year to the celebrated test case involving John T. Scopes, William Jennings Bryan and Clarence Darrow. The 11-day trial became a bitter contest between religious fundamentalism and biological theory; the judge held, however, that only evidence on whether or not Scopes had taught evolution was admissible, and Scopes was convicted. The conviction was reversed on a technicality but the law was permitted to stand.

In April of this year the lower house of the Tennessee legislature voted to repeal the statute; in May the Senate agreed and the governor approved the repeal. While the repeal bill was before the legislature a high school science teacher, Gary L. Scott, was dismissed—apparently by coincidence—for teaching evolution. He was reinstated, but he filed suit challenging the constitutionality of the statute. The suit is now expected to be withdrawn. Anti-evolution laws are still on the books in Mississippi and Arkansas, and the Arkansas law has just been upheld by the state Supreme Court.

Hotter Superconductors

Since 1954 the highest known superconducting transition temperature—the temperature at which a substance loses all electrical resistance and enters the superconducting state—has remained around 18 degrees Kelvin (degrees centigrade above absolute zero). Now two small but perhaps significant increases have been recorded in the transition temperatures of certain substances.

In a series of experiments at Stanford University researchers have explored the electron-transfer properties of various "molecular alloys," combinations of metal atoms and organic molecules, codeposited as thin films on quartz plates. They have found that out of a dozen organic compounds that were deposited on superconducting thin films of vanadium, eight compounds increased the superconducting transition temperature of the vanadium (2.83 degrees K.) by .05 to .1 degree K., whereas four compounds lowered the transition temperature by the same amount.

The experiments are considered highly encouraging for a number of reasons. First, it is the first time that organic molecules have been shown to induce a "chemical shift" in the transition temperature of a metal film. Second, a potentially useful correlation was found between molecular properties and their effects on the transition temperature. Third, all the results are consistent with a theoretical picture of the interaction of the molecules and the metal film called "conductive conjugation."

The Stanford group, H. M. McConnell, F. R. Gamble and B. M. Hoffman, report their findings in *Proceedings of the National Academy of Sciences*. They point out that although the changes in transition temperature recorded in their experiments so far have been very small, a simple extrapolation of the theory of superconductivity indicates that "the transition temperature of a metal-molecule alloy system may be expected to depend exponentially on the concentration of the molecules. In the experiments reported in this work, this concentration is indeed small; in co-deposition experiments that are under way in our laboratory, this concentration will be orders of magnitude higher."

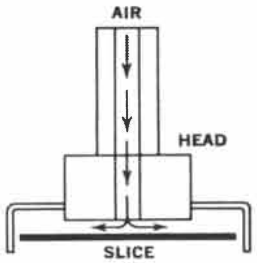
Meanwhile another group has announced the discovery of a superconductor with a transition temperature of 20 degrees K. The substance is a solid solution of niobium-aluminum (Nb_3Al) and niobium-germanium (Nb_3Ge). The discoverers, led by B. T. Matthias of the Bell Telephone Laboratories and the University of California at San Diego, conclude by analogy with their recent finding that vanadium-aluminum (V_3Al), "should we ever manage to crystallize it in the [same] structure, would be a very high superconductor. Since there is no theory for the high transition temperatures of a superconductor, it is impossible to say how much this value would be raised above 18 degrees K."

Glassy Magnets

An experimental iron-rich alloy that lacks an internal crystal structure but is strongly ferromagnetic has been produced by investigators at the California Institute of Technology. Traditionally the attraction of certain metals and their alloys to a magnet has been associ-

How Western Electric gets uplift from a downdraft

Picking something up by blowing a stream of air down on it may seem rather roundabout. But if you want to pick that something up without touching it, it turns out to be a most successful way.

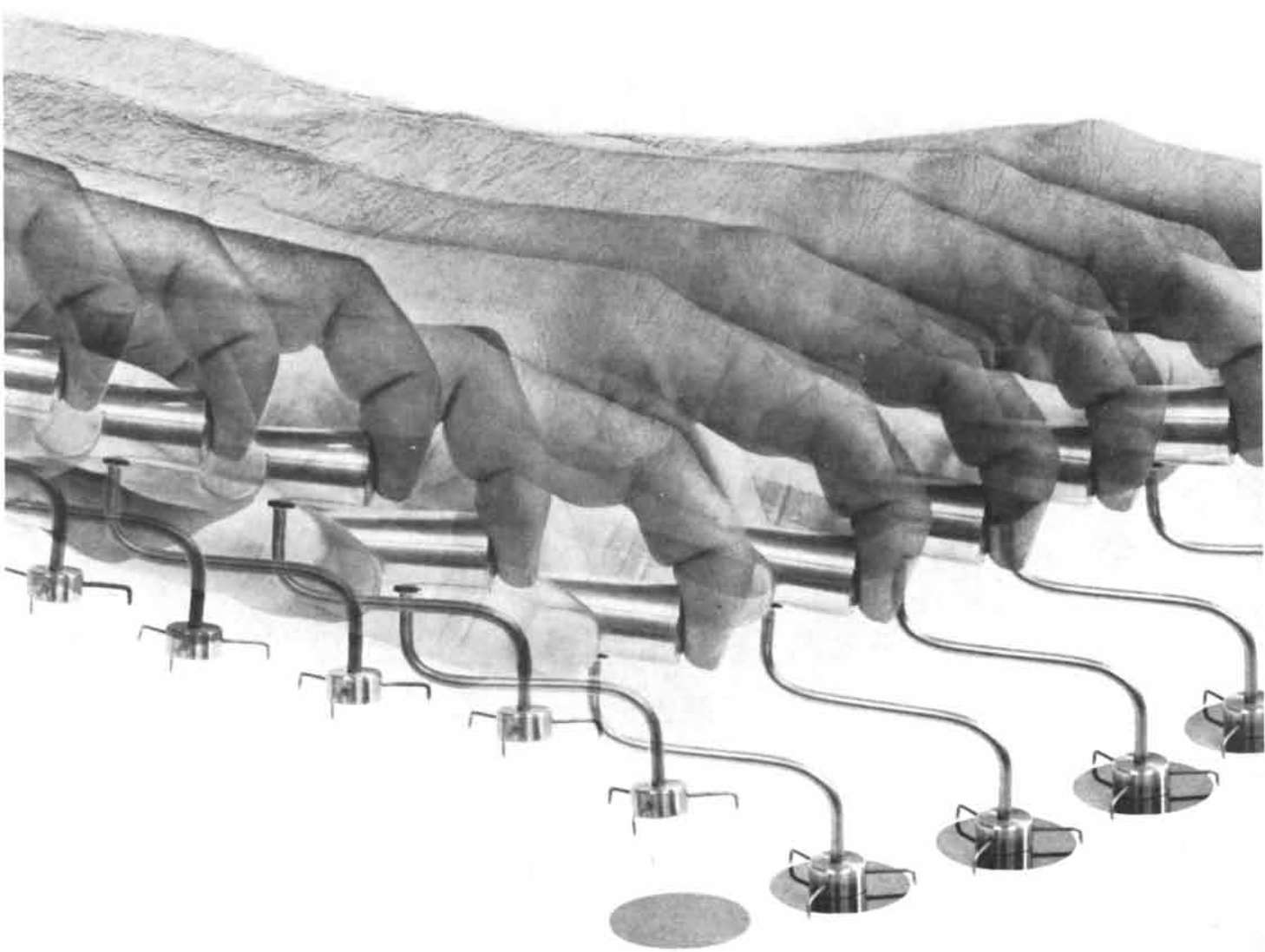


The something in question is a paper-thin, eggshell-fragile slice of silicon destined for transistors. To touch it is likely to contaminate it, and probably to break it. Tweezers are extremely risky. Even a vacuum pickup is dangerous.

And so the engineers at Western Electric's Engineering Research Center invoked the Bernoulli principle and solved the problem. They developed a pickup device that directs a thin stream of air down onto the slice. The air flows out across the slice and since *it* is moving and the air below the slice is not, the pressure below is greater than the pressure above and the slice floats. And it doesn't touch the head because the air is, after all, blowing *down*. Wire guides keep the slice from slipping off.

So now the workers in our transistor plants can pick up silicon slices handily, without worrying about breaking or contaminating them. That our engineers reached back to a classical principle of physics to help them do it only shows the extent of the ingenuity Western Electric applies in its job of manufacturing communications equipment for the Bell System.

Western Electric
MANUFACTURING & SUPPLY UNIT OF THE BELL SYSTEM



ated with the alignment of crystals in the substance. For example, a single crystal of iron, which is made up of a cubic array of iron atoms, tends to become magnetized in the directions of the edges of the unit cube. The new alloy, according to its discoverers, Pol Duwez and Stephen C. H. Lin, demonstrates that crystal alignment is not the primary reason for ferromagnetism.

Duwez and Lin resorted to a drastic method to "quick-freeze" a molten alloy of iron, phosphorus and carbon before crystals had a chance to form. They used a pneumatic hammer to slam a molten droplet of the alloy against a piece of copper, which provided a good heat-absorbing surface. In the process the alloy was cooled from a temperature of 2,400 degrees Fahrenheit to room temperature in less than a thousandth of a second. The resulting paper-thin samples of the solid alloy were observed to have a microscopic structure similar to that of a glass or a liquid, in which the atoms are not arranged in crystal formations but are distributed at random.

Control of Cell Division

The existence of specific chemical messengers that control the normal process of cell division in living tissue has recently been established by a group of British and Norwegian investigators. Each of the messengers, known as chalones, appears to act chiefly on the cells of a specific organ or part of an organ; for example, they affect the cells of the epidermis but not of the hair bulb. Each chalone, however, influences its target organ in many kinds of animals; chalones extracted from the epidermis of pigs, rabbits, guinea pigs, humans and cod all depressed cell division in mouse epidermis.

Writing in *Nature*, W. S. Bullough and E. B. Laurence of the University of London and O. H. Iverson and K. Elgjo of the University of Oslo note that chalones have been extracted not only from epidermis, hair-bulb tissue and hypodermis but also from liver, kidney, the lens of the eye and white blood cells; each chalone acts to depress cell division in the tissue in which it is found. They conclude that the mechanisms whereby the chemical message is emitted, received and acted on are essentially the same for all forms of vertebrate life.

Navigating by Sun Stone

A system of navigation used today in high-latitude regions, where magnetic compasses are subject to serious error, may also have been used by the Vikings in the 11th century. Because sunlight is polarized by atmospheric scattering, optical instruments have been available since 1948 that allow fliers in the Arctic and Antarctic to locate the sun's position even though it is obscured by clouds or hidden below the horizon during the long polar twilight. Thorkild Ramskou of the Danish National Museum now suggests that references to "sun stones" in the Scandinavian sagas mean that Viking voyagers in northern waters were able to make similar sightings of the sun.

An early Icelandic aid to navigation—a table of sun positions on the horizon at dawn and overhead at noon throughout the year—provided Ramskou with evidence that the Vikings could have usefully applied observations of the sun to navigational problems. The lodestone, or magnetic compass, was not known in Scandinavia until the 13th century; therefore an earlier saga stating that one Floke "had no guiding stone" and accordingly released captive land birds to guide him during a voyage to Iceland, suggested to Ramskou that some stone other than the lodestone was meant. An early saga from the Faroe Islands provided another clue: A thief steals a number of valuables, including a "sun stone," but mistaking the stone for a beach pebble, he throws it away.

The most detailed support for Ramskou's hypothesis is contained in an appendix to a saga concerning St. Olaf, king of Norway in the early years of the 11th century. Entitled "The Story of Rodulf and His Sons," it tells how one son, Sigurd Syr, boasts to the visiting Olaf of his familiarity with the paths of the stars, the moon and the sun. Sigurd says he can tell the time of day or night even when no celestial bodies are visible. On the next day, which is cloudy, Olaf asks Sigurd to point out the sun's position. When the youth does so, Olaf calls for his "sun stone," scans the overcast sky and, by means of the stone's telltale gleam, finds that Sigurd has located the hidden sun correctly.

Two minerals that have polarizing properties in their natural state, Ramskou finds, are sufficiently common in crystal form in Scandinavia to be possible candidates for the role of Viking "sun stones." He was recently able to check the performance of one such crystal against that of a modern "sun compass" on a flight over Greenland during which the sun was below the horizon. When pointed in the direction of the hidden sun, Ramskou discovered, the normally yellow crystal turned dark red.

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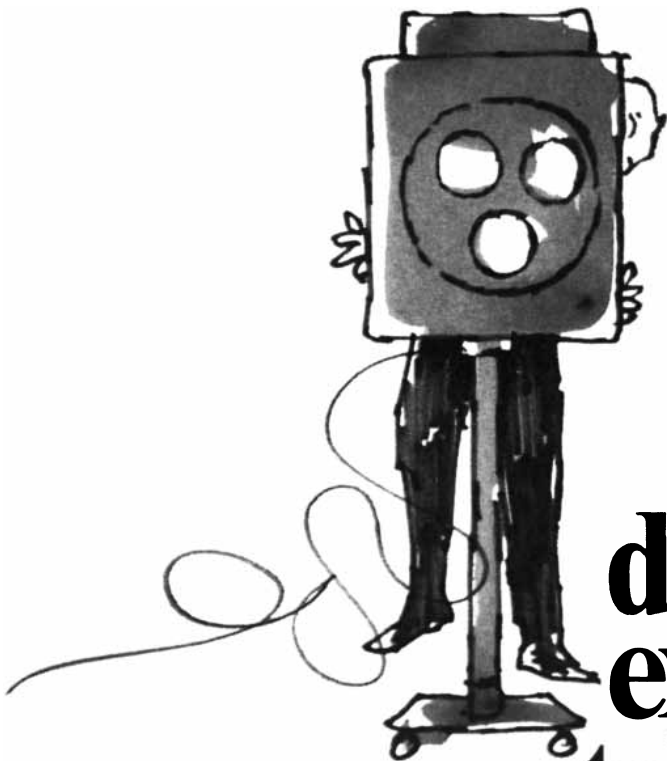

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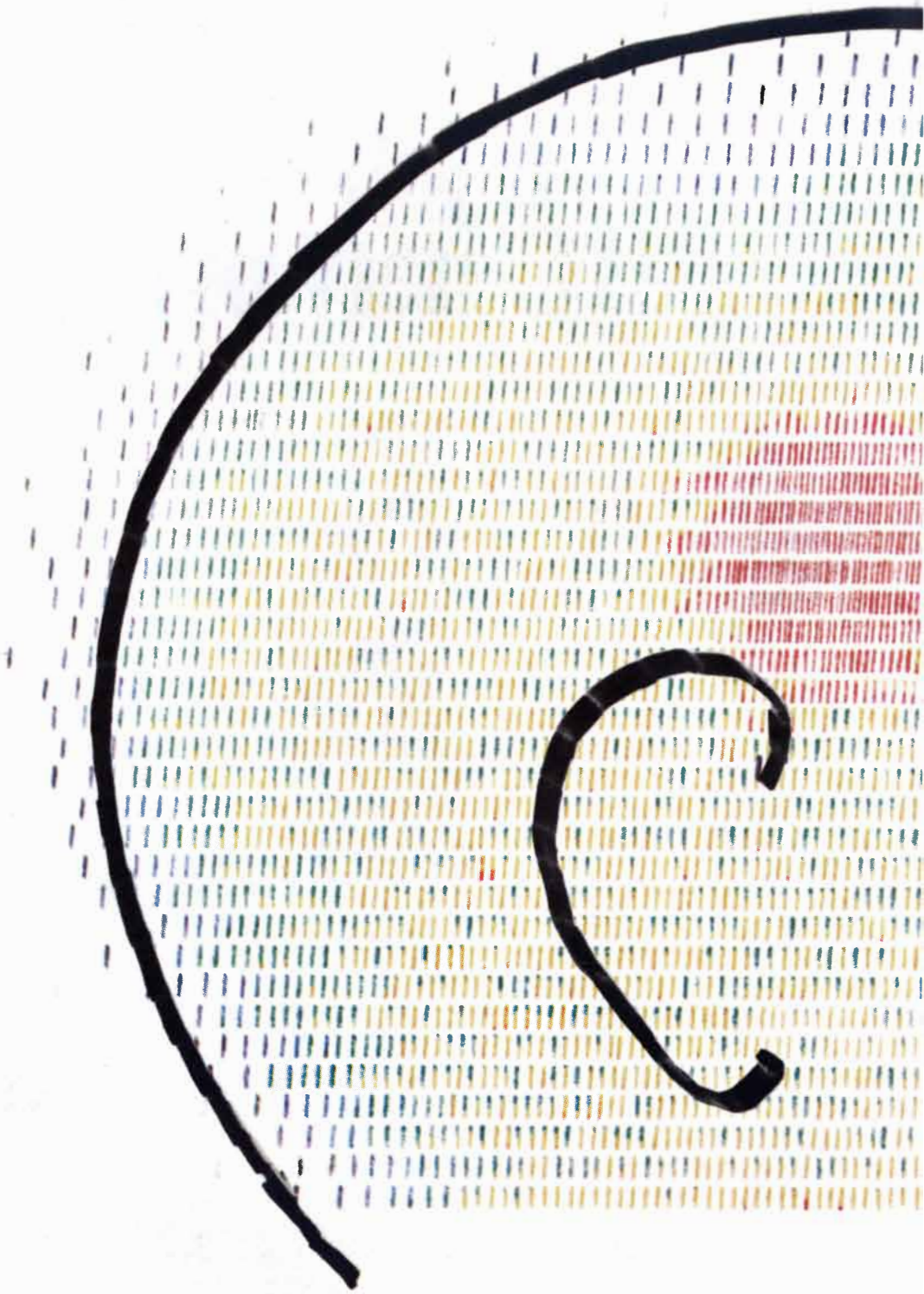

Blonde hair, blue eyes, freckles and a brain tumor.

This could be a real little girl. And this strange picture, called a scan, could be a graphic record of her brain. It was made with one of medicine's newest and most precise diagnostic aids—a radiopharmaceutical. In this case, doctors used one of Union Carbide's radiopharmaceuticals, which readily concentrates in brain tumors.

With a device that works like a Geiger counter and a typewriter combined, the rays which this substance gives off are picked up and recorded graphically as shown here.

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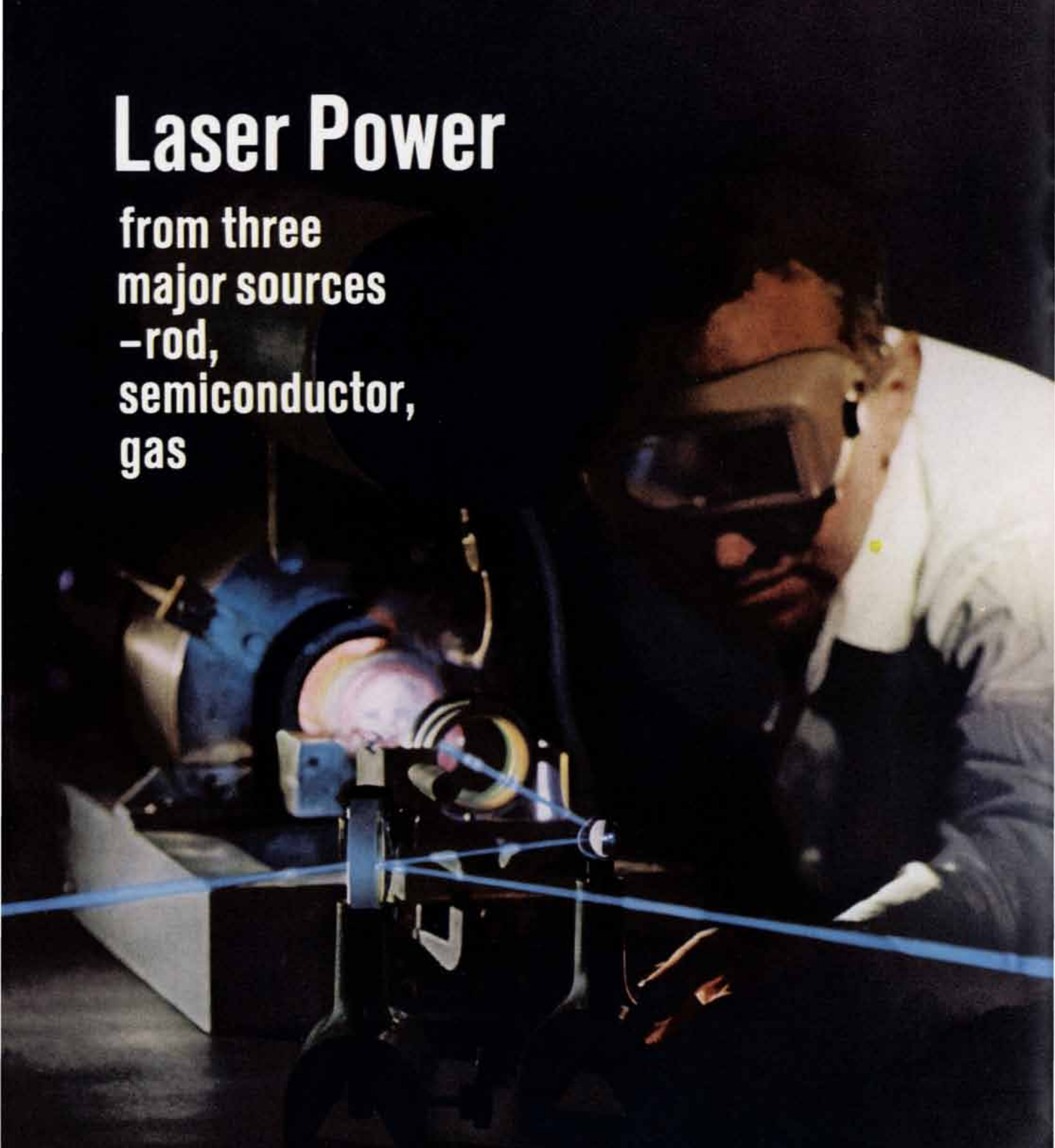

RCA knows how

This RCA-built argon gas laser, undergoing tests, is a continuous-duty, forced-air-cooled, dc-excited unit for the production of high-intensity coherent light. Its internal configuration permits selection of a minimum of six wavelengths lying in the blue-green spectrum between 4579 Å and 5145 Å with a total power output of one watt in all wavelengths.

Whatever your field of interest, the laser—an acronym for Light Amplification by the Stimulated Emission of Radiation—has already changed many basic concepts. Take information storage using holography, for example, or other disciplines such as medicine, precision measurements, optics and communications. They all are, or will be, using the applications of the laser—a new and challenging type of light source.

Since the first laser was demonstrated in 1960, three major types have been developed—rod, semiconductor and gas. As shown in *Fig. 1*, no matter what its type, a laser serves as a source of *coherent* light of essentially constant wavelengths. Ordinary illumination, such as that from the incandescent light bulb (as shown in *Fig. 2*), emits *incoherent* light in the form of scattered, multi-wavelength radiation.

Fig. 1

A large variety of substances can be made to lase (that is, to emit coherent light) under proper conditions. The first experimental RCA laser employed a man-made insulating material, in the form of a ruby rod, as the light source. It was capable of producing short pulses of light, and delivered extremely high peak powers from modest average input power. Currently available from RCA Electronic Components and Devices are lasers of the semiconductor and gas types, which can deliver varying outputs of peak as well as continuous power.

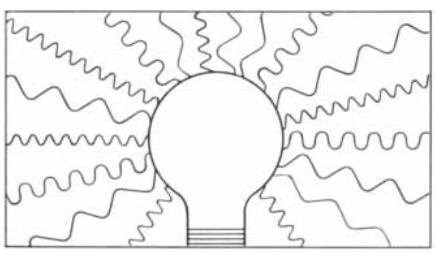

Fig. 2

RCA engineers, drawing on their company's extensive experience with the development and manufacture of electronic components and devices, have produced significant results in laser technology—particularly in the semiconductor injection and the gas types—with their newest development being the noble gas ion system. *Fig. 3* and *Fig. 4*, respectively, show the basic configurations of the semiconductor and gas lasers.

In the semiconductor laser, pure or compound crystalline substances exhibit lasing capabilities when forward-biased. Minority carriers are injected—hence the term, "injection laser." These carriers create a non-equilibrium condition within the crystal. This, in turn, causes the carriers to re-combine and emit radiation. In a lasing semiconductor device, each of the

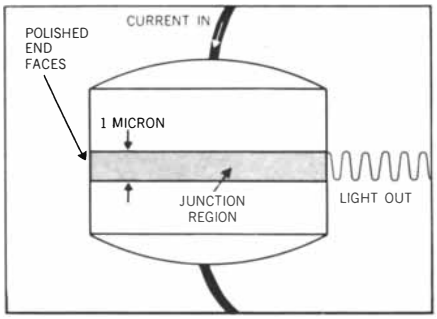

Fig. 3

many known usable crystalline substances possesses its own unique bandgap energy, and emits radiation at its own characteristic wavelength for which the line width is approximately one angstrom (Å) and in the future may range from 0.45 to 8.5 microns. These semiconductor lasers can be operated at ambient temperatures.

The gas laser uses various gases as the ion medium to generate continuous power of high-intensity, highly-collimated coherent light output. RCA recently announced the first reliable, long-life, dc-excited, noble gas laser with continuous wave (CW) output. Coherent light output results when the excited gas ions change to lower energy states. Each gas has specific energy state changes and, therefore, emits specific wavelengths of coherent light. The significance of this laser type is its ability to generate a wide variety of wavelengths from 3,000 Å to 8,000 Å—from ultraviolet through the visible light range, depending on the gas used. Argon and krypton emit light in the visible spectrum, while neon produces an ultraviolet laser beam.

RCA experience and technology are advancing the development of lasers and laser applications. Dependable lasers with proven reliability are currently available. Devices to extend the power and the spectrum are in development.

take the laser from the laboratory and put it to useful work. The chart in *Fig. 5* shows the electromagnetic spectrum covered by lasers, contrasted with the narrow capabilities of the human eye.

Day to day applications for RCA Electronic Components and Devices' injection lasers may include uses in: vehicle collision warning systems; intrusion alarms; missile guidance and controls; space vehicle navigation and docking, and infrared illumination. Applications for RCA's gas lasers may include uses in: data processing; precision measurements; meteorology; earthquake detection; satellite tracking; mili-

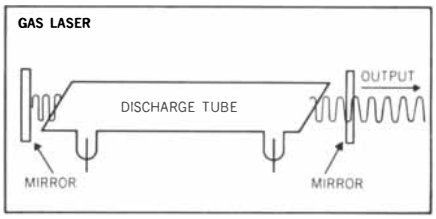

Fig. 4

tary and commercial displays; communications; optical radar, and bloodless surgery.

Also, the laser's unique characteristic of generating coherent light has made possible the practical development of holography—a lensless, photographic technique that appears to create three-dimensional pictures on a plane surface. In addition, holography may lead to the design of computer memories that store far more data per cubic inch than memories currently in use.

How can you use lasers? Whether your applications are still laboratory-bound or ready for commercial realization, RCA can show you how to develop power outputs from microwatt to multiwatt levels, both pulsed and CW. Wavelength capabilities from 3,000 Å to 9,000 Å and higher can be yours to command. Consult your

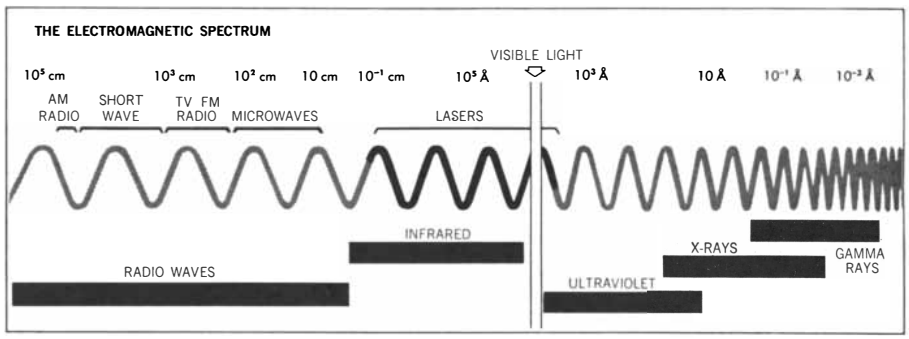

Fig. 5

Applications involving RCA's diverse interests are under active development. Some applications for military systems have been advanced through the prototype stage. RCA's nearly 50 years of electronics experience provide the means to RCA Electronic Components and Devices Field Representative on how RCA's design and advanced production skills can be of help to you. For specific product information, write RCA Commercial Engineering, Section G-95-EC, Harrison, N.J. 07029.

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ESCAPE FROM PARADOX

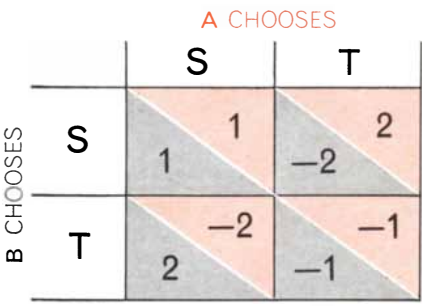
Paradoxes and other apparently unsolvable problems can sometimes be solved by broadening the logical framework in which they are presented. A stubborn paradox in game theory provides an example

by Anatol Rapoport

Twenty years ago a mathematical colleague of mine told me of an incident that has remained vividly in my memory. This colleague, flying over North Africa, found himself seated next to an elderly scholar from Morocco. They conversed in Hebrew.

"You say you are a mathematician," said the scholar. "So tell me, have you ever encountered in your studies anything so profound as what Maimonides said about the diagonal of a square? It exists, and yet it does not exist!"

I never got around to checking precisely what the 12th-century Jewish philosopher did say about the diagonal of a square, but the Moroccan scholar's remark struck me as brilliantly illuminating. His admiration of Maimonides' alleged conclusion reflected a metaphysician's love of paradox, coupled perhaps with a veiled gloating over the inability of human reason to come to grips with reality. In philosophy, as in science, contradiction is a powerful stimulus to thought. Contradiction is the stuff of which dialectics is made, and dialectics is the stuff on which philosophy feeds.



"PRISONER'S DILEMMA" game is represented by a matrix. The two players are *A* and *B*. Each has two possible strategies, *S* and *T*. The entries in the matrix are the respective payoffs to *A* (*colored segments*) and *B* (*gray segments*). For each player the "rational" choice is *T*; the paradox is that if both players choose *T*, both lose, whereas both could gain if they chose strategy *S*.

Paradoxes have played a dramatic part in intellectual history, often foreshadowing revolutionary developments in science, mathematics and logic. Whenever, in any discipline, we discover a problem that cannot be solved within the conceptual framework that supposedly should apply, we experience an intellectual shock. The shock may compel us to discard the old framework and adopt a new one. It is to this process of intellectual molting that we owe the birth of many of the major ideas in mathematics and science. The paradox of incommensurables (exemplified by the diagonal of a square, which cannot be related to the sides of the square in terms of rational numbers) led to the concept of the continuum. Zeno's paradox of Achilles and the tortoise gave birth to the idea of convergent infinite series. Antinomies (internal contradictions in mathematical logic) eventually blossomed into Gödel's theorem. The paradoxical result of the Michelson-Morley experiment on the speed of light set the stage for the theory of relativity. The discovery of the wave-particle duality of light forced a reexamination of deterministic causality, the very foundation of scientific philosophy, and led to quantum mechanics. The paradox of Maxwell's demon, which Leo Szilard first found a way to resolve in 1929, gave impetus more recently to the profound insight that the seemingly disparate concepts of information and entropy are intimately linked to each other.

Paradoxes and Logic

Faced with a contradiction that seems fundamentally irreconcilable, one can ignore it or deny it, worship it or try to remove it. The Achilles-tortoise paradox, for example, evokes the first of these reactions in most people: "common sense" and observation tell us that the faster runner always overtakes a slower one, or, if one chooses to accept Zeno's "logic," one may still deny that a contradiction exists by assuming that the evidence of the senses is an illusion.

Many philosophies, and indeed some systems of "logic," worship contradiction as a basic principle. Zen Buddhism, for example, is a philosophy of utter skepticism that finds contradictions in the most commonplace phenomena of nature and being. Georg Hegel constructed his system of "logic" on denial of the "law of noncontradiction," which states that a proposition cannot be both true and false. The dialectical materialists, who adopted Hegel's philosophy but turned it upside down "so that it finally stood on its feet" (as they are fond of saying), declare that contradiction is inherent in the "laws of motion of matter," or the very nature of reality. More recently Alfred Korzybski, the founder of the "non-Aristotelian" system called "general semantics," based his system on the theory that a fundamental contradiction exists between language and reality. "Whatever you say about something," Korzybski used to say, "it is not." (The Moroccan scholar's remark about the diagonal of a square is in a way an expression of this attitude.)

A great deal can be said for metaphysical interpretations of change, of the role of the "juxtaposition of opposites" in the unfolding of history and of the inadequacy of language as an instrument for describing reality. But no system of formal logic can be built on contradiction as a fundamental principle. The law of noncontradiction is an indispensable foundation for any rigorously constructed deductive system, and indeed no such system has ever denied this law. To be sure, some modern gen-

eralizations of Aristotelian logic have modified the Aristotelian postulate known as "the law of the excluded middle," which states that either a proposition or its negation must be true. This postulate, however, must be carefully distinguished from the law of noncontradiction—that a proposition cannot be both true and false. Moreover, even the law of the excluded middle, although not retained in the logic itself, is restored on a higher level, as it were. An example is the formal theory of probability. This can be viewed as an infinite-valued logic, the truth values ranging over the continuous interval between 0 and 1. In this logic, of course, there is no law of the excluded middle, because between any two truth values there is an infinity of other truth values. With regard to the truth values of propositions, however, one is faced with a choice between a statement and its negation: namely, that the degree of truth (probability) of a specific proposition either does or does not have a certain value. There are then only two possibilities. Thus the law of the excluded middle is restored at the level of metalogic, that is, an assertion about the proposition.

Since contradiction cannot be tolerated in formal logic, any paradox that arises must be honestly faced and if possible exorcised or removed. As I have mentioned, the resolution of paradoxes has been an immensely profitable exercise in the history of mathematics and science. I shall examine here, as a particularly interesting case, a paradox that arose recently in the new discipline called decision theory, which includes game theory.

"Prisoner's Dilemma"

The paradox in question was reported by Merrill M. Flood, then at the Rand Corporation, in 1951 and later was explicitly formulated by the Princeton University mathematician Albert W. Tucker, who gave it the name "Prisoner's Dilemma." It has to do with a game between two players, each of whom must make a choice of one of two possible strategies without knowing which strategy the other is choosing. There is a fixed set of payoffs [*see illustration on opposite page*]. Player *A* knows that if he chooses strategy *S*, his payoff will be +1 if player *B* also selects that strategy but −2 if *B* chooses strategy *T;* if *A* chooses strategy *T*, his payoffs improve, because in that case he will gain 2 if *B* chooses *S* and will lose only −1 if *B* selects *T*. Similarly, for player *B* it seems better to choose strategy *T;* he will lose only −1 if *B* chooses *T* but will gain 2 if *B* chooses *S*. Consequently for each player the rational choice is strategy *T*.

The paradox is that if both players make the rational choice, each selecting strategy *T*, both lose: the payoff for each is −1. If, on the other hand, both make the choice disfavored by the analysis (strategy S), both gain: each gets +1.

How can we escape from this paradox? It seemed clear to me that in order to cope with it we must assign a meaning to the concept of rationality that is appropriate in this context. It becomes necessary to think of "collective" rationality, which can be stated in the form of Immanuel Kant's categorical imperative: "Act in such a way that if others also acted in the same way you would benefit thereby." This principle, essentially an ethical one involving notions of solidarity or mutual trust, offers a reasonable justification for the individual players in the game to choose strategy *S*.

I was not at all disturbed by the discovery that "rationality" in the usual sense has limits: in other words, that extrarational notions (such as trust, solidarity and conscience) must be invoked to deal with the paradox. On the contrary, I derived a certain satisfaction from the idea, in view of the current overemphasis on the "strategic mode of thinking" in the analysis of public and international problems. Scholars employed as advisers to the military and other government agencies on problems involving conflict situations are strongly attached to the strategic mode of analysis as the "realistic" approach. To my way of thinking, conclusions suggested by this "realistic" mode have frequently led to disastrous consequences and are likely to lead to even more terrible ones. It is therefore a matter of crucial importance to point out that paradoxes may be embedded in decisions based on such analysis.

In any attempt to resort to "extrarational" notions to help resolve such paradoxes, however, we are confronted with a serious difficulty. Since these notions lie outside the scope of formal analysis, how are we to arrive at rigorous solutions? What kind of formulation can be devised that will be understandable and acceptable to thinkers who, although they are men of good will, speak different philosophical dialects?

Nigel Howard of the University of Pennsylvania has succeeded in eliminating this difficulty in the particular case of the Prisoner's Dilemma paradox. He developed a reformulation of the game that "solved" the paradox, and the method he used is in principle the same as the traditional one that has been employed to resolve many seemingly unsolvable contradictions or problems in mathematics. This method depends on resort to metalogic.

Mathematical Paradoxes

In order to understand the method and appreciate its philosophical impli-

ACTIONS

	A_1	A_2	A_3	A_4	A_5
OUTCOMES	O_1	O_2	O_3	O_4	O_5

SIMPLEST DECISION PROBLEM is a choice among actions each of which has a known outcome. Ranking outcomes in order of desirability ranks actions in order of preference.

ACTIONS

EVENTS	A_1	A_2	A_3	A_4	A_5
E	O_1	O_2	O_3	O_4	O_5
F	O'_1	O'_2	O'_3	O'_4	O'_5

COMPLICATION ARISES if each action has two possible results, depending on whether event *E* or event *F* occurs. If, for example, O_1 is more desired than O_2 but O'_2 is more desired than O'_1, one cannot without further information decide between actions A_1 and A_2.

cations we need to review how mathematicians have dealt with and overcome some famous problems and paradoxes in the past.

Our first example is the development of the system of numbers. It began simply with the natural numbers: 1, 2, 3.... That system, however, could not cope with an equation such as $a + x = b$, in which a and b are natural numbers and a is greater than or equal to b. To solve this "unsolvable" problem new terms had to be introduced: negative numbers and zero. Note that the new numbers were defined strictly in terms of the old ones, thereby giving logical continuity to the development. This system, the "rational integers," was extended in turn to the "rational numbers," including fractions (designated as pairs of integers). Thus, step by step, the domain of numbers was successively extended to include "real numbers" (classes of sequences of rational numbers), "complex numbers" (pairs of real numbers) and so on.

At each step toward greater generalization something was gained and something was lost. The gain was enrichment of the theory of numbers. The loss was in intuitive appreciation of the mathematical concepts involved. To our early ancestors, for whom arithmetic was merely an instrument for counting objects, a question such as "What is 3 minus 7?" would certainly have appeared absurd. As mathematicians proceeded to more and more generalization of the number system, intuition suffered more severe insults. This is reflected even in the descriptions by mathematicians themselves: complex numbers, for example, were named "imaginary" numbers, certain functions of real variables were called "pathological," and so forth.

Sometimes, however, generalization is an aid rather than a hindrance to intuitive understanding. In particular, an advance in generalization can exorcise a paradox by restoring a familiar law that may have been lost in a preceding generalization. A beautiful example is found in the theory of algebraic integers. An algebraic integer is a generalized integer, the root of an equation such as $x^n + a_{n-1}x^{n-1} + \ldots a_0 = 0$, in which all the coefficients are rational integers. It was found, paradoxically, that in some number domains algebraic integers could be factored into prime numbers in more than one way—a violation of the "law" that only one such factorization is possible for any number. Further study showed, however, that algebraic integers could be generalized into objects called "ideals," and it turned out that these can be factored into primes in only one way.

Paradoxes arise, it seems, from failure to pursue a generalization far enough. Incommensurables appeared paradoxical to the Pythagoreans (and were so unsettling that the discoverers are said to have kept quiet about their discovery) because the Greeks could not pursue the generalization of number as far as the continuum. The great unsolved problems of ancient mathematics could not be solved as long as the definitions of geometrical constructions were narrowly restricted only to those descriptions that could be arrived at by means of the straightedge and the compass. The generalizations of modern mathematics have got rid of most of the old paradoxes. Gone is the uneasiness that marked the early attitude toward imaginary numbers (which behave "paradoxically" by yielding negative squares). Gone is the bewilderment about derivatives that caused Bishop Berkeley to describe them as "ghosts of departed quantities." Gone are the birth agonies of non-Euclidean geometry, which seemed to defy reason itself (as Kant probably would have maintained).

Toward the end of the 19th century it seemed that mathematics was on the road to complete emancipation from the illusions of "common sense" and achievement of an ideal science. Many believed that with further formalization of its foundations and structure mathematics would become a perfectly self-contained, internally consistent system constructed of purely logical concepts and free of all paradoxes. This proved to be a vain hope. In the 20th century it has become clear that mathematical logic itself cannot be freed from paradoxes.

Paradoxes such as are illustrated by an ancient riddle ("Is the Cretan who says 'I am lying' lying or telling the truth?") have been found lurking in the very fabric of mathematical logic. Alfred North Whitehead and Bertrand Russell attempted to purge mathematics of all but purely logical notions in their ambitious work *Principia Mathematica* but had to give up the attempt without success. And in the 1930's Kurt Gödel finally issued a verdict that has not so far been challenged: We must resign ourselves to living with incomplete mathematical systems in which "undecidable propositions" will forever be cropping up. This follows from Gödel's proof that no mathematical system that includes the principle of transfinite induction can be both complete and free of contradictions.

Gödel's theorem asserts that there are undecidable propositions that cannot be proved to be true or false by any chain of deductive logic starting with the postulates of the system. If his theorem had been proved in an earlier age, it would

	ACTIONS				
EVENTS	A_1	A_2	A_3	A_4	A_5
E(P = .4)	$U_1 = -5$	$U_2 = 20$	$U_3 = -2$	$U_4 = 3$	$U_5 = 14$
F(P = .6)	$U'_1 = 0$	$U'_2 = -8$	$U'_3 = -3$	$U'_4 = 2$	$U'_5 = -6$
EXPECTED UTILITIES	−2	3.2	−2.6	2.4	2

DILEMMA posed in the preceding illustration can be resolved by expanding the framework in which the problem is viewed. Each outcome is given a relative utility (U) and each event a probability (P). Now a rational choice can be made. It is the action with the highest "expected utility," or sum of the probability-weighted utilities of its outcomes. On this basis action A_2 is preferred. If another player, in a game situation, chooses between rows E and F, then according to the "minimax" rule A_4 becomes the best choice.

have been greeted with disbelief as the most startling of paradoxes, because of the strongly held notion (implied by the "law of the excluded middle") that a well-formed proposition must be either true or false and that failure to prove its truth or falsity only meant that the problem had not yet been solved. Today, however, mathematicians take the implications of Gödel's theorem in stride, since it is now recognized that the "law of the excluded middle" (the assumption of a two-valued logic) is merely a postulate, not an immutable law.

In the light of Gödel's theorem, for example, the non-Euclidean geometries do not appear at all paradoxical. These geometries illustrate the theorem; by substituting other postulates for Euclid's famous fifth postulate (that one, and only one, line can be drawn parallel to a given line through a point outside the line) they relegate Euclid's postulate to the status of an undecidable proposition.

To sum up, what we have learned from this review of the growing maturity of mathematical theory is that it often proceeds by the step-by-step solution of paradoxes, involving at each stage the shedding of intuitively nurtured notions and the acquisition of an enriched, more generalized framework of thought. I have reviewed and illustrated the history in some detail because it bears directly on the solution of the Prisoner's Dilemma paradox, which I wish to discuss as a modern instance. This development in decision theory (which, like mathematics, is also a deductive discipline) is an episode in a history strikingly similar to that of the maturation of mathematics. The building of a theory of rational decision has followed a course essentially like the step-by-step buildup of, for example, the system of numbers.

Decision Theory

Let us follow such a buildup in decision theory. Consider, to begin with, the simplest of all decision problems: a choice among several courses of action whose outcomes are known. Clearly the rational choice in this case is the action that will result in the most desired outcome, and the several actions can be ranked in an order of preference corresponding to the desirability of the outcomes, the highest rank being given to the action that will produce the most preferred outcome, second rank to the action producing the second most desirable outcome and so on [*see upper illustration on page 51*].

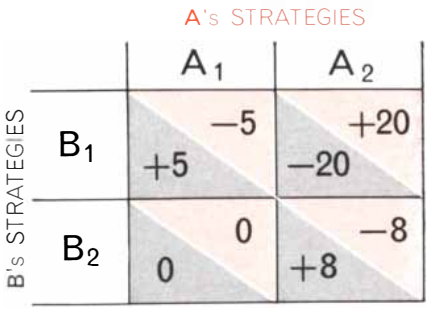
Now let us introduce a complication. We consider a situation in which the outcome of each action is influenced by one of two possible intervening events (*E* and *F*). A chosen action may produce either of two different outcomes, depending on whether event *E* or event *F* occurs [*see lower illustration on page 51*]. It may now become impossible to decide (without further information) on the rational choice of action. For example, a particular action may result in the most preferred outcome if event *E* occurs but in a less desirable outcome if event *F* occurs.

Here, then, is our first dilemma. To resolve it we need to introduce new criteria—that is to say, expand our system of concepts by adding new "postulates"—for evaluating a rational decision. Two guides come to mind. It would be helpful to rate the utility of the various possible outcomes, assigning a number to each as a measure of its relative utility. Second, we need to know the relative probabilities of the two events *E* and *F*. If we can introduce these items of information, we can again rank the order of preference of the several actions. Each action can now be assigned an "expected utility" (the sum of the probability-weighted utilities of its two possible outcomes), and the rational choice is the action yielding the highest expected utility [*see illustration on opposite page*].

Note that this new system of decision is a generalization of the preceding one. For instance, the choice in a situation in which one action can be chosen over another regardless of whether event *E* or event *F* occurs (because in either event the outcome has a higher utility) is the same as the choice dictated by the older rule; thus the old decision rule is actually a special case of the new one. The generalization has enriched the decision theory and enabled us to solve problems previously unsolvable. We have, however, paid a price. The rationality of the new rule is not so obvious. A decision based on the new rule does not necessarily yield the best result in a particular case; if the "wrong" event occurs, the decision-maker may find that he has a poorer result than he would have obtained with any other action choice. We would have to do some explaining to convince a naïve decision-maker that he had nevertheless made the best available decision (because it maximized the utility expectancy in a risk situation).

Game Strategies

Consider now an elaboration of the decision problem that translates it into a game between two opposing players. Instead of the chance events *E* and *F* we must now deal with the players' respective strategies, or moves, as variables. These can no longer be assigned fixed probabilities. They will depend not on chance but on decisions by the players, each of whom is trying to minimize his opponent's utility (that is, payoff) and maximize his own.



MINIMAX RULE is not helpful in this game situation derived from part of the preceding matrix. The distribution of the payoffs is such that neither player can ever be sure which will be his best move (*see text*).

Let us say that the game has the form of the preceding illustration, with one player (*A*) having a choice of five moves and the other player (*B*) given a choice of two countermoves. Player *A*, realizing that *B* will try to minimize his payoff, chooses the fourth column (A_4), which will give him a minimum payoff of 2 and a possible maximum of 3. Even though player *B* may correctly guess this choice and therefore select *F* as his move (minimizing *A*'s payoff), player *A* sticks to his choice, knowing that he cannot do as well by choosing any other column in view of *B*'s adoption of strategy *F*. This decision rule is known as the minimax rule.

Now let us alter the game to one in which each player has a choice of two moves [*see illustration above*]. Here neither player can find help in the minimax rule. In order to apply the rule (that is, minimize his potential loss) player *A* would choose column A_1, ensuring that his loss would be no more than −5 even if player *B* made his best reply, B_1. If, however, *A* could be certain that *B* would choose B_1, *A* could choose A_2 and thus win a payoff of +20. For his part *B*, following this reasoning, might guess that *A* would do just that and would therefore choose B_2, winning himself a payoff of +8 provided that *A* did not outguess him and decide on A_1 after all. In short, we are left without a rational new rule to replace the unworkable minimax rule.

To escape from the impasse we again

resort to our rescue formula: further generalization. The minimax rule fails in this game because it provides the opponent with too much information; if he knows that you will always follow the rule, he can always win. Each player can therefore do better by adopting a "mixed" strategy, that is, make choices at random in order not to reveal his intentions to the opponent. (Note that this is a generalization of the "pure" strategy, or special case, represented by the minimax rule.) To randomize his selections a player draws lots for each choice, and the respective choices have certain probabilities. Associated with each pair of choices by the two players is a pair of expected utilities, or payoffs. One or more of these pairs of choices will be characterized by minimax equilibrium: that is, if either player makes a choice in that pair (a "pure" strategy), his opponent's best choice is the other member of the pair. In a constant-sum game all such pairs give the same expected payoffs.

Now, this kind of strategy, turning the choices over to chance, seems to take us far afield from rationality. Is rationality compatible with a deliberate abandonment of the decision-maker's "freedom of choice"? The issue can be argued. It can be pointed out that the decision-maker is, after all, exercising choice in his selection of the mixed strategy. Nevertheless, it is clear that the new generalization requires us to take a new view of the straightforward concept that a rational decision is one that finds the best possible outcome under the given circumstances, in short, one that makes "the best possible choice." Intuitively one feels that the decision-maker has surrendered the exercise of his own judgment in turning over the choice in each case to a random device. The mixed strategy therefore suggests that we should reexamine what it means to talk sensibly about "the best possible choice." This is likely to lead to a conception of rationality so novel that it makes us uneasy until we have found a logical justification for it.

A clue to the justification is suggested by an illustrative anecdote in J. D. Williams' *The Compleat Strategyst*, a witty primer on elementary game theory. Two policemen are considering the problem of catching a bandit. One of them starts to calculate the optimal mixed strategy for the chase. The other policeman protests.

"While we're doodling," he points out, "he is making his getaway."

"Relax," says the game-theorist policeman. "He's got to figure it out too, don't he?"

The serious point of the story is that rationality must usually be defined in a social context.

The Dilemma Solved

We come finally to Howard's solution of the Prisoner's Dilemma game. The solution required the construction of a metagame that goes beyond the given strategies. Note that none of the methods I have discussed so far could lead to an intuitively satisfactory result in the game. The minimax principle would simply lead to both players' choosing strategy T (as in the illustration on page 50), which gives a bad result for both. A mixed strategy is irrelevant in this game, because the concept does not apply if each player has a strategy that is "best" regardless of what the other does. The paradox of Prisoner's Dilemma is genuine and severe.

Like other paradoxes, this one was denied by some logicians and worshiped by others. The deniers declared the unfavorable outcome of the game was a realistic fact of life that in no way changed the fact that the players' choices were based on the "rational pursuit of self-interest." The worshipers saw the impasse as a new manifestation of the unsatisfactoriness of the human condition. A number of decision theorists, however, undertook to wrestle with the paradox, and as far as I know Howard was the first to succeed.

To illustrate Howard's idea, let us begin by constructing a simplified precursor of his successful metagame. In this version we give player B the same choice as before between two strategies, or moves (S and T). Player A, however, is now provided with four conditional strategies: A_1 (choose S regardless of what B may choose); A_2 (choose as you expect B to choose); A_3 (choose the opposite of what you expect B to choose); A_4 (choose T regardless of what B may choose).

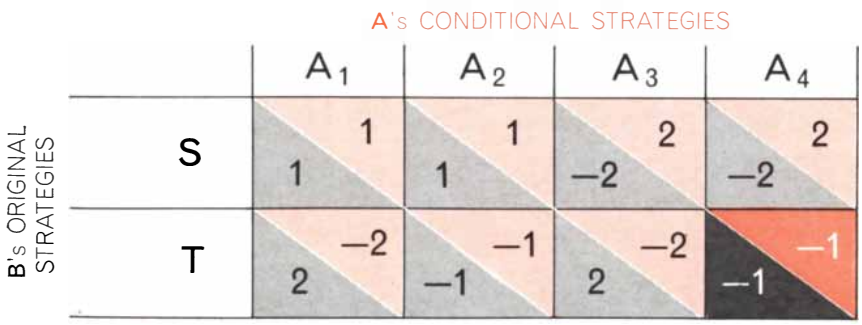
In this game [*see illustration on this page*] the rational choice for A is A_4 and for B is T, because a different choice cannot give either player a better payoff (and may give a worse one) if the other player makes the prescribed choice. In such a situation the mutual choices for minimal loss (or maximal gain) are said to be in "minimax equilibrium."

This game leaves the paradox unresolved, since the players still get less than they might. Howard solved the dilemma of the losing payoff by developing the metagame further in the same direction. In addition to giving player A four conditional strategies, he provided player B with 16 conditional strategies related to A's possible choices. To each of A's assumed four choices B can now respond with either S or T [*see illustration on page 56*]. B may choose S regardless of what A does (this is indicated in the matrix by $SSSS$); he may choose T in any case ($TTTT$); he may use the strategy $STSS$, choosing T if, and only if, he expects A to try to match his choice (A_2), and so on.

The illustration shows the respective payoffs in the 64 possible pairings of choices. It reveals that besides the minimax equilibrium, or "best choice," available in the old game (both players choosing strategy T) two new equilibriums emerge in the metagame.

The Rational Decision

Consider this metagame from the points of view of both players. In choosing "the best" strategy a rational player will examine the game matrix to see if it has an equilibrium. If so, it seems rational to choose a strategy that has this equilibrium, since one can assume that the



METAGAME is constructed from Prisoner's Dilemma. B still has two possible moves, S and T, but A has four conditional strategies, A_1 through A_4. The rational choices for both players lead to a mutual "minimax equilibrium" (*bottom right*). The paradox persists.

other player, being rational, will also choose a strategy available to him that has the equilibrium. This is so because an equilibrium is an outcome that cannot be improved by either player (and may be impaired) if one player chooses a different strategy while the other player sticks to the strategy that has the equilibrium.

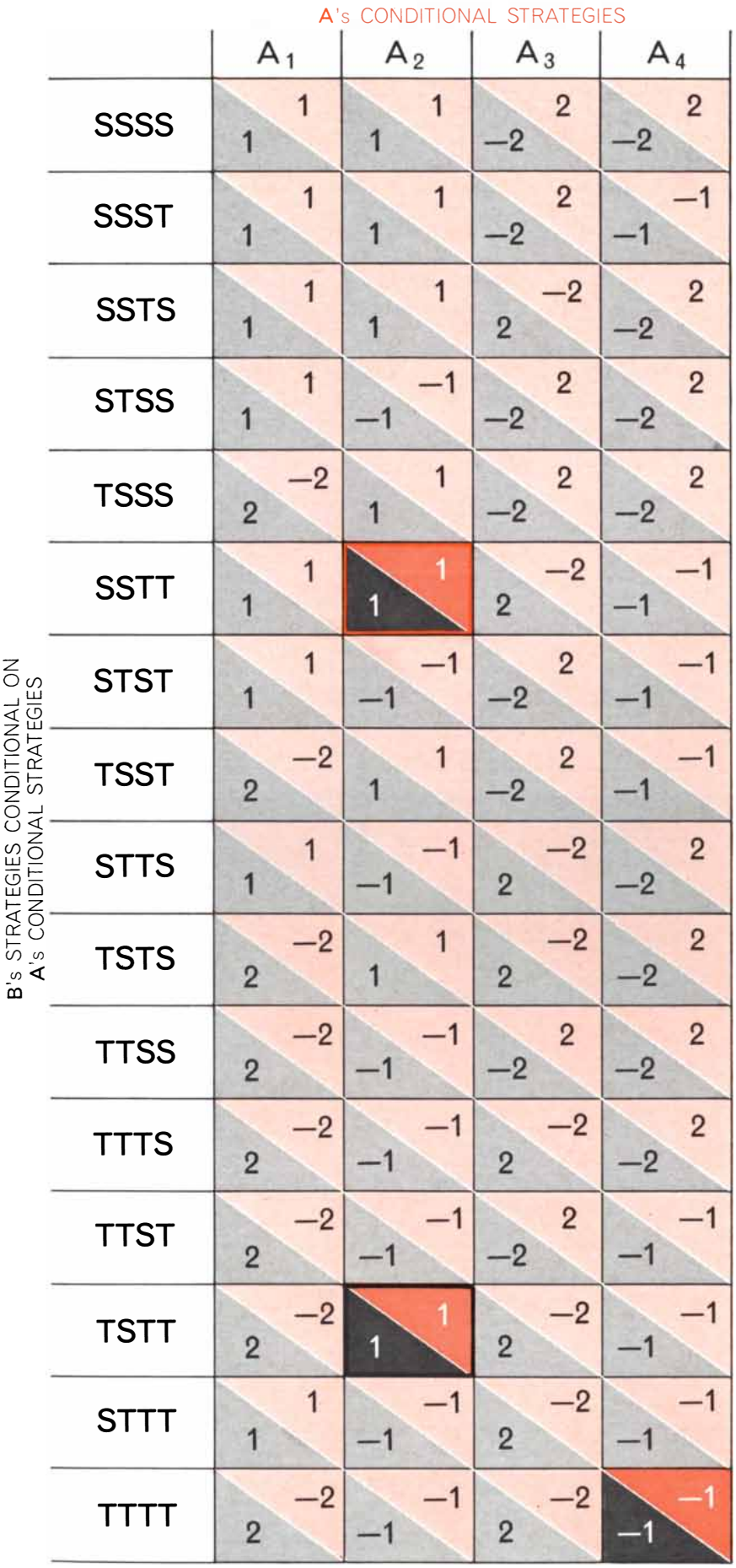
The outcome in the lower right-hand corner is an equilibrium. If player B chooses strategy $TTTT$, player A cannot get more than -1 and may get -2, if, for example, he chooses A_1 or A_3. Similarly, if player A chooses A_4, player B cannot get more than -1 and may get -2, if, for example, he chooses $SSSS$ or $SSTS$ or $TTTS$.

An equilibrium also results, however, if player A chooses A_2 and player B chooses either $SSTT$ or $TSTT$, since if either player departs from the corresponding strategy while the other does not, the departing player can only impair his payoff. It follows that the only rational choices for player A are A_2 and A_4 and for player B, $SSTT$, $TSTT$ and $TTTT$.

Given these choices, it is clearly rational for A to choose A_2, since he is sure to get -1 if he does not and may get $+1$ if he does. As for B, his rational choice is clearly either $SSTT$ or $TSTT$ for the same reason. Player A's choice has now been narrowed to a single strategy. Player B must still choose between $SSTT$ and $TSTT$. Of these two choices, $TSTT$ is the better strategy for B: he does as well with it as with $SSTT$ if A should choose A_2, A_3 or A_4, and better if A should choose A_1. The choices are now prescribed. A should choose A_2 and B should choose $TSTT$. As a result both players get $+1$, which is the most they can get jointly in this game. We have escaped from the paradox.

This game can be constructed the other way: first giving player B four conditional strategies and then player A the 16 conditional responses. In either case we get the same equilibriums. It is essential, however, that the game be constructed by the stepwise method, assigning four conditional strategies to one player and then 16 to the other. If both players are simply given four conditional strategies apiece, it is impossible for a referee to determine the outcomes of some pairs of choices, for instance the outcome of both players' choosing strategies such that each selects the same move he expects the other to make.

Thus the paradox of the Prisoner's Dilemma game was resolved. Individual rationality and collective rationality



were reconciled. Howard gave the dilemma the *coup de grace* by proving that no new equilibriums would appear if metagames of a higher order were constructed. In other words, no further extension of the process is necessary: after just two steps the set of equilibriums is "closed," as a mathematician would say.

The key to the resolution of the paradox was the introduction of a new concept: that of conditional strategy. Howard's solution of Prisoner's Dilemma is attractive because it was accomplished in the spirit of the method that has marked the steady maturation of logical and mathematical concepts. The method entails escaping from the conceptual framework in which a paradox or apparently unsolvable problem has appeared and putting the framework itself in a new perspective, so that the limitations of the old concept are revealed. Once the limitations are seen, a generalization of the concept suggests itself and a new framework can be constructed.

In order to be intuitively understood and accepted, the formal solution of the Prisoner's Dilemma paradox still needs to be translated in a social context. When and if that is accomplished, Prisoner's Dilemma will deserve a place in the museum of famous ex-paradoxes where those of the incommensurables, Achilles and the tortoise and the barbers trying to decide if they ought to shave themselves, are enshrined.

Whether or not decision theory will continue to mature along the lines suggested by the evolution of modern mathematics is not yet clear. The practical importance of developing a usable decision theory is obvious; it remains to be seen, however, if the insights obtained from abstract analysis will be so transparently useful that they will stimulate a great deal more work in this field. We can hope that the role of paradoxes in advancing mathematics to the status of the most glorious achievement of the human intellect may portend a similar future for decision theory.

PARADOX IS RESOLVED through this metagame. *A* has the same strategies as in the preceding matrix but *B* has 16 conditional strategies (*see text*). Besides the old minimax equilibrium (*bottom right*), there are two new equilibriums (*framed boxes in second column*). A rational player prefers an equilibrium with a larger payoff for both, since he can depend on his opponent to pick it. So *A* chooses A_2. *B* could opt for either of the equilibriums in the column; he chooses *TSTT* because of its better payoff if *A* should select strategy A_1. Thus individual and collective rationality are reconciled.

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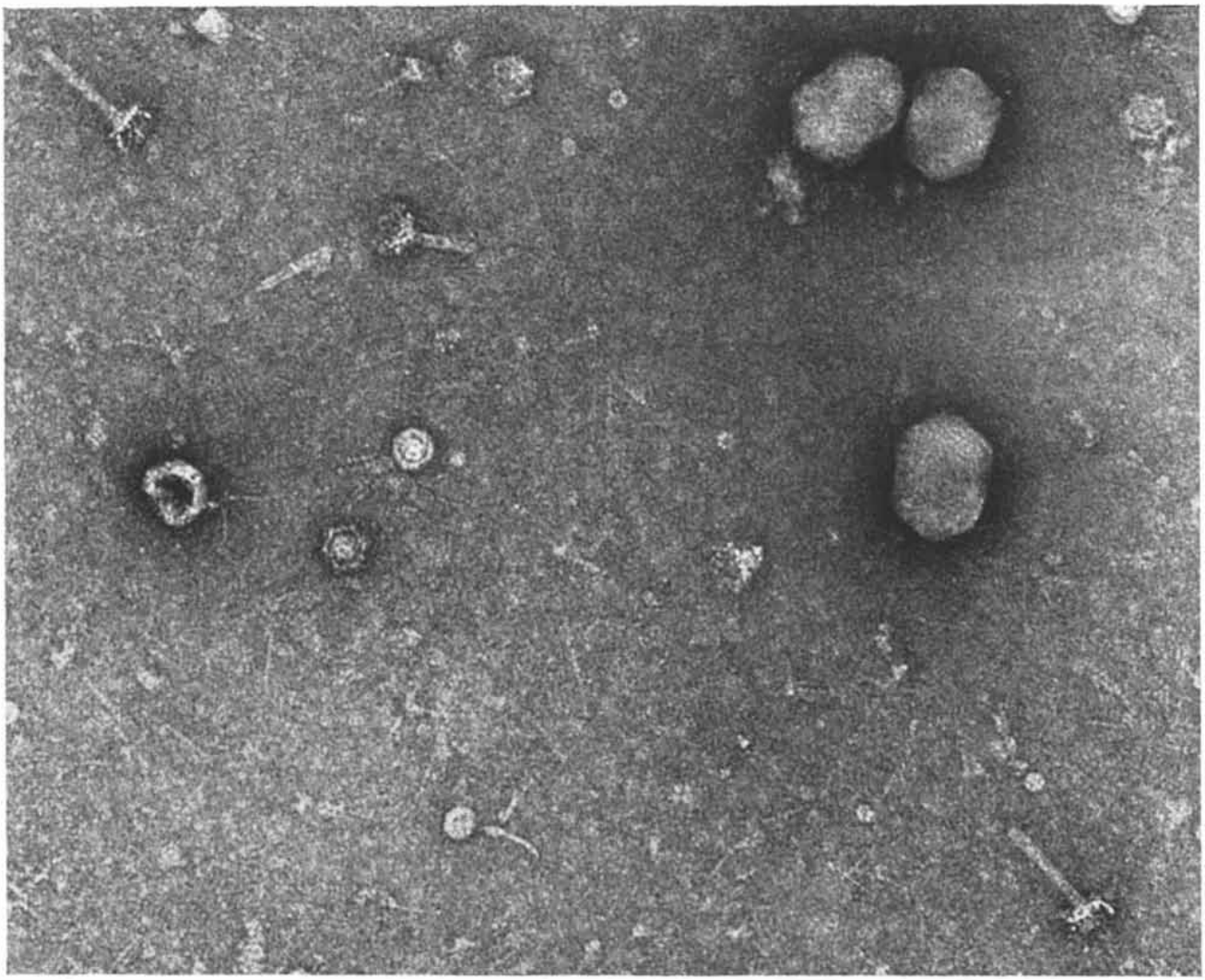
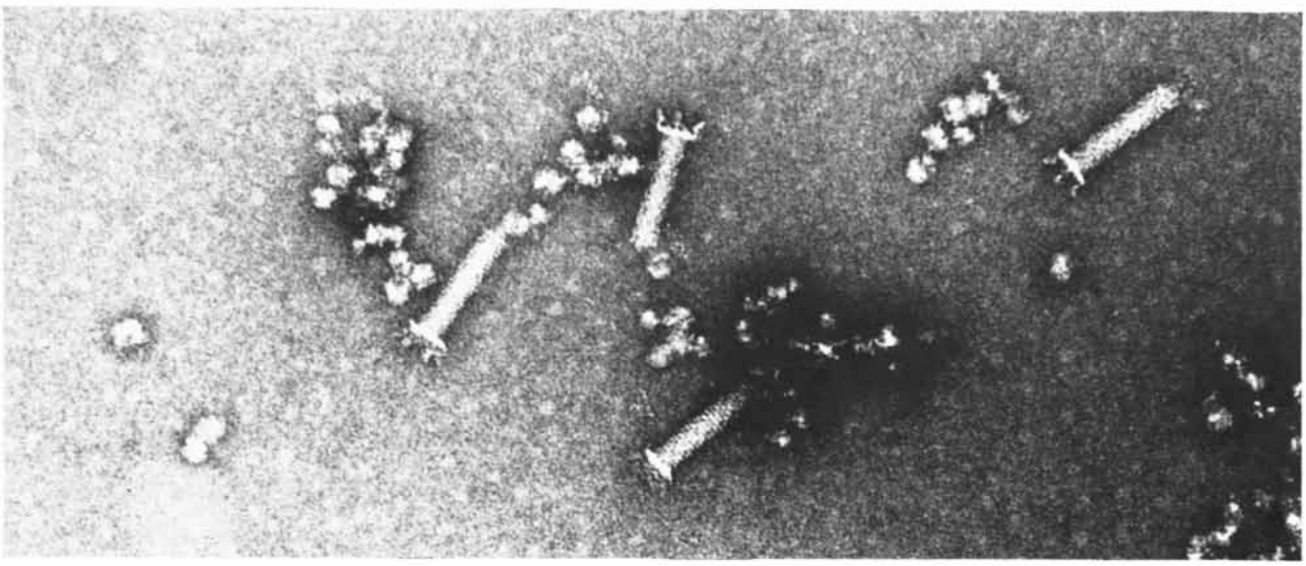


UNASSEMBLED PARTS of the T4 virus are present in this extract. It was prepared by infecting colon bacilli with a mutant virus defective in gene No. 18, which specifies the synthesis of the sheath (*see upper illustration on page 63*). The result is the accumulation of all major components except the sheath: heads, free tail fibers and "naked" tails consisting of cores and end plates.



COMPLETE TAILS, enclosed in sheaths, were produced by a different mutant, defective in a gene involved in head formation. The tails were separated from the resulting extract (along with some spherical bacterial ribosomes) by being spun in a centrifuge. If the tails are added to the extract (*top photograph*), they combine with the heads and free fibers in it to form infectious virus.

Building a Bacterial Virus

T4 viruses with mutations in certain genes produce unassembled viral components. These particles are combined in the test tube in an effort to learn how the genes of a virus specify its shape

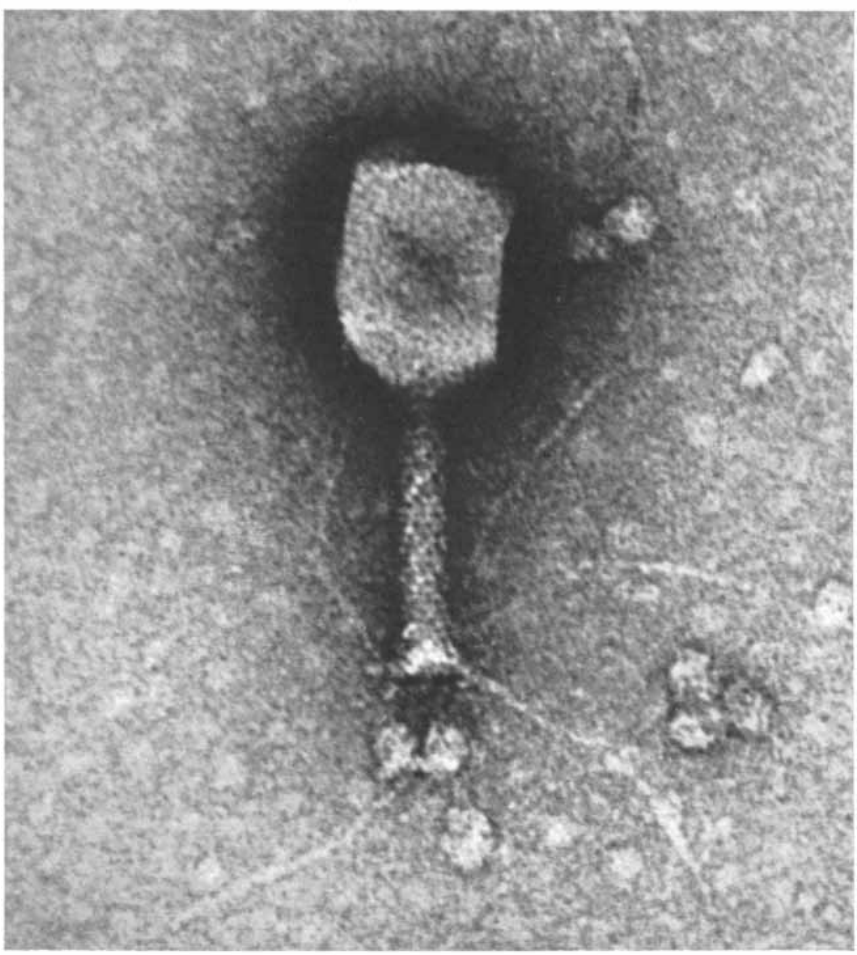
by William B. Wood and R. S. Edgar

Slice an orange in half, squeeze the juice into a pitcher and then drop in the rind. It comes as no surprise that the orange does not reconstitute itself. If, on the other hand, the components of the virus that causes the mosaic disease of tobacco are gently dissociated and then brought together under the proper conditions, they do reassociate, forming complete, infectious virus particles. The tobacco mosaic virus consists of a single strand of ribonucleic acid with several thousand identical protein subunits assembled around it in a tubular casing. The orange, of course, is a large and complex structure composed of a variety of cell types incorporating many different kinds of proteins and other materials. Yet both orange and virus are examples of biological architecture that must arise as a consequence of the action of genes.

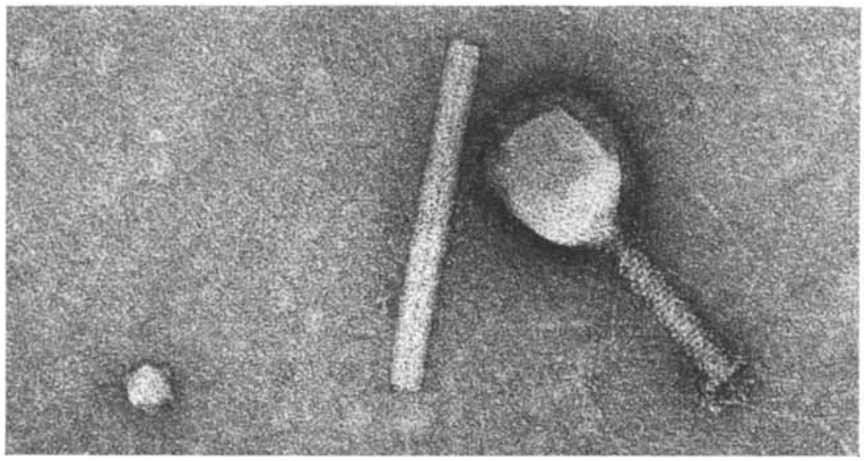
Molecular biologists have now provided a fairly complete picture of how genes carry out their primary function: the specification of protein structure. The segment of nucleic acid (DNA or RNA) that constitutes a single gene specifies the chain of amino acids that comprises a protein molecule. Interactions among the amino acids cause the chain to fold into a unique configuration appropriate to the enzymatic or structural role for which it is destined. In this way the information in one gene determines the three-dimensional structure of a single protein molecule.

Where does the information come from to direct the next step: the assembly of many kinds of protein molecules into more complex structures? To build the relatively simple tobacco mosaic virus no further information is required; the inherent properties of the strand of RNA and the protein subunits cause them to interact in a unique way that results in the formation of virus particles. Clearly such a self-assembly process cannot explain the morphogenesis of an orange. At some intermediate stage on the scale of biological complexity there must be a point at which self-assembly becomes inadequate to the task of directing the building process. Working with a virus that may be just beyond that point, the T4 virus that infects the colon bacillus, we have been trying to learn how genes supply the required additional information.

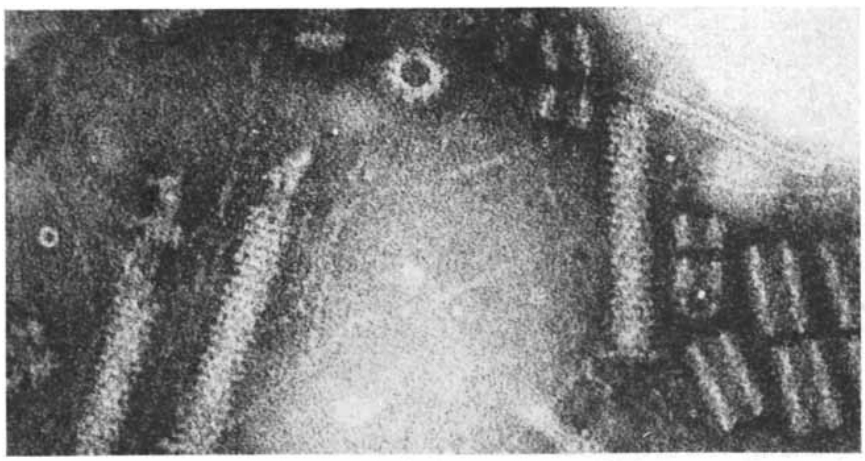
Although the T4 virus is only a few rungs up the biological ladder from the tobacco mosaic virus, it is consider-



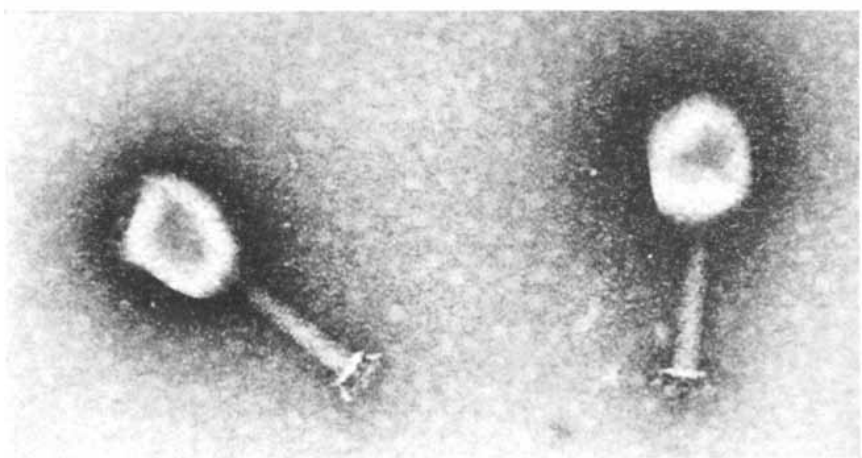
COMPLETE VIRUS PARTICLE was built by assembling component parts in the test tube. The T4 virus is enlarged about 300,000 diameters in this electron micrograph made, like the ones on the opposite page, by Jonathan King of the California Institute of Technology.



TWO SIMPLER VIRUSES are shown with the T4 in an electron micrograph made by Fred Eiserling of the University of California at Los Angeles. The icosahedral ΦX174 virus (*left*) infects the colon bacillus, as does the T4. The rod-shaped tobacco mosaic virus reassembles itself in the test tube after dissociation. The enlargement is 200,000 diameters.



COMPLEX STRUCTURE of the T4 tail is shown in an electron micrograph made by E. Boy de la Tour of the University of Geneva. The parts were obtained by breaking down virus particles, not by synthesis, which is why fibers are attached to tails. The hollow interiors of the free core (*top right*) and pieces of sheath are delineated by dark stain that has flowed into them. There are end-on views of pieces of core (*left*) and sheath (*top center*).

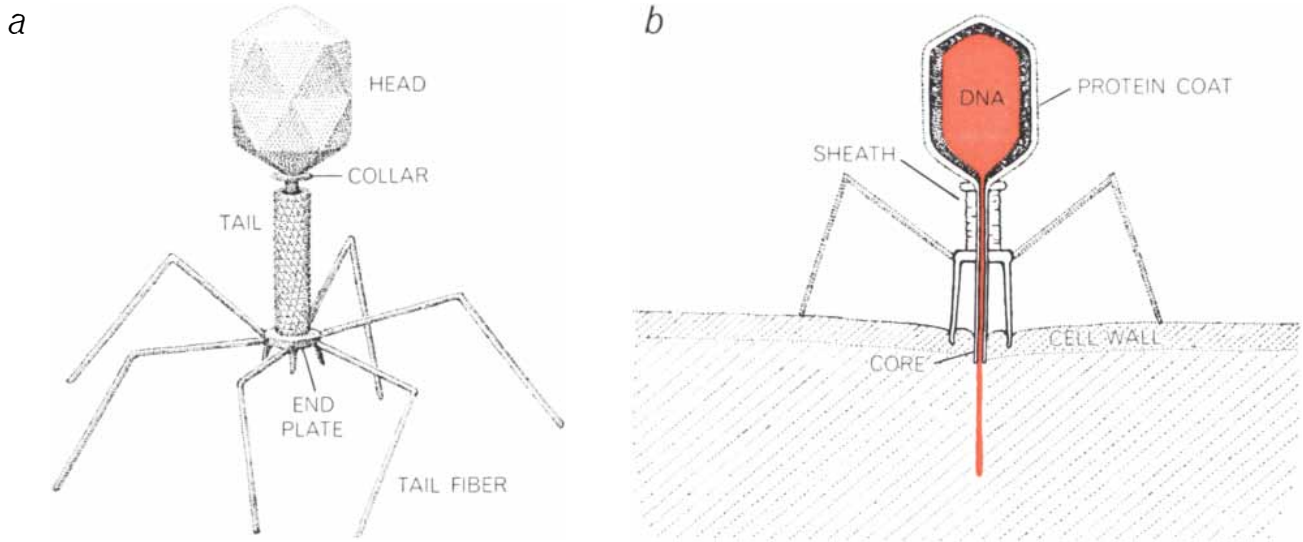


FIBERLESS PARTICLES, otherwise complete, are the products of infection by a mutant defective in one of the fiber-forming genes. Heads, tails and fibers are each formed by a subassembly line (*see illustration on page 74*). The electron micrograph was made by King.

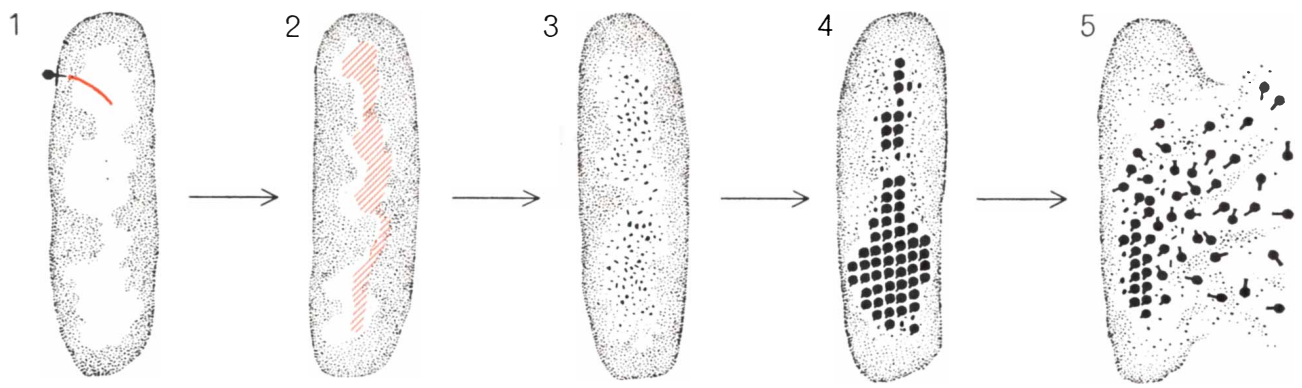
ably more complex. Its DNA, which comprises more than 100 genes (compared with five or six in the tobacco mosaic virus), is coiled tightly inside a protein membrane to form a polyhedral head. Connected to the head by a short neck is a springlike tail consisting of a contractile sheath surrounding a central core and attached to an end plate, or base, from which protrude six short spikes and six long, slender fibers.

The life cycle of the T4 virus begins with its attachment to the surface of a colon bacillus by the tail fibers and spikes on its end plate. The sheath then contracts, driving the tubular core of the tail through the wall of the bacterial cell and providing an entry through which the DNA in the head of the virus can pass into the bacterium. Once inside, the genetic material of the virus quickly takes over the machinery of the cell. The bacterial DNA is broken down, production of bacterial protein stops and within less than a minute the cell has begun to manufacture viral proteins under the control of the injected virus genes. Among the first proteins to be made are the enzymes needed for viral DNA replication, which begins five minutes after infection. Three minutes later a second set of genes starts to direct the synthesis of the structural proteins that will form the head components and the tail components, and the process of viral morphogenesis begins. The first completed virus particle materializes 13 minutes after infection. Synthesis of both the DNA and the protein components continues for 12 more minutes until about 200 virus particles have accumulated within the cell. At this point a viral enzyme, lysozyme, attacks the cell wall from the inside to break open the bacterium and liberate the new viruses for a subsequent round of infection.

Additional insight into this process has come from studying strains of T4 carrying mutations—molecular defects that arise randomly and infrequently in the viral DNA during the course of its replication [see "The Genetics of a Bacterial Virus," by R. S. Edgar and R. H. Epstein; SCIENTIFIC AMERICAN, February, 1965]. When a mutation is present, the protein specified by the mutant gene is synthesized in an altered form. This new protein is often nonfunctional, in which case the development of the virus stops at the point where the protein is required. Normally such a mutation has little experimental use, since the virus in which it arises is dead and hence cannot be recovered for study. Edgar and Ep-



T4 BACTERIAL VIRUS is an assembly of protein components (*a*). The head is a protein membrane, shaped like a kind of prolate icosahedron with 30 facets and filled with deoxyribonucleic acid (DNA). It is attached by a neck to a tail consisting of a hollow core surrounded by a contractile sheath and based on a spiked end plate to which six fibers are attached. The spikes and fibers affix the virus to a bacterial cell wall (*b*). The sheath contracts, driving the core through the wall, and viral DNA enters the cell.



VIRAL INFECTION begins when viral DNA (*color*) enters a bacterium (*1*). Bacterial DNA is disrupted and viral DNA replicated (*2*). Synthesis of viral structural proteins (*3*) and their assembly into virus (*4*) continues until the cell bursts, releasing particles (*5*).

stein, however, found mutations that are only "conditionally lethal": the mutant protein is produced in either a functional or a nonfunctional form, depending on the conditions of growth chosen by the experimenter. Under "permissive" conditions reproduction is normal, so that the mutants can be cultured and crossed for genetic studies. Under "restrictive" conditions, however, viral development comes to a halt at the step where the protein is needed, and by determining the point at which development is blocked the investigator can infer the normal function of the mutated gene. In this way a number of conditionally lethal mutations have been assigned to different genes, have been genetically mapped and have been tested for their effects on viral development under restrictive conditions [*see illustration on next page*].

In the case of genes that control the later stages of the life cycle, involving the assembly of virus particles, mutations lead to the accumulation of unassembled viral components. These can be identified with the electron microscope. By noting which structures are absent as a result of mutation in a particular gene, we learn about that morphogenetic gene's normal function. For example, genes designated No. 23, No. 27 and No. 34 respectively appear to control steps in the formation of the head, the tail and the tail fibers; these are the structures that are missing from the corresponding mutant-infected cells.

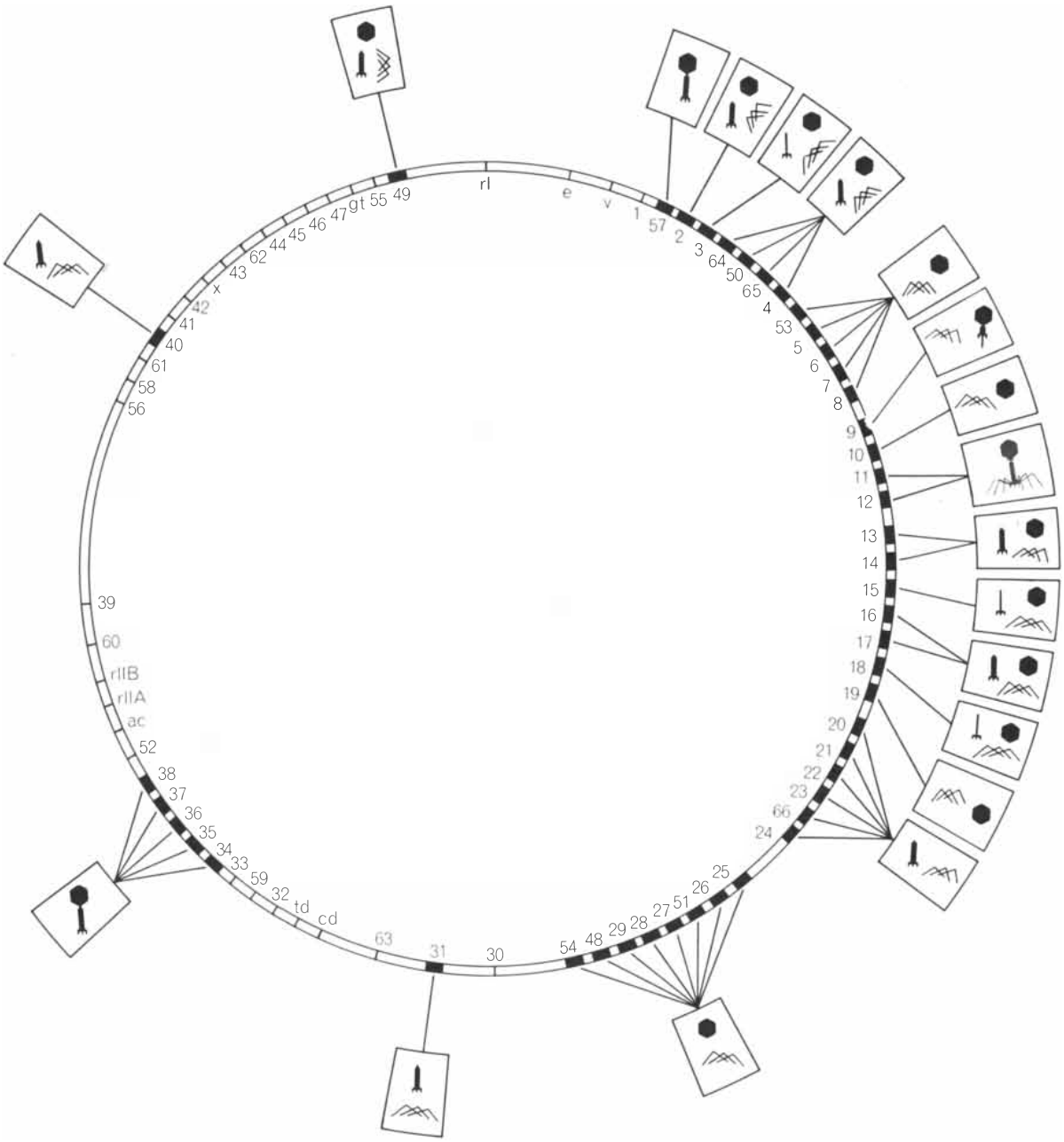
A blockage in the formation of one of these components does not seem to affect the assembly of the other two, which accumulate in the cell as seemingly normal and complete structures. This information alone provides some insight into the assembly process. The virus is apparently not built up the way a sock is knitted—by a process starting at one end and adding subunits sequentially until the other end is reached. Instead, construction seems to follow an assembly-line process, with three major branches that lead independently to the formation of heads, tails and tail fibers. The finished components are combined in subsequent steps to form the virus particle.

A second striking aspect of the genetic map is the large number of genes controlling the morphogenetic process. More than 40 have already been discovered, and a number probably remain to be identified. If all these genes specify proteins that are component parts of the virus, then the virus is considerably more complex than it appears to be. Alterna-

tively, however, some gene products may play directive roles in the assembly process without contributing materially to the virus itself. Studies of seven genes controlling formation of the virus's head support this possibility [see "The Genetic Control of the Shape of a Virus," by Edouard Kellenberger; SCIENTIFIC AMERICAN, December, 1966].

In order to determine the specific functions of the many gene products involved in morphogenesis, it seemed necessary to seek a way to study individual assembly steps under controlled conditions outside the cell. One of us (Edgar) is a geneticist by training, the other (Wood) a biochemist. The geneticist is inclined to let reproductive processes take their normal course and then, by analyzing the progeny, to deduce the molecular events that must have occurred within the organism. The biochemist is eager to break the organism open and search among the remains for more direct clues to what is going on inside. For our current task a synthesis of these two approaches has proved to be most fruitful. Since it seemed inconceivable that the T4 virus could be built from scratch like the tobacco mosaic virus, starting with nucleic acid and individual protein molecules, we decided to let cells infected with mutants serve as sources of preformed viral components. Then we would break open the cells and, by determining how the free parts could be assembled into complete infectious virus, learn the sequence of steps in assembly, the role of each gene product and perhaps its precise mode of action.

Our first experiment was an attempt to attach tail fibers to the otherwise complete virus particle—a reaction we suspected was the terminal step in mor-



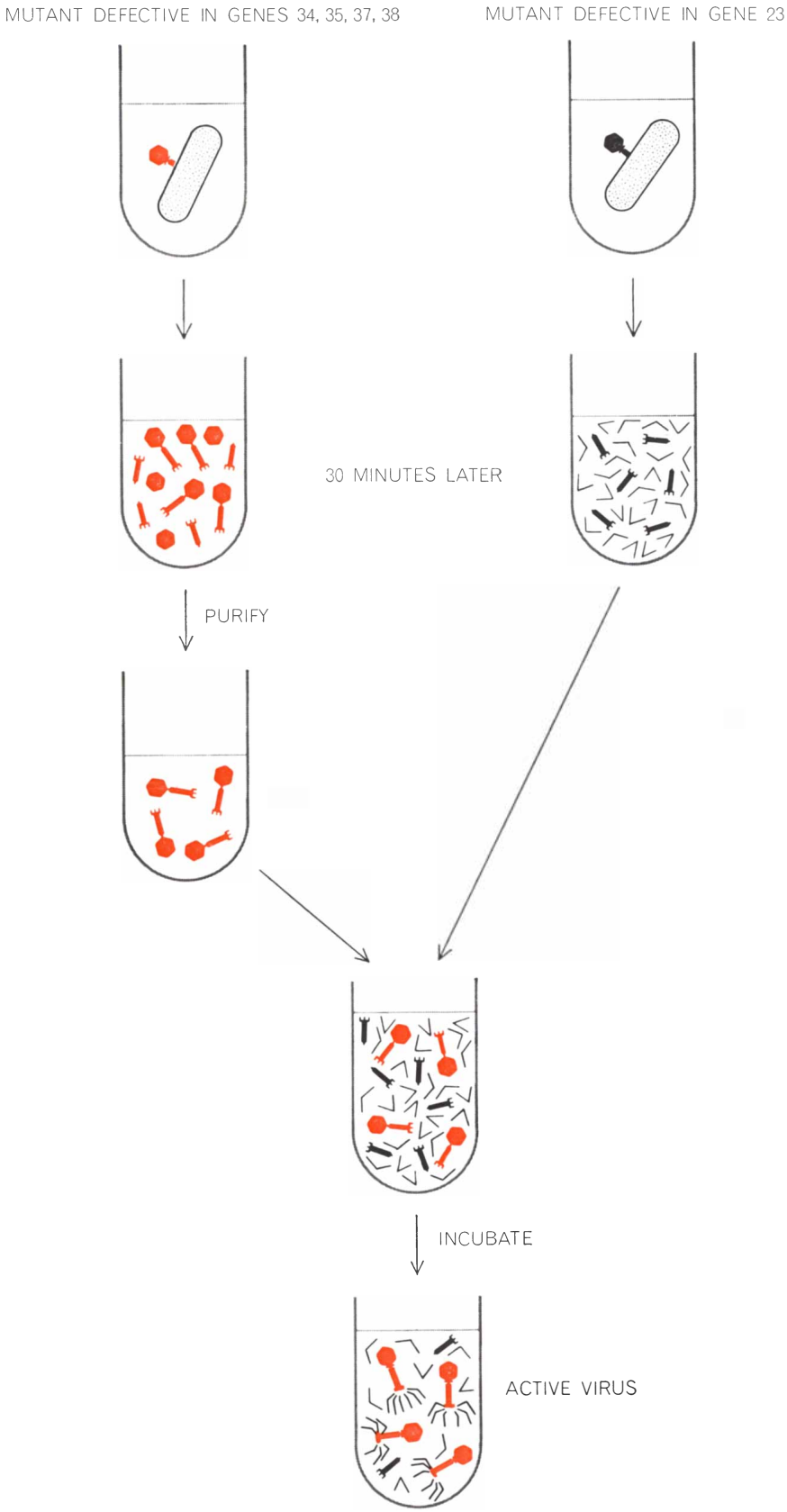
GENETIC MAP of the T4 virus shows the relative positions of more than 75 genes so far identified on the basis of mutations. The solid black segments of the circle indicate genes with morphogenetic functions. The boxed diagrams show which viral components are seen in micrographs of extracts of cells infected by mutants defective in each morphogenetic gene. A defect in gene No. 11 or 12 produces a complete but fragile particle. Heads, all tail parts, sheaths or fibers are the missing components in other extracts.

phogenesis. Cells infected with a virus bearing mutations in several tail fiber genes (No. 34, 35, 37 and 38) were broken open, and the resulting particles —complete except for fibers and noninfectious—were isolated by being spun in a high-speed centrifuge. Other cells, infected with a gene No. 23 mutant that was defective in head formation, were similarly disrupted to make an extract containing free fibers and tails but no heads. When a sample of the particles was incubated with the extract, the level of infectious virus in the mixture increased rapidly to 1,000 times its initial value. Electron micrographs of samples taken from the mixture at various times showed that the particles were indeed acquiring tail fibers as the reaction proceeded.

In that first experiment the production of infectious virus required only one kind of assembly reaction—the attachment of completed fibers to completed particles. We went on to test more demanding mixtures of defective cell extracts. For example, with a mutant blocked in head formation and another one blocked in tail formation we prepared two extracts, one containing tails and free tail fibers but no heads and another containing heads and free tail fibers but no tails. When a mixture of these two extracts also gave rise to a large number of infectious viruses, we concluded that at least two reactions must have occurred: the attachment of heads to tails and the attachment of fibers to the resulting particles.

By infecting bacilli with mutants bearing defects in different genes concerned with assembly, we prepared 40 different extracts containing viral components but no infectious virus. When we tested the extracts by mixing pairs of them in many of the appropriate combinations, some mixtures produced active virus and others showed no detectable activity. The production of infective virus implied that the two extracts were complementing each other in the test tube, that each was supplying a component that was missing or defective in the other and that could be assembled into complete, active virus under our experimental conditions. Lack of activity, on the other hand, suggested that both extracts were deficient in the same viral component—a component being defined as a subassembly unit that functions in our experimental system. By analyzing the pattern of positive and negative results we could find out how many functional components we were dealing with.

It developed that there are at least 13

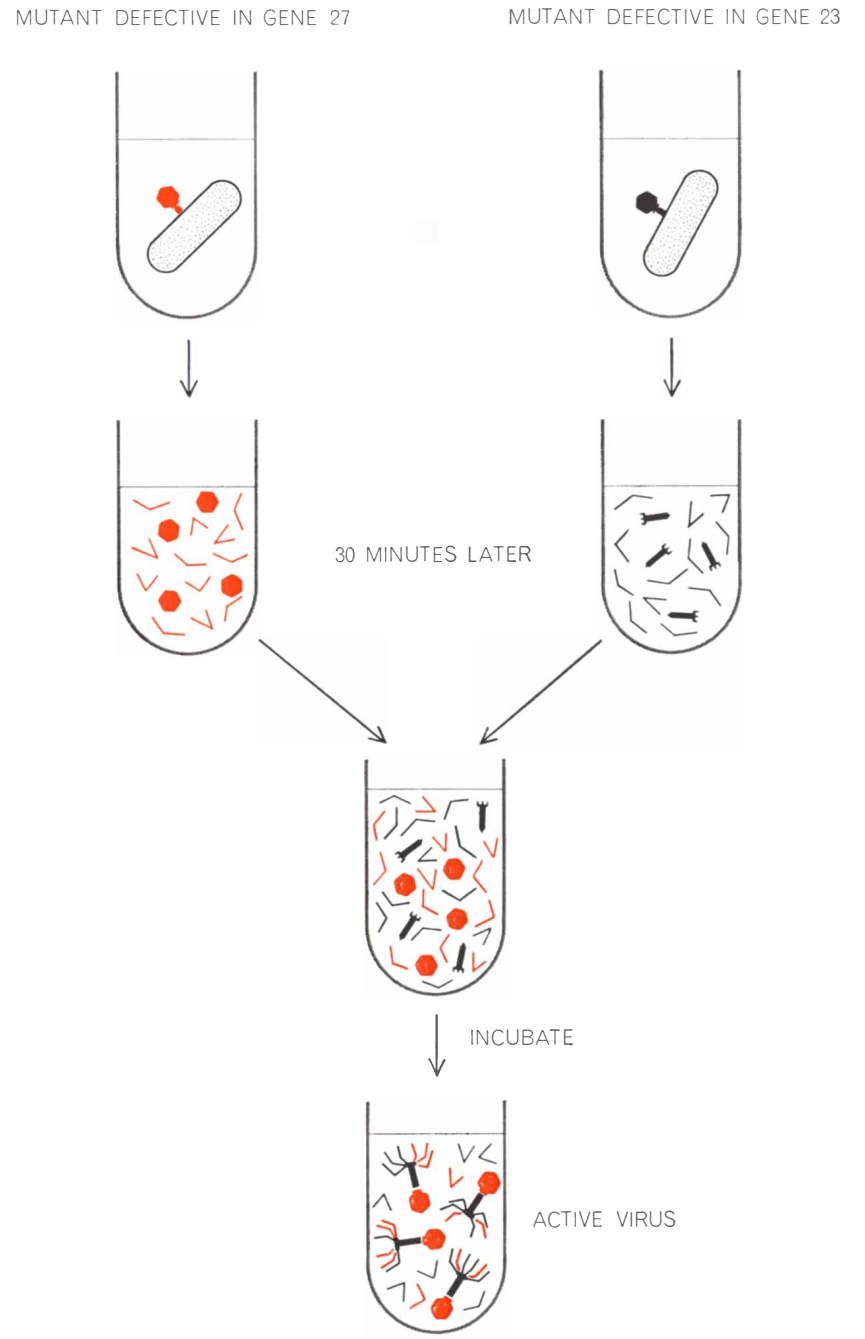


TAIL FIBERS are attached to fiberless particles in the experiment diagrammed here. Cells are infected with a virus (*color*) bearing defective tail-fiber genes. The progeny particles, lacking fibers, are isolated with a centrifuge. A virus with a head-gene mutation (*black*) infects a second bacterial culture, providing an extract containing free tails and fibers. When the two preparations are mixed and incubated at 30 degrees centigrade, the fiberless particles are converted to infectious virus particles by the attachment of the free fibers.

such components. That is, analysis of our pair combinations produced 13 complementation groups, the members of which did not complement one another but did complement any member of any other group. Two of these groups were quite large [*see illustration on opposite page*]. Since one gene produces one protein and since each extract has a different defective gene product, a mixture of any two extracts should include all the proteins required for building the virus. The fact that members of these large groups do not complement one another must mean that our experimental system is not as efficient as an infected cell; whatever the gene products that are missing in each of these extracts do, they cannot do it in the test tube.

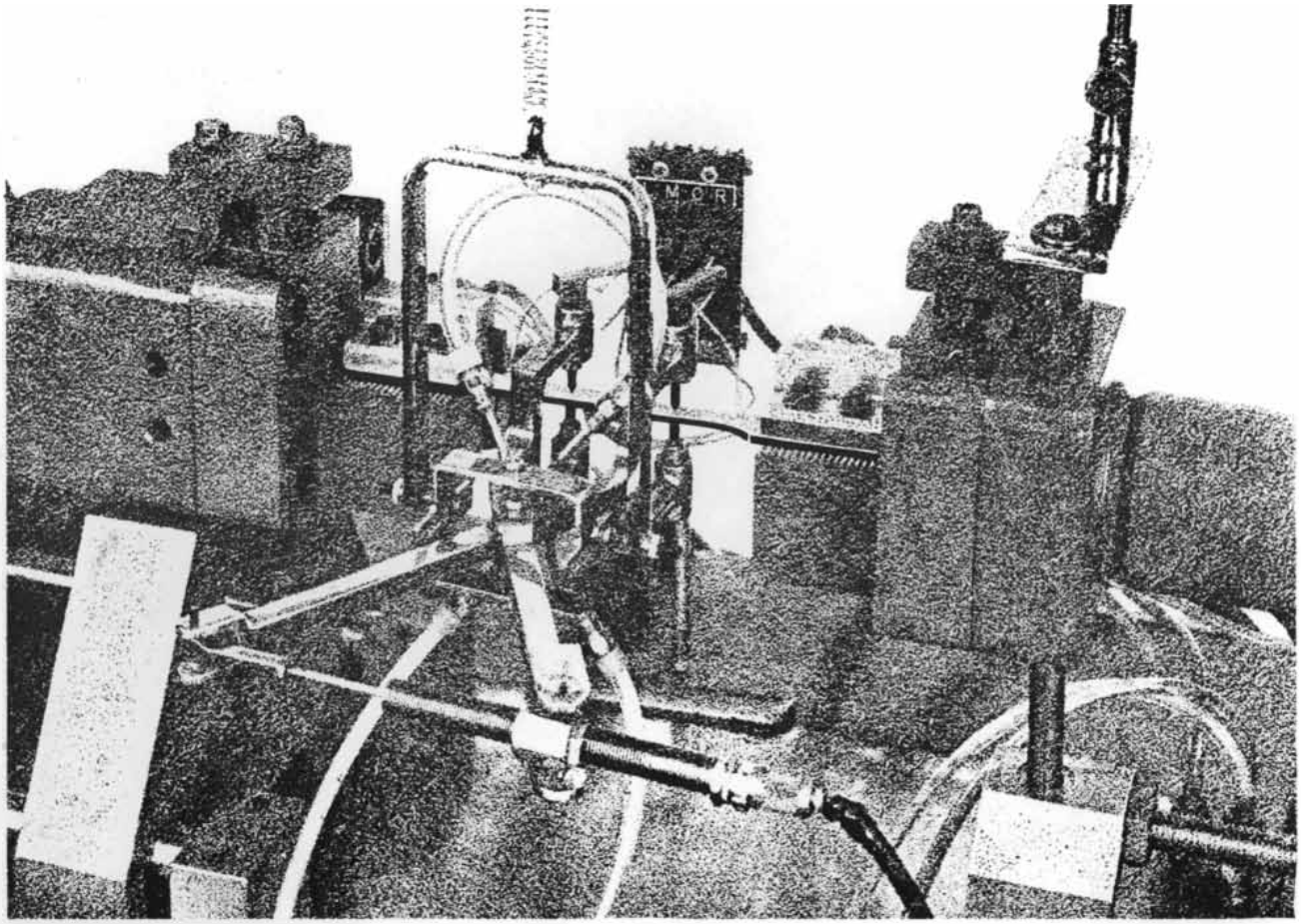
The idea that a complementation group consisted of extracts deficient in the same functional component could be checked against the earlier electron micrograph results. Micrographs of the 12 defective extracts of Group I, for example, all show virus heads and tail fibers but no tails. Each of these extracts must therefore be deficient in a gene product that has to do with a stage of tail formation that cannot be carried out in our extracts. The second large complementation group appeared at first to be anomalous in terms of electron micrography: some extracts contained only tails and tail fibers, whereas others contained heads as well. Tests against extracts known to contain active tails revealed, however, that these heads—although they looked whole—could not combine to produce active virus in the test tube. In other words, heads, like tails, must be nearly completed within an infected cell before they become active for complementation. The early stages of head formation are still inaccessible to study in mixed extracts.

The remaining defective extracts gave rise to active virus in almost all possible pair combinations, segregating into another 11 complementation groups. With a total of 13 groups, there must be at least 12 assembly steps that can occur in mixtures of extracts. The defects recognizable in micrographs suggest what some of these steps must be: the completion and union of heads and tails, the assembly of tail fibers and the attachment of fibers to head-tail particles. These, then, are the steps that can be studied further in our present experimental system. We have in effect a virus-building kit, some of whose more intricate parts have been preassembled at the cellular factory.



TWO ASSEMBLY REACTIONS occur in this experiment: union of heads and tails and attachment of fibers. One virus (*color*), with a defective tail gene, produces heads and fibers. Another (*black*), with a mutation in a head gene, produces tails and fibers. When the two extracts are mixed and incubated, the parts assemble to produce infectious virus.

Our next experiments were designed to determine the normal sequence of assembly reactions and further characterize those whose nature remained ambiguous. Examples of the latter were the steps controlled by genes No. 13, 14, 15 and 18. Defects in the corresponding gene products resulted in the accumulation of free heads and tails, suggesting that they are somehow involved in head-tail union. It was unclear, however, whether these gene products are required for the attachment process itself or for completion of the head or the tail before attachment. We could distinguish the alternatives by complementation tests using complete heads and tails. These we isolated from the appropriate extracts in the centrifuge, taking advantage of their large size in relation to the other materials present. On the basis of the evidence for the independent assembly of heads and tails, we assumed that the heads we isolated from a tail-defec-



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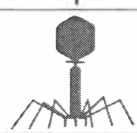
tive extract would be complete, as would tails isolated from a head-defective extract.

The results of the tests were unambiguous. The addition of isolated heads to extracts lacking the products of gene No. 13 or 14 resulted in virus production, whereas the addition of tails did not. We could therefore conclude that the components missing from these extracts normally affect the head structure, and that genes No. 13 and 14 control head completion rather than tail completion or head-tail union. The remaining two of the four extracts gave the opposite result; these were active with added tails but not with added heads, indicating that genes No. 15 and 18 are involved in the completion of the tail. All four of these steps must precede the attachment of heads to tails, since defects in any of the corresponding genes block head-tail union.

By manipulating extracts blocked at other stages we worked out the remaining steps in the assembly process with the help of Jonathan King and Jeffrey Flatgaard. The various reactions were characterized and their sequence determined by many experiments similar to those described above. In addition, more detailed electron micrographs of defective components helped to clarify the nature of some individual steps. For example, knowing that genes No. 15 and 18 were concerned with tail completion, we went on to find just what each one did. Electron micrographs showed that in the absence of the No. 18 product no contractile sheaths were made. If No. 18 was functional but No. 15 was defective, the sheath units were assembled on the core but were unstable and could fall away. The addition of the product of gene No. 15 (and of No. 3 also, as it turned out) supplied a kind of "button" at the upper end of the core and thus apparently stabilized the sheath.

The results to date of this line of investigation can be summarized in the form of a morphogenetic pathway [*see*

EXTRACT GROUP	MUTANT GENES	COMPONENTS PRESENT	INFERRED DEFECT
I	5, 6, 7, 8, 10, 25, 26, 27, 28, 29, 48, 51, 53		TAIL
II	20, 21, 22, 23, 24, 31		HEAD (FORMATION)
	2, 4, 16, 17, 49, 50, 64, 65		HEAD (COMPLETION)
III	54		TAIL CORE
IV	13, 14		?
V	15		
VI	18		
VII	9		?
VIII	11		?
IX	12		
X	37, 38		TAIL FIBERS
XI	36		
XII	35		
XIII	34		

COMPLEMENTATION TESTS defined 13 groups of defective extracts, as described in the text. Mixing any two extracts in a single group fails to produce infectious virus in the test tube, but mixing any two members of different groups yields infectious virus. Apparently each group represents the genes concerned with the synthesis of a component that is functional under experimental conditions. The precise nature of the defect in some extracts, and hence the function of the missing gene product, could not be identified on the basis of the structures recognized in electron micrographs and remained to be determined by additional experiments.

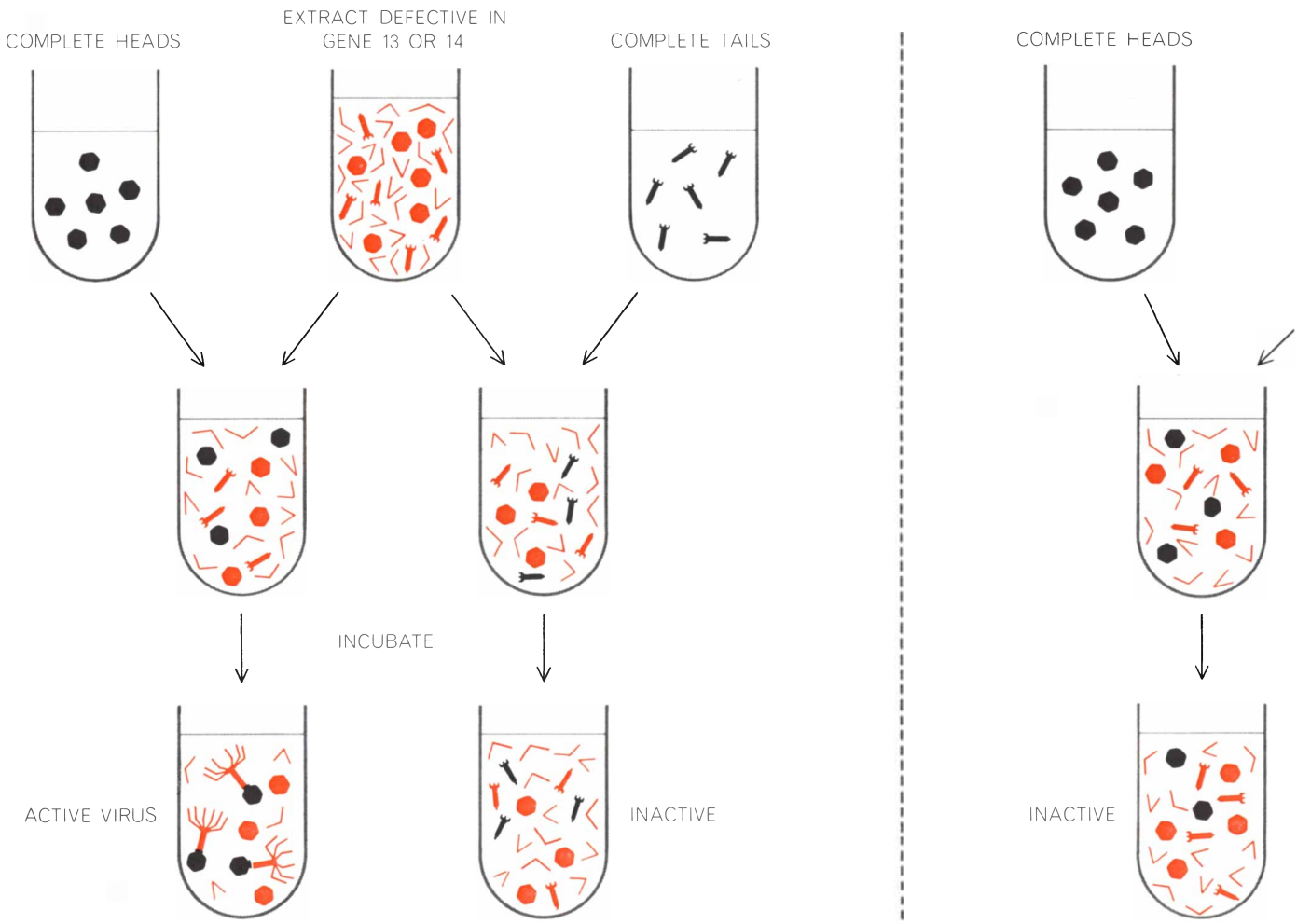
illustration on page 74]. As we had thought, it consists of three principal independent branches that lead respectively to the formation of the head, the tail and the tail fibers.

The earliest stages of head morphogenesis are controlled by six genes. These genes direct the formation of a precursor that is identifiable as a head in electron micrographs but is not yet functional in extract-complementation experiments. Eight more gene products must act on this precursor to produce a head structure that is active in complementation experiments. This active structure undergoes the terminal step in head formation (the only one so far demonstrated in the test tube): conversion to the complete head that is able to unite with the tail. The nature of this conversion, which is controlled by genes No. 13 and 14, remains unclear. A likely possibility would be that these genes control the formation of the upper neck and collar, but evidence on this point is lacking. The attachment of head structures to tails has never been observed in extracts prepared with mutants defective in gene No. 13 or 14, or with any of the preceding class of eight genes. It therefore appears that completion of the head is a prerequisite for the union of heads and tails.

The earliest structure so far identified in the morphogenesis of the tail is the end plate. It is apparently an intricate bit of machinery, since 15 different gene products participate in its formation. All the subsequent steps in tail formation can be demonstrated in the test tube. The core is assembled on the end plate under the control of the products of gene No. 54 and probably No. 19; the resulting structure appears as a tail without a sheath. The product of gene No. 18 is the principal structural component of the sheath, which is somehow stabilized by the products of genes No. 3 and 15. Tails without sheaths do not attach themselves to head structures, indicating that the tail as well as the head must be completed before head-tail union can occur. Moreover, unattached tail structures are never fitted with fibers, suggesting that these can be added only at a later stage of assembly.

Completed heads and tails unite spontaneously, in the absence of any additional factors, to produce a precursor particle that interacts in a still undetermined manner with the product of gene No. 9, resulting in the complete head-plus-tail particle. It is only at this point that tail fibers can become attached to the end plate.

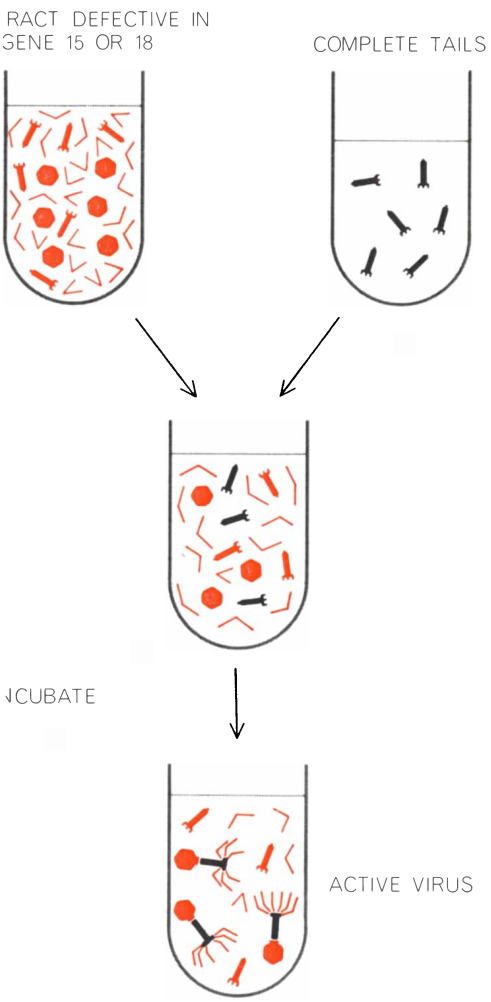
At least five gene products participate in the formation of the tail fiber. In the first step, which has not yet been demonstrated in extracts, the products of genes No. 37 and 38 combine to form a precursor corresponding in dimensions



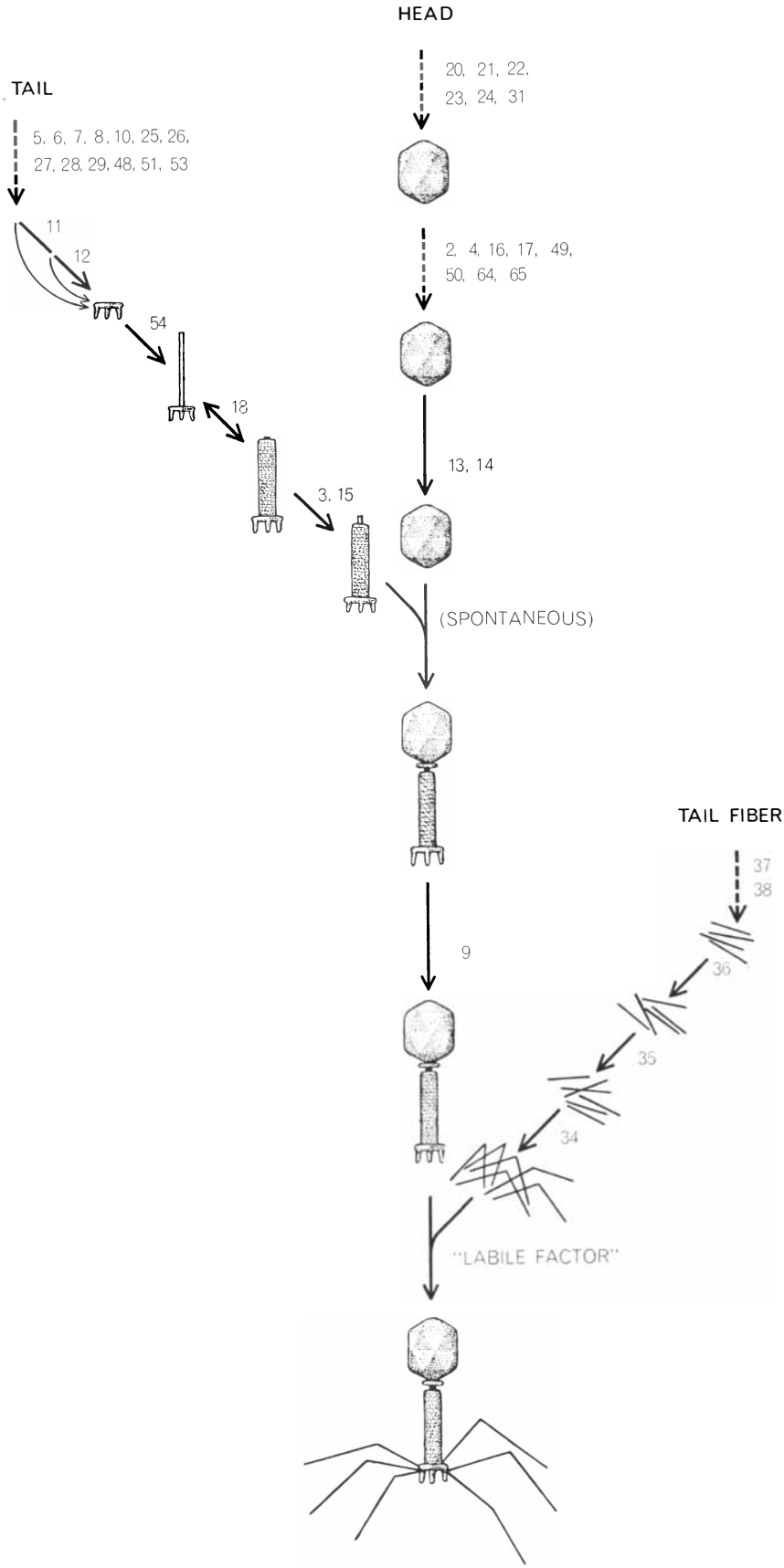
ASSEMBLY DEFECTS of mutants (*color*) that seem to produce complete heads, tails and fibers are identified, using isolated complete heads and tails (*black*) as test reagents. When complete heads are added to some extracts to be tested (*left*), infectious virus is produced, but the addition of complete tails is ineffective. This indicates that the tails made by these mutants must be functional,

to one segment of the finished fiber. This precursor then interacts sequentially with the products of genes No. 36, 35 and 34 to produce the complete structure. Again the completion of a major component—in this case the tail fiber—appears to be a prerequisite for its attachment, since we have never seen the short segments linked to particles.

The final step in building the virus is the attachment of completed tail fibers to the otherwise finished particle. We have studied this process in reaction mixtures consisting of purified particles and a defective extract containing complete tail fibers but no heads or tails. When we divided the extract into various fractions, we found that it supplies two components, both of which are necessary for the production of active virus. One of these of course is the tail fiber. The other is a factor whose properties suggest that it might be an enzyme. For one thing, the rate at which fibers are attached de-



implying that the heads must be defective. In the case of other mutants (*right*), such tests indicate that the tails must be defective.



MORPHOGENETIC PATHWAY has three principal branches leading independently to the formation of heads, tails and tail fibers, which then combine to form complete virus particles. The numbers refer to the gene product or products involved at each step. The solid portions of the arrows indicate the steps that have been shown to occur in extracts.

pends on the level of this factor present in the reaction mixture, and yet the factor does not appear to be used up in the process. Moreover, the rate of attachment depends on the temperature of incubation—increasing by a factor of about two with every rise in temperature of 10 degrees centigrade. These characteristics suggest that the factor could be catalyzing the formation of bonds between the fibers and the tail end plate. At the moment we can only speculate on its possible mechanism of action, since the chemical nature of these bonds is not yet known; we call it simply a "labile factor," not an enzyme. Although no gene controlling the factor has yet been discovered, we assume that its synthesis must be directed by the virus, since it is not found in extracts of uninfected bacteria.

The T4 assembly steps so far accomplished and studied in the test tube represent only a fraction of the total number. Already, however, it is apparent that there is a high degree of sequential order in the assembly process; restrictions are somehow imposed at each step that prevent its occurrence until the preceding step has been completed. Only two exceptions to this rule have been discovered. The steps controlled by genes No. 11 and 12, which normally occur early in the tail pathway, can be bypassed when these gene products are lacking. In that case the tail is completed, attaches itself to a head and acquires tail fibers, but the result is a fragile, defective particle. The particle can, however, be converted to a normal active virus by exposure to an extract containing the missing gene products. These are the only components whose point of action in the pathway appears to be unimportant.

The problem has now reached a tantalizing stage. A partial sequence of gene-controlled assembly steps can be written, but the manner in which the corresponding gene products contribute to the process remains unclear, and the questions posed at the beginning of this article cannot yet be answered definitively. There is the suggestion that the attachment of tail fibers is catalyzed by a virus-induced enzyme. If this finding is substantiated, it would overthrow the notion that T4 morphogenesis is entirely a self-assembly process. Continued investigation of this reaction and the assembly steps that precede it can be expected to provide further insight into how genes control the building of biological structures.

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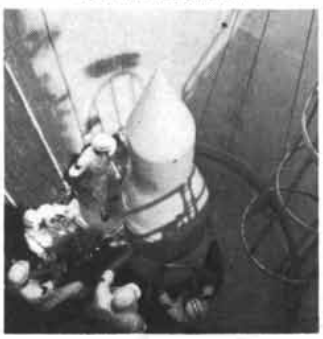

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The Leakage Problem in Fusion Reactors

To obtain useful power from thermonuclear reactions it is necessary to contain a plasma of ions and electrons in a magnetic bottle. The bottles leak, which presents the theoretician with a difficult task

by Francis F. Chen

For the past decade or so the competition between the U.S.S.R. and the U.S. in the exploration of space has attracted a great deal of public interest. The public is much less aware of another competitive international effort —which has also been in progress for about a decade—that may have greater ultimate significance. This is the effort to build a thermonuclear reactor, in which the reactions of nuclear fusion would be controlled to tap a practically unlimited supply of energy [see "Progress toward Fusion Power," by T. K. Fowler and Richard F. Post; SCIENTIFIC AMERICAN, December, 1966]. The general idea is to heat a plasma, or ionized gas, of deuterium or tritium to more than 100 million degrees centigrade and hold the plasma together by means of a magnetic field long enough for some of the ions to fuse, releasing energy in the form of radiation.

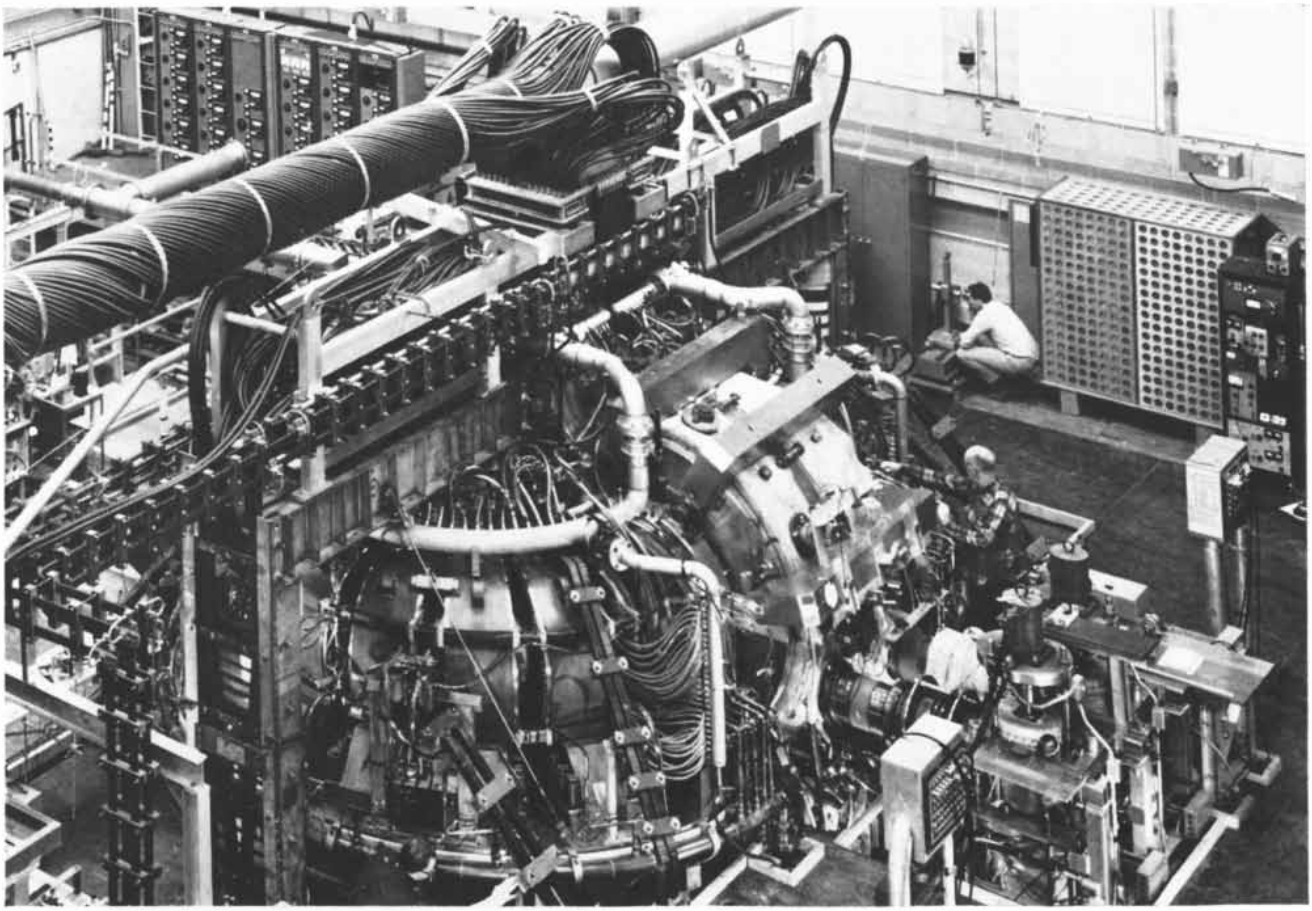
Almost from the outset the main obstacle has been the problem of confining the plasma. All kinds of "magnetic bottles" have been devised, and many have actually been built and tested, but so far all of them leak. The cause or causes of this mysterious leakage (called "anomalous diffusion" by workers in the field) have been sought for many years both in the large machines specifically built to produce fusion reactions and in smaller experimental devices. The recent theoretical discovery of "drift waves" in plasmas has thrown new light on the problem. This significant advance in understanding is the result of a truly cooperative international effort, in which the free exchange of ideas among physicists in various countries has played an essential role. Curiously, most of the research leading up to this insight was carried out in comparatively small-scale experiments.

The reason for the failure of early efforts to confine a hot plasma may lie in the way the discipline of plasma physics first developed. Because a plasma is dissociated into positively charged ions and negatively charged electrons, its behavior is much more complicated than that of an ordinary gas. To make the description of a plasma simple enough to handle, theorists began by regarding the plasma as a composite of two idealized interpenetrating fluids: a positively charged one representing the ions and a negatively charged one representing the electrons. This description is called magnetohydrodynamics, or simply hydromagnetics, and for a time all magnetic bottles were designed according to hydromagnetic theory. In the past few years, however, plasma physicists have discovered a new set of phenomena, called microinstabilities, that enter the picture only when the structure of a plasma is taken into account in considerably more detail than it is in hydromagnetic theory. Since magnetic bottles have been designed without a knowledge of these subtle microscopic effects, it is small wonder they leak. The purpose of this article is to describe how the new theory of microinstabilities differs from hydromagnetics, and to show how such a theory can be used to explain the persistent leakage of magnetic bottles.

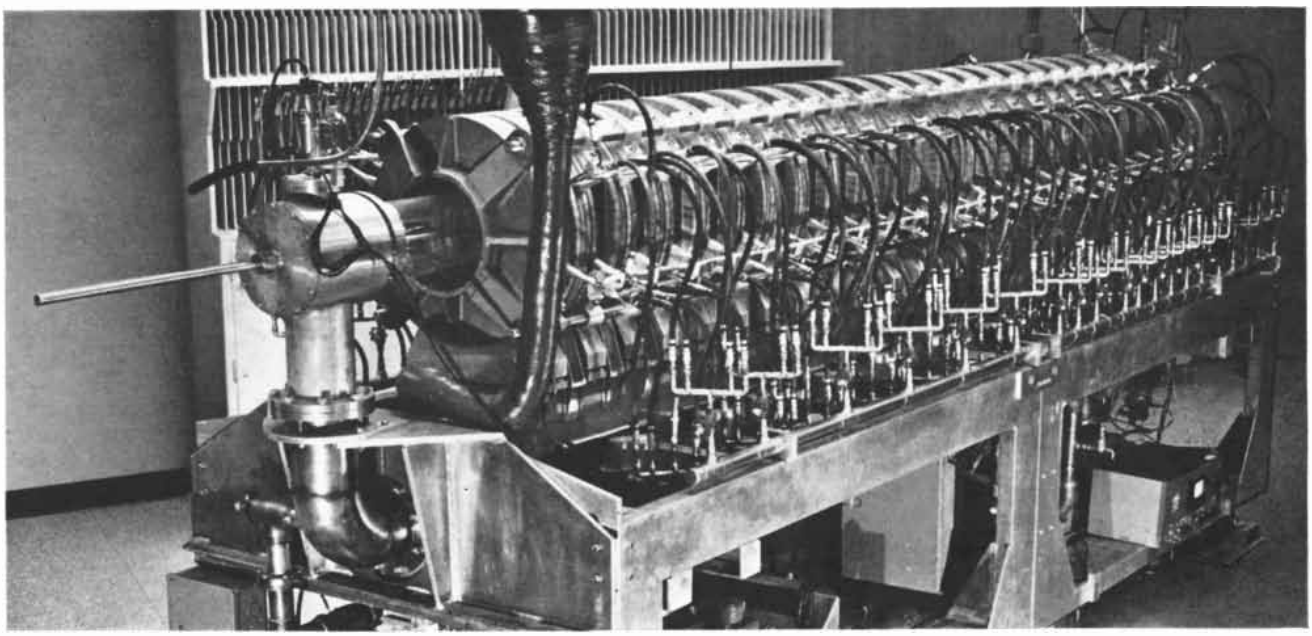
Let us begin by considering how a magnetic bottle is supposed to work. In a uniform magnetic field the ions and the electrons gyrate in opposite directions around the magnetic lines of force [*see upper illustration on page 79*]. Provided that the field is strong enough, the radius of gyration (called the Larmor radius after the British physicist Joseph Larmor) is quite small for the ions and much smaller for the electrons. Each particle can then be considered as being "stuck" to a line of force; if the lines were infinitely long, an isolated particle would not be able to move laterally across the field. The ions can collide with the electrons, however, and after each collision the center of gyration, or "guiding center," can shift to a neighboring line of force. By participating in a large number of collisions any given particle can slowly migrate to the wall of the container, where it will give up its energy before attaining the fusion temperature. This process, called classical diffusion, is not normally regarded as a serious cause of leakage because at the high temperatures required for fusion the rate of collision between ions and electrons is very low. Furthermore, the rate of escape of plasma by classical diffusion is inversely proportional to the square of the magnetic-field strength, so that the loss of plasma through this route can be greatly diminished by using a strong magnetic field.

Both the ions and the electrons can still move freely along the lines of force, however, and in order to make a magnetic bottle work one must prevent the plasma from streaming out the ends. There are two principal ways to do this, and almost all magnetic bottles fall into one of these two categories. One is the open-end, or "mirror," device; the other is the closed, or toroidal, device [*see illustration on page 78*]. In a mirror device the magnetic field is made stronger near the end walls, so that most of the particles are reflected back into the interior of the bottle and hence cannot lose their energy to the end walls. In a toroidal device the lines of force are simply bent into closed loops and given a slight twist.

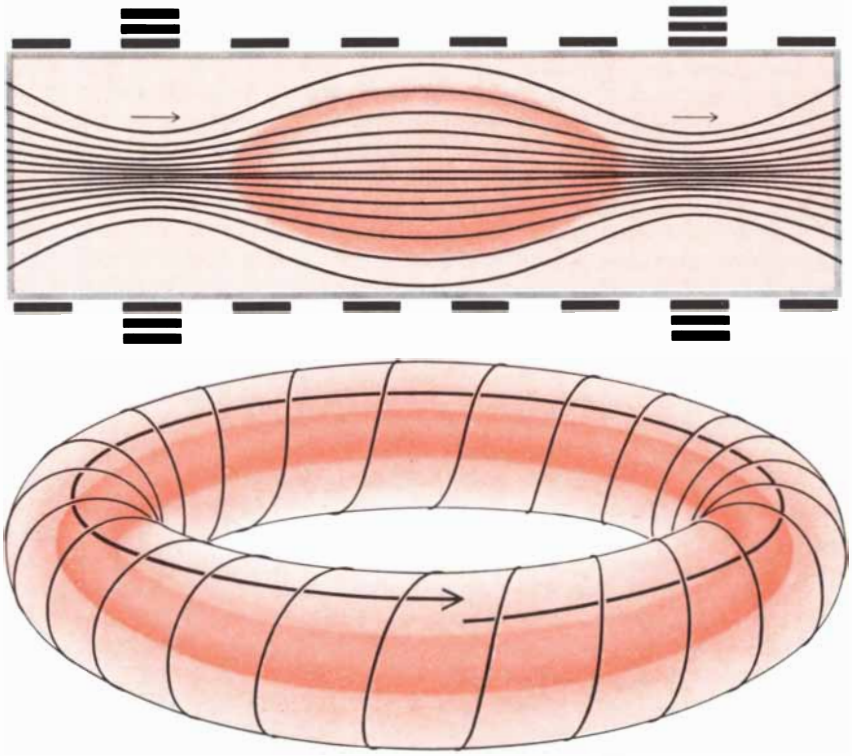
As they stand, these simple magnetic bottles will hold individual charged particles but will not hold a plasma. This is because a plasma behaves more like a fluid than like a bunch of individual particles. A useful analogy here is an invert-



MODEL C STELLARATOR is the latest and largest in the stellarator series of plasma-confinement devices built at the Plasma Physics Laboratory (formerly Project Matterhorn) of Princeton University. The stellarators are in the shape of a torus, or doughnut, at the center of which the plasma is confined by means of an elaborately "sheared," or twisted, magnetic field. The sheared field eliminates a class of plasma instability predicted by magnetohydrodynamic, or hydrodynamic, theory. The toroidal plasma vessel of the Model C has an inside diameter of eight inches and an axial length of 40 feet. It is obscured by the large confining-magnet coils.



SMALLER EXPERIMENTAL DEVICE, called the reflex-arc, or L-2, machine, was built by the author at Princeton to investigate the cause or causes of the "anomalous diffusion," or radial leakage, of plasma that occurs in every "magnetic bottle" built so far. The L-2 is typical of a number of comparatively small-scale experimental devices that have a linear rather than a toroidal geometry. Electrons emitted from hot cathodes at each end of the machine ionize a low-pressure gas in the central chamber. The entire chamber serves as an anode. The circular magnet coils set up a straight magnetic field that is parallel to the axis of the plasma chamber.



TWO APPROACHES can be used to prevent a plasma (*color*) from streaming out the ends of a magnetic bottle. One is the open-end, or "mirror," device (*top*), in which the magnetic field (*black lines*) is made stronger near the end walls, reflecting most of the particles back into the interior of the bottle. The other is the closed, or toroidal, device (*bottom*), in which the lines of force are simply bent into closed loops and given a slight twist. As they stand, these simple magnetic bottles will hold individual charged particles but will not hold a plasma, which behaves more like a fluid than like a bunch of individual particles.

ed beaker of water [*see upper illustration on page 80*]. If a leakproof and frictionless piston separated the water from the air below it, the water would be held up by the pressure of the air and would not fall out of the beaker. If the piston were removed, small ripples could develop on the surface of the water. Such a ripple would be unstable, because there would be less water pushing down on the trough of the inverted ripple than on the crest. The trough would be pushed upward and the crest would fall downward. The ripple would then grow into a wave, and of course the water would promptly fall out of the beaker. In general this process will occur whenever a light fluid (in this case air) supports a heavy fluid (water).

In a plasma the light fluid is the magnetic field and the heavy fluid is the plasma. Although real gravity is negligible here, there is an effective gravitational force due to a centrifugal effect whenever the lines are curved. To grasp how an instability develops, imagine that the plasma boundary is idealized into a sharp transition between the plasma and the surrounding vacuum and is allowed to have a small ripple [*see lower illustration on page 80*]. When the gyrating particles are pushed by a gravitational or electric force, they drift in a direction perpendicular to the force. Since a gravitational force pushes downward on all the particles, the positively charged ions drift to the left and the negatively charged electrons to the right. This causes a positive charge to build up to the left of the plasma protuberances and a negative charge to the right. The electric field resulting from this separation of charge causes a drift downward where there was already a protuberance and upward where there was a fissure. The ripple grows in size until the plasma reaches the wall. This plasma analogue of the water falling out of the beaker is called in hydromagnetic theory a gravitational instability. It is also called a "flute" instability, because the unstable plasma is marshaled along the lines of force, making the ripples long and straight like the flutes of a Greek column.

Ingenious methods have been devised to overcome flute instabilities. For instance, the magnetic-mirror device can be stabilized by adding four current-carrying rods that distort the magnetic field in such a way that the field is stronger everywhere outside the plasma than it is inside, thereby trapping the plasma in a kind of magnetic well. A flute instability cannot occur in such a situation. The toroidal device can be stabilized by giving the lines of force a twist that is larger near the walls than near the axis. This sheared magnetic field is the principle of the toroidal device called the stellarator [see "The Stellarator," by Lyman Spitzer, Jr.; SCIENTIFIC AMERICAN, October, 1958]. A flute perturbation following the lines of force on one surface no longer follows the lines on the next surface because these lines have shifted. It is as though the flute had become so confused and tangled up that it died out.

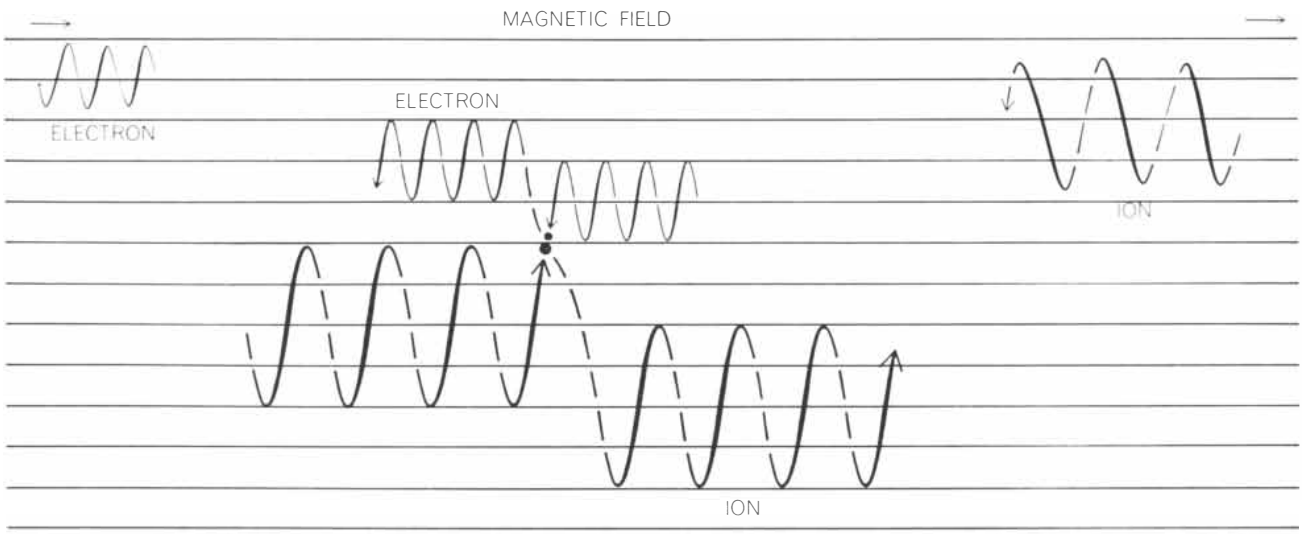
In spite of elaborate precautions to avoid flutes and other instabilities predicted by hydromagnetic theory, almost all magnetic bottles were found to leak at a rate some 1,000 times faster than that of classical diffusion. (An exception will be noted later.) At first it was thought that the methods used to heat the plasma—usually electric currents induced in the plasma itself—were the cause of the instabilities. In the stellarator, however, it was found that even when these currents were eliminated, anomalous diffusion was still present; the plasma simply refused to hold still in a magnetic field. Violent motions of the plasma were always observed, and for a long time all such inexplicable behavior was lumped under the heading "cooperative phenomena." The plasma particles apparently cooperated with one another in some way, always managing to find a way to wiggle out of the magnetic bottle. The rate of loss was not only high but was also inversely proportional to the magnetic field rather than to the square of the magnetic field, as in the case of classical diffusion; this meant that increasing the strength of the magnetic field would not help as much.

The inversely proportional, or linear, dependence of leakage on magnetic-field strength was reminiscent of an old puzzle in plasma physics called "Bohm diffusion." During World War II a group headed by David Bohm at the University of California at Berkeley, while working on the separation of isotopes by electric discharges in magnetic fields, discovered that the plasma created by an electric arc leaked across the magnetic field unexpectedly fast. Large-amplitude oscillations of the electric field were observed inside the arc, and Bohm surmised that these electric fields were the cause of the leakage. He worked out an equation that predicted that the rate of diffusion in the radial direction (at right angles to the

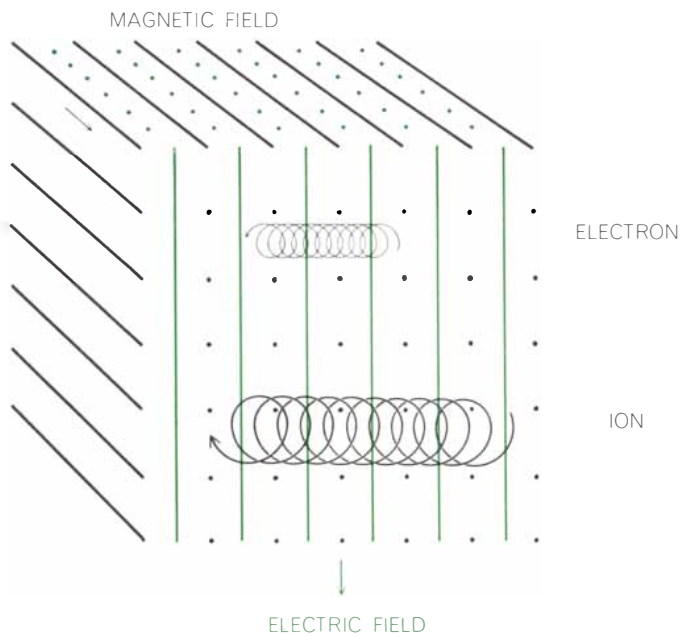
axis of the magnetic field) was inversely proportional to the strength of the magnetic field. This gave a leakage much larger than classical diffusion would give and more in agreement with the experiment. Although it turned out later that the experiment was incorrectly interpreted, many subsequent experiments did approximately obey Bohm's equation, and plasma loss following such a law has been known ever since as Bohm diffusion.

No one (not even Bohm) has been able to give a complete proof of his equation, but if one disregards certain unexplained constants, it is possible to derive the linear dependence of Bohm diffusion from a simple argument involving the physical dimensions of two factors: the Larmor radius and the frequency at which the particles gyrate.

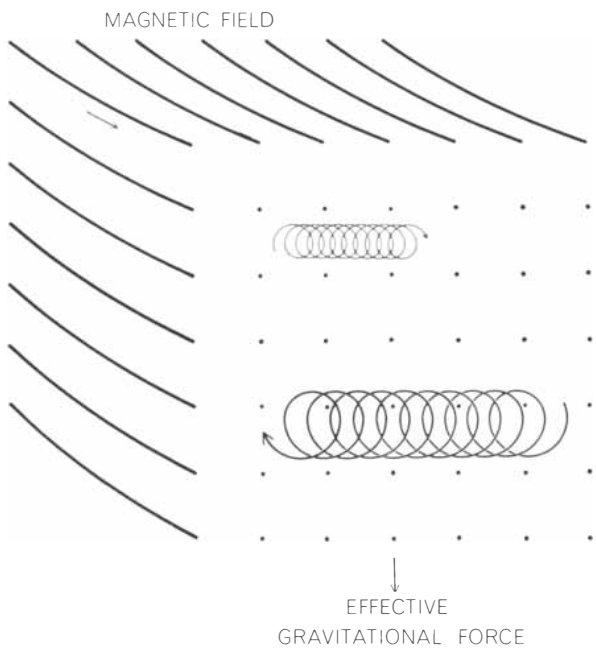
Interest in anomalous diffusion was revived by the fusion program, and in 1955 Albert Simon and Rodger V. Neidigh of



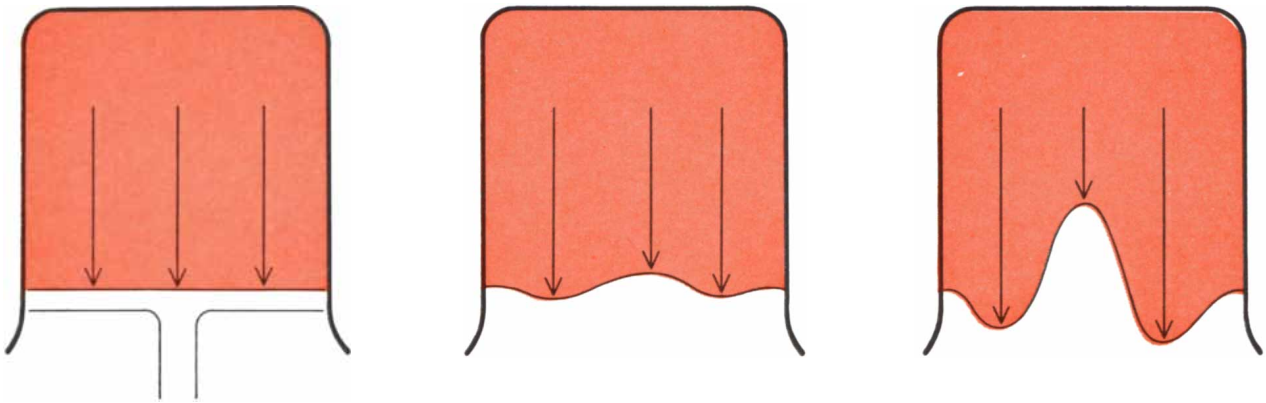
IN A MAGNETIC FIELD the positively charged ions and the negatively charged electrons that constitute a plasma gyrate in opposite directions around the magnetic lines of force. The Larmor radius, or radius of gyration, of the particles depends on their thermal velocity and mass. For a hydrogen ion this radius is about 40 times larger than it is for an electron of the same energy. When an ion and an electron collide (*center*), the "guiding center," or center of gyration, of each particle can jump to another line of force a Larmor radius away, on the average. By participating in a large number of collisions a particle can migrate across the field.



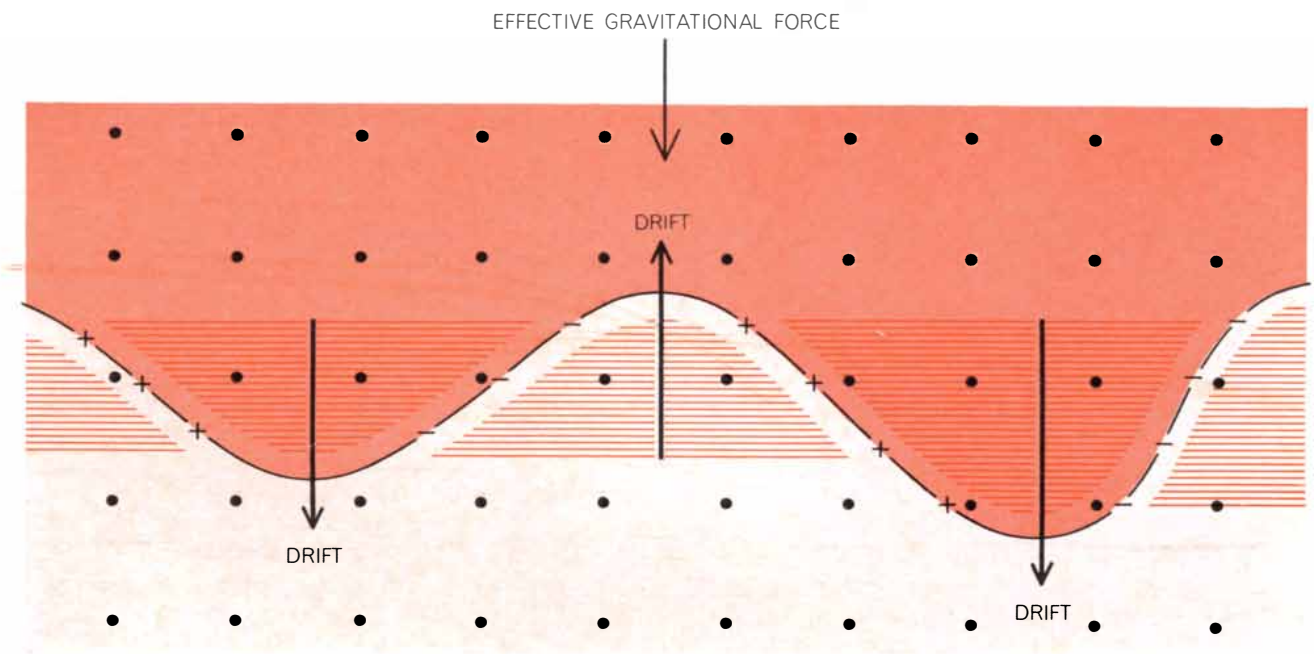
IN AN ELECTRIC FIELD that is at right angles to the magnetic field the charged particles in a plasma tend to drift in a direction that is at right angles to both fields. In the downward electric field shown here an ion drifts to the left; energy gained from the electric field during the downward part of each orbit gives the ion a larger Larmor radius at bottom than at top. An electron gyrates in the opposite sense, but the electric force acting on it is reversed because it is negatively charged, and it ends up drifting to the left also.



IN A CURVED MAGNETIC FIELD the charged particles in a plasma experience an effective gravitational force toward the outside of the curve. This force arises because as the particles move around the curve they tend to be thrown outward (in this case downward) by a centrifugal force. The effect of a downward gravitational force is to make an ion's guiding center drift to the left, gaining energy during the downward part of each orbit. An electron drifts to the right because its gyration is in the opposite sense.



INVERTED-BEAKER ANALOGY is helpful in understanding the fluid behavior of plasma in a magnetic field. As long as a leakproof and frictionless piston separated the water in the beaker from the air below it, the water would be held up by the pressure of the air (*left*). If the piston were removed, small ripples could develop (*center*). Such a ripple would tend to grow, because there would be less water pushing down on the trough of the inverted ripple than on the crest, and the water would soon fall out of the beaker (*right*).



IDEALIZED RIPPLE at the boundary between a column of plasma (*top*) and the surrounding vacuum tends to grow under the influence of the effective gravitational force created by a curved magnetic field. (In this cross section the curved magnetic lines of force appear as black dots.) The gravitational force causes ions to drift to the left and electrons to the right, with the result that an excess positive charge accumulates on the left of each ripple and an excess negative charge on the right, while the bulk of the plasma remains neutral. This separation of charge produces an electric field (*colored lines*), which causes the plasma to drift in the direction of the heavy black arrows, enlarging the ripple. This type of plasma instability is called a gravitational, or "flute," instability.

the Oak Ridge National Laboratory decided to repeat the Berkeley experiment with more care. They found that the radial-diffusion coefficient was not inversely proportional to the magnetic field at all but to the square of the magnetic field, as in the case of classical diffusion. The magnitude of this coefficient, however, was much larger than it is for classical diffusion. Simon correctly explained this discrepancy by noting that the plasma was not long enough to be considered infinitely long; when he calculated the effect of the electrically conducting end plates, he found he could explain the plasma loss rate without invoking either electric-field oscillations or anomalous diffusion.

This discovery triggered a large number of experiments both in this country and abroad in which the end plates were removed by either placing them far away or replacing them with insulators. These experiments were done in partially ionized gases, in which neutral atoms are present along with ions and electrons. Diffusion in such gases is somewhat different from what it is in fully ionized gases. In fully ionized gases ions and electrons diffuse out at the same rate, because they collide with each other and their momentum is conserved. In partially ionized gases ions and electrons diffuse out separately by colliding with neutral atoms. Since electrons have smaller Larmor radii and therefore take smaller steps, they diffuse out slower than ions. The ions leave behind a negative space charge, which creates an electric field, which in turn holds the ions back. It is the short-circuiting of this electric field by the metallic end plates

that Simon used to explain the arc experiments.

The conclusion drawn from the later experiments is that no anomalous diffusion is needed to explain the loss rate of ions, although something extra may be needed to help drain out the slowly diffusing electrons. A possible exception to this generalization may have been observed in the recent experiments of V. E. Golant and his colleagues in the U.S.S.R. They studied the decay of a plasma in long, thin tubes such that the end plates can make no difference [*see lower illustration at right*]. They found that if the tube radius was small enough, the diffusion could not be entirely explained by collisions alone. This finding strongly suggested the existence of as yet undiscovered instabilities in the partially ionized plasma.

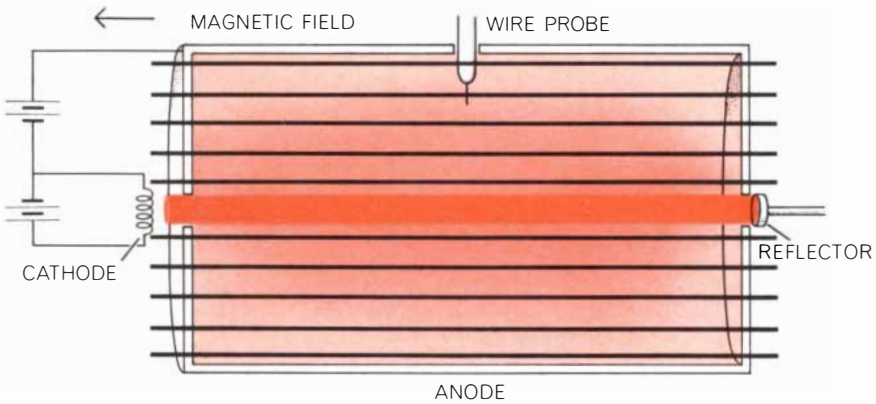
What do these experiments in partially ionized gases have to do with those in fully ionized plasmas, in which the loss rate is definitely anomalous? In stellarators, for instance, diffusion is generally found to obey Bohm's equation, provided that a somewhat different constant is used. Why has Bohm's equation come into the picture even though it is not needed for its original purpose? Are the observed oscillations actually related to Bohm diffusion? In order to answer these questions physicists began to look beyond the macroscopic decay of a plasma at the microscopic behavior of the plasma's fluctuations.

The results of one such investigation, carried out in 1961 by my colleagues and me at the Plasma Physics Laboratory of Princeton University, are shown at the top of the next page. The oscilloscope traces represent the signals picked up by a Langmuir probe, a small wire used to detect the local value of the plasma density or the electric potential. The top trace was obtained from the fully ionized plasma in a stellarator; the bottom trace was from the partially ionized plasma in a device called a reflex arc [*see bottom illustration on page 77*]. In spite of the great difference in the role played by the neutral atoms in the diffusion process, the two traces look very much alike. The oscillations seem quite random, but a single frequency predominates, usually in the range from 20 to 50 kilocycles.

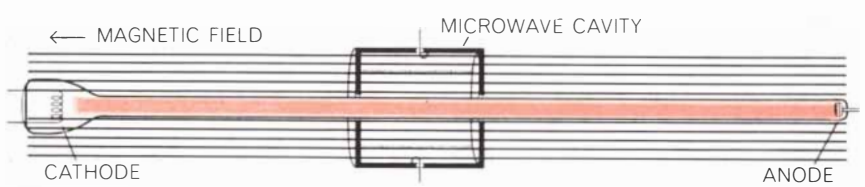
When the frequency content of these signals was analyzed, we found in each case a frequency spectrum in which there is indeed a continuum of frequencies, with a broad peak at the dominant frequency. The surprising thing about these spectra is that the power is concentrated at such low frequencies, well below any of the natural frequencies of the plasma. At the time only one type of oscillation was known to have such low frequencies: an ion-acoustic wave, the plasma analogue of an ordinary sound wave. Ion-acoustic waves, however, can exist at all frequencies up to a certain maximum, which for these experiments was an order of magnitude higher than the frequencies we were observing. If these were ion waves, it seemed strange that they should be limited to frequencies well below their natural maximum. To test the ion-wave hypothesis, Alfred W. M. Cooper and I measured the phase velocity of the waves by aligning two movable probes along the same line of force and using correlation techniques to pull out the parallel wavelength at each frequency amid the jumble of frequencies. The wave velocity turned out to be about an order of magnitude higher than the ion-wave velocity. This seemed to rule out ion waves, at least for the partially ionized plasma.

Other possibilities were examined, but none would fit even the crudest piece of data: the predominance of frequencies in the 20-to-50-kilocycle range. The trouble was that up to that time almost all plasma theory was concerned with homogeneous plasmas—plasmas with the same density everywhere. Confined plasmas, however, necessarily have an edge, so that somewhere there must be a slope of density, and the plasma is not homogeneous. When plasma theory was extended to inhomogeneous plasmas, a class of low-frequency waves called drift waves became a factor.

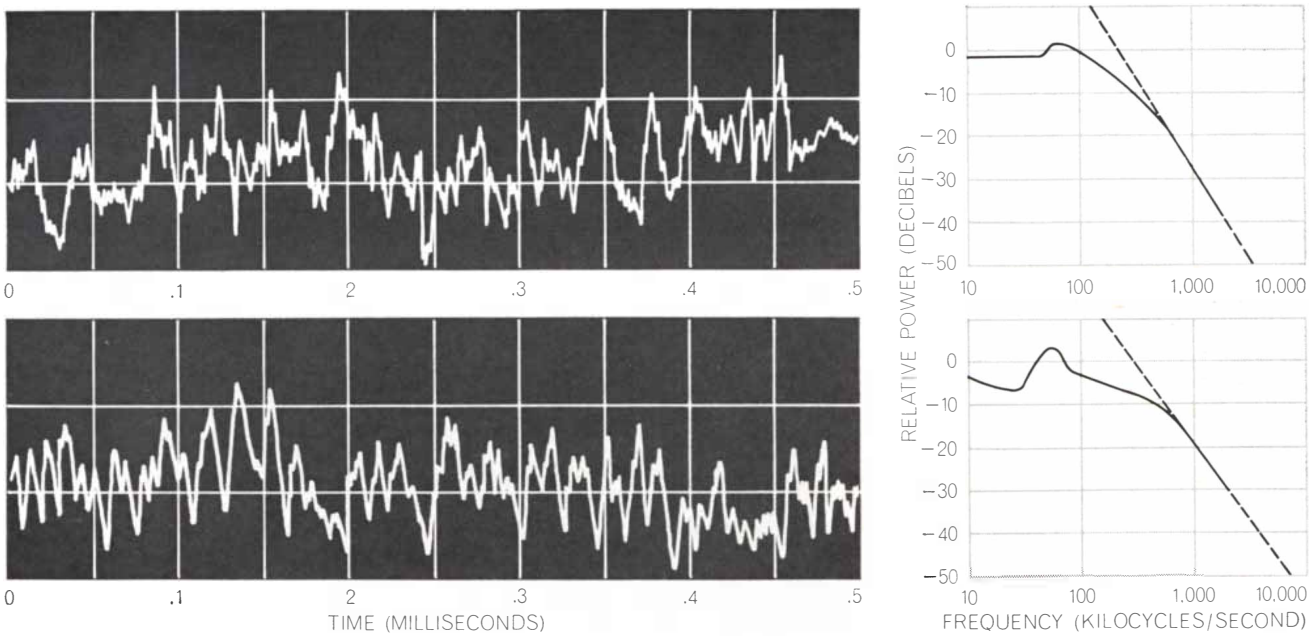
The discovery of drift waves can perhaps be traced to an experiment performed in 1960 by B. Lehnert and F. C. Hoh at the Royal Institute of Technology



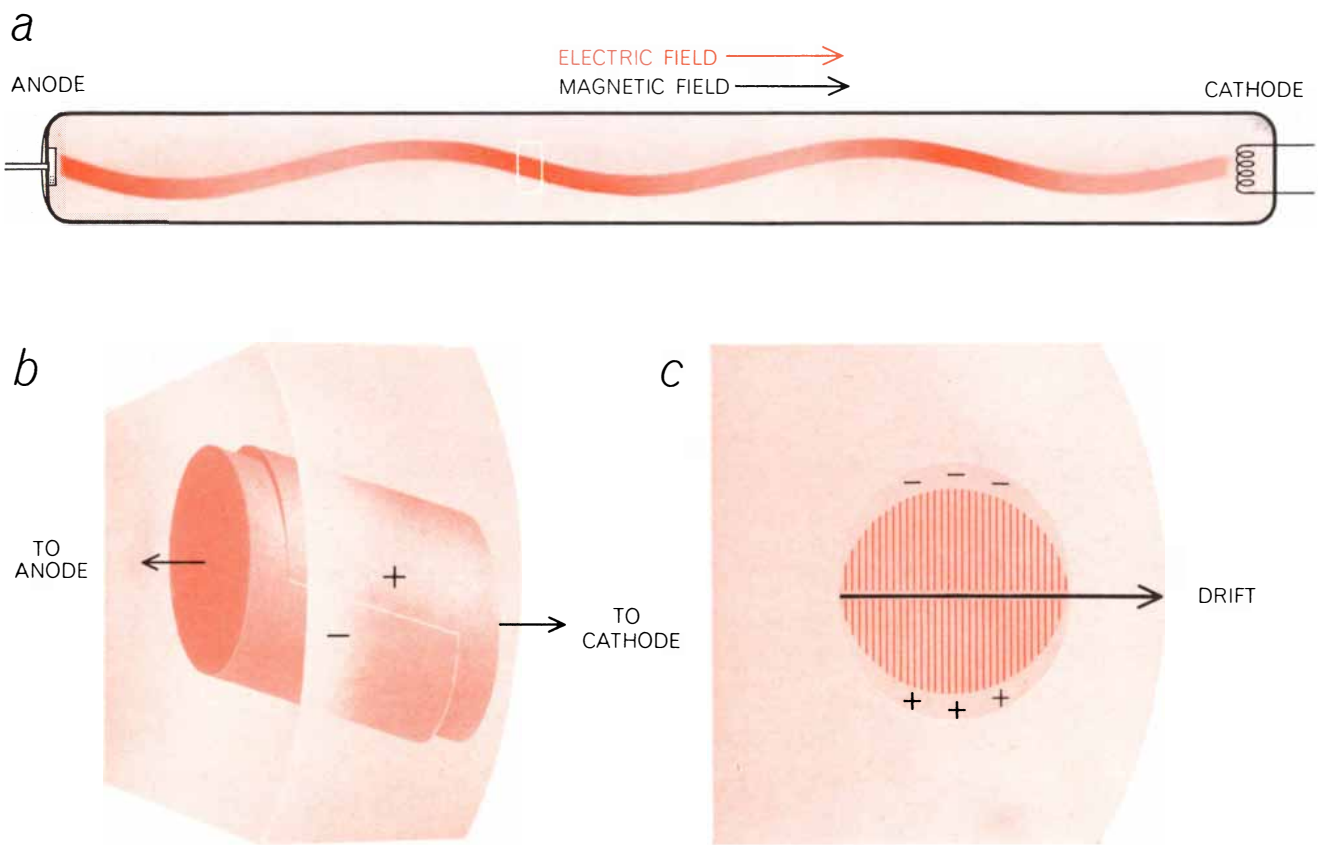
ELECTRIC-ARC EXPERIMENT was first performed during World War II by a group under David Bohm at the University of California at Berkeley and was later repeated by Albert Simon and Rodger V. Neidigh of the Oak Ridge National Laboratory. The original experiment led Bohm to formulate an equation for the fast diffusion of a partially ionized gas across a magnetic field. The equation for "Bohm diffusion" predicts that the rate of diffusion in the radial direction is inversely proportional to the strength of the magnetic field. Electrons emitted by a hot filament (*left*) were drawn into a metal chamber (*center*) by an applied voltage, ionizing the gas in the chamber and forming a plasma column. The plasma diffused outward across the magnetic field by colliding with neutral gas atoms. A wire probe (*top*) was used to measure the local density and hence the rate of diffusion. Later experiments, including the one shown here by Simon and Neidigh, showed that the Bohm experiment was incorrectly interpreted but also turned up evidence of leakage that followed Bohm's equation.



FURTHER EVIDENCE of anomalous diffusion in a partially ionized plasma may have been observed recently by V. E. Golant and his colleagues in the U.S.S.R. They studied the decay of a plasma in long, thin tubes, thereby eliminating the possible effects of the end plates. The plasma was created by a gas discharge, as in the electric-arc experiment; the rate of diffusion was measured by the change in the resonant frequency of a microwave cavity (*center*). They found that if the tube radius was small enough, the diffusion could not be explained by collisions alone. This suggested the existence of unknown instabilities.



OSCILLATIONS in the density of plasma during diffusion were observed by means of a wire probe in two quite dissimilar devices: a stellarator (*top trace*), in which the plasma is fully ionized, and a reflex arc (*bottom trace*), in which the plasma is partially ionized. The oscillations in both cases are quite random, with a single dominant frequency, usually in the range from 20 to 50 kilocycles. A frequency analysis of the signals (*graphs at right*) revealed that the power was concentrated at unexpectedly low frequencies.



CORKSCREW INSTABILITY was first observed in 1960 by B. Lehnert and F. C. Hoh at the Royal Institute of Technology in Stockholm. In their experiment a weakly ionized plasma was created by an electric field parallel to both the magnetic field and the axis of the tube (*top*). When the magnetic field was increased, a helical filament, or corkscrew, of dense plasma arose and grew outward until it reached the wall of the tube. The ions in the corkscrew were pushed to the right by the electric field and the electrons to the left (*bottom left*). In a typical cross section of the filament (*bottom right*) the longitudinal shift of the ion corkscrew with respect to the electron corkscrew produced an excess of ions (*plus signs*) on one side and an excess of electrons (*minus signs*) on the other. This separation of charge resulted in a transverse electric field (*colored lines*), which caused the plasma to drift in the direction of the heavy black arrow. This drift is always in the outward direction, so that the corkscrew expands, carrying plasma to the wall of the tube.

in Stockholm. They studied the effect of a magnetic field on the most familiar of all plasmas, the "positive column." This is a weakly ionized discharge not unlike the one in an ordinary fluorescent lamp. Diffusion of plasma to the wall of the long glass tube followed the classical pattern up to a critical field around 1,000 gauss, beyond which violent oscillations appeared and anomalous diffusion set in. After seeing the Lehnert-Hoh results Boris B. Kadomtsev and A. V. Nedospasov of the Kurchatov Institute of Technology in Moscow produced a theory in 1960 that accurately predicted the value of the critical field and even the rate of anomalous diffusion slightly beyond the critical field. The mechanism of the instability that arises at large fields was later clarified by Hoh [*see bottom illustration on opposite page*].

Suppose a filament of plasma in the shape of a corkscrew suddenly becomes denser than the rest of the plasma. The electric field in the positive column tends to pull the ions in the corkscrew toward the anode and the electrons toward the cathode. The ion corkscrew then becomes displaced from the electron corkscrew by a longitudinal shift. At each cross section this shift causes an excess of ions on one side and of electrons on the other, giving rise to a transverse electric field. The field causes the ions and electrons to drift together, and as a result the corkscrew rotates. More important, if the corkscrew is twisted in the right direction with respect to the magnetic field, the drift brings in more plasma from the dense core of the column and the small perturbation grows denser. It also moves radially outward, causing an anomalously fast loss to the walls. In a subsequent experiment at the University of California at Berkeley, G. A. Paulikas, Robert V. Pyle and T. K. Allen confirmed the existence of such a corkscrew and were actually able to watch it grow. The velocity and direction of rotation and the sense of pitch of the corkscrew all fitted the theory. This mechanism does not work at magnetic fields lower than the critical field, because the gyration frequencies become so low that collisions with neutral atoms disrupt the electric-field drifts, even for the electrons.

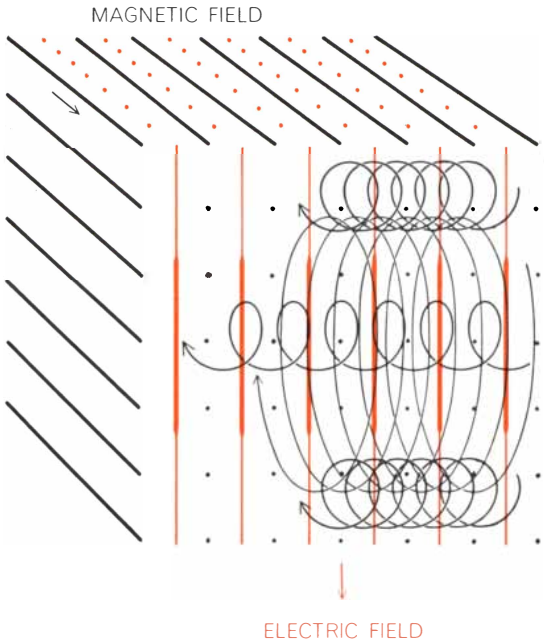
Here, then, was a case in which anomalous diffusion was definitely connected with an unstable oscillation, and the agreement between theory and experiment was as good as could be expected. The explanation of Kadomtsev and Nedospasov would work only for weakly ionized gases, however, not for the fully ionized gases needed for fusion. Physicists began to look for ways in which a fully ionized plasma could develop perturbations that were not straight flutes but were slightly inclined to the magnetic field, like the corkscrew. It was about this time that Marshall N. Rosenbluth of the University of California at San Diego first proposed a mechanism of anomalous diffusion based on the effects of the Larmor radii of the gyrating particles. Taking his lead, a group of Russian theorists then worked out a comprehensive theory of anomalous diffusion in which the plasma inhomogeneity, the Larmor-radius effects and the inclination of the flutes all play essential roles. Between 1961 and 1965 an avalanche of papers on the subject by numerous Russian authors appeared. This theoretical work was backed up in 1962, when N. D'Angelo and R. W. Motley at Princeton were the first to detect an isolated drift wave, in a low-temperature plasma of cesium ions.

To understand the difference between the new theory of microinstabilities and hydromagnetic theory, it is necessary to look a little more closely at the motion of charged particles in crossed electric and magnetic fields. Hydromagnetic theory predicts that the guiding centers of ions and electrons will drift with exactly the same velocity in a direction perpendicular to both the electric field and the magnetic field, even though the gyration of the ions is in the opposite sense to that of the electrons and the Larmor radius is much larger. This is strictly true, however, only if both fields are constant and uniform, or if the masses of the ions and electrons are both infinitely small. If the electric field varies in space or time, the finite mass of the ions will affect their drift velocity. Suppose the electric field varies in space and the magnetic field is uniform [*see illustration at top left on next page*]. Then ions with small Larmor radii (small thermal velocities) will drift faster in regions of strong electric field and slower in regions of weak electric field. An ion with a large Larmor radius, however, will spend part of its time in regions of electric field weaker than where its guiding center is. This is true even if the guiding center is not located at the point of strongest electric field. Accordingly in spatially varying electric fields ions will drift slower than electrons, because of their larger mass and larger Larmor radius.

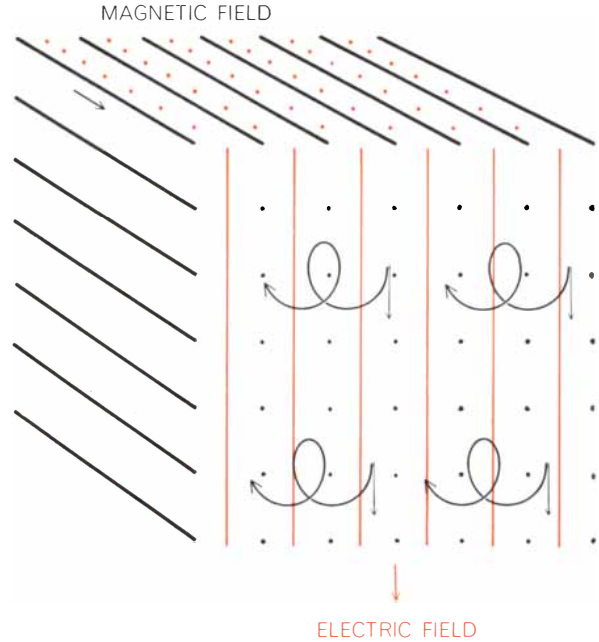
Suppose now that the electric field is uniform but fluctuates [*see illustration at top right on next page*]. Then it is the inertia of the ions that affects their drift. When an electric field is suddenly switched on, the ions that are at rest initially will, because of their inertia, be accelerated in the direction of the electric field rather slowly. Only after they have gained sufficient velocity will they begin to move in the direction perpendicular to the electric field. In this case the velocity of the guiding center has, in addition to its usual perpendicular component, an additional component in the direction of the electric field, gained during the first half-gyration. If the field is applied gradually, the parallel component is smaller but must still be taken into account. Electrons are accelerated very quickly by the electric field, and for them the parallel component due to inertia can be neglected.

When Rosenbluth took into account these two effects—the Larmor radius and the inertia of the ions—in his treatment of the gravitational flute instability, he found that the ripples traveled laterally across the magnetic field as they grew and that their growth rate was smaller than in hydromagnetic theory. Furthermore, if the ripples had a short enough wavelength, they would not grow at all; the instability would be stabilized by the Larmor-radius effect. If the flutelike ripples were not aligned along the magnetic lines of force but were at a slight angle to them, however, the instability would always arise, even for short wavelengths, as long as the wavelength was longer than the Larmor radius. Surprisingly, if one could now remove the gravitational field, unstable ripples would still grow. The same Larmor-radius effect that stabilizes straight-flute perturbations can cause instabilities of inclined, or helical, flutes. Because such instabilities need no driving force other than the ever-present pressure gradient in a confined plasma, they have been named "universal" instabilities.

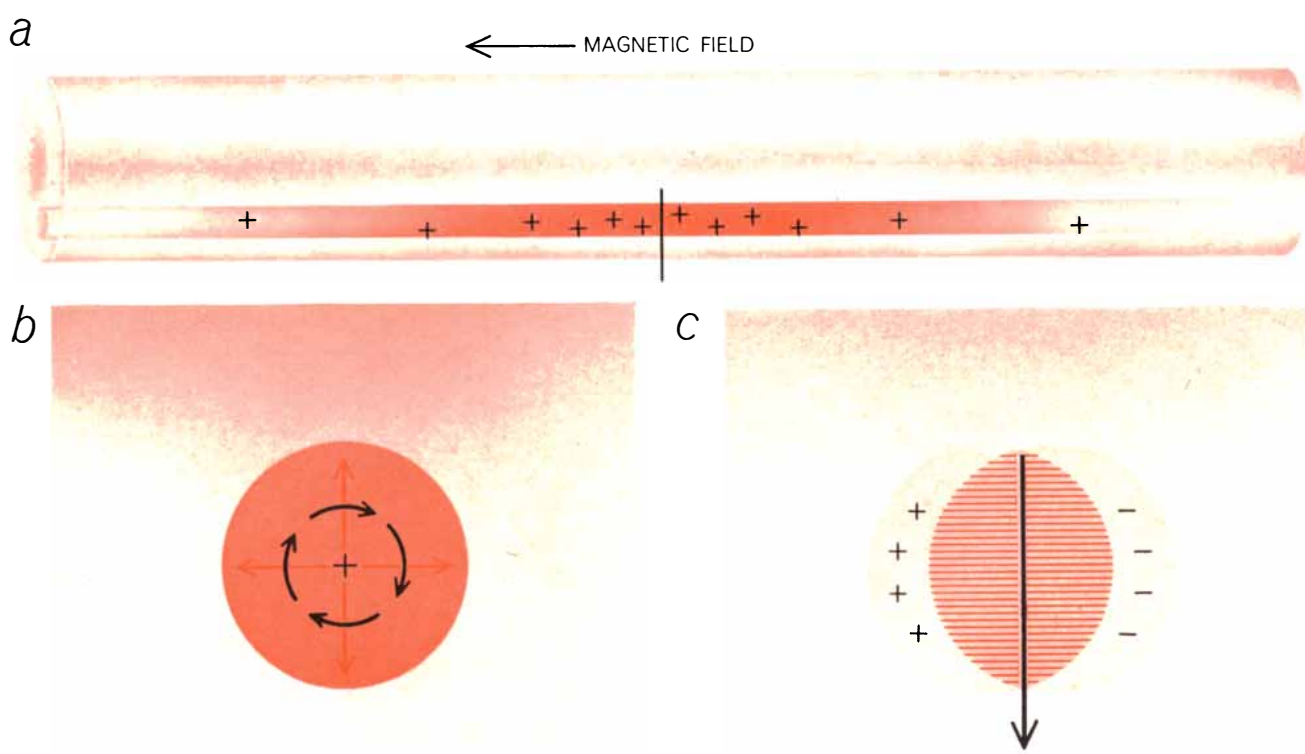
It is not difficult to see why such an instability should arise. Suppose in a uniform magnetic field one has a long column of plasma that is denser near the axis than it is near the edge [*see bottom illustration on next page*]. In the course of random thermal fluctuations of the plasma it is possible for plasma to accumulate sometimes into a long, thin filament of higher than average density. Let the filament have a length L and last for a time T. The filament must be so long that ions cannot travel the length L in a time T or the filament would be wiped out as soon as it started to form. Thus the thermal velocity of the ions is assumed to be much smaller than the ratio L/T. The thermal velocity of the electrons, on the other hand, is usually so large that it is much larger than any



LARMOR-RADIUS EFFECT influences the drift velocity of ions when the electric field (*color*) varies in space and the magnetic field (*black*) is uniform. Ions with small Larmor radii will drift faster in regions of strong electric field (*center*) and slower in regions of weak electric field (*top and bottom*). An ion with a large Larmor radius will sample regions of different field strengths during each orbit and on the average will be slowed down. As a result ions will drift slower than electrons in spatially varying electric fields.



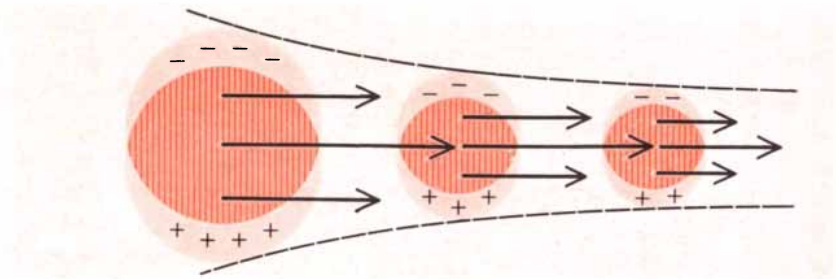
ION-INERTIA EFFECT becomes a factor in determining the drift velocity of ions when an electric field is suddenly switched on (a time-varying electric field). Then the ions that are at rest initially will, because of their inertia, be accelerated in the direction of the electric field (*short arrows*) before beginning to move in the direction perpendicular to the electric field. In this case the velocity of the guiding center has, in addition to its usual perpendicular component, an extra component in the direction of the electric field.



"UNIVERSAL" INSTABILITY needs no driving force other than the ever-present gradient in a confined plasma. Such an instability will occur whenever a long, denser-than-average filament of plasma can form within a general plasma background that is denser near the axis than it is near the edge (*a*). The higher pressure in the filament causes the electrons to move rapidly out the ends, leaving an excess positive charge near the center of the filament (*a*, *b*). This charge sets up a radial electric field (*colored arrows*), which causes the plasma to drift around the periphery of the filament (*black arrows*). Since the ions drift slower than the electrons (the Larmor-radius effect) and the background plasma is denser at the top of the filament than it is at the bottom, this difference in drift velocities causes excess positive and negative charges to build up on opposite sides of the filament (*c*). This new charge separation in turn creates a new electric field and hence a new perpendicular drift component, which is always outward. Hence the filament moves toward the wall.

reasonable value of L/T; therefore the electrons have time to move freely along the filament. Here one can consider the electrons as a fluid with regard to their motions along the magnetic field and neglect the motion of ions in this direction altogether. Now I want to show that once such a filament starts it will grow, conveying plasma toward the wall as it does so. It will be simpler to consider the Larmor-radius effect first without worrying about the inertia effect.

In a plasma the density of ions is everywhere nearly equal to the density of electrons, since a difference in charge densities of even one part in a million would lead to larger electric fields than the plasma could stand. At the center line of the long plasma filament this common density of ions and electrons is higher than elsewhere, so that a pressure gradient tends to push plasma along the magnetic field away from the center line. The ions, of course, do not have time to move at all, but the electrons start to move rapidly. As they do so they leave behind positive charges at the center line, and immediately an electric field is set up that impedes the electron motion and maintains the equality of charge densities. The balance of the pressure gradient and the electric forces on the electrons must be delicately maintained, since the electrons are so mobile. If one looks at a cross section of the plasma filament, it is clear that this accumulation of positive charges also gives rise to an electric field pointing outward from the axis of the filament. This in turn causes the ions and electrons to drift together around the periphery. Because of the Larmor-radius effect, the ions drift somewhat slower than the electrons. This would not cause any trouble if the plasma were homogeneous, but remember that the filament is superposed on a smooth slope of density from the center of the plasma column to the edge. As a result, when the drift proceeds from a region of high density to one of low density, more electrons than ions are brought in by the drift. Conversely, when the drift proceeds from a region of low density to one of high density, more ions are brought in. This results in an accumulation of positive and negative charges on opposite sides of the filament, creating an additional electric field. The additional field causes an additional drift, which is always in the outward direction. The plasma filament is unstable and grows because the outward drift brings denser plasma in from the surrounding plasma; this increases the density of the filament, thus further increasing the electric field and the outward drift. More important, the outward drift can automatically cause anomalous diffusion, because it is always in a direction such as to bring dense filaments of plasma away from the axis.



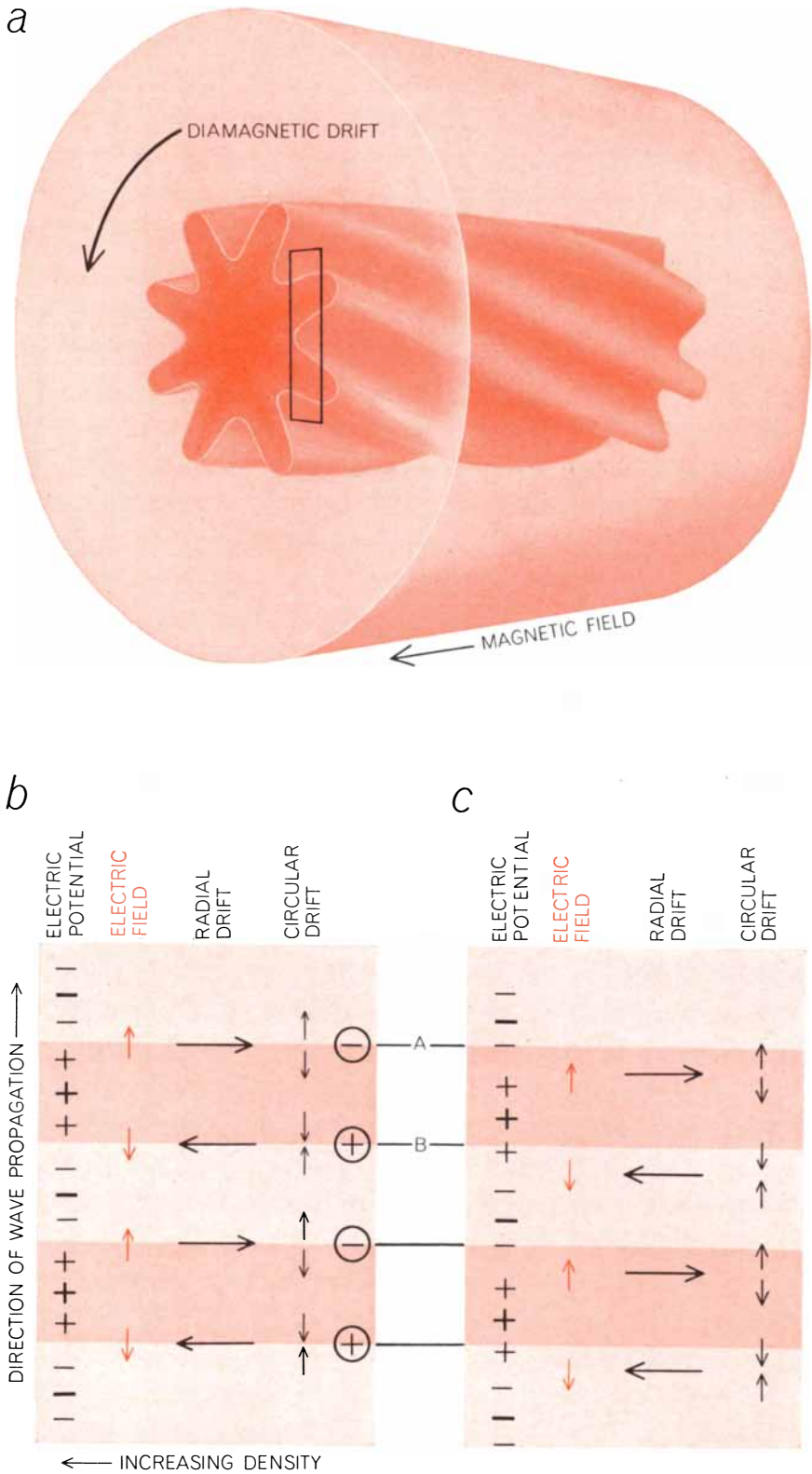
"CONVECTIVE CELL" might be created by a plasma filament that was moving outward to the chamber wall (*to the right*) under the influence of the electric field produced by the universal instability shown at the bottom of the opposite page. Successive layers of the filament would tend to get peeled off, since the electric field (*colored lines*) and hence the associated drift vectors (*heavy black arrows*) would be greater at the center of the filament.

In practice successive layers of the plasma filament would tend to get peeled off, since the electric field is strong at the center of the filament but weak in the regions of charge accumulation. This process might create an ever narrowing channel, in which plasma moves outward under the influence of the electric field [*see illustration above*]. Such a channel, called a "convective cell," could conceivably drain plasma to the wall steadily until the electric charges could somehow be dissipated.

I have glossed over a rather fundamental point in the interest of simplicity. If the electrons are so mobile, why do they not simply stream along the magnetic field to neutralize the charge separations that create the electric field? Indeed, if electrons were infinitely mobile, they would do just that, and the electric field would be vanishingly small. To get a universal instability, one must find a mechanism that limits electron mobility along the magnetic field. There are three such mechanisms: (1) collisions with ions, (2) electron inertia and (3) acceleration of resonating electrons by waves. The third mechanism is too complicated to explain here, but ironically it was the first one discovered and is known as *the* universal instability. For the last two mechanisms to be important, the length L must be very long—probably longer than can obtain in most experiments. In a stellarator, for instance, it is very likely the drag of electron-ion collisions that limits electron mobility along the magnetic field and allows the electric field to be finite.

The ion-inertia effect discussed earlier can also cause this instability. For the sake of simplicity let us now neglect the differential-drift effect discussed above, although in general both effects will occur together, and consider again a long cylinder of plasma with a gradual slope of density toward the edge [*see illustration on next page*]. A steady magnetic field but no electric field is applied. Imagine that the plasma develops a helical ripple with a wave motion proceeding circularly around the axis of the cylinder and with flutes at a slight angle to the magnetic lines of force. Let us look at a small section of this ripple—small enough so that the perturbed density does not change appreciably from left to right across the section. As before, the balance of forces on the electrons will require the electric potential to be positive where the perturbed density is high and negative where it is low. This gives rise to an electric field in the circular direction, which in turn causes both ions and electrons to drift in the radial direction. Note that this radial drift is to the right at point A, bringing in higher-density plasma, and to the left at B, bringing in lower-density plasma. A short time later, therefore, the density will be higher at A and lower at B. In other words, the ripple propagates counterclockwise in the cylinder. This propagation velocity is always in the same direction, and has nearly the same magnitude as what is called the electron diamagnetic drift velocity. Such waves are consequently known as drift waves.

As the wave passes by, the ions will "feel" an alternating electric field in the circular direction. Hence they will have a circular velocity component as well as the radial-drift one. The phase of the circular component is such that ions diverge from A and converge on B; thus an excess of positive charge builds up at B and an excess of negative charge builds up at A. Now, if one of the three electron-drag mechanisms listed above is operating, this charge buildup cannot be



HELICAL FLUTE INSTABILITY is a type of universal instability that can arise as the result of the ion-inertia effect alone. The helical ripple actually occurs at all layers of the plasma column; it is shown here on only one level for the sake of clarity (*top*). In the small cross-sectional views of the ripple (*bottom*) the curvature of the column is neglected. The excess charges, associated electric fields and ion-drift components are given at bottom left for the case in which the resistivity of the plasma is zero. If the resistivity is finite, the accumulations of charge (*circled signs*) due to the circular drift component of the positive ions cannot be entirely dissipated and the charge distribution is shifted, as in the case at bottom right. This phase shift causes the drift wave to become unstable and to grow, carrying the plasma outward. It is possible to measure the phase shift experimentally.

entirely eliminated by electrons flowing rapidly along the magnetic field from trough to crest of the twisted flute. The potential at *A* will therefore be slightly negative and that at *B* slightly positive instead of zero as before. This has the effect of shifting the charge distribution downward, and of course the electric-field distribution and the radial-drift velocities shift with it. It is now clear that there is more plasma moving to the right where the ripple has a high density and less plasma moving to the left where the ripple has a low density; this brings in even more dense plasma. The ripple grows, and in so doing transports plasma away from the axis of the cylinder. The ion-inertia effect is what caused the phase shift between the charge and density distributions that made the wave unstable. This phase shift can be measured experimentally and can be used to determine if anomalous diffusion is associated with the growth of such waves.

The effect of ion inertia, then, is to make universal instabilities appear in the form of growing drift waves. The Larmor-radius effect does not change the oscillatory nature of the instability but merely adds to the growth rate. Drift waves will occur whenever electron mobility along the magnetic field is not perfect, provided that the plasma is long enough. The drift velocity is rather low, so that as the wave passes a stationary sensing probe a potential oscillating with a low frequency will be detected, in agreement with the observed oscillation. The dominant frequency corresponds to a ripple with a long wavelength.

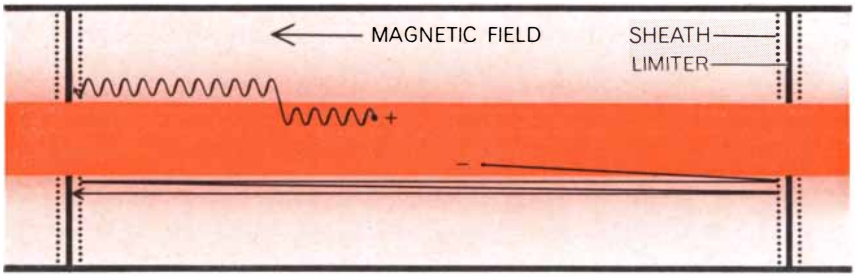
It is a peculiarity of such drift waves that the plasma particles mainly oscillate back and forth in the radial direction, but the wave (that is, the density perturbation) propagates in the circular direction. The particles' motion can change the density only because of the background density gradient. This is the reason drift waves do not exist in homogeneous plasmas. In any plane perpendicular to the magnetic field the motion of the electron fluid is incompressible, but the motion of the ion fluid is compressible because of its inertia. A compressible motion and an incompressible motion are not compatible, however, if the densities of ions and electrons are to be maintained nearly equal to each other everywhere, as is necessary in a plasma. Hence a drift wave cannot exist at all unless either the ions or the electrons (actually the electrons) can move along the magnetic field to maintain equal charge densities. This is basically the reason the flutes are inclined to the lines of force:

maxima and minima of density can be attained by electrons streaming along the magnetic field.

So far I have used the guiding-center description of particle motions in the directions perpendicular to the magnetic field but have regarded the electrons as a fluid for their motions parallel to the magnetic field. From experience this has been found to be the simplest way to explain the phenomenon, but is it compatible with viewing electrons as single particles in their parallel motions? Individual electrons zip along the lines of force so fast that they are subject to a rapidly oscillating electric field as they cross the helical flutes. Normally a rapid oscillation would leave an electron with a zero net displacement. In this case, however, the longitudinal electric field alternately accelerates and decelerates each electron in such a way that it spends more time in regions where the perpendicular electric field is making it drift outward and less time where it is drifting inward. Thus the electrons can drift outward on the average even in the single-particle picture.

The behavior of a single wave is clear enough, but many waves with different wavelengths can grow simultaneously, and as they become large they can mix with one another and give rise to the observed continuous spectrum of frequencies. The plasma is then in a state of electrostatic turbulence, which is very difficult to treat theoretically. Questions that remain unanswered include: What should the shape of the spectrum be? Does this shape depend on which of the microinstabilities is causing the turbulence? Do small eddies coalesce into large eddies, or do large eddies break up into small eddies as they do in ordinary gases? Does the turbulent state automatically lead to Bohm diffusion?

One thing is clear, and that is that plasma confinement will depend on the end plate conditions, as it did in the original arc experiment of Bohm's group. I alluded previously to an exception to the rule that all magnetic bottles leak. In some mirror devices exceptional stability has been observed, even when no precaution was taken to eliminate the simple gravitational instability. It has recently become clear that this stability is due to an effect involving the end plates of the mirror device. The plates are conducting, but the trapped hot plasma is not in contact with them. In the process of making a hot plasma, however, a cold plasma is produced incidentally; such a cold plasma is not well confined by the mirror device because its collision rate



BOUNDARY of a toroidal plasma is usually formed by an aperture-limiter, which is simply a plate with a hole in it. In this view the torus has been straightened out to show the interior and exterior regions created by the limiter. Plasma can be brought to the edge of the interior region by oscillations. Once it reaches the exterior region, it can flow easily along the magnetic lines of force to the limiter, where it is "scraped off." The "sheath," or thin boundary layer, surrounding the limiter repels electrons, causing them to bounce back and forth many times before they are lost to the limiter. This effect allows the ions and the electrons to depart at equal rates, leaving the plasma neutral, in spite of the higher velocity of the electrons. The small gyrations of the electrons have been omitted here for clarity.

is too high and particles can scatter through the magnetic mirrors. Charge fluctuations that tend to build up in the hot plasma can be short-circuited by currents flowing in the cold plasma along the lines of force to the conducting plates. Even when the end plates are insulators, the cold plasma may be dense enough to be a reservoir of charges sufficient to damp out the oscillations. Here the hot plasma is stable against straight-flute perturbations, and the machine is too short to allow drift instabilities. Unfortunately cold-plasma stabilization cannot be used in a working fusion reactor, because at the high densities needed the cold plasma would be quickly heated up.

In toroidal devices such as the stellarator there are no end plates, but it is necessary to take into account a boundary imposed by a plate with a hole in it that establishes the diameter of the plasma [*see illustration above*]. Instabilities inside the plasma can easily bring particles up to the edge of the hole in growing waves by means of the circular electric field. Beyond the hole the fluctuating electric fields are short-circuited by the plate, and only small fields can exist because of the finite conductivity of both the plasma there and the "sheath," or thin boundary layer, surrounding the plate. Once a particle reaches the edge of the hole it is swept outside during the next cycle and then streams easily along the magnetic field to the plate, where it recombines with a particle of opposite charge. There is competition between the growth of a wave and its damping by the scraping off of plasma at the edge of the hole, so that an oscillation detected by a probe can seem to be a steady one. Clearly the loss rate can depend on the geometry of the perforated plate and the region outside the plasma, and it is not surprising that the measured coefficient in Bohm's equation varies in different experiments. Another way to view anomalous diffusion is to consider that drift instabilities grow until they have destroyed the density gradient that feeds them. This leaves a very steep gradient at the edge of the hole, across which the plasma can diffuse by classical processes at a fast rate.

There is one type of plasma generator in which the end effects are particularly simple and well understood. This is the "*Q* machine" invented by N. Rynn of Princeton, in which a low-temperature plasma is produced between hot tungsten end plates by the ionization of a beam of cesium or potassium atoms. The magnetic field is straight, so that the plasma is not confined at the ends; instead the ions are replenished by ionization, and electrons are supplied by emission from the end plates. This electron emission also serves to short-circuit and thus suppress all flute instabilities. Since no currents or other destabilizing forces are needed to create the plasma, practically the only instabilities that can occur are drift waves. Recently H. Hendel of Princeton has succeeded in isolating and making precise measurements on a pure drift wave in a *Q* machine. Such experiments hold great promise of increasing our understanding of drift waves and anomalous diffusion, and indeed this line of research is being followed in many *Q* machines all over the world.

There are many other types of microinstability that may also be important; these generally are modifications of the same basic mechanisms that are at work when the magnetic field is curved or when the plasma temperature is not uniform. A common feature of all such microinstabilities is that the rotating-wave velocity is rather low. This at least explains the predominance of low frequencies in the observed spectrum of oscillations. We do not yet know, however, whether a continuous spectrum is necessary to produce anomalous diffusion or whether a single coherent wave will do. More important, we do not even know if drift waves are responsible for the observed loss rates. Although drift waves can in principle lead to increased losses, there may still be an unknown mechanism that is even more effective. Several recent experimental results have hinted that this may be the case. For example, perhaps steady-state or very low-frequency electric fields can set up convective cells in which the plasma is continuously drained to the walls. These and similar questions are scheduled to be topics of discussion at an International Symposium on Fluctuations and Diffusion in Plasmas, meeting in Princeton from June 26 through 30.

If it turns out that microinstabilities are important, what can be done about them? It is generally agreed that a new family of devices called "magnetic multipoles," invented by D. W. Kerst of the University of Wisconsin and T. Ohkawa of the general Atomics Division of the General Dynamics Corporation, have the best chance of overcoming such instabilities, because the lines of force in these machines are bent in such a way that long filamentary perturbations cannot occur. A multipole device called the spherator, invented by Shoichi Yoshikawa of Princeton, combines this feature with a large shear in the magnetic field. The first experiments with small multipoles have been encouraging. It will take a few years, however, to see how well the spherators and larger multipoles perform. It would be too much to expect that they will be stable against all types of fluctuations, but possibly those that remain will not be deleterious to plasma confinement.

Even if the instabilities discussed in this article are conquered at low densities, the dream of thermonuclear power cannot be realized until it is ascertained that no unknown phenomena occur at high densities. The low-density problem has to be solved in any case, however, because the density will be low at least near the edge of the plasma, and the understanding of anomalous diffusion at low densities must be regarded as a significant step forward.

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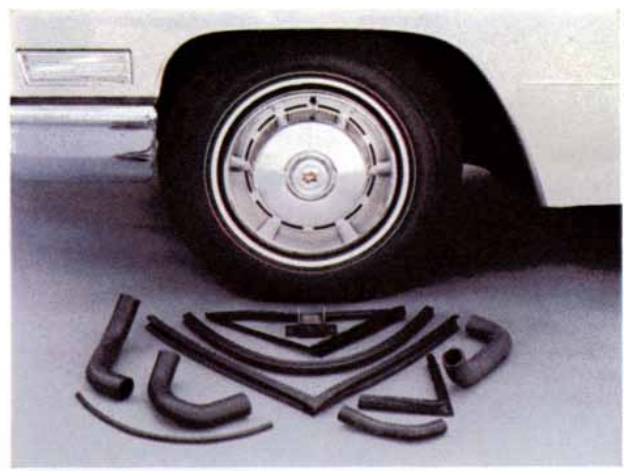

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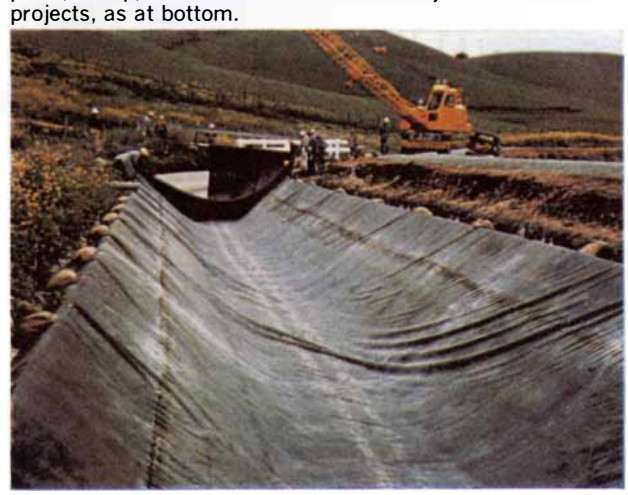

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PRE-COLUMBIAN RIDGED FIELDS

In four areas of tropical lowland in South America there are huge arrays of ancient earthworks. Many of them are ridges put up to farm land subject to seasonal flooding

by James J. Parsons and William M. Denevan

In South America thousands of square miles of tropical lowlands are submerged in shallow floodwaters for weeks or months during the rainy season and are parched by drought during the dry season. Covered either with savanna grasses or with forest, these poorly drained river floodplains have generally been considered unfit for agriculture since the Spanish Conquest. When they are exploited at all, it is usually as cattle range. In the open savanna the grass is renewed by annual burning; in some wooded areas today the trees are being cleared to make way for planted pasture.

Recently the surprising discovery has been made that areas in several such regions were once intensively farmed. The pre-Columbian farmers had a specialized system of agriculture that physically reshaped large parts of the South American continent. Aerial reconnaissance and surface exploration have now located the intricate earthworks required by this system in the tropical lowlands of four widely separated regions: eastern Bolivia, western Ecuador, northern Colombia and coastal Surinam (Dutch Guiana). Similar earthworks are said to exist in other parts of the continent, but such reports have not yet been substantiated. Here we shall describe the earthworks in the four areas that have been identified and mapped thus far, review what is known about prehistoric earthmoving for agricultural purposes elsewhere in the Americas (both lowland and highland) and then examine the implications of these early works with respect to the rise of civilization in the New World.

Except for two brief references in early chronicles, the first mention of agricultural earthworks in South America was made in the 1900's by the Swedish ethnographer Erland Nordenskiöld, in connection with his studies in the Llanos de Mojos (Plains of Mojos) of northeastern Bolivia. Located in the heart of the South American continent, between the Andes and the Brazilian highlands, most of the Mojos plains area is less than 800 feet above sea level. Bounded by the Beni and Mamoré rivers, these broad lowlands are a sea of grass in which occasional islands of forest mark the higher, better-drained ground; indeed, the vegetation is locally known as *pampa-isla*. Here for as much as seven months of the year floods cover the grasslands with a sheet of water ranging in depth from a few inches to several feet.

Faced with a hostile environment of this kind people everywhere usually adapt their lives to the circumstances; a commonplace example in areas subject to flooding is the building of houses on stilts. The modern cattle ranchers of the Llanos de Mojos do much the same: they simply select high ground for building sites. The pre-Columbian inhabitants of the area chose instead to modify the landscape. They raised mounds, causeways and serried ridges for their crops, all of which stood high enough to surmount the floodwaters. To this day the wet savannas are crisscrossed with narrow causeways that connect the natural islands of high ground. The causeways are as much as seven miles long; their total length in the Llanos de Mojos, as measured on aerial photographs, exceeds 1,000 miles. Also visible in the area are many artificial mounds that served as sites for burials, for houses and even for small villages.

The agricultural earthworks in the area cover at least 50,000 acres. They are of three kinds. West of the town of Trinidad the prevailing pattern is narrow, closely spaced ridges. South of Lake Rogoaguado the ridges are much larger: as much as 80 feet wide and 1,000 feet long. In other areas there are rows of small circular mounds six to eight feet in diameter. Whatever their form, most of the earthworks are less than two feet high. Originally they were doubtless high enough to stand above the average flood level.

In 1908 and 1909 Nordenskiöld excavated several burial mounds east of the Mamoré River that were associated with some of the Mojos causeways. Within the mounds he found fragments of elaborately decorated pottery, which he attributed to the ancestors of the region's Arawak Indians. This work of half a century ago is the only serious archaeology that has been undertaken in the area. Early Jesuit accounts of the region imply that the socioeconomic development of the Indians was advanced enough to enable them to construct the kinds of earthworks found there, but such literature, some of which is quite detailed, makes no mention of any agricultural ridges. Indeed, the extent of the ridges was not realized until 1960, when swamp buggies engaged in petroleum exploration encountered seemingly endless ridges near the town of Trinidad. Thereafter the ridge system was examined on aerial photographs. Here in Bolivia, however, the lack of archaeological investigation

ANCIENT EARTHWORKS visible in the aerial photograph of the San Jorge River area in Colombia on the opposite page are evident where the forest still stands and where trees have been cleared for pasture (*upper left*). In pre-Columbian times the inhabitants of this seasonally flooded river lowland built such ridged fields over an area of some 80,000 acres.

makes it impossible to determine exactly when the ridges and other earthworks were raised.

Another ridged area is in northern Colombia some 150 miles inland from the Caribbean coast. There the waters of the San Jorge and Cauca rivers join with those of the Magdalena in a great interior basin that is less than 80 feet above sea level. Known as the Mompos Depression, this seasonally flooded alluvial plain is covered with a constantly changing complex of lakes and swamps. When it is not covered with water, it is a rich reserve of pasturage for Colombia's two leading beef-producing provinces, Córdoba and Bolívar.

Since the Spaniards entered the region in the 16th century the western part of the Mompos Depression has also been famous for its Indian mounds and their content of gold. Neither the early settlers nor today's *colonos,* however, seem to have been aware that some 80,000 acres along the San Jorge are covered by a pre-Columbian ridged-field system.

The San Jorge ridges, like those of the Llanos de Mojos, are not easily perceived on the ground. From a dugout canoe, a common means of travel in the area, they are virtually invisible. The local people are aware of the ridges but few recognize them as man-made features. From the air the ridges are clearly distinguishable [*see illustration on page 92*]. When the Mompos Depression is partly inundated, slight differences in relief are emphasized and the ridge pattern is sharply outlined by the floodwaters. Moreover, both before and after the rains the color of the grass reflects the difference between the dry ridge crests and the damp ditches between them; for several weeks the pattern is clearly painted in tan and green.

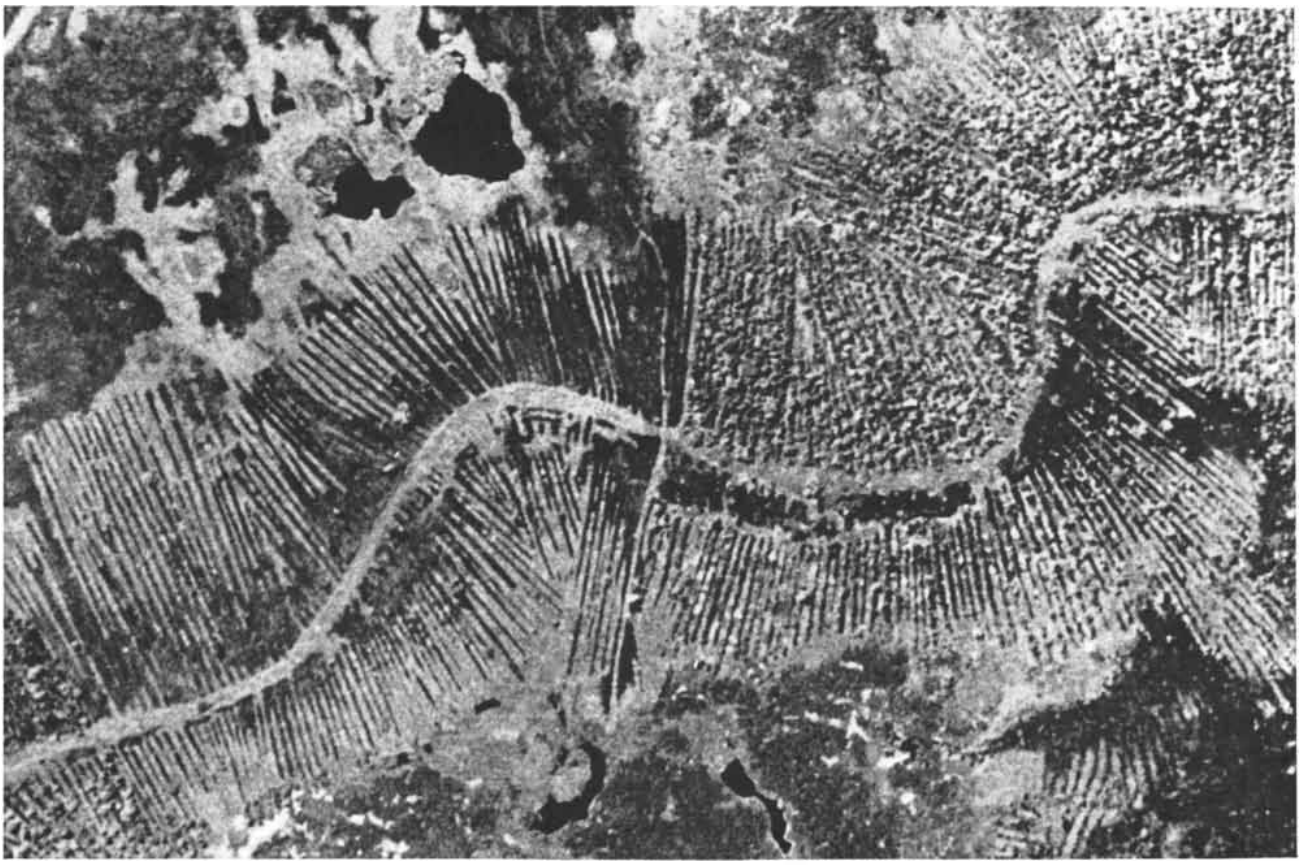
The San Jorge fields are of three kinds. In one type the ridges are on the natural levees of old stream channels and are perpendicular to the channels. In the second type short ridges are arrayed in a checkerboard pattern. In the third type the ridges are in clusters, generally parallel but unoriented with respect to the higher ground of the levees. Averaging about 20 feet in width, the ridges vary in length from a few feet to almost a mile; the ditches between them are in some places wider than the ridges and in some places narrower. The majority of the ridges are two to three feet high; a few are nearly five feet. Most of the San Jorge fields have been invaded by forest since they were abandoned. Where the trees have been cleared and the area has been planted with pasture grass the ancient ridge system gives the landscape a distinctive corrugated appearance.

FOUR REGIONS in the tropical lowlands of South America (*color*) have pre-Columbian earthworks built so that lands subject to seasonal flood and drought could be utilized for farming. Similar earthworks were also built in the Andean highlands at Lake Titicaca.

A third ridged area is immediately north and east of the airport for Guayaquil in Ecuador. To the east of the Guayas River, opposite Guayaquil and just north of the town of Durán, an extensive system of parallel ridges is visible that looks almost exactly like the ones at San Jorge and Mojos. Another area of earthworks lies some 15 miles north of Guayaquil, in the lowlands between the Babahoyo and Daule rivers, where rectangular mounds predominate. These relics of pre-Columbian agriculture in Ecuador seem not to have been recognized for what they are until we observed them in 1966. We might not have noticed them ourselves if it had not been for our familiarity with the earthworks of Bolivia and Colombia.

The ridged fields of the Guayaquil area cover substantially less ground than those of San Jorge and Mojos; the floodplain and swampland they occupy probably total some 10,000 acres. The system of ridges near Durán is currently being cleared of second-growth forest and sharecroppers are planting it mainly with rice and maize. Rice seedlings are transplanted from seedbeds into the ditches, the soil of which is heavier than that of the better-drained ridges. The ridges, which are 30 to 40 feet wide and as much as two miles long, are being planted with maize, squash, beans, sugarcane and cotton.

As in Bolivia and Colombia, serious archaeological investigation that could identify the peoples who raised the Guayaquil earthworks has yet to be undertaken. The Guayas floodplains are known to have been occupied from about A.D. 500 to the time of the Spanish Conquest by a people of the Milagro culture, noted for its elaborate work in gold. The low-lying countryside is dot-



RIDGED FIELDS in Colombia, built on the natural levees that adjoin abandoned stream channels, are usually oriented perpendicularly to the course of the stream. The height of the ridges seen in this aerial photograph is from two to five feet above the ground.

ted with thousands of *tolas,* or artificial mounds, built by the Milagro people for burial places and house sites. Some of the *tolas* appear to be associated with ridge systems and others with the rectangular earthworks. It is possible that the same culture made both. Only investigation can prove or disprove the association.

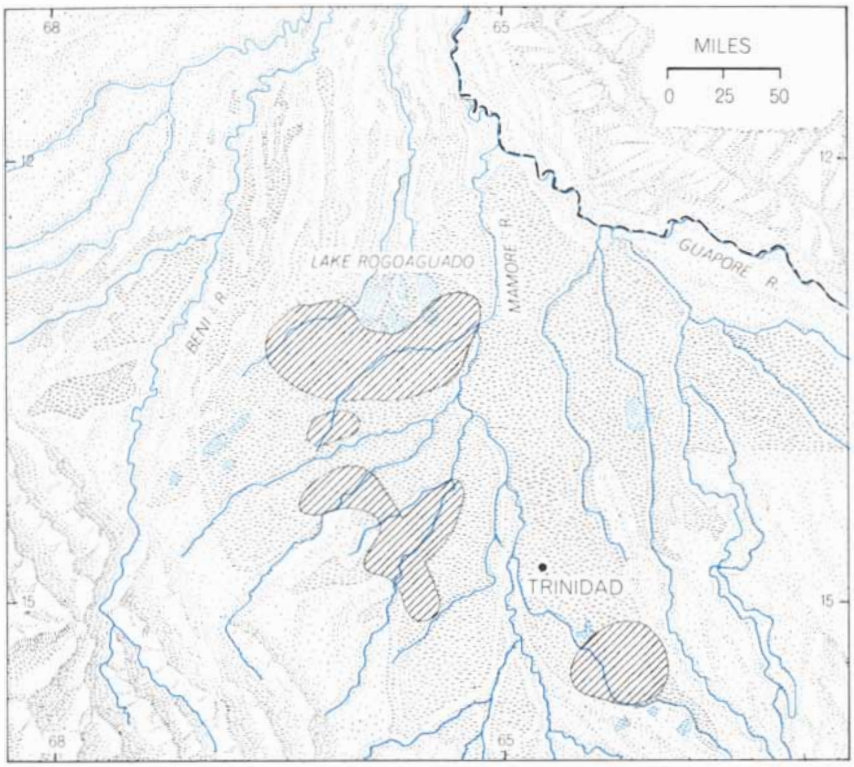
The coast of Surinam, the site of our fourth example of ridged-field agriculture, is a low-lying plain consisting of a series of ancient beaches running parallel to the present shoreline. Between these fossil beaches are swampy strips of clayey soil that support savanna vegetation. At a number of places along the coast ridged fields have been noted in these grassy swamps. The most extensive system of ridges is associated with an artificial mound known as Hertenrits, which is about 800 feet in diameter and rises six to seven feet above the level of the surrounding swamp. Hertenrits is three miles from the coast between Nieuw Nickerie and Caroní, in the middle of a long-uninhabited savanna belt that is now being reclaimed as part of a government rice-growing project. The mound is being investigated by the Dutch archaeologist D. C. Geyskes and the Dutch pollen analyst D. M. Laeyendecker-Roosenburg.

The Hertenrits ridges are short—perhaps three times as long as they are wide—and haphazardly arrayed. Some stand alone; others are clumped together like sausages in a pan. The aerial photographs indicate that the ridges rise two to three feet and that in many places they support vegetation distinctly different from that of the surrounding savanna.

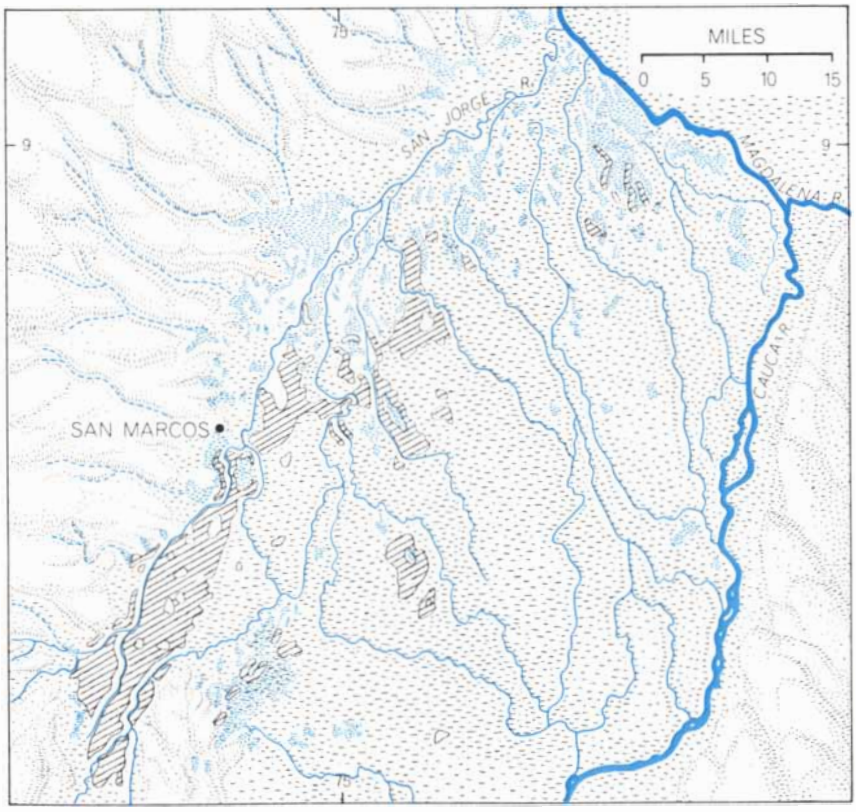
Analysis of pollen contained in peat taken from the Hertenrits mound and from an adjacent swamp indicates that the mound was raised not long after A.D. 700. At that time the sea had encroached on the area; the evidence for the encroachment is a marked increase in the abundance of mangrove pollen in the samples. The Dutch investigators suggest that, in order to continue living in the area under these conditions, the local people were obliged to build the mound as a village site and presumably also to make ridges for their crops. They calculate that the mound was occupied until at least A.D. 900 and probably later.

The pollens identified at Hertenrits do not include those of any cultivated plants such as maize. Although the evidence is admittedly negative, this fact suggests that the ridges were devoted to growing manioc, a plant that rarely flowers and is propagated not by seed but by stem cuttings. Manioc was a staple crop in much of tropical South America at the time of the Spanish Conquest, and it is still widely grown today. The cuttings are usually planted at the start of the rainy season and require good drainage. More than most crops, manioc would call for artificially raised ground in areas subject to flooding. It is probable that not only here but also in Bolivia, Colombia and Ecuador the peoples who made mile after mile of ridges were growers of manioc. It seems possible, although it is by no means proved, that the oldest earthworks in some of these areas may date back to a period before maize had arrived from Middle America.

In the absence of archaeological investigation making possible carbon-14 dating or other age determinations, one can only speculate on the antiquity of most of these early agricultural works. The ridged-field system in the Mompos



MOJOS GRASSLANDS of northeastern Bolivia have earthworks of several kinds in the indicated areas. These include causeways, settlement mounds and 50,000 acres of ridged fields.



MOMPOS DEPRESSION is the alluvial plain in Colombia where seasonally flooded ridged fields are found. Fields near San Marcos are shown on the preceding page and on page 92.

Depression of Colombia appears to be associated with the Indian mounds there, and the mounds seem to have been more or less continuously occupied for a long time before the Spaniards arrived. A hundred miles or so to the north, near the Caribbean coast, there are mounds of shells that have been dated by the carbon-14 method. These dates range from 800 B.C. at Momil to about 3000 B.C. at Puerto Hormiga, making the latter the oldest-known site in the New World where pottery is found. There is no evidence that the San Jorge fields are equally old, but it is interesting that some of the shell mounds occupy a similar ecological niche, being located on the margin of seasonally flooded lands.

One possible means of determining the age of the San Jorge earthworks arises from the fact that there the ridge pattern is often oriented at right angles to old stream channels. A reconstruction of the district's history of sedimentation might provide a key to the question of age. Many of the ridges appear to be related to the oldest and longest-abandoned channels, which are now choked with water hyacinths when they contain any water at all.

Although many other lowland regions of tropical South America have terrain suited to ridged-field agriculture, our investigations up to now have produced concrete evidence of their existence only in the four areas described here. Nonetheless, promising conditions for the discovery of similar earthworks exist over huge areas: the Orinoco delta, Marajó Island at the mouth of the Amazon, the Pantanal region of the western Mato Grosso in Brazil and the broad llanos of Venezuela and Colombia.

South of the old colonial city of Barinas in the Venezuelan llanos a complex of man-made causeways as much as six feet high, 20 feet wide and three miles long has been described by the Venezuelan archaeologist J. M. Cruxent. Both in Bolivia and Surinam similar causeways, possibly used as footpaths during periods of flooding, are associated with ridged fields. Our inspection of the available aerial photographs of the grassy Venezuelan plains has failed to reveal any ancient agricultural earthworks, but the area deserves more intensive examination. The 16th-century Spanish chronicler Juan de Castellanos, writing of the plains country, mentions "old cultivation ridges" (*labranzas viejas camellones*), an indication that the agricultural areas of this kind he had seen or heard about had been abandoned at the time of his ob-

servations. Yet some 200 years later the author of *Orinoco Ilustrado*, Father José Gumilla, clearly described the continuing use of ridged fields. "In poorly drained sites," he wrote, the Indians "without burning the grass... lift the earth from ditches on either side, mixing the grass with the earth and then planting their maize, manioc and other root crops, along with pimento."

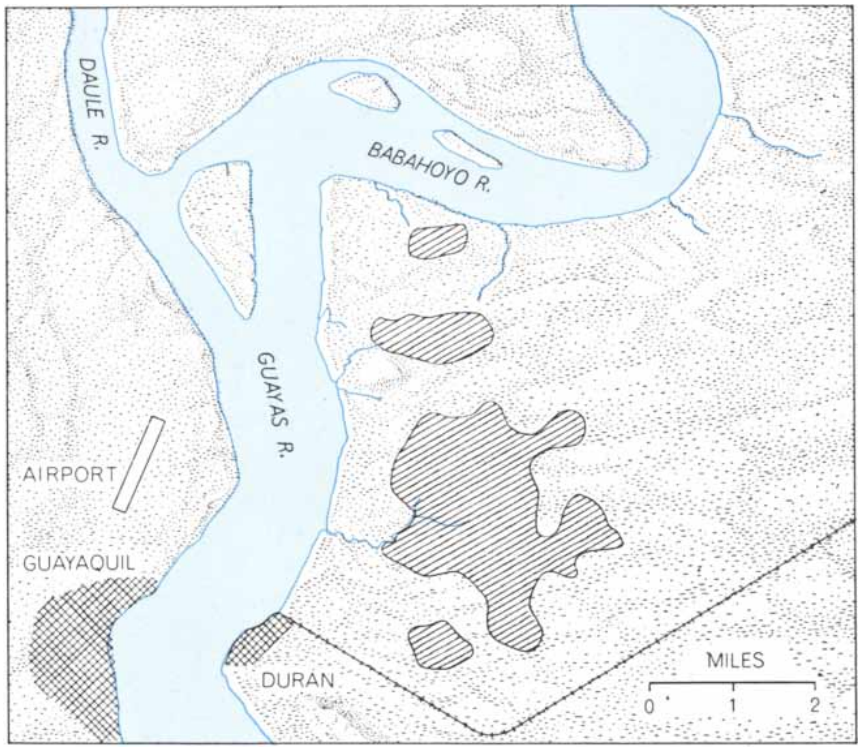
Father Gumilla does not say exactly where he observed this practice. It could have been anywhere in the llanos of Colombia or Venezuela, but visible remnants of this farming system must still persist. Bush pilots, if they are on the lookout for such ridges, may find them on the lower floodplains of such major tributaries of the Orinoco as the Apure, the Arauca and the Meta.

Several parallels to the ridged fields of the tropical lowlands are found in the highlands of South and Central America. It seems likely that the earth-moving practices in both environments were related in function, if not always in form. One of the closest approximations in both form and function are the ridged fields recently discovered along the western shore of Lake Titicaca, at an altitude of 12,000 feet in the Andes. These fields, covering some 200,000 acres, are found over a distance of more than 160 miles, from north of Lake Arapa in Peru to the Straits of Tiquina in Bolivia. Today the ditches are encrusted with alkali and the ridges are highly saline, so that cultivation is usually impossible. The fields still serve as grazing land, however, particularly during the dry season. At that time the upland pastures are parched and brown, but the high water table along the shore of the lake serves to keep the grass among the ancient earthworks green.

The Titicaca ridges are from 15 to 40 feet wide and range up to hundreds of feet in length. The height from ditch bottom to ridge crest is usually three to four feet. Most of the ridged fields are on the poorly drained margin of the lake plain and are subject to flooding in years of high water. The fields form checkerboard or ladder-like patterns or are irregular; their resemblance to the ridged fields in the Mojos area nearby in lowland Bolivia is striking.

Another form of agricultural earthworks in the Andean highlands consists of narrower parallel ridges, often built on sloping ground and running straight downhill rather than across the slope. Some of these ridge systems are old but others are new. Called *huachos*

CAUSEWAY in the level, seasonally flooded Mojos savanna of Bolivia runs among a series of ancient ridged fields made more prominent by the play of the late-afternoon shadows.



RIVER JUNCTURE near Guayaquil airport in Ecuador is area with ridged fields. To the north are found broader agricultural platforms (*see top illustration on opposite page*).

in Peru and Bolivia, they help to aerate heavy sod, to channel excess water from parts of a slope and to improve drainage on slopes so gentle that they are subject to waterlogging. In Colombia's central mountains, where old second-growth forest is being cleared to establish coffee plantations and pasture, the ancient ridge systems are so abundant that the hillsides in places give the appearance of having been combed. These pre-Columbian ridges are five to six feet wide, as much as twice the width of the *huachos* that are built today.

Huachos are usually confined to hillsides but are also found on level plains. Near Like Titicaca, for example, recently dug *huachos* can be found overlying the pre-Columbian ridge systems. Above 10,000 feet in the central Andes *huachos* are planted mainly with potatoes. To the north in the Colombian Andes, where the earthworks have been raised at much lower altitudes, they are used to grow maize, manioc and the white carrot-like root known as *arracacha*.

The well-known chinampas, or artificial islands, of the Valley of Mexico have some characteristics in common with the various drainage-promoting earthworks that are found in South America. Although many chinampas were built up in shallow lake waters, others served to convert swampy ground into useful fields. Still others were evidently formed on lake margins subject to seasonal flooding. At Xochimilco, the classic chinampas site [see "The Chinampas of Mexico," by Michael D. Coe; SCIENTIFIC AMERICAN, July, 1964], the planting areas are quite large. They are squares 100 yards or more on a side, surrounded by navigable canals edged with alders and willows. In the poorly drained basin at the headwaters of the Balsas River in the nearby state of Tlaxcala another example of artificial-island agriculture is found; it is apparently a variation on the Valley of Mexico pattern.

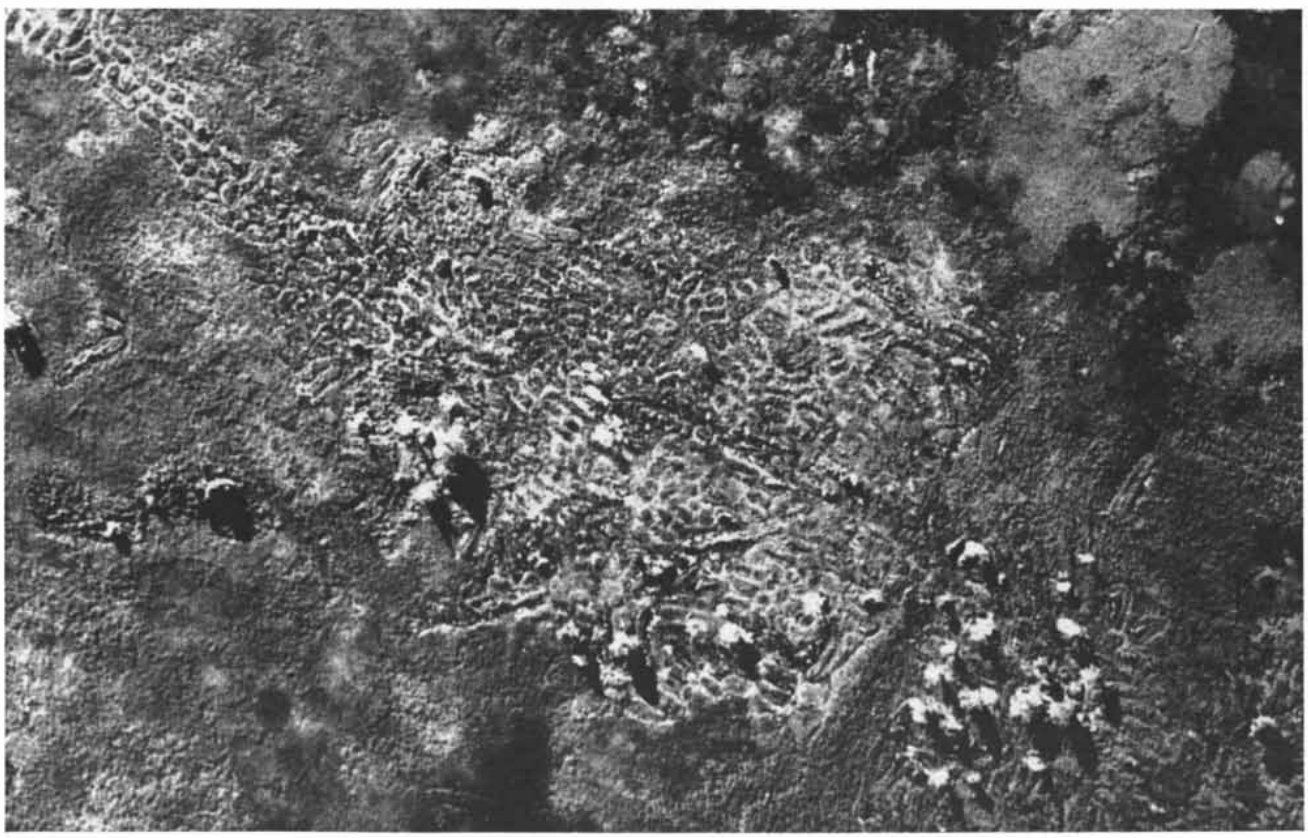
Raised fields built to avoid the hazards of floodplain agriculture are not confined to Latin America. Henry Schoolcraft, a pioneer ethnographer who worked in the U.S. Middle West in the middle of the 19th century, described agricultural earthworks or "planting beds" in valley bottoms extending from the vicinity of Fort Wayne, Ind., to the St. Joseph, Kalamazoo and Grand rivers in Michigan. Parallel ridges were laid out in rectangles with "paths" between them; some were as much as 300 acres in extent. Similar tracts existed in Illinois, Wisconsin and Missouri. Observing that the contemporary Indian inhabitants of the region cultivated maize only by "hilling," Schoolcraft concluded that the ridged fields were the work of an earlier culture, perhaps the then little-known Mound Builders. The possibility of some link between these garden farmers of the Mississippi valley and the ridged-field farmers of Latin America invites further study, particularly by those who are reluctant to accept the idea that similar environmental adaptations are independently invented again and again.

Putting together all our evidence concerning pre-Columbian agriculture in the seasonally flooded lowlands of tropical South America, we find that remarkably little is known other than what can be deduced from studying the ridged fields themselves. In the absence of any but the scantiest of early accounts, the means used to build the earthworks, the crops raised on them and the ways in which the crops were fertilized and rotated remain matters for speculation. It is especially difficult to attempt a projection of the number of people who could have supported themselves on the produce of the ridged fields, although some useful insights can be gained by examining the populations of areas where similar agricultural systems are used today.

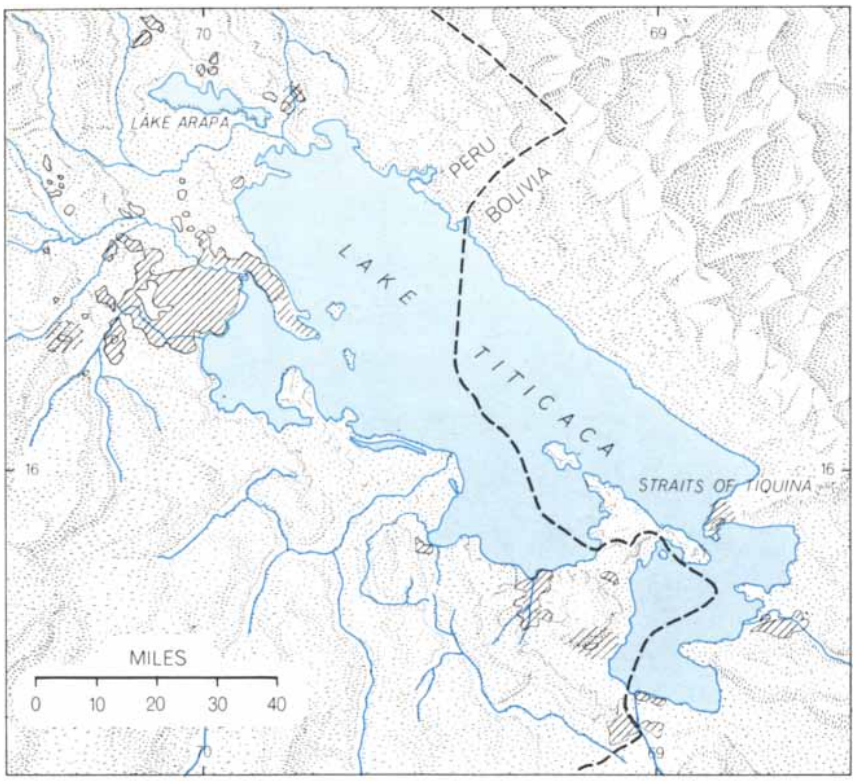
Before considering this question it is only fair to mention several explanations of the earthworks that deny them any agricultural function, or at least rule out the role of improving drainage. Some observers have suggested that they might be fortifications, others that they might be the remnants of sluice-mining systems. They have been called fishponds, irrigation channels or enclosures for the culture of freshwater mussels. They have even been declared to be the result of natural sedimentation processes and not the works of man at all. The last is the easiest of the alternative claims to disprove. The evidence of the aerial photographs—in particular the variety of intermingled patterns they reveal—makes it clear that man is responsible for the raised ground. The tremendous extent of the works may seem to present a puzzle. What we know from the construction of contemporary chinampas in Mexico and from gardening practices in New Guinea indicates, however, that simple digging sticks and wooden spades are the only tools needed for similar earth-moving projects today.

What are the advantages that floodplain rivers and their associated swamps offer as a habitat for a settled people? For one thing, the rich protein resources of such an environment would have allowed a settled way of life even before the development of agriculture: In the tropical lowlands of South America the rivers, swamps and even the flooded grasslands harbor abundant

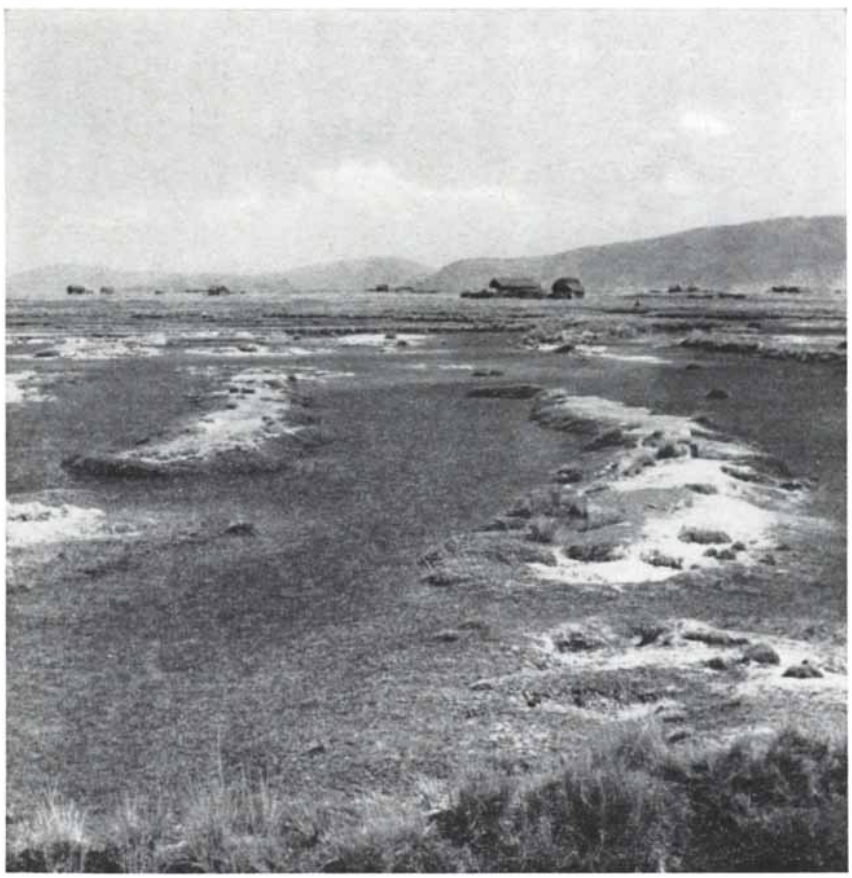
ANCIENT ECUADORIAN FIELDS are being cleared of trees and cultivated by local sharecroppers today. Between the 30-foot-wide platforms the damp ditches (*darker areas*) are used for rice. Maize and other staples are planted on the higher and drier platforms.



SWAMPY SAVANNA near the coast of Surinam has numerous examples of raised fields. The clusters of sausage-shaped ridges in the vertical aerial photograph are near a large, man-made earthwork, known as Hertenrits, that was put up soon after A.D. 700.



EXTENSIVE ARRAY of ridged fields lies in the Andean highlands on the poorly drained western shore of Lake Titicaca. Spread over 160 miles, the fields cover 200,000 acres.



TITICACA RIDGES, three to four feet high, are white with the accumulated salt that makes farming difficult today. When the photograph was made, the ditches were filled with water.

fishes, turtles (both land and water), iguanas, manatees and large rodents such as capybaras, pacas and agoutis. There is also a large and diverse population of waterfowl. Even after farming had become an established way of life, tropical agriculturists whose main food was a starchy root crop such as manioc would have valued the animal protein available in this environment.

A dual economy of this kind—ridged-field agriculture supplemented by hunting and fishing—should have been able to support far larger populations than the ones that scratch a living from the tropical forests today. Estimates of population density based on the extent of the ridged fields, however, are risky. For one thing, we do not know what fraction of the fields in a given area were under cultivation at any one time. The fields along the San Jorge River in Colombia, if they were all cultivated at the same time, could have supported as many as 400 people per square mile. In 1690 the Llanos de Mojos of Bolivia had a population of about 100,000 Indians. A century earlier, before the first contacts with Europeans resulted in deadly epidemics of Old World diseases, the population very likely numbered several hundred thousand. There is no reason to believe it was any smaller when the pre-Columbian ridged fields were under cultivation.

New archaeological evidence and new analyses of historical records attest to the existence of a surprisingly large aboriginal population in many parts of tropical South America. Both the extent of the seasonally flooded tropical farming areas and the evidence for a massive human effort that they provide suggest that the early lowland cultures had achieved a highly complex adjustment to their environment. The direction of flow of early cultural influences between the highlands and the lowlands of South America is a matter of continuing controversy. Those students of the question who contend that major cultural elements moved upstream from the lowlands of the Amazon, Orinoco and Magdalena regions into the Andean highlands in the past 2,000 or 3,000 years may find their arguments supported by the evidence for a complex, socially stratified lowland culture in pre-Columbian South America presented here. It is certain that future archaeological studies of South America's tropical lowlands and the complex ecological relations worked out by the region's early farmers should contribute much toward a more precise reconstruction of New World culture history.

Tin Free Steel

Metallic chromium and a chemical passivation combine to produce a coating on steel strip that is extremely thin, highly corrosion resistant and likely to result in superior steel containers.

by E. J. Schneider, Research Supervisor

Tin cans, which are, of course, made from a sheet of steel covered by a thin layer of tin, are the most familiar of all metallic containers. In recent years, however, the container industry has been undergoing a revolution in materials, and the prominence of the tin can is now challenged by competitors such as the aluminum can and the latest entry into the field, the "tin free steel" (TFS) can.

Replacement of tin plate by a substitute material is not simple. Tin permits soldering the side seam of the can at high speeds and provides corrosion resistance. Therefore, the new product has required the development of alternate ways to join the side seam, such as with adhesives, and the use of other types of protective coatings, such as improved organic enamels. It has been shown that bare steel will not serve as an adequate base for the enamels, or provide corrosion protection in the area of a ruptured film. These requirements have led to the evolution of a new class of coated product, a chromium plated can stock.

During early phases of seeking a coating system for steels for application in the enameled, adhesive side seam container, researchers examined various metallic and non-metallic materials which could be deposited on steel strip at high strip line speeds (1,000 feet per minute or greater). It soon became evident that chromium-based systems offered both the required physical and chemical properties, plus ease of application.

Chemical passivation treatments involving chromium salts (such as CrO_3 or $Na_2Cr_2O_7$) have long been employed to provide increased corrosion resistance to steel, galvanized steel and tin plate. However, chemical passivation treatments did not by themselves provide the combination of corrosion resistance and enamel adhesion required. On the other hand, deposits of metallic chromium alone afforded more corrosion resistance, but tended to stain under the organic coating when made into cans and packed with certain foodstuffs. However, by applying metallic chromium plus a chemical passivation treatment the properties required by the can manufacturers were obtained. If we consider the amount of surface covered by rust on a steel sample after exposure to a laboratory corrosion test, we find a striking decrease in the rusting of a sample given the duplex (chromium plus passivation) treatment. This is shown in Table 1.

Treatment	% Rust
Chemical Passivation	90
Chromium Only	3
Chromium + Chemical Passivation	<1

Table 1—Rust after exposure

The chemical treatment permits reduction of the metallic chromium to very thin layers (.2 to .4 microinches, or 50 to 100 Ångstroms).

Some of the more interesting information on these coatings arises from attempts to characterize the films. Problems are encountered because of the very thinness of the films (a .2 microinch coating of chromium, if distributed evenly, would be only on the order of 20 atoms thick). Several techniques are used to evaluate the thickness and nature of the films. For example, the direct measurement of extremely thin chromium layers in the tin free steels is very difficult by even advanced metallographic techniques. However, if a sample is placed in an electrolytic cell and made the anode, the films are dissolved as current flows through the cell. This is the reverse of the electroplating process. When the potential of the sample is measured against some standard electrode, a plot of potential vs. time will reveal the thickness of the chromium layer, since the time required to remove a uniform coating is proportional to the amount of material in the coating.

Electrolytic techniques which determine thickness, however, give us only part of the story.

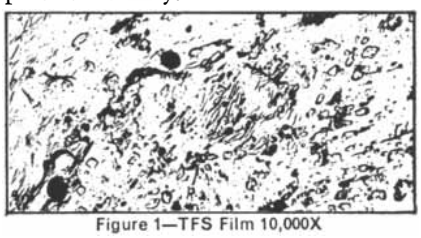


Figure 1—TFS Film 10,000X

Figure 1 shows an electron micrograph of a composite surface coating removed from a sample. By electron diffraction, the presence of metallic chromium and Cr_2O_3 has been verified in this film. The integrity of the film, i.e., its relative freedom from cracks or voids as might be anticipated in chromium electro-deposits, is undoubtedly due to the extreme thinness of the deposit, and plays an important part in the corrosion protection which it provides.

These characterizations are, by themselves, only of limited interest. Simultaneous programs involving research on the plating process and evaluation of the coated steels in both laboratory tests and actual use (pack) tests are also under way. In this way, research correlates all phases of the container material investigation. By gaining insight into the structure and properties of coatings like the one described above, steel researchers can develop superior products which can be effectively produced.

The work on TFS and other coatings for steel is only a small part of the continuing investigations being conducted at Youngstown's Research Center on steel as a basic material. If you believe that Youngstown Research could help you as a user of steel, call us or write Department 251B8.

Youngstown Steel

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WEDDING OF TOM THUMB and Lavinia Bump in 1863 united two midgets who were protégés of Phineas T. Barnum. They were photographed in wedding costume after the ceremony, which took place at Grace Episcopal Church in New York. The groom, whose real name was Charles S. Stratton, was three feet two inches tall; the bride, also known as Lavinia Warren, was two feet eight inches.

General Tom Thumb and Other Midgets

He was a midget of a type that has not been known to lack pituitary hormone. Now it is clear that such midgets have a deficiency of the pituitary's growth hormone, which indicates that they can be treated

by Victor A. McKusick and David L. Rimoin

On February 10, 1863, in New York's Grace Episcopal Church, Charles S. Stratton was married to Lavinia Bump. The wedding was an unusual one in that the groom, better known as General Tom Thumb, was three feet two inches tall and the bride only two feet eight inches. The maid of honor and the best man (the bride's sister and her fiancé) were also midgets. All four were protégés of Phineas T. Barnum, who one assumes was not unaware of the opportunity the wedding afforded to bring them to public attention.

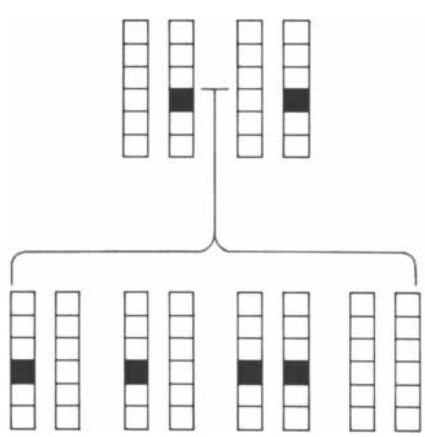
Physicians refer to any very short person as a dwarf, but in common usage a distinction is drawn between midgets and dwarfs. A midget is a short person whose proportions are normal or nearly so and a dwarf is someone whose proportions are abnormal: his torso and head are large with respect to his legs. Dwarfs with abnormal proportions usually suffer from one or another of the chondrodystrophies, genetic disorders in which faulty metabolism of the cartilage at the end of the long bones inhibits their growth. In the past decade progress has been made in distinguishing these disorders, and at least some of them have been traced to a defect in the production of the substances called mucopolysaccharides. Here, however, we shall be concerned not with dwarfs but with normally proportioned midgets.

What was responsible for the diminutive stature of the four principals in the wedding party of 1863? Stratton's parents were both of normal size. His puritanical father (his great-grandmother was a relative of the theologian Jonathan Edwards) is said to have considered his son "the living evidence of God's wrath against the Strattons." Recent discoveries made in connection with cases that are similar to General Tom Thumb's suggest a more satisfactory explanation. We now know that a lack of the kind of growth hormone usually manufactured by the pituitary gland is responsible for the failure of such people to grow normally. The production of the hormone is undoubtedly controlled by the genes, and it is likely that both Tom Thumb's father and his mother carried a recessive gene that was defective in this respect. Thus he could inherit two defective genes and lack the normal genetic apparatus for the production of growth hormone. Significantly his parents were first cousins; therefore if a mutation in one of their common ancestors had given rise to the defective gene, the probability of their both carrying it would have been considerable.

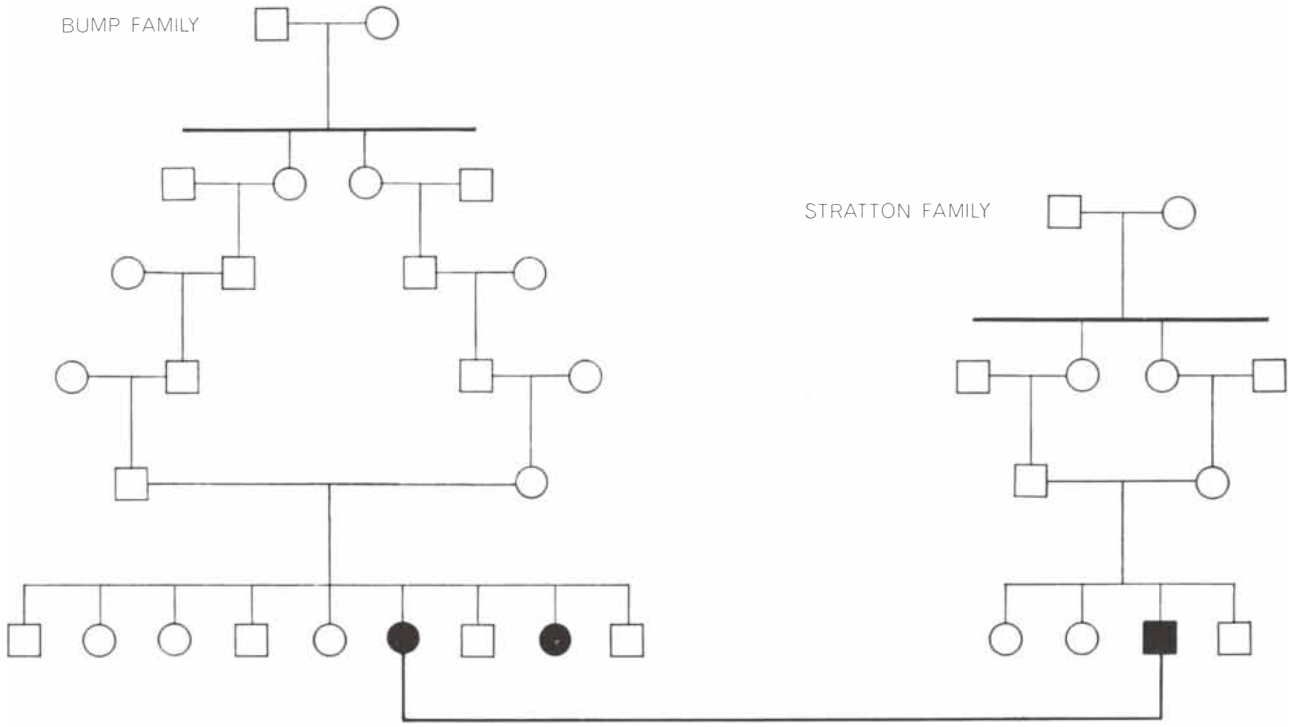
It is almost certain that the same genetic disorder was responsible for the stature of Lavinia Bump. (Barnum exhibited her as Lavinia Warren, Warren being her mother's maiden name.) Her parents too were of normal size, and they were third cousins. Moreover, two of their nine children were midgets (Lavinia and her maid of honor Minnie).

Except for their size, Tom Thumb, his bride and their attendants were apparently normal and healthy. Their weight and length at birth fell within the normal range; the retardation of their growth was not recognized until late in their first year. There was no indication of any chondrodystrophy: their bodies were all normally proportioned. Nor was there a sign of any intellectual deficiency. Lavinia taught school at the age of 13 before going into the circus. (She stood on a desk so that her pupils could see her.) Tom Thumb is said to have delighted Queen Victoria and other European rulers with his easy manner and witty remarks. Presumably their sexual development was normal also. A photograph of Tom Thumb shows him with a beard (after the style of Napoleon III), and he displayed a strong interest in the opposite sex. According to some reports Lavinia gave birth, on December 5, 1863, to a daughter weighing three pounds. It must be said, however, that on other occasions Barnum hired babies from their parents to pose as the offspring of his midgets. In Lavinia's autobiography no child is mentioned. On the other hand, her midget sister Minnie is known to have died in childbirth.

At the turn of the century an English physician, Hastings Gilford, coined the word "ateliosis" to distinguish normally proportioned dwarfs from others. (The term is derived from the Greek meaning "not arriving at perfection.") He recog-



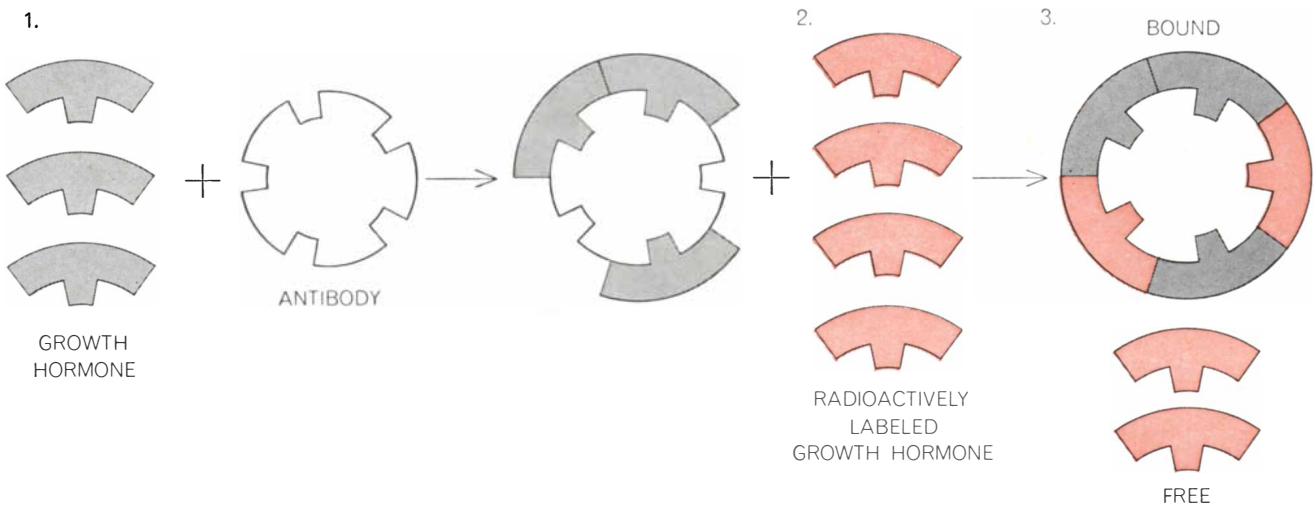
RECESSIVE GENE probably caused the small stature of Tom Thumb and his bride. These schematic chromosomes show how a recessive gene (*black*) in the paired chromosomes of both parents (*top*) could be combined in different ways in the paired chromosomes of their offspring (*bottom*). A combination of two recessive genes (*third from left*) would give rise to the recessive trait.



BUMP AND STRATTON PEDIGREES show the marriage of Lavinia Bump (*black circle*) to Charles Stratton (Tom Thumb) (*black square*). The blood relationship between Lavinia's parents can be traced back to two sisters three generations earlier. Tom Thumb's parents were first cousins. Siblings are omitted except for those of Lavinia (whose sister also was a midget) and Tom Thumb.

nized two types of such dwarfs in which the birth weight is normal, one that displayed normal sexual development and one that did not; he called the conditions sexual and asexual ateliosis. It would appear that both Tom Thumb and his wife suffered from sexual ateliosis.

In Gilford's time it was recognized that the anterior (forward) part of the pituitary plays a role in growth, but it is only now that we know it is involved in sexual ateliosis. It had been observed that individuals with an overactive pituitary grew too much and that others whose pituitary had been destroyed by a tumor during childhood grew too little; this suggested that underactivity of the gland might account for midgets. In the case of asexual ateliosis the suggestion was amply, although somewhat indirectly, confirmed. People with the condition were found to be deficient in the hormones produced by the anterior pituitary in its role as conductor of the endocrine symphony: the gonadotropins, thyrotropin and adrenocorticotropin (ACTH), which respectively regulate the function of the gonads, the thyroid gland and the cortex (outer part) of the adrenal glands. Somewhat later it



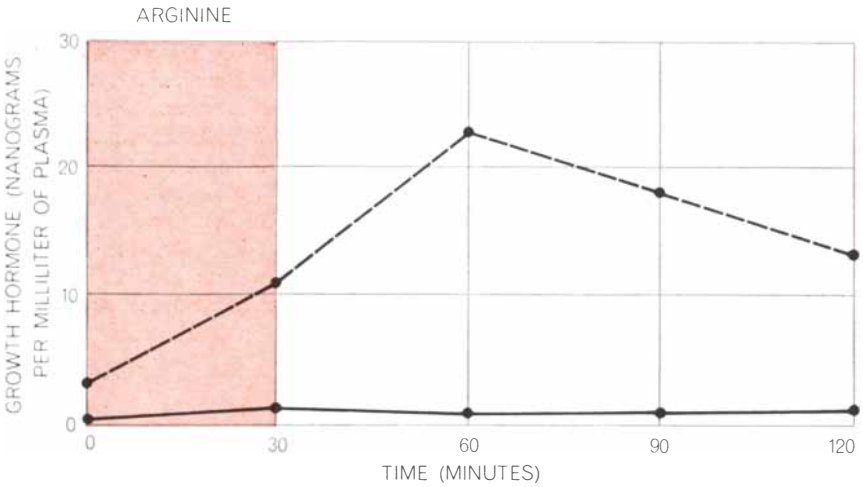
GROWTH HORMONE RADIO-IMMUNOASSAY utilizes the reaction of a hormone and an antibody to it. If both are present in a blood sample, they will combine (*1*). When radioactively labeled growth hormone is added to the sample, it combines with antibody that has not already taken up growth hormone (*2*). Labeled hormone bound to antibody and unbound labeled hormone (*3*) are measured. The relative radioactivity of the two is a measure of the concentration of growth hormone in the blood sample under assay.

was discovered that such people were also lacking in another hormone of the anterior pituitary—the growth hormone. This was demonstrated by giving them the hormone; when they subsequently grew to some degree, it was indirect proof that the hormone had been absent. More recently, as we shall see, it has become possible to show the deficiency of the growth hormone directly.

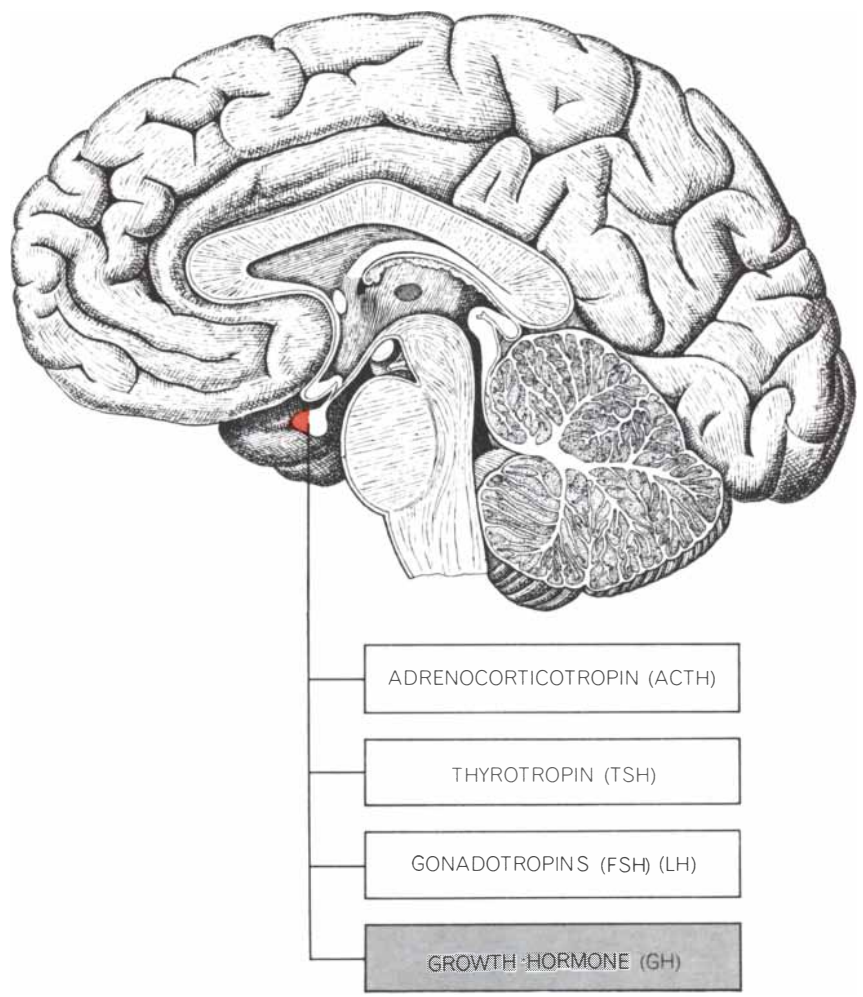
When it was found that asexual ateliotics lacked the gonadotropins, thyrotropin and ACTH, it was quite properly assumed that the pituitary was involved in their dwarfism. Indeed, asexual ateliosis came to be known as panhypopituitarism (lacking all the pituitary hormones). These three hormones were not deficient, however, in people with sexual ateliosis. For many years it was assumed that sexual ateliosis is not related to the pituitary; it was placed in a heterogeneous group of conditions called "primordial." The implication was that it is due to an inherited insensitivity to growth-promoting substances.

About 10 years ago the growth hormone was isolated and found to be a protein. Recently Choh Hao Li and his colleagues at the University of California at Berkeley have determined the complete sequence of amino acids in a molecule of human growth hormone; it consists of 188 amino acids in a single polypeptide chain. In 1960 Rosalyn S. Yalow and Solomon A. Berson of the Bronx Veterans Administration Hospital devised a remarkably sensitive means of assaying the amount of the hormone insulin in the blood. Known as radio-immunoassay, it has become a prototype for the assay of other polypeptide hormones, including the growth hormone. Working in association with Thomas J. Merimee of the Johns Hopkins School of Medicine, we have used the method to study individuals with sexual ateliosis.

Radio-immunoassay is based on the reaction between a hormone and an antibody that combines with it. The antibody to growth hormone is prepared in rabbits or other animals by giving them repeated injections of the hormone. For the purposes of the assay one also needs a supply of purified growth hormone labeled with radioactive iodine (I-131). When both antibody and labeled hormone are added to a sample of blood taken from an individual, whatever growth hormone was originally present in the sample will compete with the labeled hormone to combine with the antibody. If the amount of labeled hormone is precisely known, that fraction of it which



GROWTH-HORMONE LACK in the blood of sexual ateliotic dwarfs (midgets such as Tom Thumb and Lavinia Bump) was demonstrated after infusion of arginine, which stimulates production of the hormone. A control group of normal-sized adults (*broken line*) responded to arginine infusion. The response of sexual ateliotics remained close to zero.



FOUR TYPES OF HORMONE made by the anterior (forward) part of the pituitary gland are adrenocorticotropic hormone (ACTH); thyrotropin, also called thyroid-stimulating hormone (TSH); the gonadotropins, follicle-stimulating hormone (FSH) and luteinizing hormone (LH), and growth hormone (GH). ACTH stimulates cortex of adrenal glands, TSH the thyroid and FSH and LH the gonads. GH stimulates growth of cells in various parts of body. Asexual ateliotics lack all these hormones; sexual ateliotics lack growth hormone only.

does not combine with antibody is a measure of the amount of hormone in the sample.

With this method we have found a marked deficiency of growth hormone in the blood of dwarfs with sexual ateliosis. Many of these individuals belong to families that include other sexual ateliotics; the pattern suggests the inheritance of a recessive gene. Their production of gonadotropins, thyrotropin and ACTH is normal. Our findings therefore indicate that people who suffer from sexual ateliosis have a "pinpointed" deficiency of the growth hormone.

A child of two such midgets inherits a pair of recessive genes for the defect and hence will be a midget also. We have studied several midget couples and some of their children. (All children of midget mothers must be delivered by Caesarean section.) At birth the children are of normal weight and size. Thus it appears that neither maternal growth hormone nor pituitary growth hormone produced by the fetus is essential to growth during gestation. A substance that has growth-hormone properties is known to be produced by the placenta; it is called placental lactogen, and its role in intrauterine growth is being studied. The fact that the retardation of growth becomes apparent when ateliotic dwarfs are a few months old suggests that a switch to dependency on the growth hormone occurs during the period immediately following birth.

The midget mothers we studied produced milk normally. This is interesting

HUTTERITE MIDGETS with a brother and sister of normal stature are grouped (*left to right*) in the order of their ages, the oldest first. They are Sarah Mandel, 32; John Mandel, 26; George Mandel, 24; Elizabeth Mandel, 22, and Lawrence Mandel, 20. These midgets suffer from inherited asexual ateliosis, a rare form of the glandular condition. The Hutterites are a religious sect who live communally.

A championship bout in Mexico City and half the audience is here in Japan.

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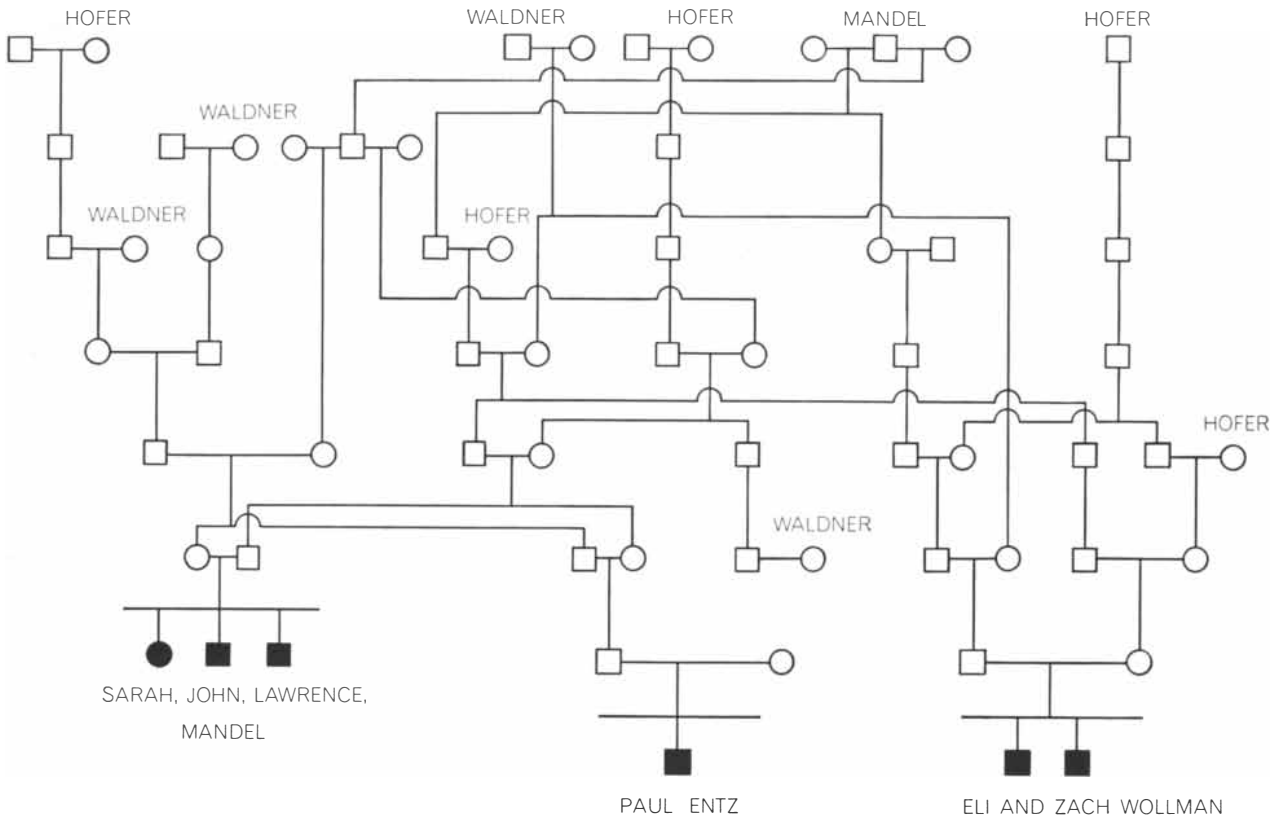


HUTTERITE MIDGETS' GENEALOGY shows a background of consanguineous marriages. Six children who are midgets (*black circle and squares*) are in three families of a Hutterite group. Family lines of the children can be traced back to individuals named Hofer, Mandel and Waldner, so it is likely that the children's size is due to an inherited disorder. Cases of inherited asexual ateliosis have been observed in other inbred communities. Siblings of the midgets and individuals not in direct line of descent are omitted.

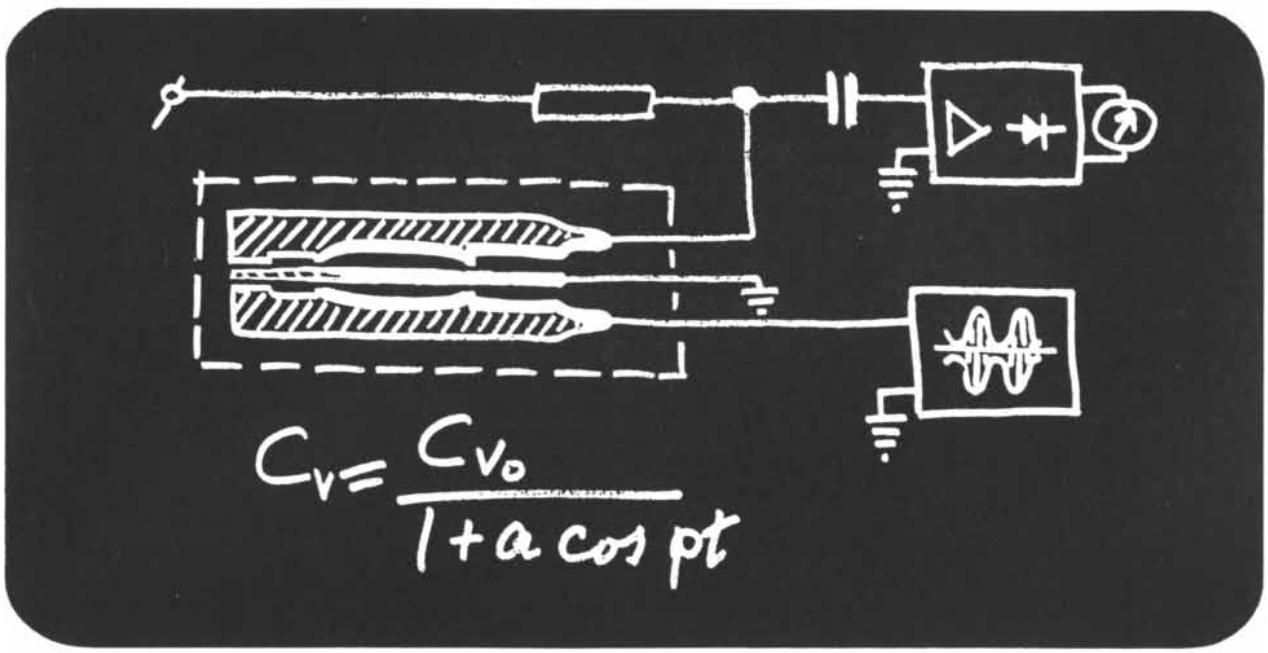
because lactation is controlled by the pituitary hormone prolactin, and it has proved impossible to achieve a definite chemical separation between this hormone and the growth hormone in man and monkeys. (The two hormones can be separated in other species.) The fact that lactation can occur in individuals with a pinpointed deficiency of growth hormone indicates that in man prolactin is probably a separate molecule. It is possible, however, that the lactation and growth factors are represented by different parts of the same molecule, and that the mutation that gives rise to sexual ateliosis is only in the growth-factor part.

Of the eight adult males whose deficiency in growth hormone we have documented four had shown a late spurt in growth accompanying a somewhat delayed puberty. Tom Thumb also grew several inches when he was in his late twenties. Although sexual ateliotics do not lack sex hormones, their voices are high-pitched. Their facial skin is characteristically soft and wrinkled, and they tend to look much alike. Barnum is quoted as saying that when Tom Thumb was not available for a show, he exhibited instead the midget known as Commodore Nutt and no one detected the deception.

All the clinical similarities of Tom Thumb and Lavinia Bump to the midgets we have studied make it virtually certain that they (and the other two members of their wedding party as well) had a pinpointed deficiency of growth hormone with a recessive pattern of inheritance. This conclusion is supported by the fact that recently we had an opportunity to study a midget who is a distant relative of the Bump sisters and found the same deficiency of pituitary growth hormone associated with normal production of other hormones.

A recessively inherited defect of the pituitary resulting in dwarfism in mice was discovered in 1929 by George Snell of the Jackson Laboratory in Bar Harbor, Me. Since that time other types of pituitary dwarfism have been detected in mice; sexual ateliosis in man may be similar to one of them. We do not know the biological mechanism through which the mutation is expressed. It may be a failure of the production of growth hormone or the production of an inactive molecule. The defect also might consist of a failure related to the factor that is manufactured in that part of the base of the brain known as the hypothalamus and that controls the production and release of growth hormone from the pituitary gland.

Panhypopituitarism—Gilford's asexual ateliosis—is usually not genetic. A rare form of the condition that is inherited (as a simple recessive) has been identified, however, in certain inbred groups from the Island of Krk off the coast of Yugoslavia and from isolated valleys in the Swiss and Tyrolean Alps. With the help of John Hostetler, a sociologist at Temple University, we have had an opportunity to study similar cases in a group of Hutterites, an inbred religious sect whose people live communally in the prairie provinces of Canada and in some of the U.S. Plains states. In this group six people in three families suffer from panhypopituitarism. Presumably every one of the six normal-sized parents bears one mutant gene that, when it is paired with a similar gene, gives rise to the condition. The precise consanguineous relationships in the parents' ancestry cannot



A new approach to measuring small currents

(From a lecture by Mr. A.G. van Nie)

Long, long ago - about 40 years or so - vibrating capacitor electrometers were used for measuring small currents. The dc current was converted into an ac voltage by a varying capacitor and a resistor and then amplified.

The method is still in use, in a more refined set-up which enables currents down to some 10^{-16} amperes to be reliably measured. In this set-up, limits are set on sensitivity by zero-drift and low conversion efficiency which in turn makes amplifier noise an important factor. So some years ago we started to investigate these fundamental limitations.

We knew that zero-drift was mainly caused by variations in contact potential of the condensor plates. Since this was due to surface impurities, the remedy was simple. Clean the surfaces. In practice, this means annealing the whole condensor at a rather high temperature and keeping it sealed off afterwards. The only trouble is that coils are a bit fussy about being baked out. So we discarded the magnetodynamic drive in favour of an electrostatic one. Our set-up for the vibrating condensor and its drive can be seen on the blackboard.

We clamp the edges of a thin (0.135 mm) metal-coated glass membrane between two hollow-ground, coated glass insulators. This gives us two capacitors, each from one coated insulator and a surface of the membrane. One capacitor is used in the measuring circuit and the other for driving the membrane electrostatically. Now when we use the drive in the straightforward way, we run into all sorts of troubles with stray fields entering the measuring circuits. However, our Dr. Zaalberg van Zelst pointed the way to a solution. He remarked that since the force between the condensor plates is proportional to the square of the voltage, a high frequency modulated with the desired low vibration frequency would provide the required drive. In this way, the stray fields do not contain the low frequency and cannot disturb the measuring circuit.

Dr. Zaalberg van Zelst also indicated an elegant means of deriving the required waveform. One of the capacitors is used to form part of the hf oscillator circuit, in such a way that its hf voltage (at $\sim$ 1MHz) is automatically modulated with the natural mechanical vibration frequency p of the membrane ($\sim$ 6kHz). For those who like formulae, the voltage generated in the circuit is expressed by the equation $u = (1 + m \cos pt)\, U_0 \cos \omega t$, with the frequency p excluded from its spectrum. When squared, it shows a periodic component p (the component 2p is also present but this is of no consequence in view of the sharp resonance of the membrane).

So what does all this add up to? A dc/ac conversion efficiency of 40% which, together with a rather high vibration frequency, keeps the noise contributions low. And the "clean" condensor, with its small and stable contact potentials, works with a minimum of zero-drift. This overall set-up enables currents to be measured down to 10^{-17} amperes or 60 electrons per second, whichever you prefer.

be traced because the genealogical records are inadequate. Among the ancestors of each parent, however, there are individuals with the surnames Hofer, Mandel and Waldner. It is therefore probable that the parents have at least three ancestral couples in common.

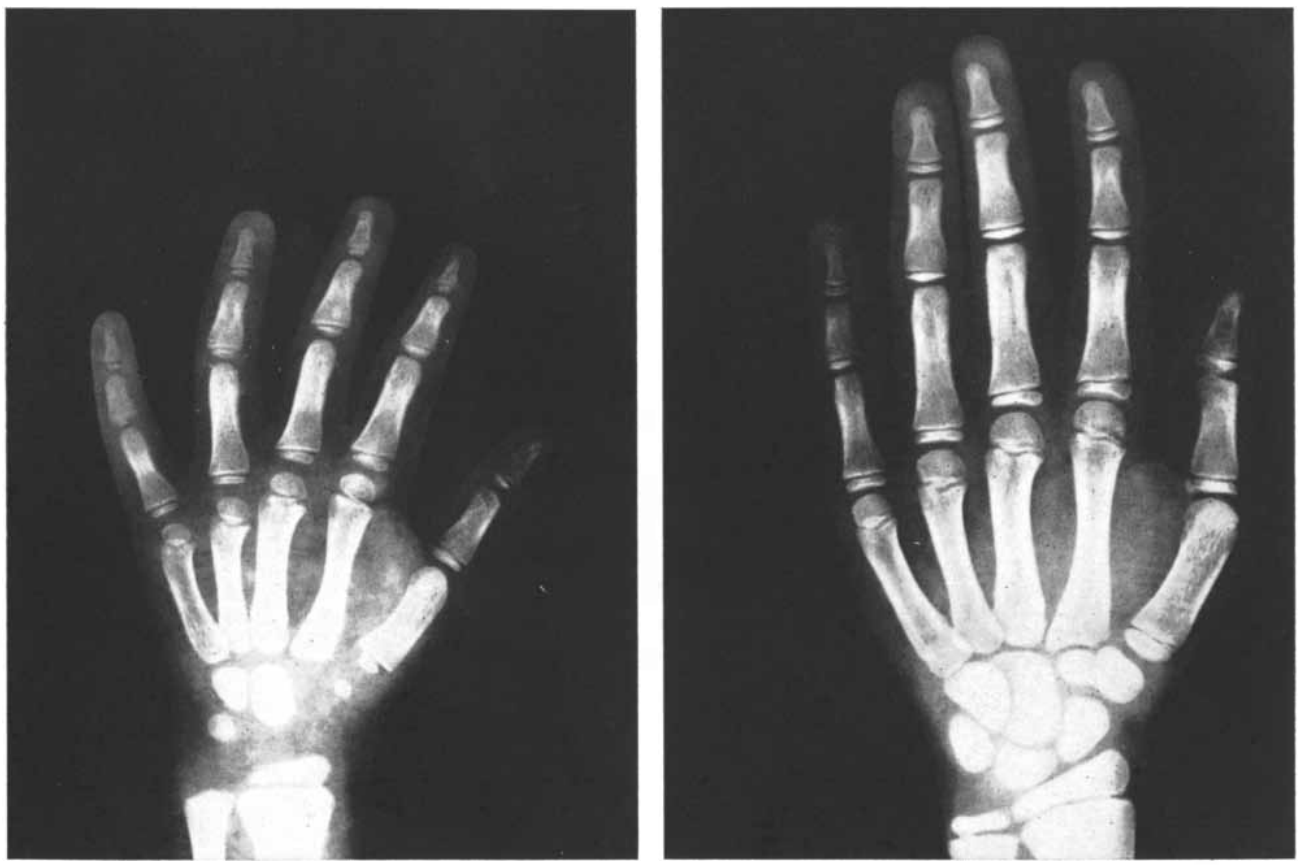
The midgets in the Hutterite group we studied, being asexual ateliotics, are deficient in gonadotropins, thyrotropin and ACTH as well as growth hormone. They are not only sexually undeveloped but also show signs of thyroid disfunction and are deficient in the hormones normally produced by the adrenal cortex. Another striking difference between these midgets and sexual ateliotics is that at the ends of their long bones are epiphyses: small floating structures that can be seen in an X-ray picture of a normal child but are absent in a normal adult because they have fused with the bones. These epiphyses are present even in the oldest midget we studied, who is 36.

What this means is that midgets suffering from panhypopituitarism are still capable of growth. If the epiphyses can be stimulated to grow and fuse with bone as they do in a normal individual, the entire body will grow, at least to a certain extent. Panhypopituitary dwarfs respond to treatment with growth hormone even if it is given as late as middle age. Two of those in the Hutterite group, one of whom is four years old and the other 20, are under such treatment and are responding satisfactorily.

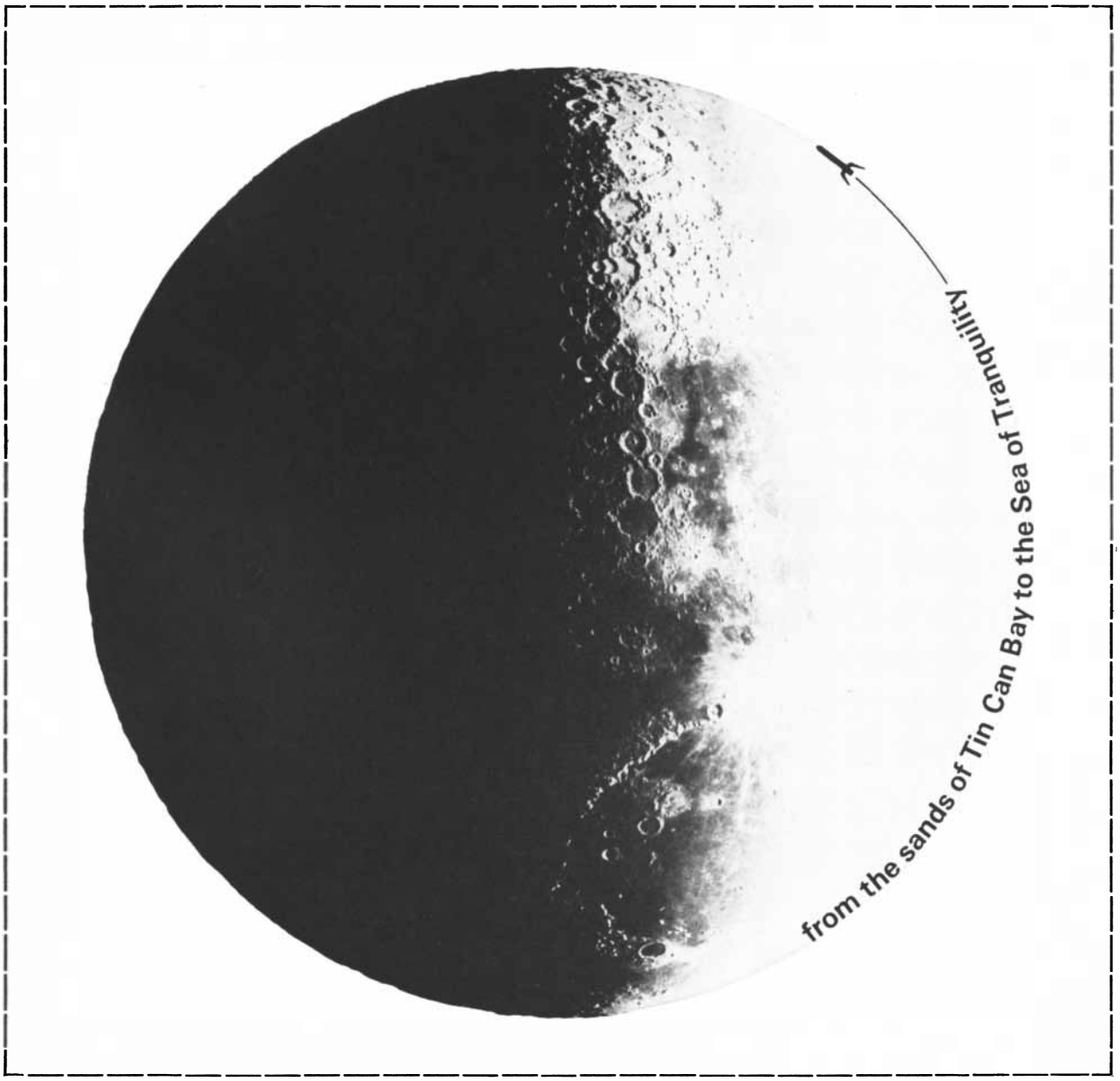
In normal growth the epiphyses fuse with the bones at puberty, and in sexual ateliosis they fuse soon after puberty. Since asexual ateliotics, whose epiphyses do not fuse at all, never reach puberty, it would appear that the sex hormones, androgen and estrogen, are much more important to epiphyseal fusion than the growth hormone is.

A happy feature of the discovery that sexual ateliotics have a hormonal deficiency rather than some kind of inherited insensitivity to the growth hormone is that the door is opened to treatment. At present there are practical difficulties in such treatment: it is necessary to use human growth hormone, which can be obtained only from the pituitary of someone who has just died. Recently questions have been raised about the legality of using pituitaries without the explicit permission of the nearest of kin. In most states, however, it is agreed that any nonprofit use is adequately covered by the routine autopsy permission. If sufficient amounts of human growth hormone could be obtained and administered to a sexual ateliotic during childhood, the outward manifestations of the condition should be completely correctable. Preliminary results of such treatment indicate that when it is begun before the epiphyses fuse, growth can take place.

One might wonder whether pygmies also have a deficiency of growth hormone. In collaboration with Luca Cavalli-Sforza of the University of Pavia we have studied a group of pygmies in the Central Africa Republic. No deficiency of growth hormone was found in the 21 individuals whose blood was assayed. There are suggestions, however, that the growth hormone of pygmies may have reduced biological activity. We plan a further expedition to look into the matter by examining the pygmies' metabolism.



BONES OF A CHILD'S HAND appear in X-ray plates made when the normal-sized subject, a boy, was (*left*) four and (*right*) eight years old. At the finger joints and wrist small coin-shaped bones, the epiphyses, are visible. The gap between these and the adjacent long bones gradually closes during childhood until, ordinarily at puberty, the bones fuse. Epiphyseal closure is moderately delayed in sexual ateliosis; it does not take place in asexual ateliosis. Midgets can grow if treated with growth hormone before their epiphyses close.



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MATHEMATICAL GAMES

Of sprouts and Brussels sprouts, games with a topological flavor

by Martin Gardner

"A friend of mine, a classics student at Cambridge, introduced me recently to a game called 'sprouts' which became a craze at Cambridge last term. The game has a curious topological flavor."

So began a letter I received in April from David Hartshorne, a mathematics student at the University of Leeds. Soon other British readers were writing to me about this amusing new pencil-and-paper game that had sprouted suddenly on the Cambridge grounds in February. Sprouts is now under intense analysis by a number of mathematicians and bids fair to become a popular game throughout the world.

I am pleased to report that I have successfully traced the origin of this game to its source: the joint creative efforts of John Horton Conway, professor of mathematics at Sidney Sussex College of the University of Cambridge, and Michael Stewart Paterson, a graduate student working at Cambridge on abstract computer programming theory. (Conway was mentioned in this department last September for his work on the "Mrs. Perkins' Quilt" problem.)

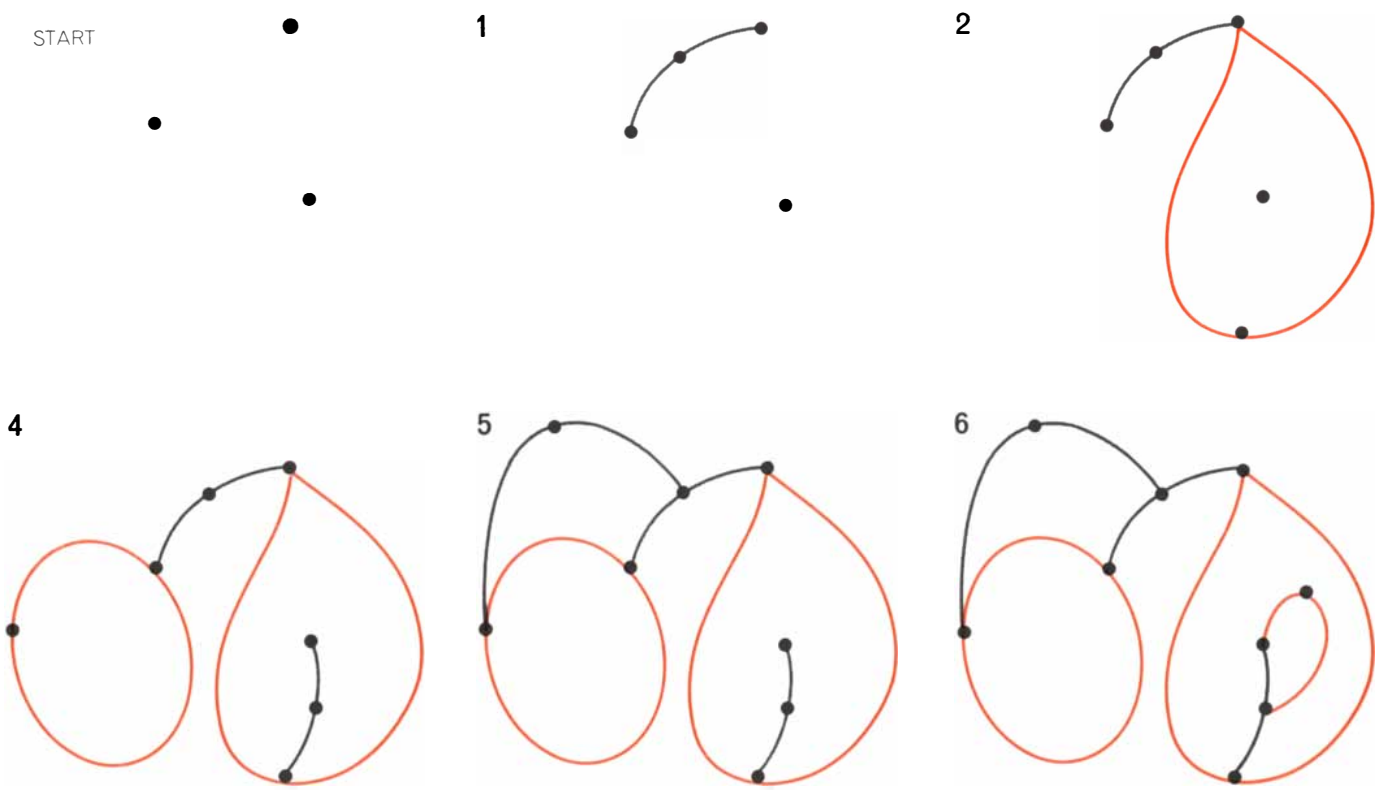
The game begins with n spots on a sheet of paper. Even with as few as three spots sprouts is more difficult to analyze than ticktacktoe, so that it is best for beginners to play with no more than three or four initial spots. A move consists of drawing a line that joins one spot to another or to itself and then placing a new spot anywhere along the line. These restrictions must be observed:

1. The line may have any shape but it must not cross itself, cross a previously drawn line or pass through a previously made spot.

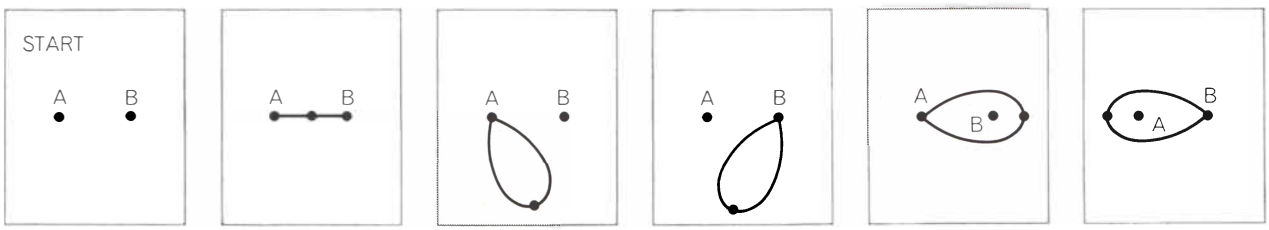
2. No spot may have more than three lines emanating from it.

Players take turns drawing curves. In normal sprouts, the recommended form of play, the winner is the last person able to play. As in nim and other games of the "take away" type, the game can also be played in "misère" form, a French term that applies to a variety of card games in the whist family in which one tries to *avoid* taking tricks. In misère sprouts the first person unable to play is the winner.

The typical three-spot normal game shown below was won on the seventh move by the first player. (Moves of the second player are shown in color to make the pictures easier to follow, although in actual play there is no need to distinguish the moves in this manner.) It is easy to see how the game got its name, for it sprouts into fantastic patterns as the game progresses. The most delightful feature is that it is not merely a combinatorial game, as so many connect-the-dots games are, but one that actually exploits the topological properties of the plane. In more technical language, it makes use of the Jordan-curve theorem, which asserts that simple



A typical game of three-spot sprouts



Initial spots (A *and* B) *and first player's possible opening moves in two-spot game*

closed curves divide the plane into outside and inside regions.

One might guess at first that a sprouts game could keep sprouting forever, but Conway offers a simple proof that it must end in at most $3n - 1$ moves. Each spot has three "lives"—the three lines that may meet at that point. A spot that acquires three lines is called a "dead spot" because no more lines can be drawn to it. A game that begins with n spots has a starting life of $3n$. Each move kills two lives, at the beginning and at the end of the curve, but adds a new spot with a life of 1. Each move therefore decreases the total life of the game by 1. A game obviously cannot continue when only one life remains, since it requires at least two lives to make a move. Accordingly no game can last beyond $3n - 1$ moves. It is also easy to show that every game must last at least $2n$ moves. The three-spot game starts with nine lives, must end on or before the eighth move and must last at least six moves.

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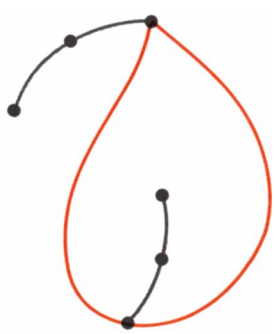

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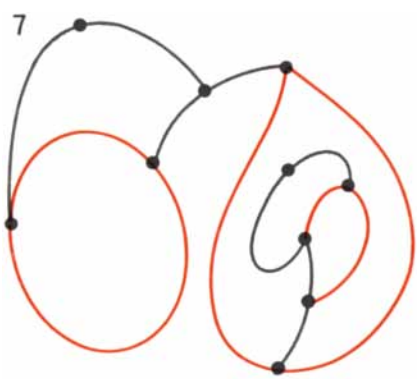


The one-spot game is trivial. The first player has only one possible move: connecting the spot to itself. The second player wins in the normal game (loses in misère) by joining the two spots, either inside or outside the closed curve. These two second moves are equivalent, as far as playing the game is concerned, because before they are made there is nothing to distinguish the inside from the outside of the closed curve. Think of the game as being played on the surface of a sphere. If we puncture the surface by a hole inside a closed curve, we can stretch the surface into a plane so that all points previously outside the curve become inside, and vice versa. This topological equivalence of inside and outside is important to bear in mind because it greatly simplifies the analysis of games that begin with more than two spots.

With two initial spots, sprouts immediately takes on interest. The first player seems to have a choice of five opening moves [*see illustration above*], but the second and third openings are equivalent for reasons of symmetry, the same holds true of the fourth and fifth, and in light of the inside-outside equivalence just explained, all four of these moves can be considered identical. Only two topologically distinct moves, therefore, require exploring. It is not difficult to diagram a complete tree chart of all possible moves, inspection of which shows that in both normal and misère forms of the two-spot game the second player can always win.

Conway found that the first player can always win the normal three-spot game and the second player can always win the misère version. Denis P. Mollison, a Cambridge mathematics student, has shown that the first player has the win in normal four- and five-spot games. More recently, in response to a 10-shilling bet made with Conway that he could not complete his analysis within a month, Mollison produced a 49-page proof that the second player wins the normal form of the six-spot game, but this has not yet been checked out. The second player wins the misère four-spot game. No one yet knows who has the win in misère games that start with more than four spots. With seven spots the complexity is so enormous that Conway believes it will require a computer and a sophisticated program to determine who has the win in either form of the game.

This assumes that no general strategy for perfect play will be found. One can, of course, often see toward the end of a game how to draw closed curves that will divide the plane into regions in such a way as to lead to a win. It is the possibility of this kind of planning that makes sprouts an intellectual challenge and enables a player to improve his skill at the game. But sprouts is filled with unexpected growth patterns, and there seems to be no general strategy that one can adopt to make sure of winning. Conway estimates that a complete analysis of the eight-spot game is far beyond the reach of present-day computers.

Sprouts was invented on the afternoon of Tuesday, February 21, 1967, when Conway and Paterson had finished having tea in the mathematics department's common room and were doodling on paper in an effort to devise a new pencil-and-paper game. Conway had been working on a game that originally involved the folding of attached stamps and Paterson had put it into pencil-and-paper form. They were thinking of various ways of modifying the rules when Paterson remarked, "Why not put a new dot on the line?"

"As soon as this rule was adopted," Conway has written me, "all the other rules were discarded, the starting position was simplified to just n points and sprouts sprouted." The importance of adding the new spot was so great that all parties concerned agree that credit for the game should be on a basis of 3/5 to Paterson and 2/5 to Conway. "And there are complicated rules," Conway

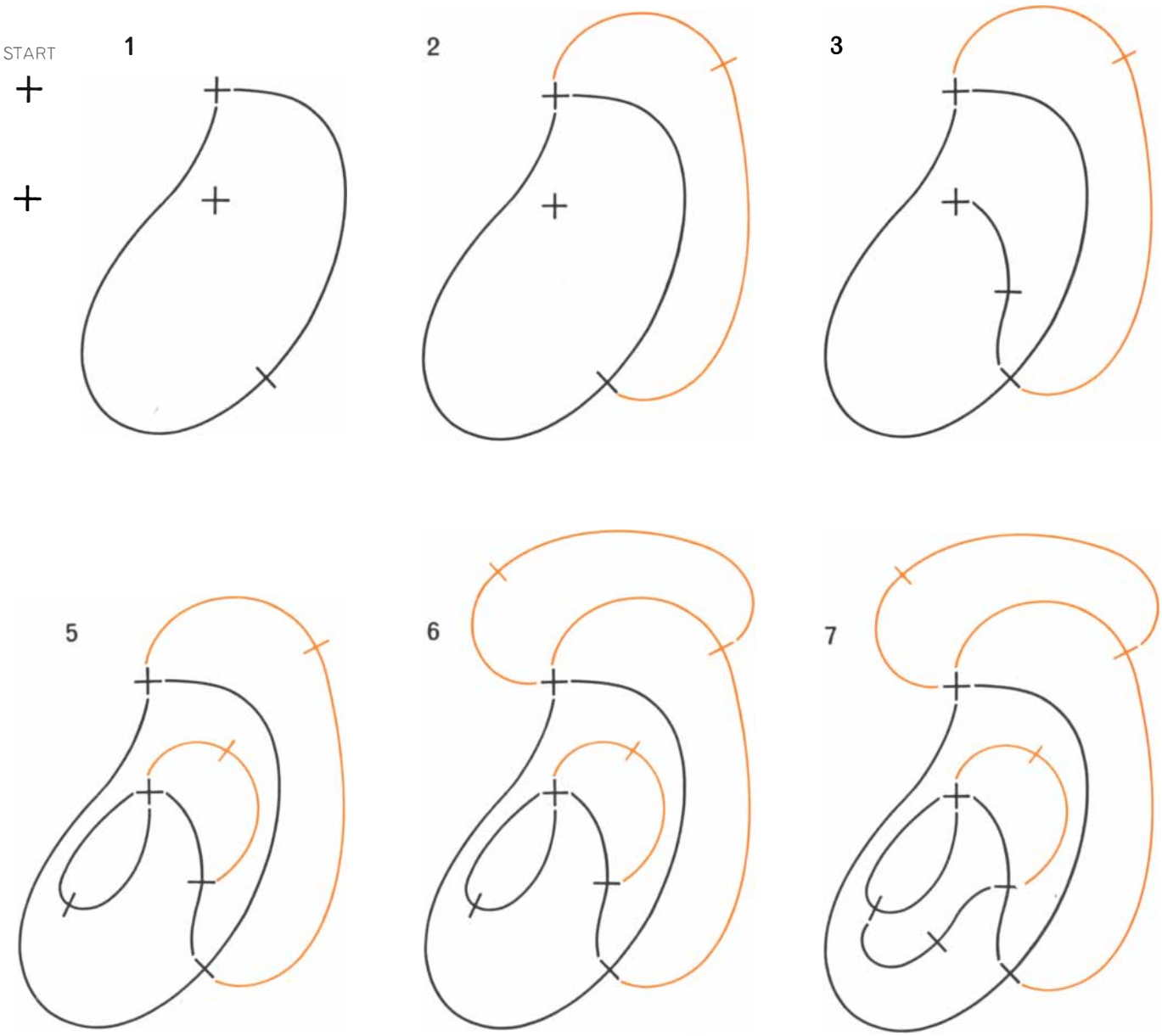
adds, "by which we intend to share any monies which might accrue from the game."

"The day after sprouts sprouted," Conway continues, "it seemed that everyone was playing it. At coffee or tea times there were little groups of people peering over ridiculous to fantastic sprout positions. Some people were already attacking sprouts on toruses, Klein bottles and the like, while at least one man was thinking of higher-dimensional versions. The secretarial staff was not immune; one found the remains of sprout games in the most unlikely places. Whenever I try to acquaint somebody new to the game nowadays, it seems he's already heard of it by some devious route. Even my three- and four-year-old daughters play it, though I can usually beat them."

The name "sprouts" was given the game by Conway. An alternative name, "measles," was proposed by a graduate student because the game is catching and it breaks out in spots, but sprouts was the name by which it quickly became known. Conway later invented a superficially similar game that he calls "Brussels sprouts" to suggest that it is a joke. I shall describe this game but leave to the reader the fun of discovering why it is a joke before the explanation is given next month.

Brussels sprouts begins with n crosses instead of spots. A move consists of extending any arm of any cross into a curve that ends at the free arm of any other cross or the same cross; then a crossbar is drawn anywhere along the curve to create a new cross. Two arms of the new cross will, of course, be dead, since no arm may be used twice. As in sprouts, no curve may cross itself or cross a previously drawn curve, nor may it go through a previously made cross. As in sprouts, the winner of the normal game is the last person to play and the winner of the misère game is the first person who cannot play.

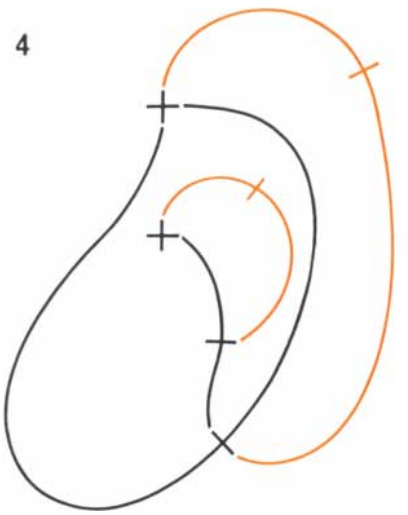
After playing sprouts, Brussels sprouts seems at first to be a more complicated and more sophisticated version. Since each move kills two crossarms and adds

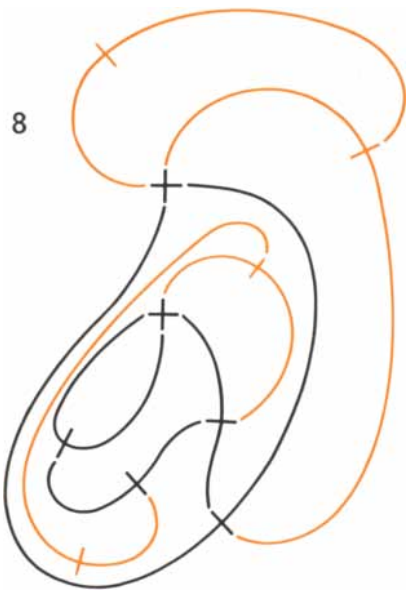


Typical game of two-cross Brussels sprouts

two live crossarms, presumably a game might never end. Nevertheless, all games do end and there is a concealed joke that the reader will discover if he succeeds in analyzing the game. To make the rules clear, a typical normal game of two-cross Brussels sprouts is shown that ends with victory for the second player on the eighth move [*see illustration on these two pages*].

A letter just received from Conway reports several important breakthroughs in sproutology. They involve a concept he calls the "order of moribundity" of a terminal position, and the classification of "zero order" positions into five basic types: louse, beetle, cockroach, earwig and scorpion. The larger insects and arachnids can be infested with lice, sometimes in nested form, and Conway draws one pattern he says is "merely an inside-out earwig inside an inside-out louse." Certain patterns, he points out, are much lousier than others. And there is the FTOZOM (fundamental theorem of zero-order moribundity), which is quite deep. Sproutology is sprouting so rapidly that I shall have to postpone my next report on it for some time.

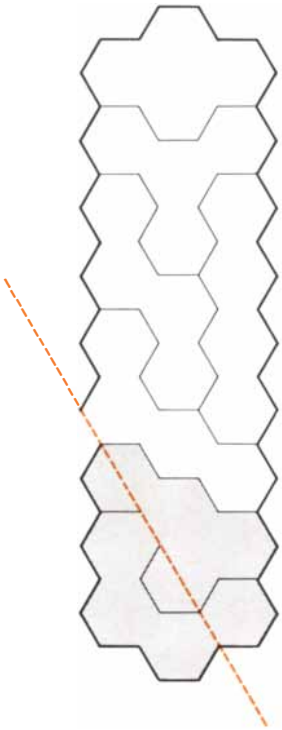




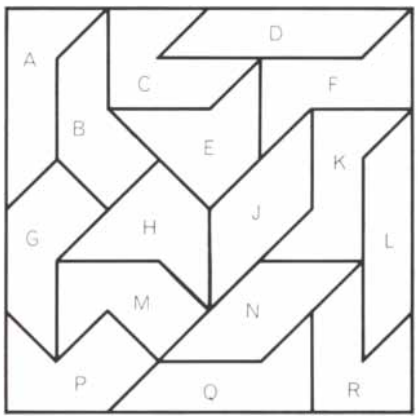
The eight problems presented in March prompted many informative letters. The dragon curve of problem No. 3 aroused the most interest. George P. Darwin, Chandler Davis, Robert R. Keegan, John S. Littler, Peter Murray, J. D. Pryce, Larry Rantapaa, E. Salamin and Charles L. Seitz found other ways of generating the curve. David C. Hamilton discovered a more general family of curves to which the dragon belongs, and Donald E. Knuth proved that four dragons of order infinity would fit together and completely cover the plane. William F. McGill and John V. Olson, using a computer at the University of California at Los Angeles, and Robert A. Phillips, using a computer at the Milwaukee Institute of Technology, made beautiful plottings of order-15 and smaller-order dragons of different colors, fitted together in various ways.

One of the "quickie" problems pointed out that the integers 1, 3, 8 and 120 form a set with the property that the product of any two integers is one less than a perfect square, and asked for a fifth integer that could be added to the set. The trivial answer was zero. Many readers wondered if there might not be a sixth integer. This question was first called to my attention by W. A. Resch, and I have since learned that it appeared about 10 years ago as a mathematical competition in the *Sunday Times* of London. No one at that time found a number higher than 120. M. G. Harman of London sent me his proof that, if there is such a number, it must be greater than 10 to the power of 580. As far as I know there is no proof that a sixth number does not exist, or even that there is a finite number of integers in this curious set.

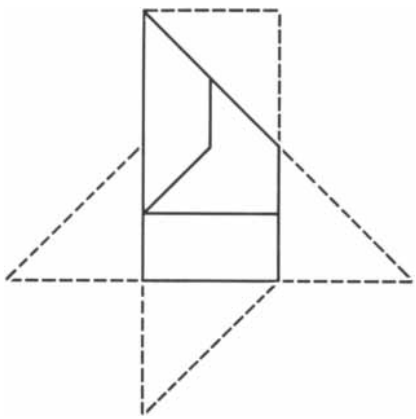
Problem No. 4 asked for the lowest order of polyomino a number of replicas of which can be placed on the plane in such a way that, if each is given a color, four colors are necessary to prevent two polyominoes of the same color from sharing a common border segment. The answer given in April showed how six dominoes could be placed so that four colors



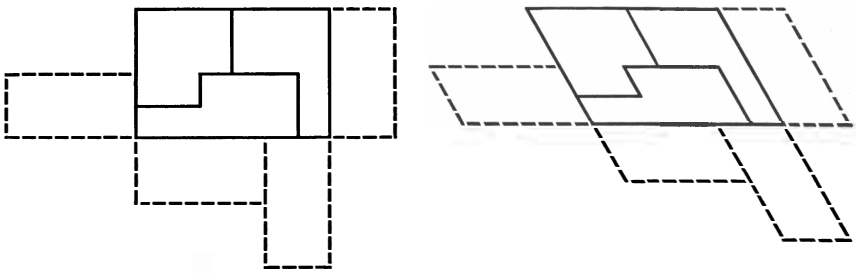
The tower pentahex



Solution of difficult tetrabolo problem



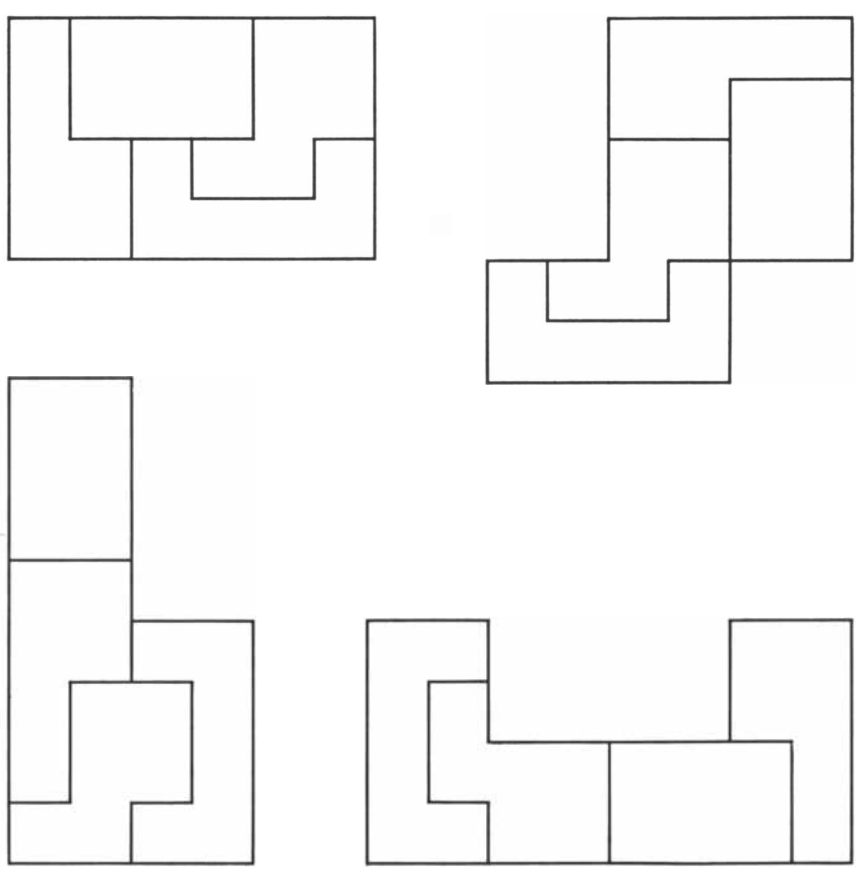
Solution of tetrabolo-replication problem



Octomino solution with infinite variants

were required. I had convinced myself that no set of unit squares (monominoes) could be so arranged as to require more than three colors. To my astonishment several readers found ways of putting 12 or 13 monominoes on the plane to form a "map" that needed four colors. (Spaces between squares are not considered regions of the map.) Bent Schmidt-Nielsen, a chemistry student at the University of California at San Diego, was the first to send me a way of doing this with as few as 11 unit squares, and E. S. Ainley of London made the same discovery a few weeks later. Eleven is apparently minimal, although no one has yet proved it. Finding an 11-pattern is a pretty problem. Can the reader arrange 11 unit squares on the plane in such a way that, if each square is a solid color, four colors are needed to prevent two squares of the same color from being adjacent along a common segment of their borders? I shall show how to do it next month, and should be pleased to hear from anyone who can lower the number below 11 or prove that 11 is minimal.

George Groth wrote from Chicago to ask a related question involving cubes. What is the smallest number of cubes, all the same size, that can be put together in such a way that every pair of cubes is touching along a common surface? In other words, if n is the number of cubes and each cube is a solid color, n colors will be required to prevent two cubes of the same color from having a surface in common. A common surface need not, of course, be an entire side of a cube, but it must be a surface and not a line or point. This also will be answered next month.



Hexomino solution to replication problem

The impossible tetrahex figure among those displayed last month is the triangle. David Klarner was able to prove it impossible, but only by a tedious argument that begins by observing the limited number of positions in which the propeller can be placed.

In Klarner's solution for the difficult tower figure [*see top illustration on preceding page*], note that the shaded portion has an axis of symmetry allowing it to be reflected and thus providing a second solution. Has any reader found a pattern that differs from these two?

One way to form a square with the eight asymmetric tetraboloes and their mirror images (no turning over being allowed) was independently discovered in 1962 by two Britons, R. A. Setterington of Taunton and A. F. Spinks of Letchworth [*see middle illustration on preceding page*]. Pieces *G*, *H* and *M* form a shape that can be rotated and reflected; *JKN* and *FJK* can each be rotated, and *CE* can be interchanged with *MP* to provide many variant solutions. Thomas H. O'Beirne of Glasgow recently found a different way to arrange *A*, *B*, *C*, *D*, *E*, *F*, *G* and *H* to form a pattern in which rotations and interchanges of parts produce still other variants. The number of distinct solutions is far from known.

Four tetraboloes can be put together to make larger replicas of each [*see bottom illustration on preceding page*]. Only the triangle need be moved. Note that still other positions of the triangle produce replicas of four more tetraboloes, making the total eight, or more than half of the entire set.

Are there other sets of four different shapes with the same property? Maurice J. Povah of Blackburn, England, has proved the number to be infinite. His proof derives from the solution shown at the left in the top illustration on this page, in which four octominoes form replicas of themselves. An affine transformation [*right*], varying the angles, furnishes an infinity of solutions. Povah also discovered a solution with four hexominoes [*see bottom illustration on this page*]. These pieces will replicate 15 different hexominoes, including themselves. Povah believes this is a maximum for the hexominoes. With pentominoes, the best he could do with four pieces was to form four replicas of other pentominoes, not including any of their own shapes.

RESEARCH AND ENGINEERING

Function

The Research and Engineering organization is the principal source of all programs that originate at the Fort Worth Division of General Dynamics. R&E personnel undertake the basic and applied research which leads to the definition and design of new aerospace systems. The broad scope of the R&E functional responsibility includes the continuous development of new programs and the technical management of major hardware projects from the conceptual stage through the operational phase.

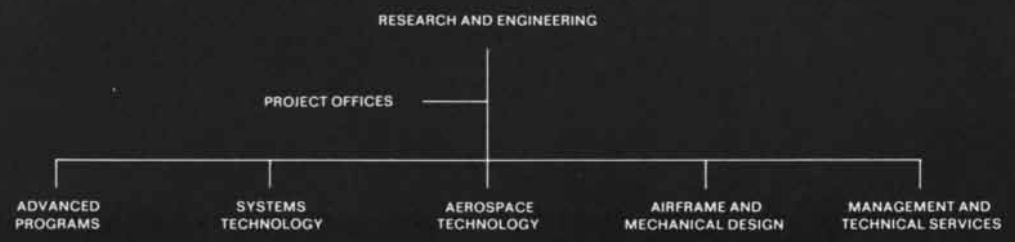
Organization

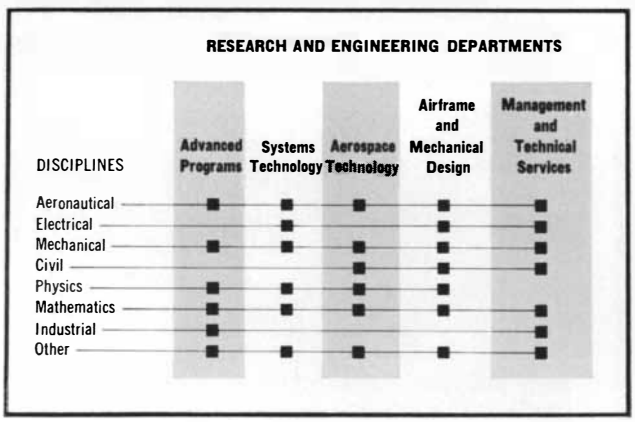
Research and Engineering is organized essentially in terms of principal engineering functions. Each of the five departments is responsible for the tasks which fall within its technical surveillance whether this task entails research, development, design or production. As a result of this functional organization structure, individual engineers have an opportunity to be familiar with a variety of programs simultaneously. The diversity of experience not only prevents overspecialization but it allows the individual to benefit from a fertile flow and interchange of ideas. When technical management activities must be coordinated across the functional departmental lines, project offices are established within the R&E organization; this project management experience provides another dimension to professional growth.

Activities

Engineering resources are being utilized on the complex tasks associated with preparing the F-111 A and B airplanes for their operational roles and with designing and developing other members of the 111 family. Engineering skills are being used, also, in the formulation of completely new aircraft product lines and space surveillance systems.

To accomplish these activities, R&E personnel research, analyze, design, integrate, test, plan, implement, manage, monitor, administer, and support. Methods and techniques have to be updated, unique capabilities have to be expanded, facility needs have to be identified and enlarged, expertise has to be enhanced, experimental and analytical data has to be added to—all a continuing set of activities. And a purposeful set of activities that an engineer finds technically rewarding.





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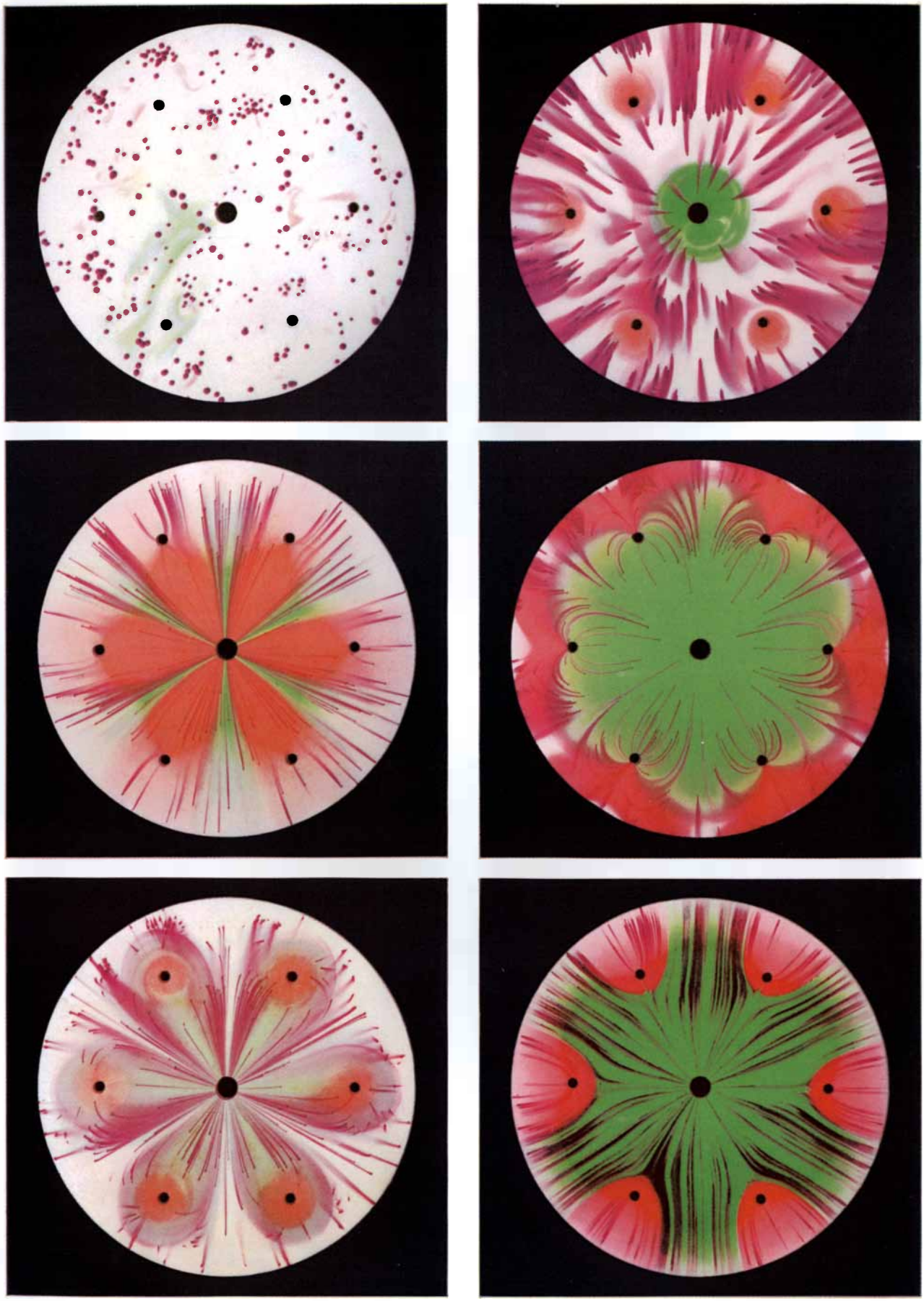


Patterns randomly generated in fluid mapper designed by A. D. Moore

THE AMATEUR SCIENTIST

How to construct fluid models that simulate fields of force

Conducted by C. L. Stong

The patterns of force known as potential fields are of interest to many experimenters. Such fields surround magnets and electric charges and arise in heat conduction. Related patterns appear in the flow of liquids or gases through permeable materials such as oil sands and also in the path of electric currents through conducting substances.

Some potential fields can be made visible by simple procedures. A familiar example is the use of iron filings to show the magnetic field of a horseshoe magnet. The magnet is placed on a level, nonmagnetic surface and covered with a sheet of paper. When the filings are sprinkled on the paper, they form a pattern of curving lines that trace the magnetic field in two dimensions. Some potential fields can be investigated mathematically and by graphical means. Others can be simulated optically with moiré patterns.

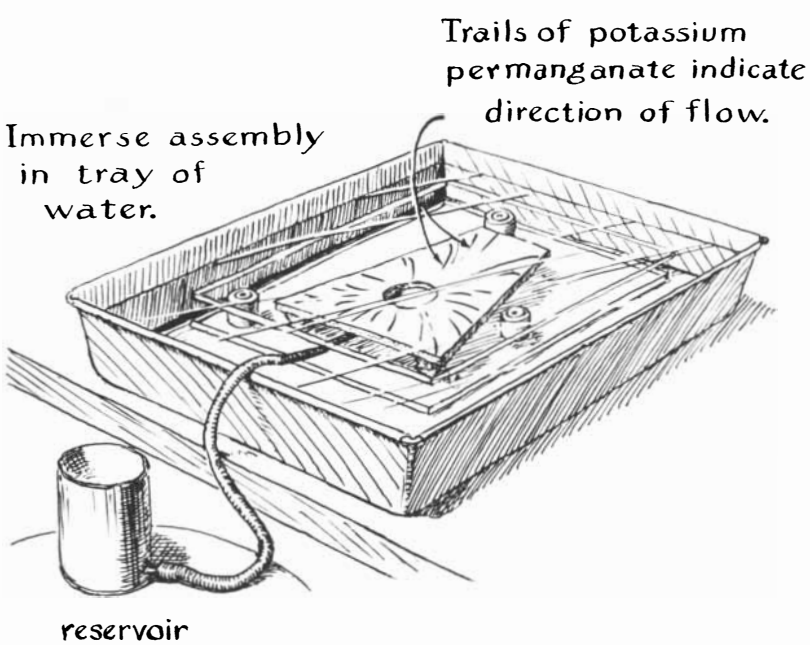
Perhaps the most versatile and inexpensive instrument available to amateurs for depicting and analyzing potential fields of many kinds is the fluid mapper. The device simulates potential fields by thin lines of dye that form in the flow of a sheet of water or some other fluid representing the phenomenon under investigation. In addition to the lines of dye, portions of the fluid can be colored to identify selected areas in the field. The color not only increases the power of the fluid mapper as an analytical tool but also transforms it into an engrossing plaything with which one can generate abstract designs that resemble the colorful abstractions made by harmonographs and kaleidoscopes [*see illustration on opposite page*].

The fluid-flow method of simulating potential fields was originated some 65 years ago by H. S. Hele-Shaw of the University of Oxford. His ideas suffered a long period of neglect. A. D. Moore, now professor emeritus of electrical engineering at the University of Michigan, revived the method some years ago; in the past two decades he has devised numerous techniques for making and operating fluid mappers. Moore explains the construction and use of the devices as follows:

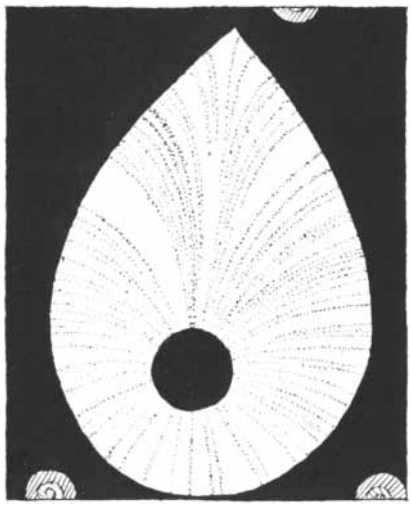
"The fluid mapper consists essentially of a pair of closely spaced plane surfaces immersed horizontally in a shallow pan of water. The upper surface might consist of a sheet of plate glass and the lower one of a specially shaped slab of plaster. Usually the surfaces are spaced about .035 inch apart, but flow spaces of half or twice that can be used. The plaster slab may have in it one or more holes of various shapes and sizes. Some of them may be partly filled with sand, depending on the nature of the potential field that is to be depicted.

"The holes, known as wells, are usually connected at the bottom to rubber tubes for admitting a controlled flow of water from movable reservoirs, which ordinarily are quart-sized cans equipped at the bottom with nipples that fit the rubber tubes. Flow is generated in the space between the plaster slab and the glass plate by moving the reservoirs above or below the level of the water in the pan. Water within the thin flow space moves either in the direction of the forces that constitute the potential field being simulated or at right angles to the forces, depending on the nature of the field. The direction of flow within the thin space is made visible by inserting fixed particles of dye between the glass and the plaster slab when the apparatus is assembled. Typically the dye consists of small crystals of potassium permanganate, which dissolve slowly to form thin purple trails in the water.

"The flow space between the plaster slab and the glass functions as a scale model of the potential field under investigation. The field of a horseshoe magnet, for example, can be simulated



Components of a fluid mapper

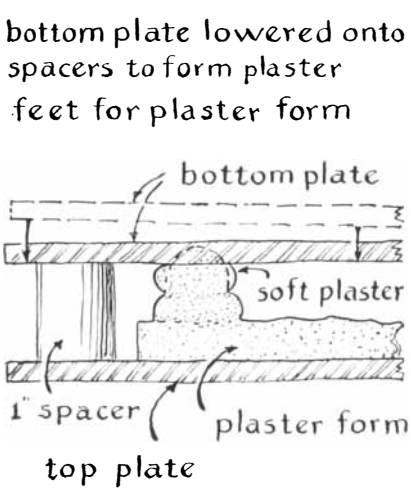


Plaster slab with curving sides

by a rectangular flow space with two wells that represent the poles of the magnet. The reservoirs that supply the wells can be manipulated so that one well functions as a source of flowing water and the other as a sink. Dye lines in the flow space surrounding the wells portray the potential field, in this case the magnetic flux.

"Experimenters sometimes need to know the electrical resistance of an irregularly shaped sheet of conducting material. An example might be the resistance from the center to the edges of a sheet of copper in the shape of a keystone. The problem can be solved easily by means of a fluid mapper, which shows the path the current would take through the copper. The example will illustrate the procedure of constructing and operating a fluid mapper.

"A well in a keystone-shaped slab of



Molding feet for the slab

plaster represents the electrical connection to the inner edge of the copper sheet [*see illustration on preceding page*]. The outer boundary of the slab represents the outer edge connection. The slab is equipped with four plaster feet, which rest on a horizontal sheet of plate glass. A second horizontal sheet of plate glass is supported .035 inch above the plaster slab by three spacers, which also rest on the lower sheet of plate glass. The lower end of the well is closed except for a rubber tube that admits water to the well from a reservoir in the form of a tin can.

"The plaster slab is made first. Almost any plaster can be used, but after much experimentation I found that the best material is the plaster commonly used by dentists in making dentures. I prefer the type known as Duroc, a product of the Ransom and Randolph Company of Toledo, Ohio. Duroc comes as a yellow powder; when it is mixed to the consistency of soft paste, it sets to stone hardness in from 10 to 20 minutes. The cost varies roughly from 15 to 25 cents per pound (or pint) of powder, depending on the quantity bought.

"Typically the slabs are cast in shallow, boxlike molds that have bottoms of plate glass and sides that can consist of narrow strips of metal temporarily fixed to the glass on the outside by dabs of plaster. Slabs with curving sides, such as the one shown in the accompanying illustration [*top left on this page*] can be formed of flexible strips. Usually I solder a short, right-angled strip to one side of each straight rail near the center; the strips serve both as handles for manipulating the rails and as braces.

"To make a slab in the form of a keystone I cut a template of cardboard to the planned size, say eight inches long and six inches wide at the broad end [*see illustration on opposite page*]. A square hole is cut in the cardboard in order to admit a cylindrical ring for molding the well. Such inserts are usually made with a slight taper and greased with Vaseline for easy removal from the hardened plaster. I center the template on a level sheet of plate glass, place the cylindrical ring in the square hole of the template (holding the ring with the narrow end down) and cement the ring in place by pouring in some plaster. The metal rails are placed snugly against the four sides of the template and similarly cemented in place. After the plaster has set I remove the template and pour the slab. Slabs approximately 3/8 inch thick work nicely. Larger slabs are made thicker.

"The quantity of plaster required for casting a slab is determined by the volume of the slab. For the slab I have been describing the volume is about 12 cubic inches. A pint of Duroc powder, when added to six ounces of water, yields plaster of about optimum consistency. Pour the powder into the water and stir the mixture with a spoon until the lumps are gone.

"Ladle about two-thirds of the mix into the mold and spread it around with a spoon. Air bubbles will be trapped in the corners and on the upper surface of the plate glass. They must be dislodged or indentations will appear in the finished slab. To remove the bubbles probe the wet mix with a small stiff brush. Jiggle the brush up and down, particularly in the corners and along the rails. The air bubbles will rise into the mix, where they will do no harm.

"Add and distribute the rest of the plaster. Agitate the entire surface with the bowl of a spoon, using a jiggling up-and-down motion. As a result of this procedure the mix flows into a relatively smooth upper surface. After about 20 minutes the slab will have hardened adequately.

"Wet the whole assembly in a container of water or under a tap. Absorbed water will release the plaster from the glass. The plaster will slide off the glass readily. The cylindrical ring can now be removed. Invert the slab. The face that was in contact with the glass should appear glossy.

"The slab is now equipped with supporting legs. This operation requires the use of two sheets of plate glass and three cylindrical spacers about an inch long. The length of the spacers is not critical, but all three must be equal in length to within .0005 inch. They can be made of metal or plaster.

"Select three wood screws that have flat heads and, with a file, dress down the points of the two longer screws until they match the shortest one as closely as possible. Make three cylinders of gummed paper tape about 3/4 inch wide and 3/4 inch long. Center the paper cylinders upright on a level sheet of plate glass. Stand the wood screws on their heads near the edges of the glass in the largest possible triangular configuration. Place the cylinders close together at the center. Fill them with plaster, heaping the mix on top to a height of about 1¼ inches. Lower the second glass plate horizontally over the first until it rests on the three wood screws. After 20 minutes wet the castings to release them from the glass. These spacers may

be enough alike to be used. If not, repeat the procedure, except this time substitute the plaster spacers just made for the three wood screws. Discard the spacers that were made first. The second set will be almost identical in length.

"Wash and dry the two glass plates. Place one of the plates on a level surface. Center the keystone slab on the plate with the glossy side down. Place the plaster spacers in a triangular array near the edges of the glass. Thoroughly wet the slab but mop off standing water. Apply small dabs of plaster to the four corner areas. These dabs will become a set of feet. Add more plaster on top of each to make a pile about 1¼ inches high.

"Lower the second sheet of plate glass horizontally over the first until it comes to rest on the spacers. The glass will press the piled plaster to a height that matches the height of the spacers. When the plaster has set firmly, wet it and separate the plate from the feet.

"The slab is now equipped with its own permanent set of four feet. The well must next be closed at the bottom and fitted with inlet tubing. Place the slab, glossy side down, on a glass plate. Cut a four-inch length from a piece of rubber tubing with an inside diameter of approximately 1/8 inch. I use the type of tubing called handmade tubing, which is characterized by a rough outside surface.

"From thin sheet aluminum, heavy tinfoil or wet cardboard cut a disk about half an inch larger in diameter than the well in the slab. Heavily coat one end of the rubber tubing with plaster for half an inch or so (being careful not to plug it) and lay it on the slab with the plastered end at the edge of the well. Bend up the disk or patch at one edge to make it fit roughly down over the tubing, place it over the well and apply plaster all over it. Be sure to seal it all around to prevent leakage. This operation completes the slab.

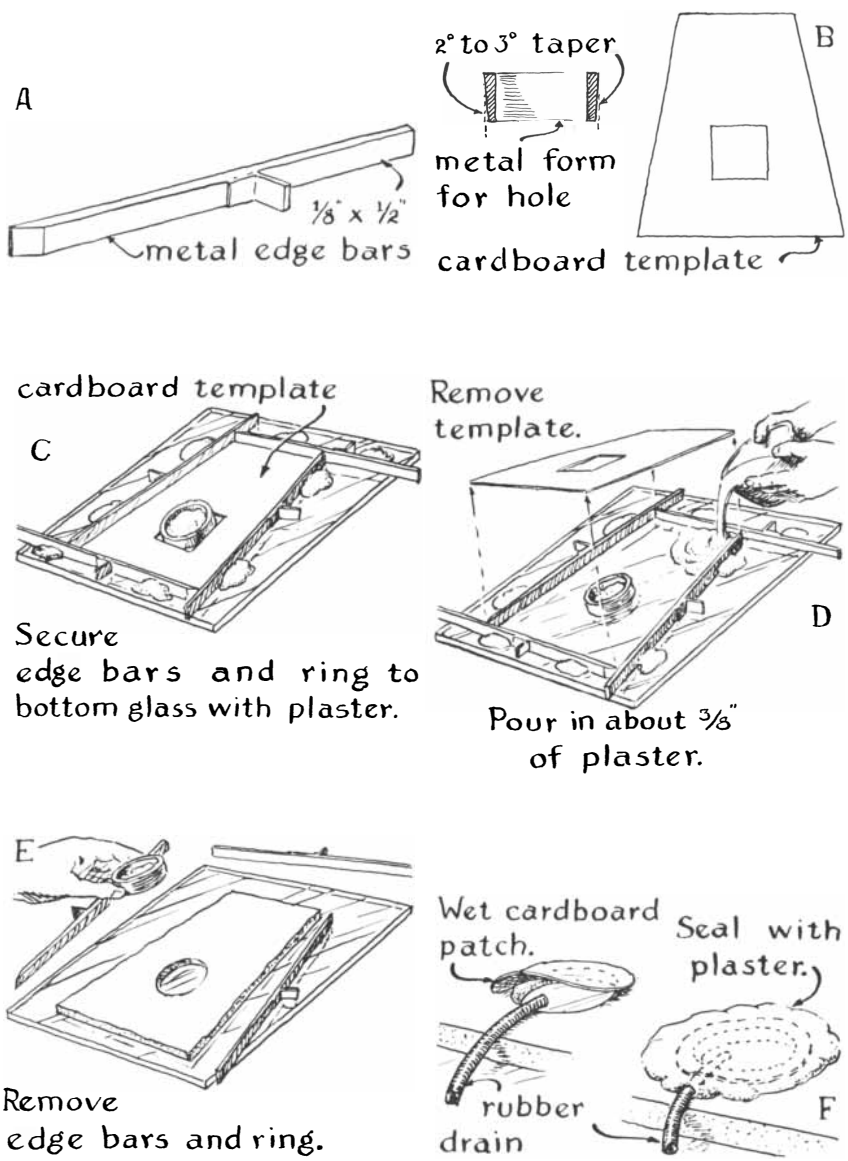
"A sheet of plate glass is centered in the bottom of a rectangular baking pan, preferably one made of aluminum or some other nonrusting metal. Place the completed slab, glossy side up, on the plate glass. Arrange the spacers around the slab in triangular array and fairly close to the edges of the plate glass. The tops of the spacers are now flush with the glossy surface of the slab. They will support a second sheet of plate glass above the slab, but the length of the spacers must be increased to provide a flow space about .035 inch thick between the slab and its glass cover. This is done by placing a shim on top of each spacer. I use brass washers 7/16 inch in diameter for shims and adjust their thickness by rubbing them on grit paper.

"I start with seven washers. Both sides of all seven are first ground lightly to remove burrs. Three are then placed in a widely spaced triangular array between the two sheets of plate glass. The remaining four are slid one at a time between the plates to test for fit. The three thinnest washers are substituted as the plate separators. Thereafter, by cut and try, the remaining washers are alternately ground and tested. Ultimately the three that are most nearly equal in thickness are selected for use.

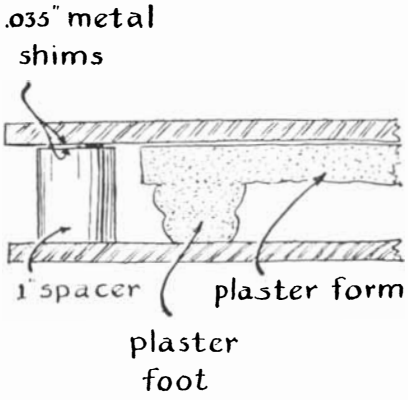
"After completing the shims I solder a nipple into the bottom of a quart-sized tin can. The nipple is connected to the well inlet by a 30-inch length of rubber tubing of the same size and type as the tubing used for the well inlet. For the coupling I use a short length of metal tubing.

"Pour enough water into the pan to immerse the apparatus to a depth of about half an inch. Put an inch or two of water in the can. Alternately raise and lower the can to force out any bubbles trapped in the tubing. Sometimes one must use a rubber ear syringe to force water in and out of the tubing and thus dislodge firmly trapped air. Some water contains a large amount of absorbed air that must be removed by boiling or prolonged standing.

"Dye in the form of crystals of potassium permanganate is now prepared. If the crystals appear to be larger than



Steps in the construction of a plaster slab



Spacing technique

about one millimeter, grind them lightly in a mortar. Sift the grindings through two screens, one with spacings slightly less than one millimeter in diameter and the other with spacings slightly larger. A tea strainer can serve as the finer screen. Crystals that remain in the finer sieve but pass through the coarser sieve are transferred to a saltshaker in which all holes but one are covered by adhesive tape. Warning: Potassium permanganate is toxic. Do not inhale the dust or get it in the eyes.

"Sprinkle the water above the immersed slab with a circle of crystals spaced about five millimeters apart. A circle that lies midway between the well and the edge of the slab will yield a nice field pattern. The crystals sink through the water and come to rest on the slab. Try various sprinklings for the best effects on a new slab.

"Finally, lower a sheet of plate glass gently on the shimmed spacers. Avoid abrupt movements that would disturb the water enough to wash the crystals off the slab. Incline the glass slightly so that one edge enters the water first; in this way the formation of bubbles on the lower surface of the glass is minimized. When this cover glass is in place, slowly lower the reservoir a few inches. Thin lines of dye will flow from the crystals to the well. Return the reservoir to its former position and then slowly elevate it somewhat. The lines of dye will flow from the well to the crystals. In addition, lines will now flow from the crystals to the edges of the slab. Thus by manipulating the reservoir one can cause a complete pattern of the potential field to extend from the well to the edges of the keystone.

"The pattern can be photographed. Alternatively, the lines of dye can be made to register permanently on the slab itself. I discovered this technique quite by accident. (Indeed, many of the other procedures were learned by trial and error.) On one occasion I applied a thin coat of rubber-emulsion paint to a slab, hoping to prevent the erosion of the glossy face. After operating the apparatus with potassium permanganate dye I was surprised and pleased to observe that the dye lines reacted chemically with the paint and made a permanent imprint. At present I use Sherwin-Williams' Super Kem-Tone (white) for this kind of record-making. A record of the pattern made by a keystone slab is depicted in the accompanying illustration [*bottom left*].

"With this pattern at hand it is relatively easy to determine the electrical resistance that would be introduced in a circuit by a conductor of this shape. To determine the numerical data from the pattern I place a sheet of translucent paper over the slab and trace about 24 lines that happen to form a radial pattern of reasonably uniform spacing. If the resulting figure, which I call a 'map' of the field, is characterized by symmetry, as in the case of a keystone, only half of the pattern need be traced [*see illustration at bottom right*].

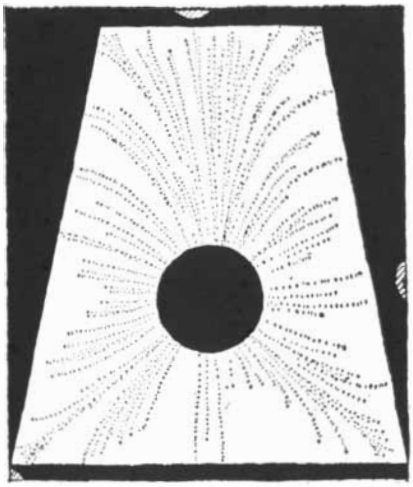
"The space between adjacent flow lines of the map is then subdivided into increments known as curvilinear squares. Two properties characterize the curvilinear square. First, approximately but usually very closely, each side will touch an inscribed circle at some point. Second, as a curvilinear square is successively subdivided into smaller and smaller increments—into quarters, eighths, sixteenths and so on—progressively smaller increments approach more and more closely the shape of a true square.

"This property is particularly useful because true squares of any size cut from a given sheet of conducting material are equal in electrical resistance. Assume, for example, that opposite edges of a conducting square are connected in an electrical circuit and that one volt applied across the square will induce in the square a current of one ampere. The resistance of the square is equal to the quotient obtained by dividing the voltage by the current; in this case the resistance is one ohm.

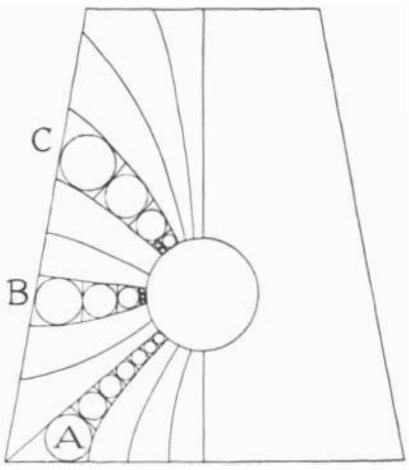
"Assume that the sheet is divided down the middle so that half of the current is confined to each half of the sheet. A measurement of the voltage would show half of the voltage across each half of the resulting rectangular strip. Each quarter of the original square would then have imposed across it .5 volt that would induce a current of .5 ampere. The resistance of each quarter of the square would equal one ohm, because 1/2 divided by 1/2 is 1. Because curvilinear squares approach true squares in shape when they are sufficiently subdivided, the electrical resistance of all curvilinear squares is independent of their size if the squares are all cut from the same material.

"Three pairs of flow lines form three tubes; these have been mapped into curvilinear squares in the illustration below. I made the subdivisions with the aid of a drawing instrument known as a circle template. It is a sheet of plastic with a series of holes of graduated diameter. Such templates can be bought in stores that deal in artists' and engineers' supplies.

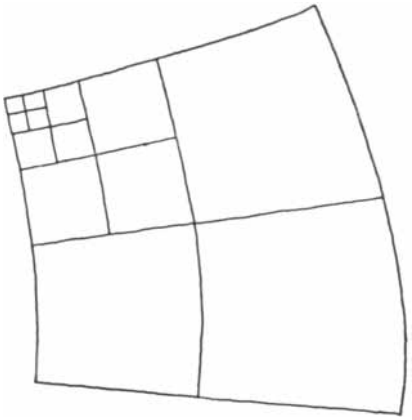
"The template is placed over a tube. Through an opening of appropriate size I draw a circle that is tangent to the flow lines and also tangent to the end, after



Fluid map of a potential field



Partially subdivided map



Division of a curvilinear square

which the resulting curvilinear square is closed by drawing a line that is also tangent to the circle. The template is then shifted for similarly subdividing the rest of the area. Subdivision can proceed from either end or both ends. Occasionally a tube will divide exactly into a whole number of curvilinear squares, as at *A* in the illustration. More often a fractional rectangular area will remain. The remainder is subdivided just as though its sides were flow lines, as at *B* and *C*.

"Electrical resistance is evaluated by analyzing the subdivided map; other physical quantities can also be studied in this way. In the case of electrical resistance each curvilinear square is tentatively assumed to have a resistance of one ohm. I call this a 'relative' ohm. The value is later converted to true ohms. In making the evaluation curvilinear squares are treated as though they were resistors in a circuit.

"The total resistance of a number of adjacent curvilinear squares in series is equal to their sum. The total resistance of a group of curvilinear squares in parallel is equal to the reciprocal of their sum. The string of seven curvilinear squares enclosed by the flow lines at *A* in the illustration, for example, has a total electrical resistance of seven relative ohms. The total resistance of the tube at *B*, which has three full curvilinear squares and is also connected to the three little parallel curvilinear squares that constitute the fractional remainder, is equal to 3 plus 1/3, or 3⅓ relative ohms. At *C* the total resistance amounts to three relative ohms plus one relative ohm in parallel with two relative ohms in series, or 3⅔ relative ohms.

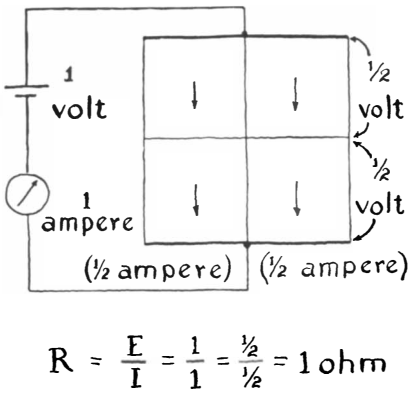
"The total relative resistance of one half of the symmetrical keystone is found by adding the reciprocals of all the relative ohms of all tubes on that side, then taking the reciprocal of that value. The total relative resistance of the entire keystone is equal to half of the resistance of one side of it because the sides are in parallel.

"To convert relative resistance into true resistance cut a true square from the conducting material of which the keystone will be made. Measure or otherwise determine the true resistance of the true square. Multiply the total relative resistance of the keystone, as determined by the fluid-mapping technique, by the actual resistance per square of the conducting material. The resulting product is equal to the true resistance of a keystone made of that material. Electrical capacitance, heat conductivity and like physical quantities can be similarly determined by substituting appropriate equations and data.

"Occasionally an experimenter wishes to analyze the potential field of a distributed source, such as when heat is developed in the whole volume of a conductor or in an electrical coil, the heat having to flow to the surface and then be conducted away through surrounding material with the same thermal conductance. Fields associated with such distributed sources are simulated by a well filled with sand or fine metallic shot. The sand or shot rests on braced screening placed partway down the well; the surface of the sand bed is made exactly flush with the upper surface of the plaster slab. The sand would simulate the cross section of the coil. Other variations in fluid-mapper technique include adjustments in the thickness of the flow space to simulate discontinuities in conductivity.

"Slabs equipped with multiple wells are frequently used to simulate interactions of potential fields. An example is the interaction of electrostatic fields in a radio tube equipped with three electrodes: a cathode, a grid and a plate. A circular slab would represent a horizontal cross section through the vacuum tube. A central well would simulate the negatively charged cathode. The edge of the slab would represent the positively charged plate. A circle of six equal intermediate wells would represent the grid electrode.

"Water, colored green by vegetable dye, would flow from the central well. Water colored red would similarly flow from the six interconnected 'grid' wells. Dye lines formed by potassium permanganate crystals would depict the direction of the electrostatic forces within the tube. A fluid map made by a slab of this

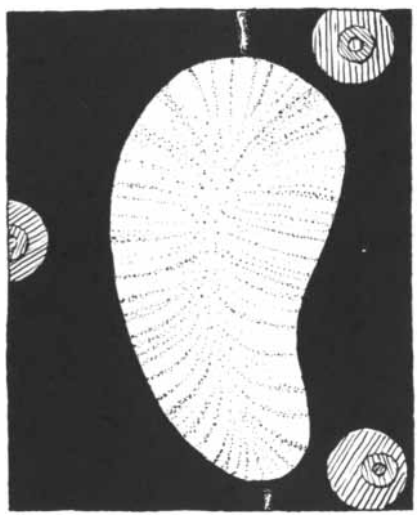


The "ohms per square" concept

type appears on the cover of this issue. The relative potentials and polarities imposed on the simulated electrodes are varied by adjusting the relative heights of the reservoirs with respect to the level of clear water in the pan.

"Colored water sometimes comes up in the pan, goes over the plate and obscures the flow pattern. One can prevent this by using water in the reservoirs that is slightly cooler than the water in the pan.

"Having made a numerical analysis of the potential fields in the vacuum tube, the experimenter may wish to explore a lighter side of the apparatus: its potential for generating abstract designs in color. This is accomplished by randomly changing the elevation of the reservoirs with respect to the water level in the pan. The accompanying photographs [*page 118*] of the vacuum-tube mapper depict six patterns that appeared during a constantly changing color show that lasted 15 minutes."



Use of a sand-bed well

BOOKS

H. G. Wells reconsidered

by Robert M. Adams

H. G. WELLS, by Richard Hauer Costa. Twayne Publishers, Inc. ($3.95).

With his hundred volumes, his effusive topicality and a certain quality of genial untrustworthiness H. G. Wells "covers" the last decade of the 19th century and the first two of the 20th after a special fashion. If only in bulk of output and variety of impact, he ought to outgun most Edwardians and Georgians and any but the supercruisers of the immediate postwar period: James Joyce, D. H. Lawrence and the collected Bloomsburians. But he does not, he never did and apparently he never will. As a tribute to the magnitude of his potential and the immensity of his failure, the Twayne English Authors Series has now consecrated to him a volume of apology, eulogy and elegy by Richard Hauer Costa.

These small lifeworks-and-significance summaries that, linked in publishers' series, are so numerous nowadays had better be trim in their composition and planning, comprehensive in their view of the facts and incisive in their critique. If they are not *multum in parvo,* they are nothing. Particularly in dealing with a figure as protean and disorderly as Wells, a little book that is not on its toes is likely to fall flat on its prat, and that, alas, is where Costa lands more often than not. No critic could reasonably object to his dodging the full story of Wells's social existence: the vicissitudes of his several careers, the multiple allegiances and disillusionments, the innumerable political and personal quarrels and the freewheeling love life. One can likewise accept his disregarding most of Wells's journalism and dismissing many of his novels or pseudo-novels as long-winded, ephemeral trash. In one form or another most of this discarding and discounting is inevitable. The problem is not with what Costa has thrown out but with what he has left in. Although he is writing a small book, he repeats himself unconscionably, not only in his opinions but also in his facts and citations. He has an instinctive gift for the approximate epithet, the overcrowded sentence, the blurred metaphor, the indiscriminate authority, the bald conclusion shorn of the particular judgments that make it meaningful. As a result his book is a genuine chore to read. He is addicted, as a climactic misfortune, to a special variety of compromise that takes all the edge off his judgments when it does not reduce them to abject self-contradiction. He tells us, for instance, that *The War of the Worlds* is vintage Wells because it is "mythopoeic," and he promptly describes it as the prototype of Grade-B movies and things of that sort. The books of the later Wells are described on one page as "all dead, dead as mutton" and on the next as the work of "the greatest public teacher of our time." These are two different speakers, to be sure (in the first instance Wells himself, in the second Sir Arthur Salter), but the author, in different rhetorical veins, is capable of agreeing with both of them, and this is not enlightening. Even within a single sentence two unresolved attitudes are sometimes allowed to scuffle. Wells's orphic pomposities at the end of *An Outline of History,* for example, inspire this verdict: "What makes judgments such as these closing words from his best-known work appear so shallow to scoffing intellectuals is that they stem from the soul, not of the artist, but of the pamphleteer—albeit the inspired pamphleteer of a commendable pamphlet."

In brief, Wells's statements are hogwash, but inspired and commendable hogwash, and anyone who calls them hogwash is a scoffing intellectual. When one finds Costa reporting that Joyce solicited Wells in 1928 for an opinion about *Ulysses* (*Ulysses* had in fact been published six years earlier, Joyce was working in 1928 on *Finnegans Wake* and that was the book about which he wrote to Wells), one is in a fair way to concluding that his book—even on a factual level—is a modest catastrophe. A reader who wants to see the premises of this new study worked out cleanly and with good command of the information to some orderly conclusions had better consult the book to which Costa himself has had rather liberal recourse: Bernard Bergonzi's standard study *The Early H. G. Wells.*

But Wells—indefatigable, jerry-built, upstart Wells, this sub-suburb of English literature—still remains to be sorted out. Costa is certainly right when he proposes, in the wake of Bergonzi, to get rid of the social pundit, the pseudo-religious prophet, the outliner of history. He does not perform this surgery with a sufficiently sharp knife, and he feels uneasily that we ought to read Wells's *The World of William Clissold* on the say-so of "the modern Existentialist, Colin Wilson." But in his better moments he knows this won't do. (In fact, he doesn't even pause to explain why "the modern Existentialist" grants his limited and special cachet to this patently inferior book.) Costa's true line is more straightforward, more traditional. He proposes to find the permanent artist, wherever he lurks in Wells, and untangle him from the stuffed-shirt public-affairs commentator who for the last 30 years of his life maundered publicly through books such as *William Clissold.* The trouble, for Costa, is that he finds in Wells two kinds of artist, a writer of comic novels generally arch and intimate in tone, and a teller of scientifically colored tales of the imagination, prevailingly somber in mood. What he wants to say is that the doom-ridden Wells is authentic—without, however, implying that the comic semicaricaturist author of *Kipps* and *Mr. Polly* is unauthentic. It is an adjustment of some subtlety, not altogether to be solved by deciding that "in the main" or "at bottom" Wells was a pessimist. Quite apart from his personal temperament, he was capable of both sad and buoyant effects, and this may have more to do with his choice of subject and emphasis than the notion of a

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"fundamental" nature. Who Wells was depended a good deal on what he happened to be contemplating; like any other man who writes for a living, he had to give full consideration to what he could get out of his material. This approach moves us rather quickly past the question of optimism and pessimism and somewhat closer to the artist, or artists, at the bottom of the Wells.

Is Wells the scientific romancer perhaps a maker of myths for our time, and redeemable on that score? One cannot make the point as categorically as this; Wells was nothing if not versatile, and his early extravaganzas constitute a very mixed bag. Some of the stories describe adventures in space and time, with other planets, other galaxies, other aeons; the exchanges are made by their visiting us as well as by our visiting them. Some of the romances involve tricks of genetic adaptation, schemes for abolishing one quality or another of matter, unusual sensory modes, loops in time. There are a good many hardware romances—stories of tanks and airplanes, interesting chiefly because they were written before there were any such machines. There are little farces and japes of boyish revenge, in which nosy outsiders get their comeuppance when they try to meddle with cool scientists who know the ropes. There are moralities and parables, there are stories that amount simply to a moody brooding over the possibility of spirit worlds beyond our conscious ken. Out of this medley the stories that seem most deserving of the title of "mythmaking" are those in which the author suggests or assumes an extremely long perspective, either cosmic or temporal. But these are precisely the stories in which Wells had the most predecessors and seems to have generated the least momentum. In "The Time Machine," for example, the gadget, having transported its operator to the year 802,701, deposits him in a world declining toward the condition described 75 years earlier by Byron in his poem "Darkness." In the other direction, *The War of the Worlds,* although it has been widely imitated and many variations have been played on the basic components of hominoids and flying saucers, has not developed in the way a myth, in the usual sense of the word, normally does. It hasn't acquired any new human meanings—hasn't grown, so to speak, from the inside out. Martian conflict, as far as modern writers contemplate it at all, is an opportunity to display various picturesque devices; otherwise it figures in the imagination of the time simply as a freakish accident, like a celestial collision or the extinction of the sun, which can scarcely be described as "myths."

The truth is that Wells, like most imaginative writers, had trouble domesticating himself in the world of science, or the world of science in the minds of fiction-readers. (He was thoroughly ambivalent, in fact, toward fiction as well as toward science, tending to despise the first and fear the second, although professing to admire both.) His scientists are a curious medley of figures whose variety of configurations suggests his own uneasiness of attitude. Dr. Moreau is a mad fiend derived from the pages of *Frankenstein;* there are various other prestidigitators, practitioners of magic both black and white. The Martians are not to be distinguished from their machines; they are, in fact, simply malicious brains within them. Heroic humanity, overridden by this insane technology, prepares to go tough and live underground, like incipient Morlocks, the blind underground proles of "The Time Machine." Occasionally scientists are represented as Fabian bureaucrats—the calm, omnicompetent engineers of "The Land Ironclads," for example, who can be either admired or loathed, depending on the needs of the story. Almost always the achievements of science seem to deform or destroy or disfigure humanity, and a schematic parable such as "The Lord of the Dynamos" sets in conflict the brute who has been victimized by the machine and the brute who has mastered it. There is little to choose between them.

The most positive achievement of the scientific mind, as Wells portrays it, is always flight, and flight represents a climactic and revelatory action in the fiction as well. Flying, literal as well as figurative (evasion, skipping town, "rising above it," floating aloft on a bag of wind), is generally a way out for the Wellsian hero, whose problem is usually defined as some sort of suppression or oppression. Getting out from under is often the great adventure, getting squashed or stifled a recurrent nightmare. Perhaps it is because science looms before the Wellsian agent now as an escape hatch from the present, now as a supremely efficient machine that will crush him in the future, that so much of Wells's scientifically oriented fiction seems today like mere pastiche, contrived for an effect that is itself arbitrary. From pieties and servilities and the "snug" absurdities of a caste system in which everyone knew his own place, and everyone else's as well, science indeed provided escape. But it often landed Wells's imagination in a cold and alien world, where he was in as much danger of being buried under clanking machinery or lost in the cosmic void as he was before of being stifled in intimacy.

I think it is this sense we have of Wells as a man torn between two worlds —loathing the old one but unable to leave it behind, impressed by the new one and eager to exploit it but fearful of it too—that gives so much of his fiction a sense of being somewhat out of control. This is not just the "science fiction" or the mixed genres; it is the most traditional novels as well. *Kipps* and *Mr. Polly,* for instance, are often referred to as post-Dickensian comedies, and it is true that in both novels Wells plays with his puppets and delineates their quirks of appearance from a position of immense superiority, as the Victorian novelists of character and caricature sometimes overtly did. The chief actors are funny little people, subject to so many squeezes from society and alienated by so many mannerisms of behavior and dialect as to seem easy to control. Their redemption is not particularly difficult either; by a combination of dumb luck and timely selfishness both Kipps and Mr. Polly manage to escape the trap society has set for them. Mr. Polly burns down his shop, ducks out of his marriage and succeeds in becoming something like a tramp-handyman; Kipps stumbles into one fortune, samples the life of a gentleman and finds it hateful, is swindled out of his money but is given more, which this time he is wise enough to enjoy in the 'umble state for which he was destined. Nothing would seem easier to manage than these unambitious immoralities. But there are angry and bitter overtones in both novels, perspectives that won't fit within the frame of social comedy. Masterman, an incidental character in *Kipps,* is a sick, angry, ruined man, far outside the protagonist's range of social comprehension; "Kipps," the hero's name, echoes traditional slang for a whorehouse, and the hero's true love is Ann Pornick, a name stemming from the Greek word for whore, *pornē.* It is as if Wells were snarling at his own social comedy from somewhere outside it.

No doubt it is a cramped and degraded world that *Kipps* portrays, and Wells, viewing it from the windy perspectives of Utopia, was bound to snarl at it energetically. But his Utopias too are often snarled at, are often anti-Utopias, sometimes by intent and sometimes "unconsciously," in spite of Wells's evident efforts at idealization. More awful things than admirable ones happen in the course of evolution. Time's multiple corrosions, the distorting at-

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MATERIALS

To be published in September, 1967

rophy and hypertrophy of specialization, rigid class distinctions, mechanical brainwashing or conditioning—all reduce man to macabre exterior shapes and alienate the working of his mind beyond sympathetic imagination. *When the Sleeper Wakes* is one of Wells's largest-scale fantasies about the future shape of things; beyond question it contains a number of extraordinarily clever prophetic hits. But the action of the hero within the new society is undiluted late-Victorian melodrama against Ruritanian agents of compulsion, conformity and repression. The voyager into the future finds himself preaching to the inhabitants of the glittering new megalopolis, and what he preaches is Victorian liberalism. Yet at the same time he finds himself admiring communal kitchens where the diners are fed soup from taps, imbibe chemical wine at plastic tables "with gracefully designed trade advertisements" and are enabled by a skillful device to wash their individual dinner plates between courses, thus effecting an immense saving in kitchen help. In such passages as this one feels Wells divided between admiration for a technical gadget and revulsion at a mechanical inhumanity he feels to be implicit in technical civilization. The overtones of this conflict are quite beyond his control; his ingenuities are likely to disgust us, his dramatics to reduce us to helpless laughter. For these reasons it now appears that Wells (like Bernard Shaw and Rudyard Kipling, among his contemporaries) must be seen as an artist flawed by incongruities—not adventitious but inherent in the two basic impulses on which his fiction was founded. The best of his work is built on a facing of this fact. As Shaw remarked, with characteristic cheek and common sense: "If you cannot get rid of the skeleton in your closet, you had better make it dance."

It is no crashing novelty at this date to say that the most successful of Wells's books is *Tono-Bungay*, nor is it hard to find the reason. The book is one in which Wells divided himself into two parts, incorporated himself, so to speak, in a man of science, George Ponderevo, the narrator, and his Uncle Teddy, a man of words, dreams and inflated verbiage. They are fliers of all the varieties in which Wells was interested—sneaky, imaginative, intrepid. Not only did he divide his hero; Wells also happily splintered his plot. There are at least five major actions in *Tono-Bungay*, a cheerful plethora of plot that gives the book, among English novels, the look of a Rube Goldberg contraption in overdrive. Several of Wells's favorite (and traditional) romances are here: our hero escapes from the retail dry-goods trade and from domestic monogamy, has an ill-fated romance with a *princesse lointaine*, learns to fly and finally escapes his enemies through flight. But there is also the great interpolated fable of a search after radioactive quap (it is hard not to suspect a Wellsian pun here too), not to mention the rise and fall of the empire built on Tono-Bungay itself, a wholly worthless patent medicine. This immense and lively novel is by no means free of false notes. Miss Beatrice Normandy, the fire-lipped *femme fatale* of the decadent British aristocracy, supplies the worst of them, but Ponderevo himself, in his capacity as a cosmic thinker, is responsible for quite a few. Still, just because there is so much going on all at once, the reader is under no compulsion to take any of it with deadly seriousness. The book is about bubble-bursting, and at its conclusion comparatively few of them are unpricked. That Ponderevo winds up unconcernedly building and testing destroyers for the lesser breeds beyond the law to use against English stupidity is but one rather striking evidence of its unaccented yet perfectly unashamed moral obliquity. The fact isn't even salved with any rhetoric—such as disfigures *Major Barbara*—about giving power to the underdog for use against the overdog. For Ponderevo, who says he loathes "the philosophy of the loose lip and the lax paunch," all things are flow, and he gives no loyalty to any momentary form, including the British Empire. The British public of 1908 found this a rather strong dose, as well they might; they refrained from buying the book in striking numbers, and Wells, who after all had a parvenu's sensitivity to sales, trimmed his, and never tried so hard in a novel again. But the high jinks, debunking and destructive tomfoolery of *Tono-Bungay* seem to flow from a vein deeper than that of the cosmic seer and prophet who is sometimes offered to us as "mythopoeic" Wells.

There is, indeed, something about good Wells fiction that is reminiscent of his imaginary airplanes. Nothing slick or streamlined about these contraptions. They are snorting, whistling, flapping monsters, intricate of strut and strap, lavish of canvas and wicker baskets, with lots of leather joints, much piano wire and sometimes gasbags; they are in fact immense, eclectic birds as they might have been constructed by a committee of architects working with the Crystal Palace as its inspiration. In all kinds of ways they are ungainly mechanisms,

launched along rackety trolleys by creaking catapults and requiring the intrepid passengers, before embarking, to fortify themselves against altitude with doses of ergot. Yet once in the air how they do swoop and flutter, these Victorian-Gothic air-machines! The stable, majestic flight of the jet liner is not for them; they whoosh, they zoom, they scream, they flap, and although their resources in combat are limited to butting one another, they contrive to do so most acrobatically. Just so with the fictions Wells contrived. He was essentially a man in motion. His novels succeed, when they do so at all, through variety of material, mobility of attitude and improvisational *élan*. They have little or no purity of intention; they are thickets of layered episode through which the Wells-agent fights his fantastic way toward an austerity that is itself crusted with rhetoric. Of the great novelists, Wells has most in common with Stendhal. Charles Maurras, who called *Le Rouge et le Noir* "un chef-d'œuvre de coquinologie comparée" (it translates, approximately, to "a masterpiece of comparative crumbology"), would not have been at a loss to appreciate *Tono-Bungay*.

An early Wells grotesque, *The Invisible Man,* comes close to formulating his fictional career in a parable. The hero of this quite serious jape is a man trapped belowstairs by the social order, who works inhumanly hard at a scientific problem for many years and finally murders his stupid, virtuous old father in order to escape the drabness closing in on him. At last he succeeds in rendering himself invisible; he does in fact make his escape from the world of the humdrum. His triumph is also his despair. He is at perfect liberty to observe other people without being observed himself; his mobility is unparalleled. But he has become a monster not only physically but morally. At first our sympathies are all with the invisible man in his escape from bumbling ineptitude and petrified stupidity; then he becomes megalomaniac, oppressive, inaugurates a one-man reign of terror. We are relieved as well as horrified when at the end of the story he is beaten to death with shovels by some normal navvies. Science gave Wells's imagination a freedom of mobility in new dimensions but at the expense of a humanity that always took its revenge. The deftness with which this melodramatic moral succeeds in short-circuiting *The Invisible Man* before it can resolve any of its basic attitudes may be one reason for our feeling that Wells at his cleverest is more like a good sewing machine with lots of attachments than is altogether compatible with being a great novelist.

Short Reviews

THE TRADITIONAL CRAFTS OF PERSIA, by Hans E. Wulff. The M.I.T. Press ($25). The low hills between Baghdad and Teheran were the scene of man's invention of the settled life. The ores from northern Persia were the first ever smelted; the Persian empire of Darius was the opulent foe of old Greece; to Persia came the caravans from China, bearing the silk and marvelous lore of the Far East—tales of paper, clocks and windmills; under Islam, Persia shone again with craftsmanship and a great science; India found unity under Persian swords and Persian manners. Through this tapestry of eight or 10 millenniums the craftsman's skill has woven a strong warp, and even today the bazaars of Shiraz and Isfahan harbor the stalls of artisans plying ancient trades.

Professor Wulff, trained in Germany as an engineer, spent five years in Persia before World War II as principal of the Technical College at Shiraz. He was under an injunction to be certain that his college taught not only the Western skills but also the traditional crafts such as silversmithing and brocade weaving. This book is the fruit of his painstaking study of a wide variety of skills, begun then and continued, after a long interval, in postwar Iran. A fluent speaker of Persian, he has assembled a 50-page technical glossary containing such terms as *maku* for the old shuttle and *morgak* for the iron dead center of the wooden turning lathe. Scholars will permanently cherish this record of a technical language slowly disappearing; the general reader will admire more the 400 photographs and the clear, precise, knowing accounts of a wonderful assortment of craftsmen, from the maker of sesame candies to the potter, the coppersmith, the woodturner and the engineer-contractor of underground water conduits. To his own observations and his careful questioning of his craftsmen informants the author adds the support of wide reading in the history of science and technology, braiding the strands into readable, often fascinating chapters on every trade under the sun. The picture of man's skills over all history is remarkably complete, all drawn from a close look at contemporary Persia.

It is copper that opens the story. Native copper is found worked at Siyalk from Neolithic times, and on the base of widespread ores of copper was founded Persian metalworking, the first in the

world. The bazaars still ring with the hammers of the coppersmiths, working now on factory-rolled sheet, although sheet beaten from ingots has only just passed out of use. Here is the story of mining, smelting, alloys and fabrication, in many forms and metals. The ironsmiths now rely on imported scrap; ironmaking ceased half a century ago.

Time is annihilated in the crafts of Persia. The author bought in Shiraz in 1937 some antique copper coins, evidently freshly minted. When the coppersmith was pressed, he produced a working set of dies made 800 years earlier of a hard silver-bronze for minting the coins of a local prince. In the town of Qom, some 100 miles south of Teheran, the masters and their work teams hold a monopoly over all Persia, each year making millions of glazed turquoise-colored beads, widely sold today even in the gift shops of Cambridge, Mass., and Palo Alto for a dime or so apiece. These beads, whose tart blue comes from copper oxide dissolved in the alkaline glaze, are made from a body of nearly pure quartz mixed with a potash-silica frit, wholly unchanged in its composition, and probably in every detail of fabrication, since the first known production in predynastic Egypt of about 4000 B.C.! The method of making the beads with their unbroken glaze is a remarkable exploitation of the mutual wetting properties of the ingredients as they fuse in firing.

Three-fourths of the water of modern Iran comes from *qanāt*. These are underground conduits dug into the alluvial fans that rise out of the dry valley of the plain into the low slopes of the mountains. They are tunnels with a cross section of about three by five feet, usually five or 10 miles long. More than 100,000 miles of *qanāt* are in use in Persia. Since their beginnings under Sennacherib in 700 B.C. or even earlier they have spread east to Chinese Turkestan and west to Spain. They are still used in Algeria, where they are called "Persian work." The tunnels are dug with pick, spade and bucket along the upper surface of an impervious underground layer, reaching from the bottom of the wells dug 50 or 100 feet into the gravel slopes of the hills. They follow a grade of some five feet per mile and at last discharge their 10 gallons of water per second above ground level in the plains below. The *qanāt* are built between guide shafts that fix depth and position every 1,000 feet or so; many intermediate ventilation and debris-removal shafts are also made. Level is controlled underground by sights taken over oil lamps; on the surface careful surveys are made with water levels and plumb line. New bearings underground, when the tunnel has detoured around a refractory boulder, are found by listening for the sound of the shaft-diggers ahead. Unsafe segments are lined with large fired clay hoops, for which an entire little industry exists. It is not surprising that *qanāt* are often called "the murderers." It costs today some $3,000 to $10,000 per mile to build a *qanāt;* it is reckoned as yielding in crops a good 10 percent per year as an investment, allowing for maintenance. Diesel-driven pumps begin to compete.

The old mines are being reopened with modern methods; the engine is everywhere; cement is replacing sunbaked brick. But the ancient crafts form the securest of bases for the productive growth of a future industrialized Iran.

THE HANDBOOK OF PRESCRIPTION DRUGS: OFFICIAL NAMES, PRICES AND SOURCES FOR PATIENT AND DOCTOR, by Richard Burack, M.D. Random House ($4.95). There are three desiderata for drugs: they should be safe, effective and cheap. So the old physician's adage goes, with the wry conclusion that no drug meets all three ends, except perhaps aspirin. This book is aimed at the third end. The author, a Boston internist of wide experience in teaching and in practice, planned this work first as a list for use in the teaching hospitals where he worked. The book begins with a well-argued and temperate appraisal of the pharmaceutical industry, its methods of sales, promotion, information distribution and research. Then there follows a complete list of the several hundred cases of drug recall (in 1965) under the Food, Drug and Cosmetic Act, a list included to make the point that "no one is in a position to make ironclad guarantees." Half of the recall list is products from the big names, the Lillys, Squibbs and Pfizers. The output of the small fellows is under much more frequent sampling scrutiny. The case seems clear enough: patients ought to buy drugs and doctors to prescribe them not by their brand names but by their generic nature. The preferred form of penicillin, penicillin G, is unpatented, and *by law* every single lot of antibiotics sold in the U.S. is tested and certified by the Food and Drug Administration. The only price component in such a product that should depend on brand name, then, is distributive costs. Yet Squibb, the highest-priced, sells for $6.62 the same number and kind of Government-tested tablets that many other companies sell for less than $2 and one,

Pennex, sells for less than $1. Most of the book is a helpful detailed account, drug type by drug type, of the generic names of drugs, how to buy them, the suppliers and their prices. Armed with this book, a physician and his patients need not submit to the remarkable policy of what seems an extortionate markup.

There is, of course, the important fact that research and development costs are not in some cases paid for by the firms that sell the generic drug on which patents have expired, or have never been issued. These smaller firms do not supply the rare but necessary drug. Someone should pay for that service, but it ought not to be the welfare patient, the Medicare patient or any other captive consumer. Some patients might elect to take that burden; they will find it useful to know that the large companies spend nearly four times as much on advertising and promotion as they do for research. Finally, generic drugs alone are prescribed for a patient such as General Eisenhower or the President whenever he enters Walter Reed or Bethesda Naval Hospital. Medical care like that ought to be available for all. A list of companies eligible to sell drugs to the Defense Supply Agency, as inspected reliable contractors, ends the book.

THE EMPTY FORTRESS: INFANTILE AUTISM AND THE BIRTH OF THE SELF, by Bruno Bettelheim. The Free Press ($9.95). Joey, the mechanical boy, is well known to *Scientific American* readers. His story is here complete (with a warming postscript of an interview with Joey, now a high school graduate and working at electronics), an eight-year-old near mute surrounded with a self-made, coherent, complex, almost infectious system of compulsions—tubes and wires to sustain him, an inseparable heavy electric motor, a constant ritual of plugging in, tuning up, switching on. Most of the book is the painstaking, devoted and reflective narrative of the cases of three children treated for infantile autism in the Sonia Shankman Orthogenic School. This pathology, first named and described in 1943, is a type of detachment from reality, observed in children from the age of two, that can be summarized as a radical disturbance of affective contact with people. Dr. Bettelheim treats such children with signal success (results are at least fair in about 37 out of 45 cases) on the basis of a psychoanalytic theory of the origin of the condition in early experience, most particularly in the interaction in infancy with the mother. The writing is eloquent and frequently moving; the therapy is demonstrably successful; the scientific conclusions are provocative but not compelling. The pragmatic argument of successful therapy is generally powerful in medicine, but the humanity, intelligence, self-sacrifice and endurance of the therapy given by Dr. Bettelheim and his devoted staff seem to outweigh the specific content of any theory.

This rich and complex essay cannot be summed up in a few paragraphs, but it is worth calling attention to two directions taken in the account that stray unexpectedly far from the Orthogenic School. There is a description of "moslems" (*Musulmänner*), those prisoners in the death camps of the SS whose emotional reaction was a total and contagious resignation to doom, a shuffling walk, a withdrawal of all interest, a surrender of hearing, of reacting, of seeing, the death of all hope, and then death itself. The analogy is strong, and the suggested parallel of cause is at once terrible and striking. Second, there is a brilliant explanation of the old myth of the wolf children, young children reared by wolves, found by chance and returned to humanity. These children, who remain mute, detached, withdrawn and walk on all fours but who violently snatch raw food and sometimes explosively attack their fellows with tooth and nail, are held to be autistic, strayed from or abandoned by their hopeless parents, found by strangers who impute their behavior to rearing by animals. The argument is many-sided and strong; clear motives exist for the perpetuation of the myth, and direct parallels, not only in all particulars of the children's behavior but also in the onlooker's reactions, are found around autistic children today. The only evidence against this view is the generally unsupported claim of finding the children actually in a wolves' den, as in the case of two children near Mindapore in India a generation ago.

Is infantile autism widespread? We do not know. The cases seen for treatment are rare, but many are diagnosed as incurable feeblemindedness and relegated to confinement, decline and the fulfillment of that grim diagnosis. At a still lower economic level autistic infants do not stay alive long; their lack of expression of pain and discomfort exposes them to all sorts of undetected illness. Writes Bettelheim: "A study of all three-year-old children in one of our metropolitan areas... would be startling."

Frederick II, the 13th-century Emperor of Sicily, we are told, wished to learn what was the natural language. He arranged for foster parents to rear children mutely, without speech or prattle,

to see whether they would spontaneously speak Hebrew or Greek or whatever. "But he labored in vain, because the children all died. For they could not live without the petting and joyful faces and loving words of their foster mothers." So wrote Salimbene of Parma 600 years ago.

THE ELECTRON MICROSCOPE IN MOLECULAR BIOLOGY, by G. H. Haggis. John Wiley & Sons, Inc. ($3.95). An inexpensive annotated guide to the architecture of the living world at a magnification around 100,000, the 30-odd brief chapters of this book each display a large page of electron micrographs and explanatory drawings, plus a careful and convincing page of comment and the key references. This is a book of both methods and results, centering on the 1960's and spanning most of the successes of electron micrography in some detail.

The treatment of specimens is the true hero of the work. Once the magnetic-lens electron microscope became a reliable tool at the hands of its university and industrial developers, it was up to the microscopists to learn how to use the tool. Master craftsmen such as Keith Porter, George Palade and Fritiof Sjöstrand are only the ornaments of a skilled worldwide profession. It was such men, working by patient insightful trials without benefit of any theory, who found the means of the present-day analysis of the cell. That probing is carried on by extending the methods of the classical cytologists of late Victorian years, but at a gain of a million or more in volumes resolvable, reaching down almost to the natural limit of structure, small atomic groups. The first successes were views of isolated particles, such as viruses, and of thin casts of surfaces, called replicas, made by the evaporation of metals onto the specimen. Nothing more could be done, because the electron beam will penetrate only extremely thin sections; whole cells were much too thick to be examined. The work remained at the surface until in the 1950's it was learned how to treat the living cell chemically—to fix it, as they say—so that its delicate structure remained more or less intact while being embedded in epoxy resin or Lucite to give it strength. The hard plastic block is cut into a folded ribbon of serial slices, floated out onto a water surface from the edge of a knife made of the freshly broken edge of a piece of ordinary plate glass. Slices a couple of hundred angstrom units thick are made down through the structure, studied one by one, and from them all the full spatial nature of a very complex structure can be made out. Here one can see, for example, the plates of the mitochondrion, studded with enzyme capsules held on stalks, an oxidative chemical factory with machinery visible at a scale of 50 or 100 angstroms. Here too are wonderful metal-shadowed pictures, often rotated during shadow-casting to bring out all directions equally—such as one of the DNA tape spewing out of a burst bacteriophage. A bacterial flagellum cable is seen in negative contrast, surrounded by a heavy-atom salt, exactly as the optical microscopist sometimes put a drop of India ink on his specimen to show it clear against a dark background.

There are other and grander atlases of ultrastructure, and there is even a weighty international annual review of the subject published, but this clearly written and intelligently prepared book should be outstandingly useful for students and for the interested reader. What penetrating high-energy beams will do for biology once the living cell can be examined this book can only suggest.

HUMAN BIOLOGY, by G. A. Harrison, J. S. Weiner, J. M. Tanner and N. A. Barnicot. Oxford University Press ($8). ORIGINS OF MAN, by John Buettner-Janusch. John Wiley & Sons, Inc. ($9.95). This is the modern physical anthropology, freed from the dusty skulls and the big calipers to reflect on the subtle animal man, warm-blooded, growing, evolving. Squarely set on the propositions of genetics, evolutionary theory and the fragmentary paleontology of our genus, both books begin with a look at man's primate legacy. The first text, by four British scholars, then proceeds to consider human genetics in general, biological variation in modern populations, the growth and development of the individual and finally human ecology—the adaptations to diet, climate and disease. The second, by a Duke anthropologist with the disarming history of having been a high school dropout who now admits to four degrees, emphasizes the primates, to the tune of more than half of his book, and concentrates in the second half on genetics, both the formal and the biochemical.

Here is the story of the gene pools of men, sampled by blood typing, amino acid sequences and such oddities as color blindness, twinning rate, tasting abilities and certain rare congenital disorders. Twins are eight times as frequent in Ibadan as in Japan (the extremes listed), a phenomenon surely related to the great psychic weight, for good and for bad, attached to twins in West Africa. Professor Weiner has a remarkable section on nutrition, showing the metabolic flexibility of man, from the Kikuyu to the Eskimo and from London to the West Indies. It seems indicated that genetic differences are not important for human adjustment, even to intakes differing in protein and carbohydrate by a factor of eight each way (in calories consumed). Hunters grow used to eating up to 20 pounds at a single sitting; kills are few and far between. The body weight of Gambian peasants shows an annual regular dip of nearly 10 percent in the months of cultivation, when work is hard and food reserves smallest. The population-density tables show the figures dominant throughout human history: fewer than one person per square mile at the stage of the hunters, an increase of a factor of 10 in the food-growing Neolithic, another increase of a factor of 10 to the present day. Life expectation in the distant past can be judged in skeletal remains by tooth eruption, wristbone development and closure of the cranial sutures. Among Neanderthal men only one of the 40 individuals known had passed the age of 50, and only three or four people out of 100 did so even in the Neolithic. Hobbes was at least partly right.

For evolutionists Buettner-Janusch is complete and up to date; for general reading, for reference and for a wealth of curious and useful graphs and tables the other book is first-rate.

HUMAN EVOLUTION, by Bernard Campbell. Aldine Publishing Company ($8.95). MANKIND IN THE MAKING, by William Howells. Doubleday & Company, Inc. ($5.95). These two books are broadly in the same vein as the two listed above. They run more to text and line drawings than to graphs and frequency tables. The first is a fluent account of the evolution of man, treated in terms of the various important features: body structure, walking, grasping, feeding, sexuality, family life and finally speech and culture. The second is a revision of an attractive, personal and witty undergraduate text that lightly and deftly surveys the entire field; it looks rather more at bones than at blood.

MINERAL RECOGNITION, by Iris Vanders and Paul F. Kerr. John Wiley & Sons, Inc. ($11.95). A mineralogical museum without walls, 300 color photo-

graphs of the finest mineral specimens form the seed around which this fine book has grown. Here is an incredible skein of natural silver wire, there six different color varieties of tourmaline. They are, to be sure, passport photographs—small, identical in size (scale carefully given), posed on bland backgrounds, but they form an invaluable reference for collectors at any level of proficiency, for clubs, schools and libraries. There are many black-and-white photographs and line drawings, and pointed descriptions mineral by mineral, with chemistry, crystallography, distribution and differential diagnostic hints for the identification of minerals, familiar since the classic work of Edward Salisbury Dana. Directions are clearly set out, and tabulations of results given, for 10 collector's tests: streak, density and so on.

Around all this is a terse but wide-ranging array of lore: the phase diagram of carbon in the region diamond-graphite, an account of the precipitation origins of the sapphire star, a map of the iron ore deposits of the world. All of this quite agreeably complements the narrower center of the book. What remains is a very quick, definition-centered review of the depths of solid-state physics, from a clear but rather incomplete summary of crystal group theory to a sentence or two on the uncertainty principle and a full-page drawing of a screw dislocation. Although such accounts, more or less limited to titles, often annoy rather than clarify, in this book they somehow work, and support the rest of the text. Perhaps it is the strong sense of reality added by all those marvelous mineral crystals that makes these sensible, if telegraphic, remarks add up to success. There is a good index and an up-to-date and extensive set of references.

TEXTURES: A PHOTOGRAPHIC ALBUM FOR ARTISTS AND DESIGNERS, by Phil Brodatz. Dover Publications, Inc. ($2.25). More than 100 full-page photographs in black and white form this inexpensive and stunning book. They show surfaces, deftly lighted and sharply printed in halftone: cheesecloth and raffia, woven aluminum mesh, lizard skin, hop flowers, beach sand, a grass lawn and many others. Most of these are presented life-size or two or three times magnified. They fascinate the eye, and they stand as a metaphor for the atomic fabric of all the world. More mundanely, they are free for reproduction as backgrounds in all kinds of graphic work.

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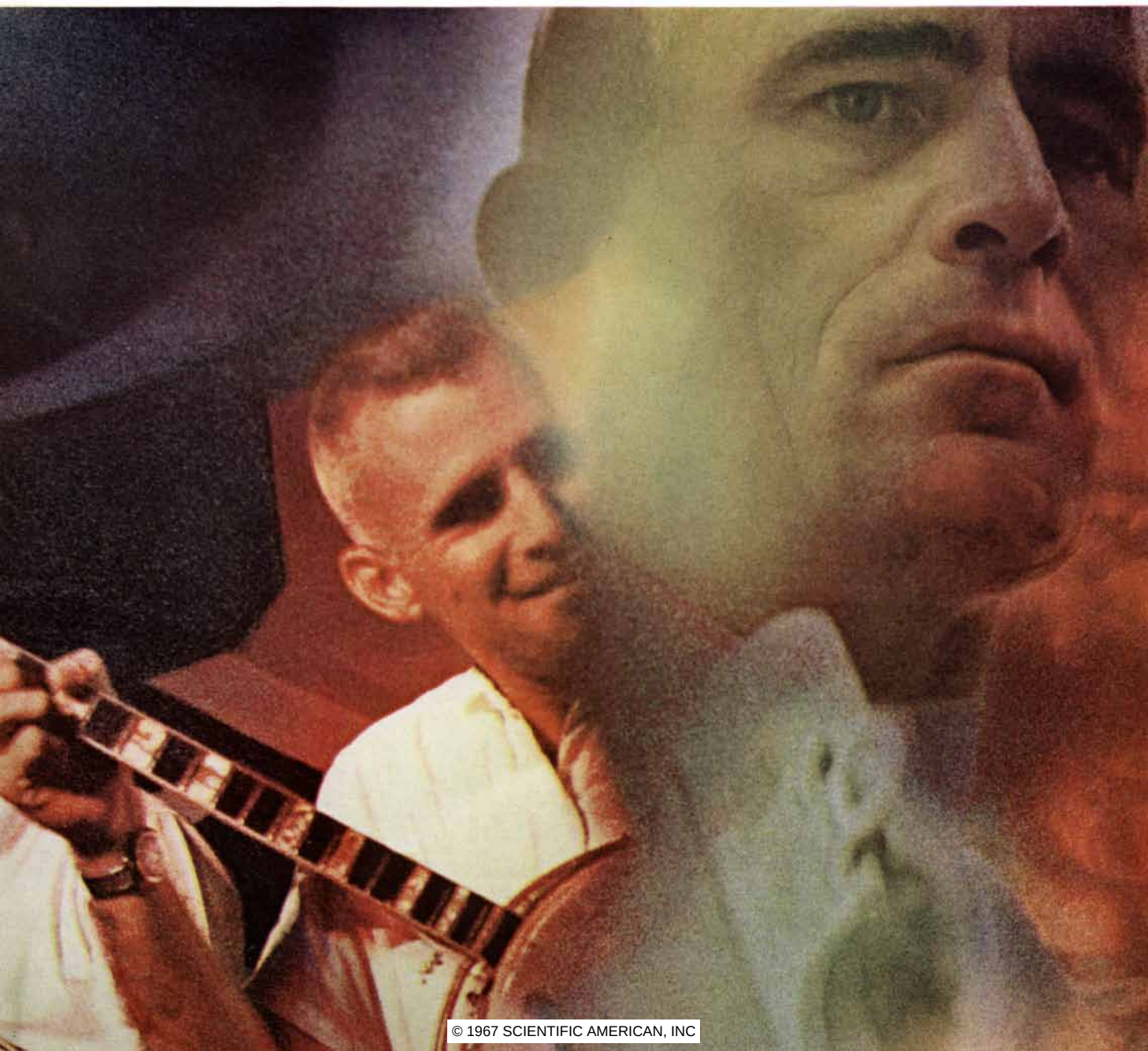
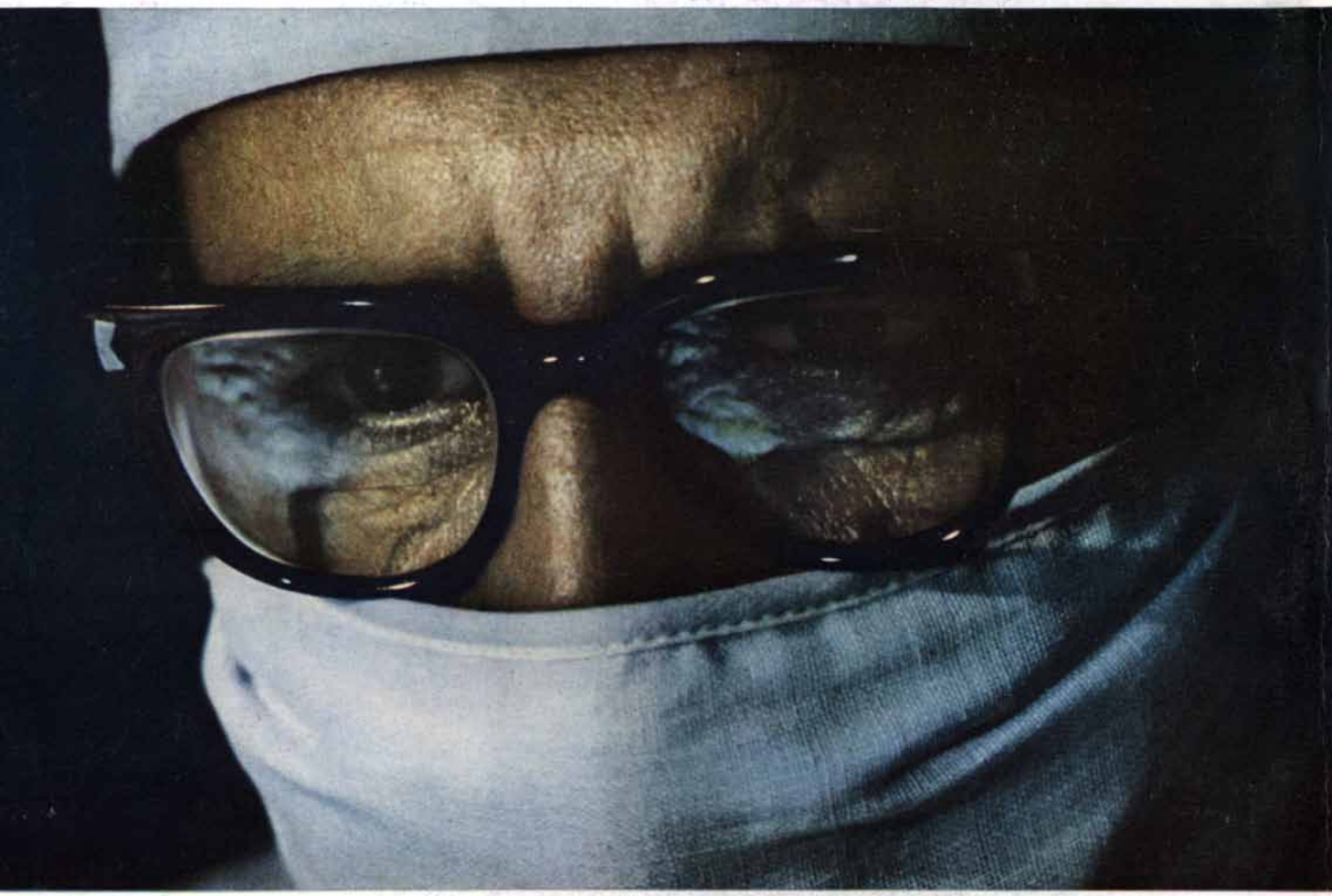


SAVE LIVES

Repair damaged hearts with "spare parts" made of plastic.



Allied Chemical makes the plastic that helps save lives. It's Halon®TFE, a new plastic material. Today, it's being used in mending sick organs: kidneys, liver, intestines—and parts of the heart. Tomorrow, it may well be the key element in building a complete artificial heart to replace the old, sick one. Halon is another example of how Allied Chemical puts chemistry to work.

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