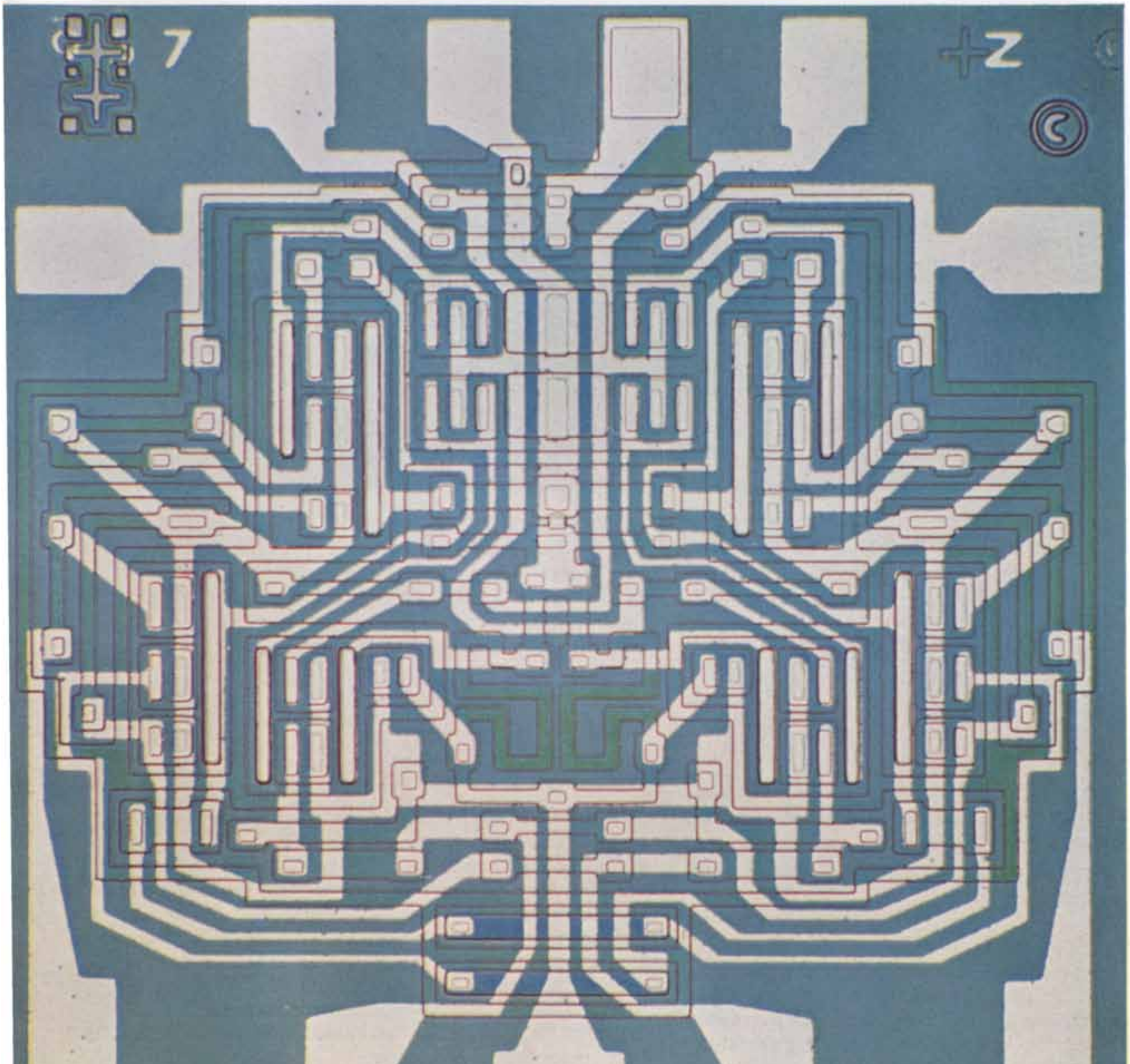
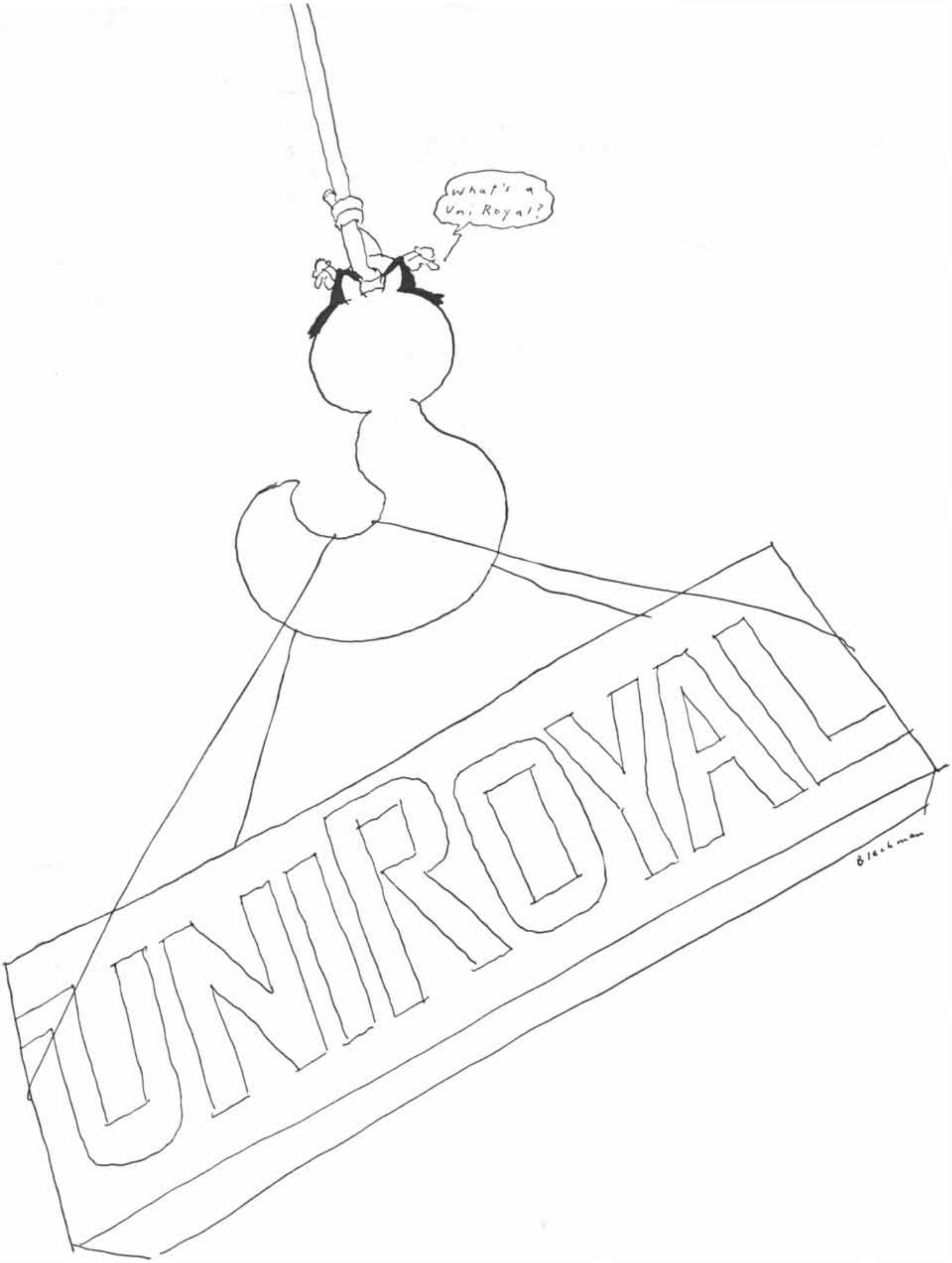
SCIENTIFIC AMERICAN



MICROELECTRONICS

SIXTY CENTS

November 1965



About 18 months ago, the U.S. Rubber Company took a good look at itself in the mirror, and said:

"You know what?

"I look like U.S. Rubber. They call me U.S. Rubber. But deep down, I've changed. I don't feel like U.S. Rubber any more."

What U.S. Rubber feels like today is a company that's doing exciting work in chemicals, plastics, fibers and footwear, as well as in synthetic rubber.

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U.S. Rubber feels like its exciting new Vyrene® spandex elastic fiber, which has nothing to do with rubber.

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It feels like its revolutionary thermoplastic auto body material, Royalex,® which is tougher than steel and lighter than aluminum. Never rusts or rots. And if dented, pops back to shape when heated!

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UNIROYAL
U.S. RUBBER

The Countess of Lovelace (1816-1851)

Woodcarving by William Ransom photographed by Max Yavno

COMPUTER BIOGRAPHY—"The distinctive characteristic of the Analytical Engine, and that which has rendered it possible to endow mechanism with such extensive faculties as bid fair to make this engine the executive right-hand of abstract algebra, is the introduction into it of the principle which Jacquard devised for regulating, by means of punched cards, the most complicated patterns in the fabrication of brocaded stuffs. . .We may say most aptly, that the Analytical Engine *weaves algebraical patterns* just as the Jacquard loom weaves flowers and leaves."[1]

[1] Augusta Ada, Countess of Lovelace, *Sketch of the Analytical Engine Invented by Charles Babbage,* note to her translation of the original edition, Geneva, 1842.

INTERACTIONS OF DIVERSE DISCIPLINES - 2

Jacquard's new technology of the industrial revolution gave impetus to the classical mathematics of Babbage. Today's management and behavioral sciences, interacting with the classical disciplines, can solve many complex problems of governments and industry. Over a decade ago Planning Research Corporation began the successful use of this approach to problem solving, employing multidisciplined teams.

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ARTICLES

DEPARTMENTS

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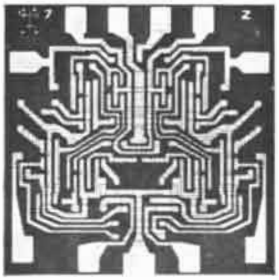

THE COVER

The mazelike pattern that appears on the cover is a 130-diameter enlargement of a complete electronic circuit containing 22 transistors and 46 resistors. The actual circuit is only an eighteenth of an inch square; the circuit layers are so thin that they produce interference colors. Manufactured by Fairchild Semiconductor, it illustrates the remarkable technology described in the article "Microelectronics" (*page 56*). Such circuits were originally developed for use in small computers carried in ballistic missiles. (The circuit on the cover can perform various logical functions.) Increasingly, however, these tiny objects, known as integrated circuits, are being adopted for nonmilitary computers and other electronic systems because of their low cost, high performance and extraordinary reliability.

THE ILLUSTRATIONS

Cover photograph by Richard Steinheimer

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LETTERS

Sirs:

I should like to comment on the exchange of correspondence between Stirling A. Colgate and Henry H. Kolm and Arthur J. Freeman published in the July *Scientific American.* This was concerned with the early history of the revival of interest in the production of intense magnetic fields that took place in 1955. Since I was involved in many discussions that took place at the time of the original work by H. P. Furth and R. W. Waniek and by Simon Foner and Henry H. Kolm a few further observations on the sequence of events may be of interest. In the remarks below I have had the benefit of referring to a rather extensive file of correspondence that took place between the various participants during the summer of 1955.

This seems to be a case, frequent in the history of science, where two groups became interested in the same line of research and made important advances independently and nearly simultaneously. Furth and Waniek used direct underdamped capacitor discharges through single-layer bronze coils prior to June, 1955. The coil design was of a type, originally devised by Francis Bitter, that used slotted disks sandwiched between insulators. With this design they achieved fields of 500,000 gauss at room temperature. Later, by introducing a pulse transformer and using copper coils cooled in liquid nitrogen they reached fields of 600,000 gauss, but with some permanent deformation of the coils.

Foner and Kolm independently realized the advantage of the underdamped capacitor discharge and also conceived the idea of constructing the coil out of a solid helix. This coil design proved to be mechanically much superior to the Bitter design and represented a major advance. With this coil design they were able to reach fields of 750,000 gauss repeatedly without mechanical deformation of the coil in the fall of 1955. In the meantime, during the early part of 1956 M. A. Levine, Furth and Waniek used a two-million-ampere current source to generate million-gauss fields in single-turn coils, but with some irreversible damage to the coil.

To summarize, the use of underdamped capacitor discharges with hard metal coils was developed independently by Furth and Waniek and by Foner and Kolm. Furth and Waniek were the first to reach fields of about 600,000 gauss, but with some coil expansion. It was apparently the success of this work, plus their success in reaching 500,000 gauss repeatedly, that revived interest in the field. Foner and Kolm conceived the idea of the solid helix and were the first to reach fields substantially above 500,000 gauss with no irreversible damage to the coil.

HARVEY BROOKS

Dean
Division of Engineering and Applied Physics
Harvard University
Cambridge, Mass.

ADDENDUM

In the article "Calcutta: A Premature Metropolis" (SCIENTIFIC AMERICAN, September) the caption for the input-output table on page 97 did not mention the source of the table. The table was adapted from "An Input-Output Table for West Bengal and Metropolitan Calcutta," by R. Dhar. This paper was published as Calcutta Research Study No. 13 by the Institute of Public Administration in New York.

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

NOVEMBER, 1915: "Out of a threatened calamity to American manufacturers dependent on dyestuffs has arisen a great and ever-increasing industry during the past 12 months. At the outbreak of hostilities in Europe last August, textile and allied interests in the United States were brought face to face with a threatened shortage in the supply of dyestuffs from Germany. Before the war was 12 months old the output of American coal-tar colors had been doubled. This naturally involved a notable increase in the production of coal-tar dyes, which called into existence a number of new companies engaged in the manufacture of intermediates, especially aniline."

"According to a report on the 1909 opposition of Mars, just published under the direction of E. M. Antoniadi, 'the alleged existence of a geometrical network of canals has received a lasting and unanswerable confutation.' Mr. Antoniadi had the advantage of using on Mars the great Meudon refractor, the most powerful telescope in the Old World. In working with smaller instruments he himself had, like other observers, obtained frequent glimpses of narrow, straight lines, but in the Meudon instrument these lines were seen only when the definition was bad and the image of the planet 'flaring.' With good seeing, a complex natural structure of the so-called 'continental' regions of the planet was revealed, a variety of irregular bands and shadings, replacing the sharp, narrow lines drawn by Schiaparelli, Lowell and others."

"The use of clouds of chlorine and bromine by the Germans in trench warfare has forced the Allies to use sponges or gauze soaked with some solution able to absorb the noxious gases. Ordinary 'hypo' of the photographer, called sodium thiosulphate in the laboratory, is excellent for this purpose and is in common use. Unfortunately the reaction with chlorine or bromine liberates some hydrochloric acid and sulphuric acid, neither one very desirable in a sponge attached to a soldier's nose. The addition of sodium carbonate neutralizes these two acids, but a French formula used a good deal does not call for enough sodium carbonate to take care of all the acid liberated."

"Only a misguided enthusiast would venture to make claims at the present time for the possible future usefulness of applied eugenics. The doctrines of heredity on which the new postulates are based must first be subjected to critical investigation. It is well enough to maintain in a general way that vitality is partly inherited and partly acquired. Many individuals have assumed, however, that the new science is primarily intended to foster a scheme of governmental interference with marriage. The most earnest students of the subject have at best hoped to promote the gradual establishment of standards in public opinion."

Scientific American.

NOVEMBER, 1865: "In Pittsburgh, Cincinnati and other cities west of the Alleghanies, where bituminous coal is generally used for fuel, the smoke that constantly hangs in the atmosphere is a very great nuisance. The principles of the problem are very simple. The elements in bituminous coal that burn are carbon and hydrogen, and the burning is the combination of these with the oxygen of the atmosphere. When smoke is formed, it results from the fact that a portion of the carbon does not combine with oxygen—in other words, is not burned. One of the successful plans for burning smoke in the furnaces of steam boilers is that patented in England by Charles Wye Williams. The flame and gases resulting from the partial combustion of coal are carried into a chamber behind the grate and are here mixed with a fresh supply of air. The situation of the chamber causes the smoke to be maintained at a sufficiently high temperature to effect combustion."

"Fraunhofer, in 1823, and Donati, in 1862, had described the spectra of a few stars, but more recently Professor Miller and Mr. Huggins have constructed an instrument with which they have compared the spectra of the moon and planets and some of the fixed stars, and even of the nebulae, with the spectra of the principal metals. They observe that 'the

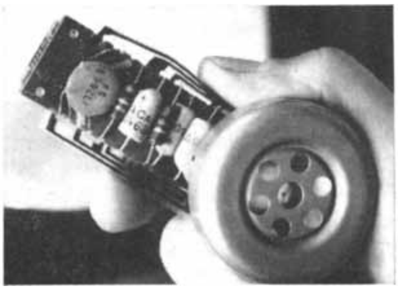
Report from

BELL LABORATORIES

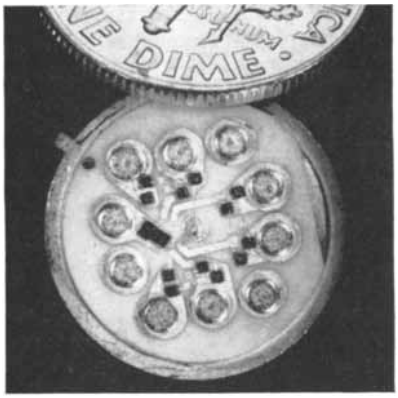
New circuits for communications

The success of a modern large-scale communications system depends importantly on the circuits of which it is built. For this reason Bell Telephone Laboratories places great emphasis on exploring new approaches to high-performance, economical circuit design. The circuits illustrated below are but a few examples of recent Bell Laboratories developments that are helping to advance the techniques of communications.

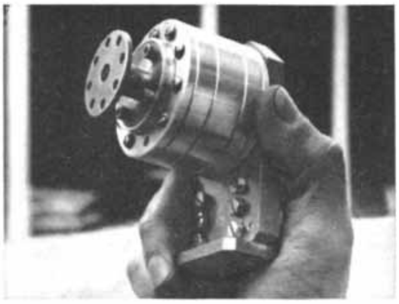
Bell Telephone Laboratories
Research and Development Unit of the Bell System



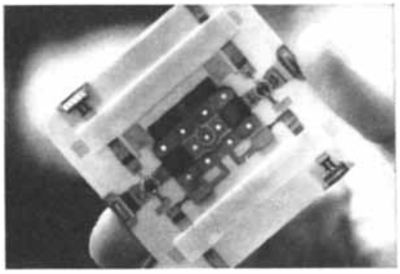
Circuit for mounting inside telephone handset for use by people with impaired hearing. Circuit includes one PNP transistor, provides up to 25 db gain, and has negative feedback for stability and to compensate for variations in component characteristics. Power is derived by taking a small part of direct current supplied to the telephone transmitter. Circuit board is flexible to permit part of conducting path to be bent and entire unit to fit snugly in narrow handset.



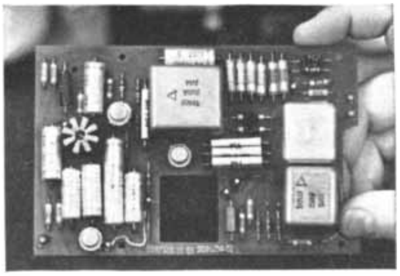
High-speed integrated logic package consists of 3 separate flip-flop circuits assembled together on a single header. On the 11-lead ceramic header, all circuit interconnections are made using gold thermocompression bond wires. This device contains 6 transistors (2 are required for each flip-flop) and 12 resistors. The individual flip-flops perform their switching functions with typical operating times of approximately 6 nanoseconds.



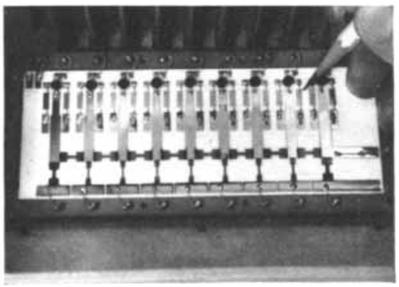
Parametric amplifier used in new microwave radio system will provide low-noise amplification to a radio frequency signal which is frequency-modulated by 1200 telephone conversations. It is a reflection type parametric amplifier operating in the 4-gigacycle range, providing approximately 13 db of gain using a varactor diode pumped at approximately 12 gigacycles. Its very low noise figure, typically 3.5 db, permits increased systems capabilities which are used to increase the number of telephone channels per radio channel.



Integrated balanced microwave amplifier makes use of high-frequency germanium transistors for precise wideband applications. Each stage of amplifier (one stage shown) consists of a pair of electrically similar transistors whose inputs and outputs are combined by 3-db couplers. This arrangement eliminates tuning adjustments and provides excellent gain flatness and impedance matching. Multistage amplifiers of this type have been designed to operate with bandwidths of 1000 mc in the 0.5- to 3-gigacycle range, with noise figures of about 6 db.



Compressor circuit used in several telephone carrier systems raises volume of soft voice sounds and lowers volume of loud voice sounds. This new circuit effects a 2-to-1 reduction in dynamic range of a telephone signal, which is then transmitted with an improved signal-to-noise ratio. Nearly perfect compression is achieved over greater than the normal voice range, as a result of circuitry that varies the impedance of two precise silicon diodes. A 3-stage feedback transistor amplifier maintains desired stability and provides the required transmission characteristics.



Thin-film decoder for high-speed pulse code modulation systems converts binary pulse sequences into analog signals. Circuit consists of precision resistor network and multiply-encapsulated control diodes. Precision resistors (pointer) generate reference currents that are switched into resistive ladder network (I-shaped elements at bottom of unit). Output voltage is proportional to binary code applied to diodes. Precision sufficient for decoding 9-digit binary codes is obtained, at code rates up to 12 mc (108 mb/s pulse rates).

elements most widely diffused through the host of stars are some of them most closely connected with the constitution of the living organisms on our globe, including hydrogen, sodium, magnesium and iron. On the whole we believe that spectrum observations on the stars contribute something toward an experimental basis on which a conclusion, hitherto but a pure speculation, may rest, viz.: that at least the brighter stars are, like our sun, upholding and energizing centers of systems of worlds adapted to be the abode of living beings.' "

"Among those men who have devoted themselves to the study of that department of medical science which relates to the cure of disease—therapeutics—one of the most eminent is the Frenchman Pierre Charles Alexandre Louis. Previous to his labors, while anatomy, physiology and pathology contained a great mass of ascertained and unquestioned facts, almost every thing in the department of therapeutics was the subject of disputes among physicians, so constant and so universal that they were the theme of universal ridicule. To illustrate Louis's method, it had been the most general practice to give antimony in lung fever. He selected for experiment 100 patients sick with lung fever, and divided them into two parts as nearly equal as possible in regard to age, strength of constitution, force of the disease and all other conditions. To 50 he gave antimony in the usual quantity and to the other 50 he gave no medicine whatever. The effect on each patient was carefully observed and recorded. The experiment was then repeated in another 100 patients divided in the same manner."

"At the last meeting of the Polytechnic Association in New York, Mr. Carter of Chicago gave some particulars in relation to the work of lowering the bed of the Illinois and Michigan canal, for the purpose of draining the Chicago River into the Mississippi. The citizens of Chicago have for some time been desirous of having the canal deepened, in order to drain the waters of the Chicago River into the Illinois River and thence into the Mississippi, instead of allowing them to flow, as at present, into Lake Michigan, where they foul the harbor by the sewage of the city. It has been decided to do this work at the expense of the city, and numerous gangs of workmen are to commence the task so as to complete it with the least possible delay."

THE AUTHORS

RUTH C. SILVA ("Reapportionment and Redistricting") is professor of political science at Pennsylvania State University, to which she went in 1948 after two years as instructor at Wheaton College. Previously she had obtained bachelor's, master's and doctor's degrees at the University of Michigan. She has written extensively on apportionment and districting. In the course of various consulting activities she has served as research consultant to the U.S. Department of Justice on constitutional law and to the State of New York on legislative apportionment.

FRANK PRESS ("Resonant Vibrations of the Earth") is head of the Department of Geology and Geophysics at the Massachusetts Institute of Technology. He went there after several years as director of the Seismological Laboratory at the California Institute of Technology. Press is a graduate of the City College of the City of New York and received a Ph.D. from Columbia University. In 1959, 1960 and 1963 he was a member of the U.S. delegation to the international conference on banning nuclear tests; from 1961 to 1964 he was a member of the President's Science Advisory Committee. In recognition of his work with the U.S. program for the International Geophysical Year a mountain in Antarctica was named Mount Press. His current interests are the structure of the earth's crust and mantle and designing equipment for investigation of the moon and the planets. As a Government consultant he is concerned with arms control and the role of science and technology in the foreign-aid program.

WILLEM J. KOLFF ("An Artificial Heart inside the Body") is professor of clinical investigation at the Educational Foundation of the Cleveland Clinic Foundation and head of the Department of Artificial Organs at the Cleveland Clinic. Born in the Netherlands, Kolff received an M.D. degree from the University of Leyden in 1938 and a Ph.D. from the University of Groningen in 1946. He joined the Cleveland Clinic in 1950 and became a U.S. citizen in 1956. Kolff developed the first artificial kidney in 1941. His interest in an artificial heart began when he started work on a heart-lung machine in 1948. Kolff's clinical work is in the treatment of uremia, application of the artificial kidney in uremia, kidney transplantation and the application of heart-lung machines. His experimental work, besides that on the artificial heart, includes development of blood oxygenators and new types of artificial kidneys and development of techniques for preserving organs for transplantation.

WILLIAM C. HITTINGER and MORGAN SPARKS ("Microelectronics") are both at the Bell Telephone Laboratories; Hittinger is executive director of the Semiconductor Device and Electron Tube Division, and Sparks is executive director of Development-Components and Solid State Devices. Hittinger, a graduate of Lehigh University, joined Bell Laboratories in 1954 after six years with the Western Electric Company and two years with the National Union Radio Corp. Sparks, who received bachelor's and master's degrees from Rice Institute and a Ph.D. from the University of Illinois, has been with Bell Laboratories since 1943. He has written extensively on transistors, junctions in transistors and the properties of semiconductors. Sparks and Gordon K. Teal built the first junction transistor in 1951.

ARMIN C. BRAUN ("The Reversal of Tumor Growth") is a member of and professor at Rockefeller University (formerly the Rockefeller Institute) and is head of the university's laboratory of plant biology. He joined the Rockefeller Institute in 1938 after obtaining undergraduate and advanced degrees at the University of Wisconsin. He has held visiting professorships at the University of Nebraska and Cornell University and has been a visiting lecturer at Harvard University and at the conference on pathobiology sponsored by the University of Colorado in 1964. Braun writes that he became interested in the biological sciences as a boy because "my father and older brother were enthusiastic naturalists, and throughout my youth I was exposed to the wonders of the microscopic as well as the macroscopic world of living things." He adds that he has little time for hobbies but "I do derive pleasure from growing tropical plants, mostly orchids, in a small greenhouse adjoining my home in Princeton, N.J."

RICHARD HELD ("Plasticity in Sensory-Motor Systems") is professor of experimental and developmental psychology at the Massachusetts Institute of Technology. As an undergraduate at

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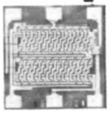

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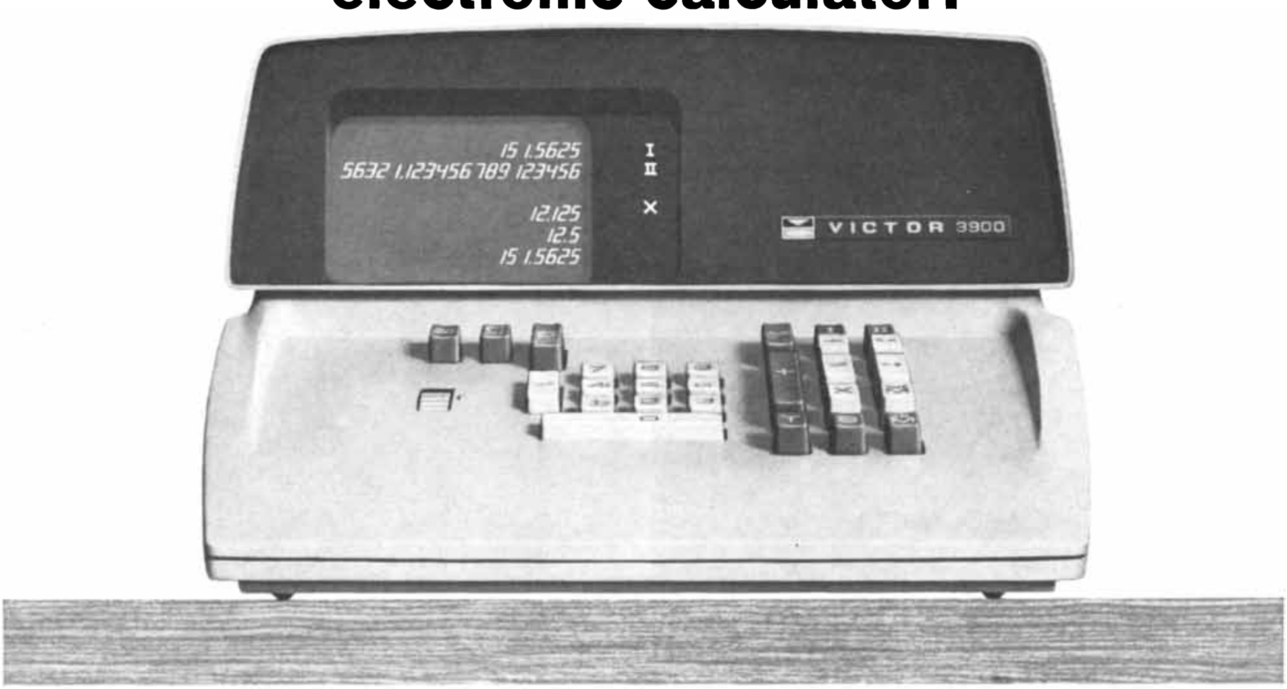

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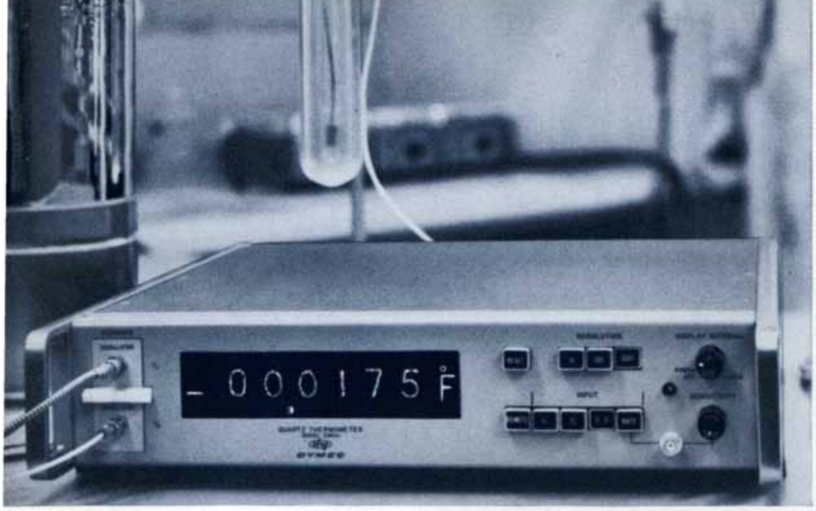
Columbia University, from which he was graduated in 1943, he majored in science and engineering. Becoming interested in the work of the psychologist Wolfgang Köhler, he joined Köhler at Swarthmore College and obtained a master's degree in psychology there in 1948. Four years later he received a Ph.D. in experimental psychology from Harvard University. Held taught at Harvard and at Brandeis University before going to M.I.T. in 1962; he also spent a year at the Institute for Advanced Study in Princeton, N.J. He has been interested in questions of space perception for many years; his work with Köhler at Swarthmore was on electrical responses of the brain to visual stimulation.

HAO WANG ("Games, Logic and Computers") is professor of mathematical logic at Harvard University. Wang was born in China and received a bachelor's degree in mathematics from the National Associated University in Kunming in 1943. He came to the U.S. in 1946 and obtained a Ph.D. in logic at Harvard, remaining there as research fellow and assistant professor for several years. In 1954 he went to England as a fellow of the Rockefeller Foundation. He was John Locke Lecturer in Philosophy at the University of Oxford in 1955 and reader in the philosophy of mathematics from 1956 to 1961, when he took up his present position at Harvard. Wang is the author of *A Survey of Mathematical Logic*.

JOHAN T. RUUD ("The Ice Fish") is professor of marine biology at the University of Oslo, an institution he has also served as dean of the science faculty and as rector. Born in a Norwegian seaport, Ruud went to sea in a merchant steamer before going to the University of Oslo as a student. There he became interested in the scientific problems of Norway's whaling industry, and after graduation he spent many seasons with the whaling and sealing fleets. That work led in 1938 to his appointment as director of the State Institute for Whale Research. Ruud has also served as chairman of the Norwegian Research Council for Science and the Humanities. He was the discoverer of the Chaenichthyidae, the family of fishes without red blood cells that is discussed in his article.

ERNEST NAGEL, who in this issue reviews *Hegel: Reinterpretation, Texts, and Commentary*, by Walter Kaufmann, is John Dewey Professor of Philosophy at Columbia University.



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1. High resolution and simple use of the DY-2801A Quartz Thermometer are shown in this actual readout of the temperature difference between the ice-point and triple-point of water.

2. One probe of the DY-2801A is pictured actual size; longer and shorter probes also are available. The probe is only .375 inch in diameter.

3. Because the DY-2801A derives digital temperature information from frequency rather than voltage variations, accurate measurements at great distances are easier, less error-prone and free from typical voltage-measuring problems such as noise, cable resistance and inaccurate amplification. It is therefore useful in oceanography, temperature measurement beneath the surface of the earth and industrial processing. The instrument's high resolution, repeatability and stability make it particularly valuable in the laboratory.

4. Permanent digital recordings of temperature measurements are easily available.

5. The traditional mercury lab thermometer is crude in relation to more advanced platinum resistance thermometers or thermistor devices. New techniques in the Hewlett-Packard quartz thermometer offer high accuracy and resolution, combined with ease of use.

6. The sensor crystal (shown about 5 1/2 times actual size) resonates at 28.208 megacycles at 0° C. Frequency change is linear at 1000 cycles per second per degree centigrade. The Hewlett-Packard thermometer, whose probes contain this crystal, then measures and displays frequency in terms of degrees C or F.

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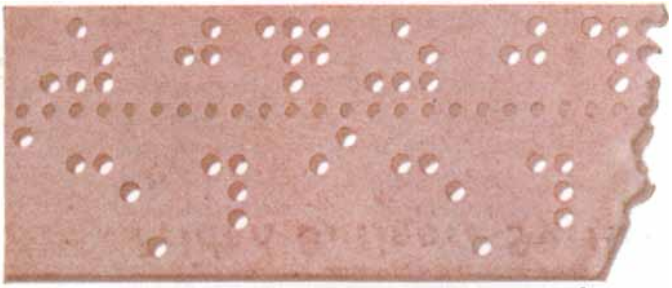

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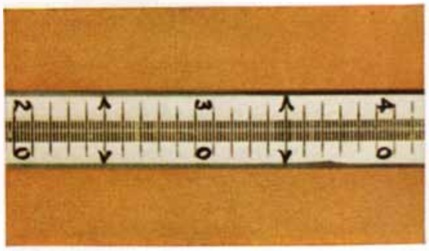

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Reapportionment and Redistricting

The court decisions that reinforce the concept of "one man, one vote" are now operating to change two aspects of U.S. political structure: apportionment of elective offices and the form of election districts

by Ruth C. Silva

In *Baker* v. *Carr,* its historic decision of March, 1962, the U.S. Supreme Court implied that the Constitution precludes inequality of population between state legislative districts. In various subsequent decisions the Court has partially spelled out its view of what "population equality" is required: the apportionment of seats and districting in the state must be so arranged that the number of inhabitants per legislator in one district is substantially equal to the number of inhabitants per legislator in any other district in the same state.

It is easy to state this rule of thumb but rather difficult to put it into practice, as the halting efforts of the states to comply have made abundantly clear. The difficulties are not only political; some of them are technical. In particular, a great deal of confusion has arisen from a failure to appreciate that apportionment and districting are two quite distinct aspects of the problem, each of which must be carefully examined in order to arrive at a rational solution. This article will discuss techniques that have been proposed by political scientists (including the author) to put apportionment and districting on a sound footing for a more nearly accurate representation of the voters.

Let us first review briefly the circumstances that precipitated the Supreme Court's ruling in the case of *Baker* v. *Carr*. This suit was brought by a group of voters in Tennessee against state officials, the voters contending that they were denied the equal protection of the laws accorded by the 14th Amendment because the value of their votes was "debased" by inequities in the state's existing apportionment and districting. Tennessee was still electing its state legislators on the basis of an apportionment adopted in 1901, although in the intervening 60 years the number of the state's voters had grown from 487,380 to 2,092,891 and there had been radical shifts in the distribution of the population (mainly, of course, from rural areas to cities and suburban areas). As an example of the resulting inequalities, the petitioners charged that one vote in Moore County (rural) was equal to 19 votes in Hamilton County (containing Chattanooga), since the number of inhabitants per legislator was 19 times greater in the latter than in the former.

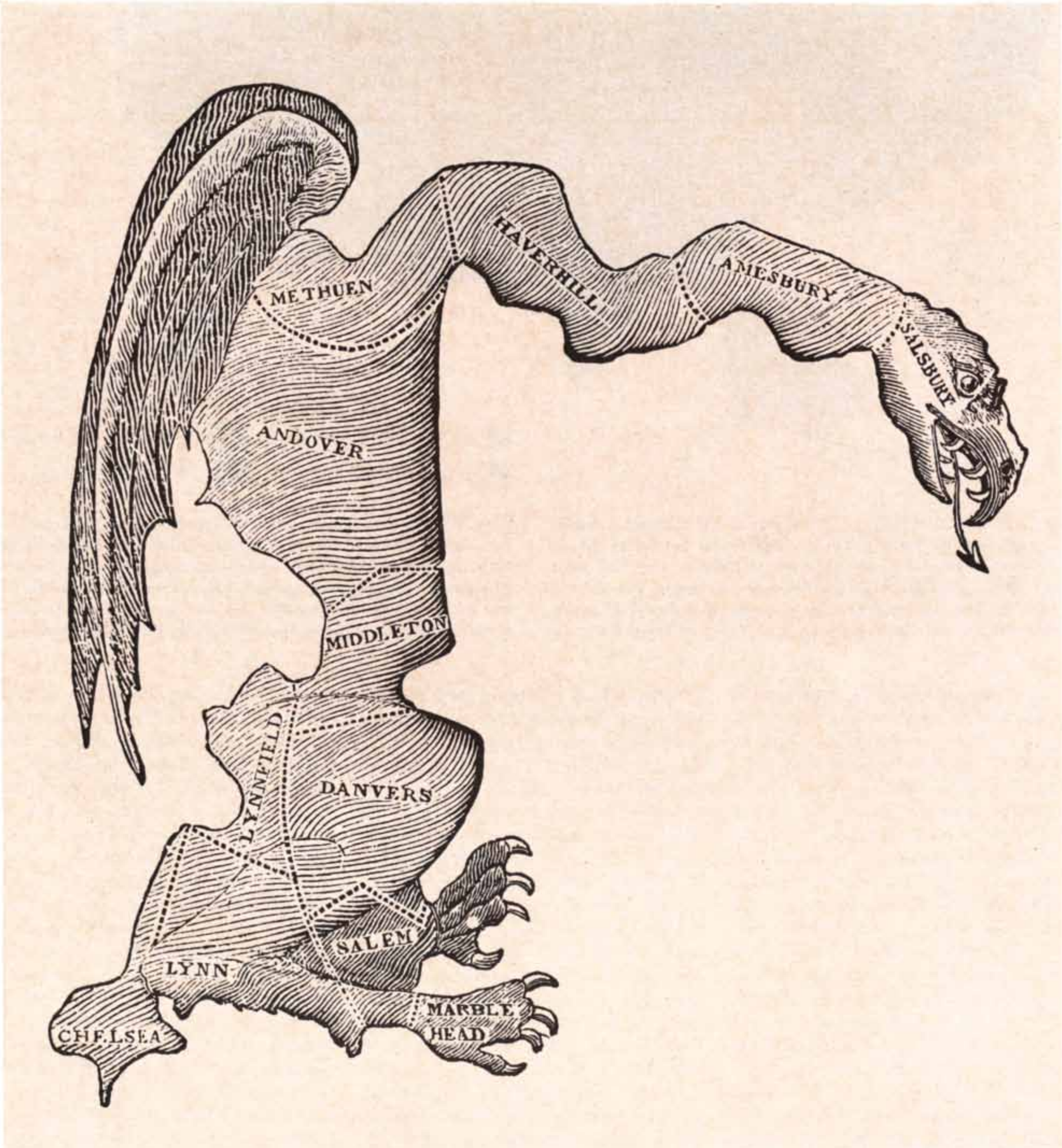
The Supreme Court ruled that the petitioners had standing to challenge the constitutionality of the state's legislative apportionment and districting under the equal-protection clause of the 14th Amendment, that Federal courts have jurisdiction over the subject matter of apportionment and districting and that the petitioners had a justiciable grievance, that is, a grievance for which the courts could grant relief if the facts were proved as stated. The Supreme Court sent the case back to the Federal District Court to decide what the appropriate relief would be if the alleged facts were proved.

The decision amounted to an open invitation for similar challenges by voters in nearly all the states. The arrangements for legislative representation in many states were soon demonstrated to be a wonderland of alleged inequities. The prize went to the state of Vermont, where it was found that the most populous district had 987 times more people than the least populous district. Similar population inequalities were found in congressional districts. In Texas, for example, one district with a representative in Congress had a population of 951,527 and another a population of only 216,371; thus a ballot cast in the latter was said to have 4.4 times the weight of a vote cast in the former. Throughout the nation a spate of suits was filed for "reform" of state arrangements for apportionment and/or districting. At this writing the courts have already ordered revision of the systems in 37 states.

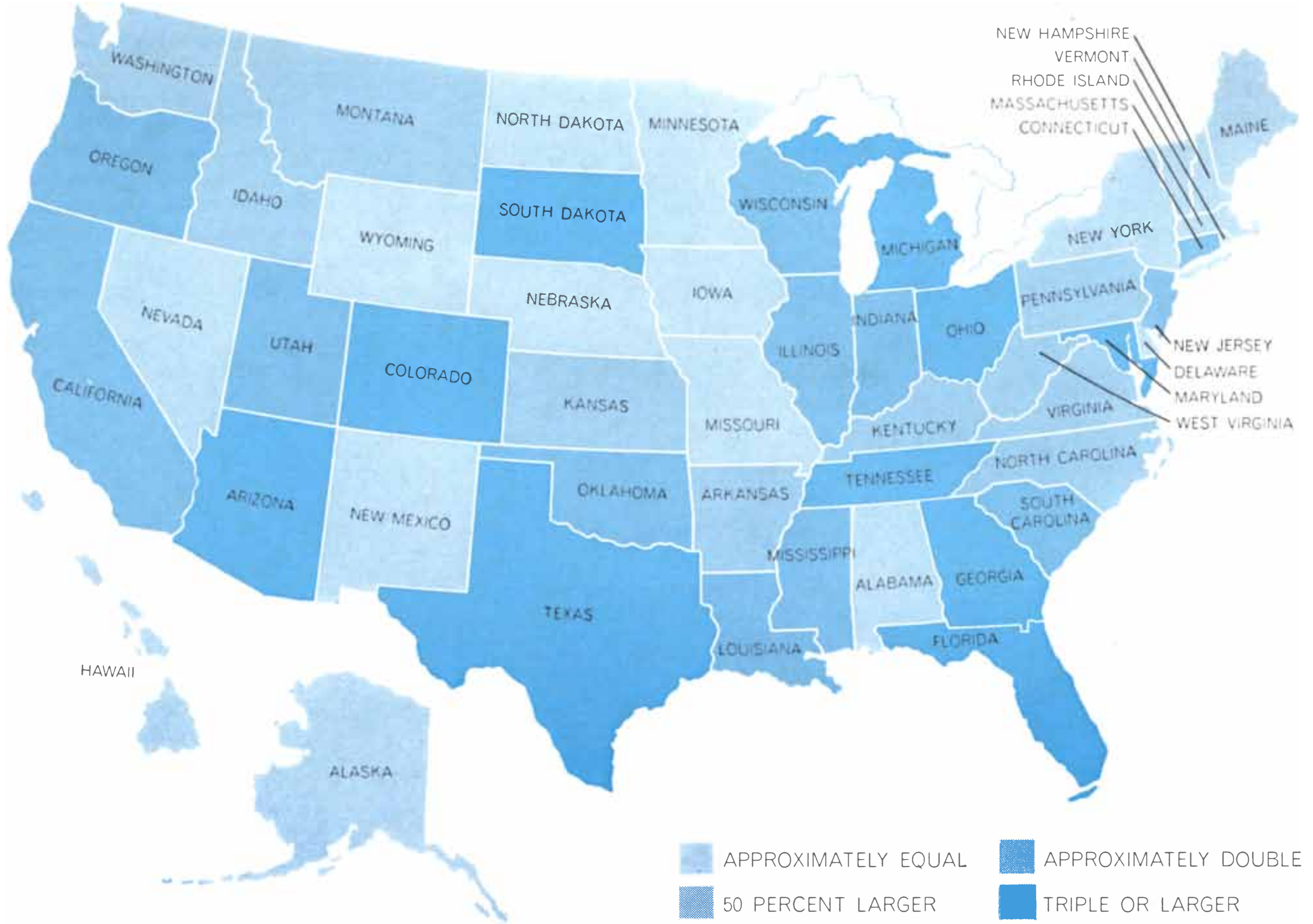
A year after the Baker case the Supreme Court decided an appeal in the case of *Gray* v. *Sanders,* this time invalidating Georgia's county-unit system of nominating candidates for statewide office. In an *obiter dictum,* or incidental comment, the Court spoke of "one person, one vote." Although this catchy phrase was only a dictum, it indicated how the Court was thinking. In February, 1964, the Court cited the

Gray decision as authority for invalidating Georgia's congressional districts on the ground of population inequality (*Wesberry* v. *Sanders*). The Court, again in an *obiter dictum,* repeated the "rule" of equality in slightly more definite terms: "As nearly as practicable one man's vote in a Congressional election is to be worth as much as another's." In June of 1964 the Court ruled in an Alabama case (*Reynolds* v. *Sims*) that both houses of the state legislature must be apportioned on the basis of population equality. In this decision the Court asserted that equality of population should be the controlling criterion in the construction of legislative districts. Justice Hugo Black in his opinion said that states could not be permitted to "dilute the vote" of some of their citizens "through the device of districts."

These, then, are the guidelines from the Supreme Court. What is so complicated about putting them into practice? One might suppose that the establishment of equality in apportionment and districting should be only a matter of arithmetic. It is not, however, that simple. We shall consider first the prob-



ORIGINAL GERRYMANDER was depicted in the *Boston Gazette* of March 26, 1812. The district, produced by an anti-Federalist law setting up the senatorial districts in Massachusetts in such a way as to concentrate the Federalist vote in a few districts, was at first likened to a salamander but later came to be known as a gerrymander after Governor Elbridge Gerry, who signed the districting law.



UNEVEN DISTRICTING of U.S. congressional districts is depicted as the situation existed after the 1960 census but before the effects of the Supreme Court's decision in *Baker* v. *Carr* had been felt. (That case pertained to the Tennessee legislature but focused attention on all types of districting.) "Approximately equal" means either that the state had congressional districts of about the same population or that it elected its U.S. representatives at large; "50 percent larger" means that the congressional district with the highest population had about half again as many inhabitants as the one with the lowest, and so on. Largest spread, from 177,431 to 802,944, was in Michigan, which redistricted last year and now has congressional districts ranging from 403,263 to 417,026 in population.

lems of apportionment and then those of districting. At the national level in the U.S. they are treated as separate functions and are handled separately. The Federal Government *apportions* to each state a certain number of seats in the House of Representatives according to the state's population, as counted in the latest census. The state then *districts* itself geographically on the basis of the number of seats, each district to elect one representative. Many states use a similar procedure for their legislatures. They apportion seats to each county, town or other type of political unit, and each unit is then divided into districts corresponding to the number of legislators to be elected in that unit. Some states skip the apportionment step: they simply carve up the state into legislative districts.

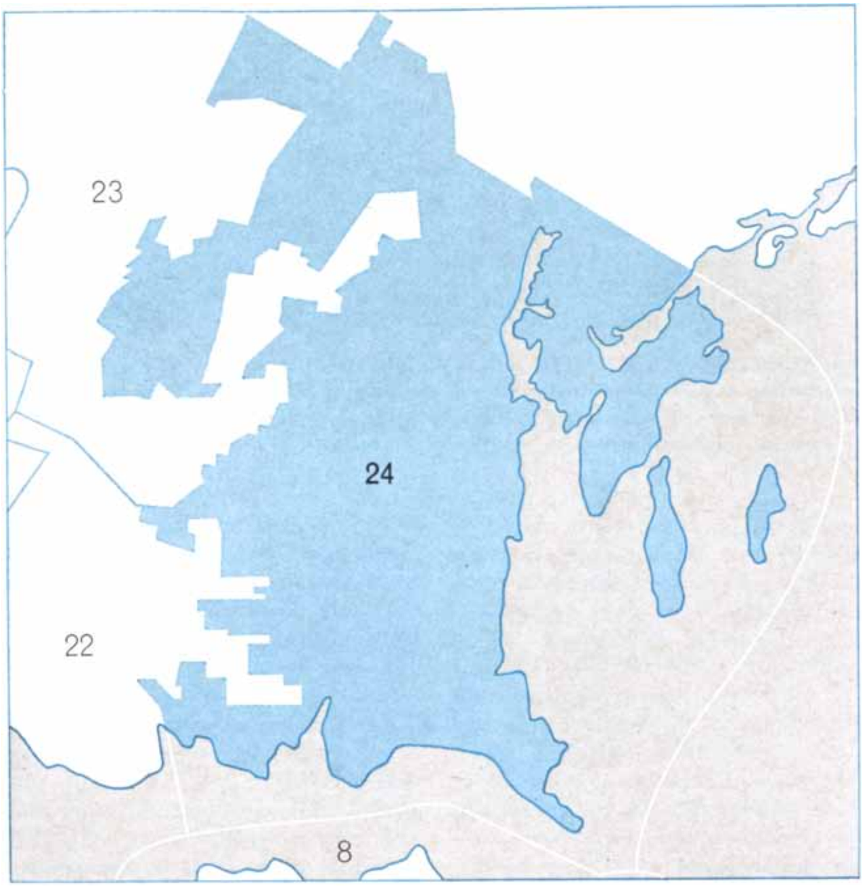
The most straightforward method of apportionment is to assign seats according to a ratio: so many seats per thousand (or larger number) of population. For example, if a nation's total population were 100 million and its legislature had 100 members, the ratio would be one to a million, and the states or provinces in the country would be apportioned one seat in the legislature for each million inhabitants. This general method was used for apportioning seats in the U.S. House of Representatives among the states up to 1911, and it is still widely used in apportioning seats in state legislatures to counties or towns. Although the method works reasonably well in many cases, it encounters the awkward problem of fractions in cases where a unit's population is not an exact multiple of the ratio.

In 1911 a more sophisticated method of apportionment was adopted. One seat is assigned to each state to begin with. After that the successive seats are apportioned one by one on the basis of priority numbers. These priorities are calculated for each state by dividing that state's population by a certain divisor, which depends on the number of the last seat apportioned to the state. There are five different divisors that might be used. One is the number of the last seat itself. For example, in the second round of assignments (that is, determining the priorities of the various states for a second seat) the divisor would be one (the number of the first seat). A state with a population of 11 million therefore would have a priority number of 11 million for a second seat; the priority number of a state with 10 million population would be 10 million. Similarly, in calculating the priorities for the 10th seat, the divisor would be nine. Another possible divisor is the number of the seat that is to be assigned: two for the second seat to be assigned to a state, three for each state's third seat, and so on until the last seat has been apportioned. Other possible divisors are the arithmetic mean between the numbers of the two successive rounds (for instance, 1.5 in the second round) or the geometric mean between them (1.414 in the second round) or the harmonic mean (1.333 in the second round).

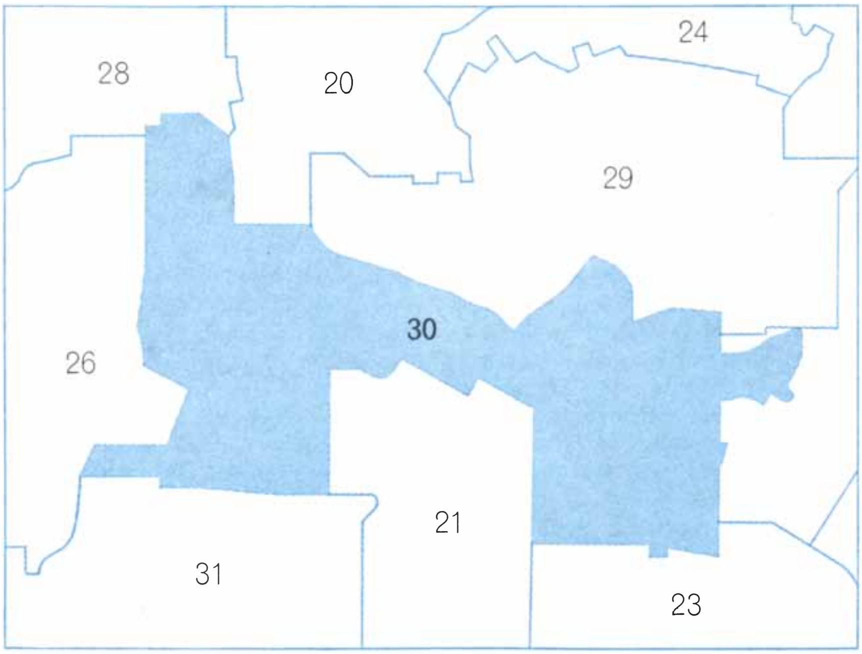
Using any one of these methods, seats are assigned to various states having the highest priority numbers in each successive round until all the seats are apportioned. It turns out that the divisor that comes the closest to apportioning the number of seats precisely according to population is the geometric mean, called "the method of equal proportions." In practice, however, the arithmetic mean (termed the "major fractions" method) also almost always yields the same distribution of seats.

In the congressional apportionments of 1911 and 1931 the major-fractions formula was used. In the last three apportionments (1941, 1951 and 1961), Democratic congresses turned to the formula of equal proportions instead. As it happened, in those particular cases the formula gave the 435th seat in the House of Representatives to Democratic states, whereas the major-fractions formula would have given it to a Republican or doubtful state that had a larger population than the one receiving the seat.

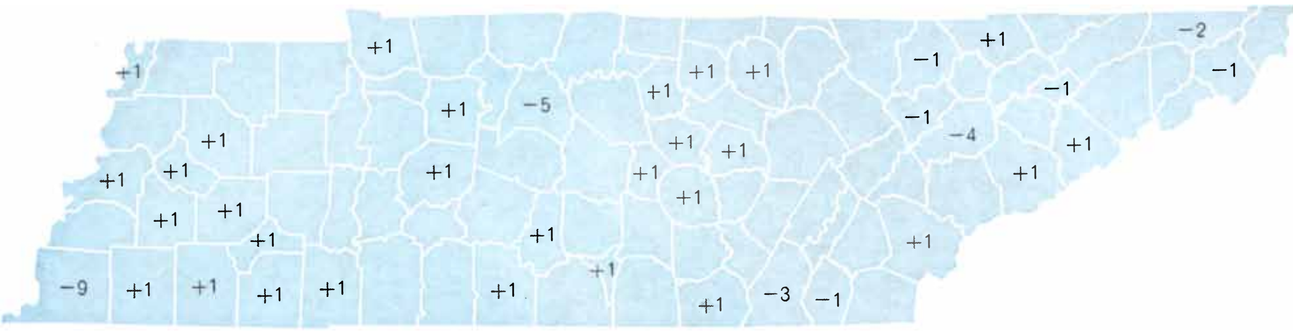
The states have been far less precise than Congress in apportioning their own legislative seats among their counties and towns. Indeed, before the Supreme Court's ruling most of the states used one device or another to deliberately give extra seats to the less populous areas. Thirty states produced this result by assigning at least one seat to each county or town, however small in population. Thus in Kansas each of the 105 counties was guaranteed a seat in the lower chamber of the legislature. Since there were only 125 seats in all, only 20 seats were left for apportionment according to population; as a consequence the four most populous counties, containing 37 percent of the state's population, had only 12 percent of the seats in the chamber. Some states gave the rural areas an outright grant of a lower ratio of population per seat than was required for cities; New Hampshire's towns and city wards, for example, were required to have a double ratio of population to qualify for each seat after the first seat. Still another method used by some states was the placing of a maximum on the representation of the large cities; in Pennsylvania, for example, the state constitution limited Philadelphia to no more than a third of the seats in the state House of Representatives. Then there was the



REPUBLICAN DISTRICTING, described by Democrats as a gerrymander, produced this congressional district (the 24th) in the Bronx section of New York City. Although the Bronx is predominantly a Democratic community, the area occupied by the district has returned Paul A. Fino, a Republican, to the U.S. House of Representatives for many years.



DEMOCRATIC DISTRICTING, described by Republicans as a gerrymander, produced this congressional district (the 30th) in Los Angeles. It elects a Democratic congressman. In a metropolitan region, where heavy population can produce several districts in a small area, the party drawing district boundaries can try to assure itself of favorable situations.



TENNESSEE'S DISTRICTING for seats in the state House of Representatives showed several inequalities at the time of *Baker* v. *Carr*. The figures show the extent to which counties were overrepresented or underrepresented in relation to the formula in the state constitution for election of direct representatives, meaning those not shared with another county. The formula, which the legislature had long ignored, based representation on a ratio of county to state voting population. Tennessee redistricted recently.

traditional practice, still in effect in eight states until the Supreme Court decision, of simply assigning the same representation to all units regardless of their population; in Vermont, for example, each of the 246 towns had one, and only one, representative in the lower house of the legislature. In four states, among them Delaware, apportionment on the basis of population was made all but impossible by the fact that the original apportionments were written into the state constitution, so that reapportionment required a constitutional amendment.

All these devices must now, under the law of the land, be abandoned and replaced by formulas that will equalize representation as closely "as practicable." The Supreme Court has in effect ruled that population is the controlling and most important basis for apportionment and districting. Since representation is apportioned to territorial subdivisions such as states (U.S. congressmen), counties (New York assemblymen), towns (Connecticut representatives) or some other such territorial unit, it is often mistakenly said that area as well as population is a base for apportionment as well as districting. This confusion has been confirmed by the resolution now being pressed in Congress by Senator Everett M. Dirksen of Illinois: it would authorize the states to district and apportion in certain cases on the basis of "factors other than population."

Except for Michigan and abortive efforts in Nebraska and Wisconsin, no state has attempted to apportion representation on the basis of acreage or some other such territorial measure. In *Reynolds* v. *Sims* the Supreme Court said: "Legislators represent people, not trees or acres. Legislators are elected by voters, not farms or cities or economic interests."

The problem of districting is a great deal more complex than apportionment. In districting the equal-population rule is not in itself sufficient to guarantee that various economic, political, and cultural subgroups will be adequately represented in the legislature. All the districts within a state may be absolutely equal in population and yet fail to give the various subgroups in the population the representation that is commensurate with their popular support; that is, the political parties, religious groups, ethnic or racial groups, income groups and so on may enjoy more or less representation than their membership would warrant. As everyone knows, "gerrymandering" to enhance or to minimize the voting weight of one group or another has been a common practice in every state. The state of Delaware, for example, is gerrymandered to favor the Democratic party; New York, to favor the Republicans.

Districting bodies have used two methods for legally packing the legislature. One is to split up a stronghold of the opposition party and form districts each of which has a stronghold of one's own party attached to it, so that the opposition can carry few, if any, districts. This is often accomplished by combining in one district a section of a city with an adjacent suburban or rural area. The other method concentrates the opposition's vote in a few districts where it is wasted in "overkill." For example, the districting of New York by Republican legislatures has distributed the Republican votes to much better advantage than Democratic votes. In the elections to the state senate in 1962 the Republicans polled a minority of the votes in the state but nevertheless won the senate 33 seats to 25; they won in their districts by an average margin of 20,963 votes as the Democrats were winning in theirs by an average margin of 27,883.

Gerrymandering can often be far from obvious. For example, in South Dakota, which has two representatives in Congress, an approximately straight line from north to south dividing the state into eastern and western halves would probably result in the election of two Republicans, but division of the state into northern and southern halves would probably elect one Republican and one Democrat. At the other extreme, New York exhibits one of the most obviously gerrymandered districts in the country: Manhattan's famous "silk stocking" district. There the boundaries of the district wind around street corners to include the affluent residential sections and to exclude Negro and Puerto Rican neighborhoods.

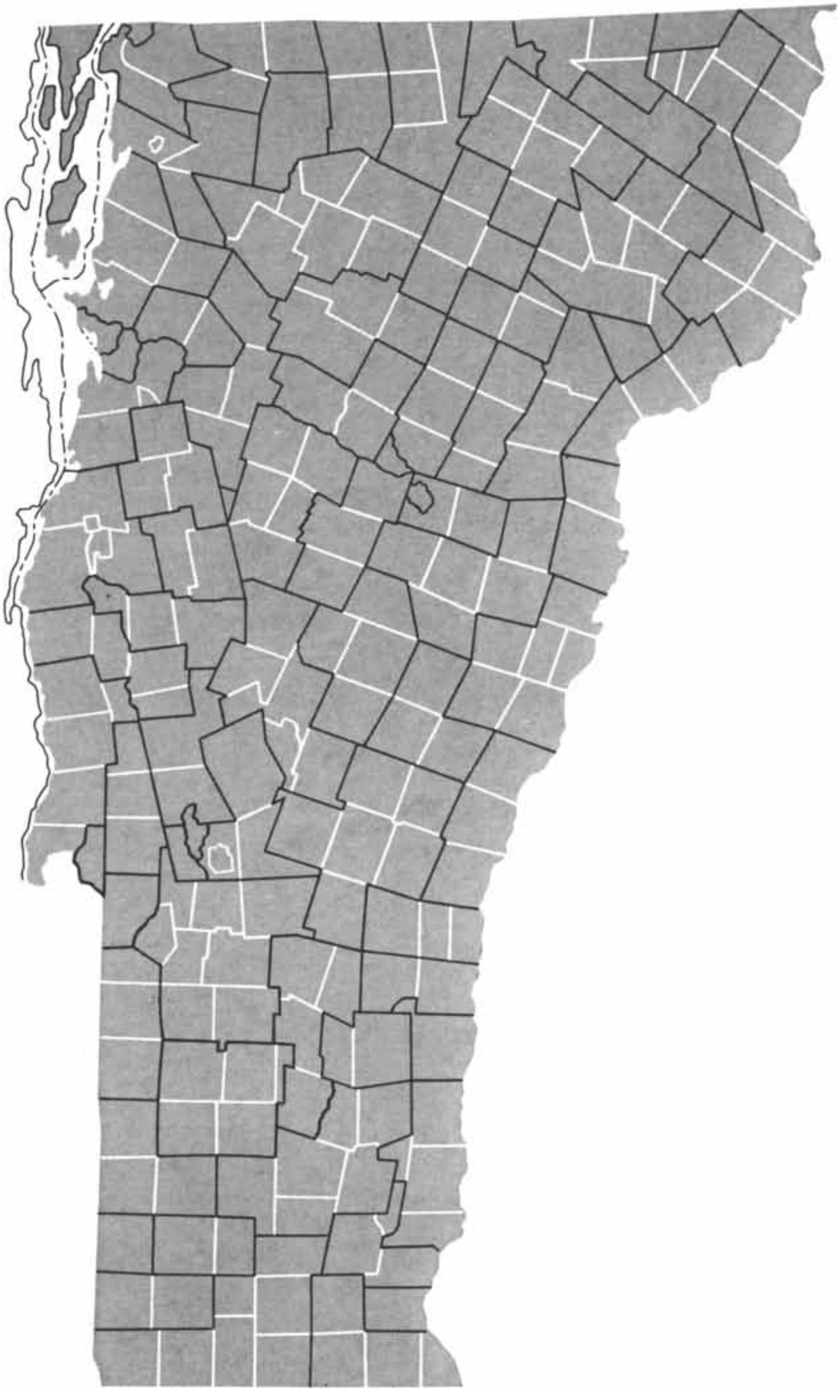
Provisions in state constitutions designed to prevent gross gerrymandering have not been very effective. The U.S. Supreme Court itself has shied away from the thicket of political gerrymandering. In 1960, in the case of *Gomillion* v. *Lightfoot*, the Court invalidated a racial gerrymander in Tuskegee, Ala. When New York's silk-stocking district was haled before the Court in 1964 (*Wright* v. *Rockefeller*), however, the Court held that the petitioners had failed to prove a *racial* gerrymander.

Perhaps the Court has avoided the question of political gerrymandering because precise criteria for districting have not been established. The Court has ruled that districts must be substantially equal in the number of representative inhabitants, but even the word "population" has not yet been clearly defined. Does it mean the total population, the citizen population or only the voting population? Federal courts have not been consistent in their opinions on this issue. One Federal district court recently upheld Hawaii's use of registered voters as the population base for senatorial districting on the ground that inclusion of nonvoting military personnel stationed in that state would result in "unfairness." On the other hand, in a Virginia congressional districting case, a Federal court ruled that "population" meant all residents in the state, including military personnel. The question is not an idle one, because many states have large pockets of nonvoters whom the voters do not necessarily represent. In the Southern states where most Negroes are not registered to vote each voter's ballot for a U.S. representative carries several times more weight than that of a voter in the North.

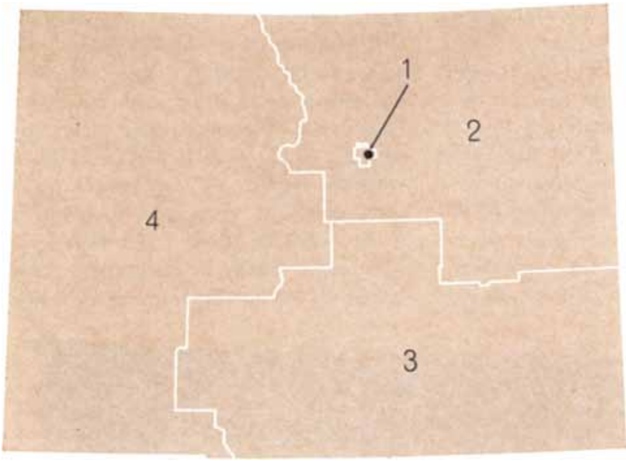
Apart from the definition of the representative population there is the question of the meaning of "practicable equality" between districts. There has been considerable litigation on how much leeway this phrase allows. As the measure of inequality the legislatures and courts have most often used the difference between the least and the most populous districts in the state. Such a measure, based only on the extremes, is not a significant index of the prevalence of inequality among the districts. A somewhat better measure, also commonly used, is the extent of departure of the various districts from the mean: the average size of all the districts. A bill now pending in Congress (introduced by Representative Emanuel Celler of New York) would require that every district in a state be within 15 percent of the mean in population. Some courts have applied a somewhat more significant measure of whether or not a state's districting is equitable. This measure, called the Dauer-Kelsay index, indicates how far the state's districting system departs from the ideal of assuring majority rule. In New York, for example, the index shows that in the 1964 election of the state assembly the 76 least populous districts, accounting for a total of only 33.4 percent of the state's citizen population (according to the 1960 census), elected a majority of the assemblymen.

The Dauer-Kelsay index is a reasonably adequate measure of inequality (or equality) in districting, but statisticians prefer two other indexes that are considerably more sensitive and provide a better picture of the entire distribution of representation. These, known as the Gini index and the Schutz coefficient, are summary indexes of the whole distribution. They are sensitive to inequalities in all parts of the distribution, and make noncomparable data comparable.

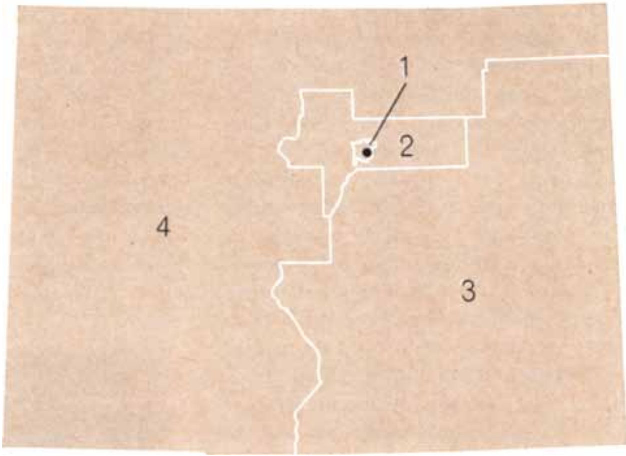
Finally there is the important question of how well the construction of a district provides for representation of the people composing it. It has often been alleged that if the selection of a representative is to be meaningful, the voters must have a community of interest on which they can express themselves. A fragmented or patchwork district, lacking any common denominator, will make it very difficult for the electorate to bring certain issues to a common focus or to speak with a coherent voice. For the most part legislative districts in the U.S. have been laid out without regard for considerations of community of economic, political or social interest; they have been constructed primarily in geographic terms. Most political scientists are agreed, how-



VERMONT'S DISTRICTING for the state House of Representatives formerly provided one representative for each town (*white lines*). The arrangement produced large inequalities: the legislator elected from the most heavily populated town represented 987 people for each person represented by the legislator elected from the least populated town. This year the state established new district boundaries (*dark lines*) for fairer representation.



COLORADO VOTERS were unevenly represented by the congressional districts existing before *Baker* v. *Carr*. Range of population was from 195,551 in the 4th district to 653,954 in the 2nd district.



REDISTRICTING IN COLORADO, done last year under impact of *Baker* v. *Carr* and other decisions, yielded districts with a population range from 405,899 (4th district) to 493,887 (1st district).

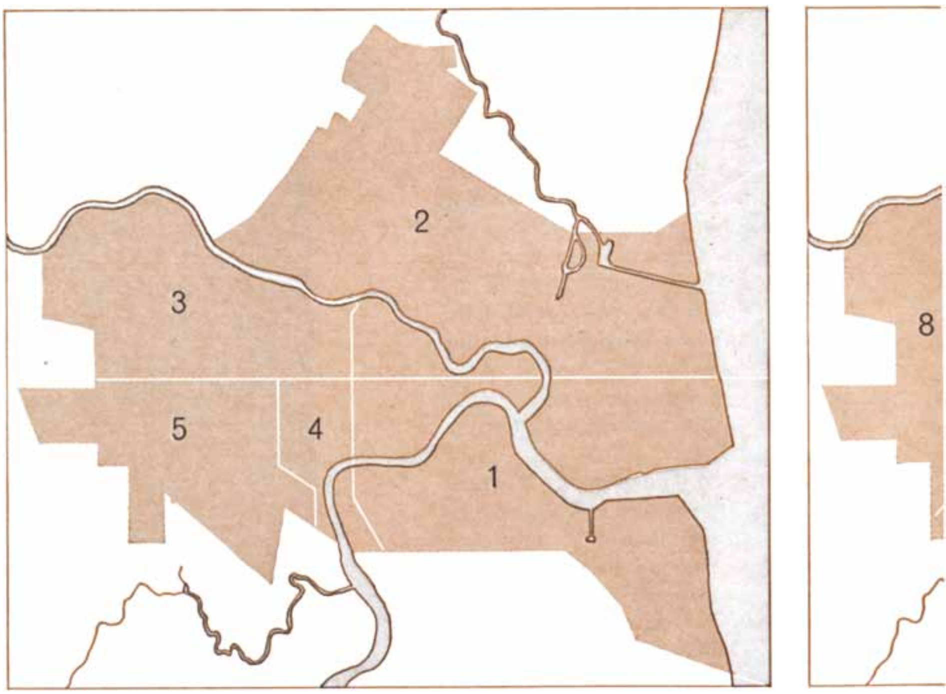
ever, on some general criteria for construction of a constituency. The district should be in one piece; it should be "compact" (a word formerly defined in terms of topography and the means of travel and ease of communication between various parts of the district) and, as nearly as practicable, it should have common social, political and economic interests.

Most views and measures of compactness have been conceived solely in geographic terms and have ignored population distribution and factors such as community of social, political and economic interest. Recently, however, James B. Weaver and Sidney W. Hess, engineers at the Atlas Chemical Industries, have devised a measure of "compactness" that indirectly recognizes such "area factors" as community of interest as well as topography and the means of transportation. The Weaver-Hess plan enlists the aid of a computer in the districting process.

The Weaver-Hess formula measures the proximity of the district's population to the district's center and aims to construct districts of maximum compactness around population centers. The closer the population is to the district's center, the more compact is the district. Since topography and the means of transportation often influence the distribution of population, and since population patterns often coincide with interest patterns, the Weaver-Hess concept of compactness tends to avoid splitting communities of economic or other interests to the extent that these interests coincide with areas of high or low population densities.

This new concept of compactness is essentially a "center of population gravity" idea. It is based on the moment-of-inertia principle and uses the statistical technique of least squares, which locates the line of "best fit" to a series of data points in order to minimize the sum of squared distances from the points to the line. This "moment of inertia" measure utilizes both area and population.

If a legislative district is composed of precincts with known populations, it is possible to make a calculation analogous to moment of inertia about any given point in the district. The moment of inertia for each precinct would be the product of the precinct's population and the square of the distance between the precinct's center and the given point. To obtain the moment of inertia around that point for the whole district—in other words, the district's compactness—the precincts' moments of inertia are summed. The sum will be smallest when the point around which the moments of inertia are calculated is the population center of the district, which is to say the district's center of population gravity. If the population is distributed evenly throughout the district, the center of population gravity will be in the geographic center of the district.



COMPUTER DISTRICTING of state legislative districts in Wilmington, Del., is compared with other plans. The former districts (*left*) were declared unconstitutional, so the Demo-

If there is a more populous city in the northwestern part of the district, the district's center of population gravity will move toward the northwest.

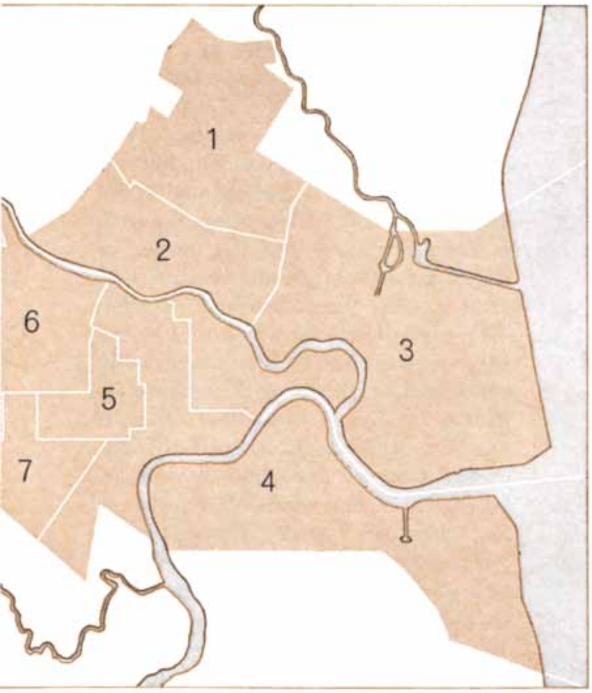
This concept of compactness suggests methods of area and demographic analysis that social scientists have long used successfully in drawing the boundaries of marketing, school and service districts. Weaver and Hess have combined their concept of "compactness" with contiguity and population equality (as measured by deviation from the mean) into a districting procedure that is essentially a linear program of a transportation problem. The aim of the computer program is to construct legislative districts by combining smaller areas of known population—such as census enumeration districts if total inhabitants are the population base or voting precincts if the number of voters is the base—into a given number of contiguous districts of approximately equal population and relatively maximum compactness. Discretion is involved, of course, in defining the population base and in specifying the permissible deviation from absolute population equality and relative weight of population equality to compactness.

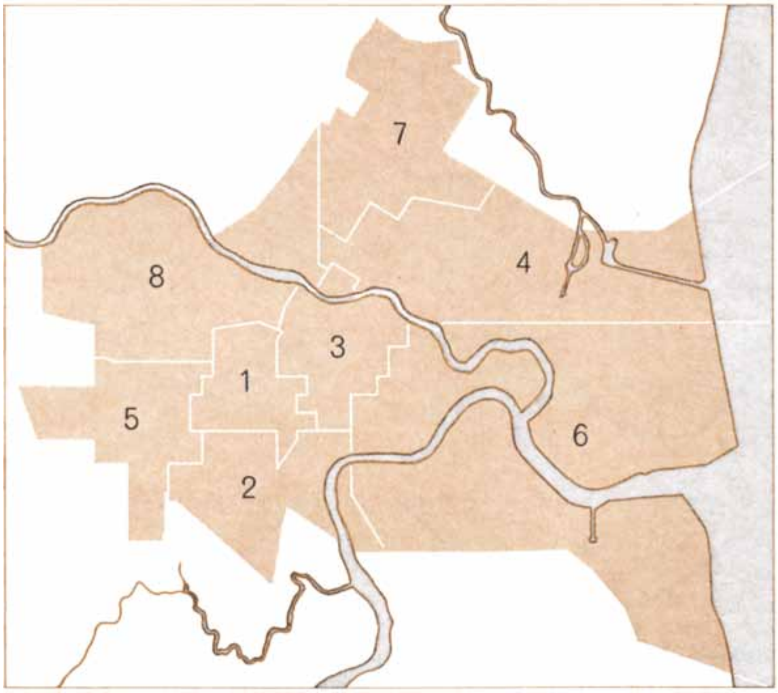
The Weaver-Hess program calculates the distance from each precinct's or other unit's center to any given point, computes the moments of inertia, sums them and districts by minimizing these sums. This is analogous to determining school location by minimizing child-miles of travel between home and school. The larger the indivisible units to be combined, the greater will be the population inequalities between districts. The smallest unit of population provided by the U.S. census is the "enumeration district," which usually has boundaries of the kind thought desirable for legislative districts—rivers, highways or railroad tracks. Since enumeration-district populations average fewer than 1,000 inhabitants, legislative districts are usually sufficiently large to allow rather precise population equality even though each enumeration district must be contained wholly in the same legislative district.

A program that applies the idea of computer districting in a highly refined and practicable form has been worked out by Stuart Nagel of the University of Illinois. Its instructions to the computer include the number of units in the state that are to be combined into districts, the number of districts to be constructed, the average population size of the districts, the permissible deviation of individual districts from this average size, and the weight to be given to compactness with respect to population equality. (Nagel gives the two factors equal weight.) The program also allows the introduction of a "political factor," so that at the outset the proportion of the seats to be won by each party will be the same as that party's share of the votes cast in the last statewide election or some other election. This assumes, of course, that each party's share and geographic distribution of the vote will be substantially the same as at the given election.

The Nagel program is highly flexible. It can adjust districting to special conditions by only minor changes in the instructions and data cards fed into the computer. For example, if for economic or other reasons it is desirable to ensure that two or more population units will be placed in the same legislative district, they can be treated as a single unit by combining them on one data card.

Districting by computer has a number of technical advantages. It minimizes the chance for arithmetic error and automatically checks various figures at each stage of computation. It produces alternative districting proposals and directly compares these alternatives for adherence to the accepted criteria. It minimizes bias and political manipulation. Moreover, compared with the costly present process of redistricting in the political arena—costly in time as well as in money and general confusion—districting by computer is objective and strikingly inexpensive. Once the general principles of representation have been agreed on, the legislative districting of a state can be accomplished in a few days at a cost of only a few hundred dollars.





cratic state legislature drew new districts (*center*) that are nearly equal in population but have been criticized as favoring Democrats. Some hypothetical districts (*right*) drawn with the aid of a computer emphasize compactness in both population and area.

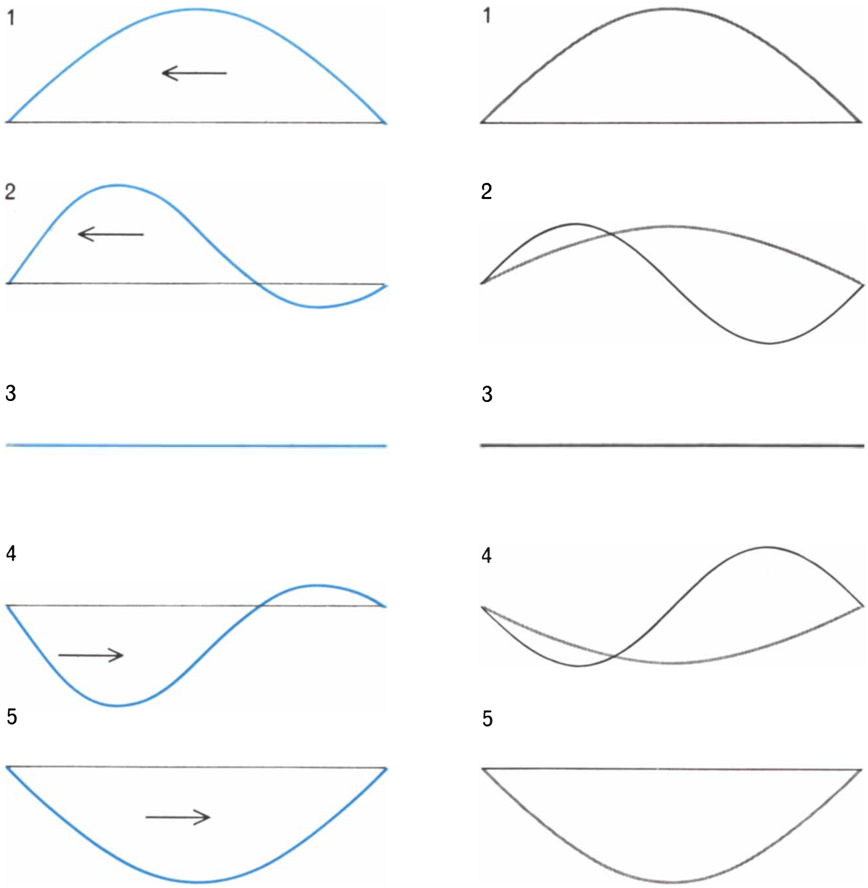
RESONANT VIBRATIONS OF THE EARTH

When a major earthquake occurs, the entire earth vibrates like a ringing bell. These extremely slow "free oscillations" yield information on the structure of the earth's crust and mantle

by Frank Press

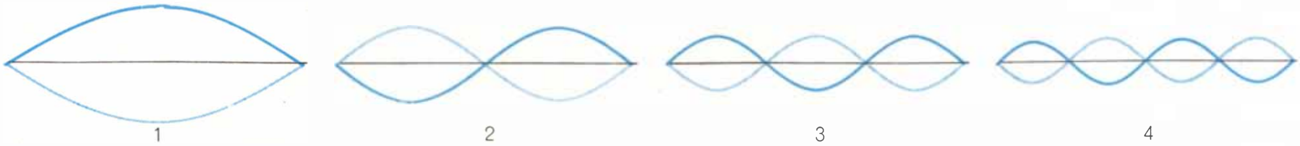
Pluck a taut string and it vibrates; strike a bell or a gong and it vibrates. The vibrations are called free oscillations, and they are excited in any mechanical system that is disturbed from equilibrium and then left alone. The earth also vibrates when it is disturbed: an earthquake sets the entire globe to oscillating like a bell for weeks or months. In the past five years geophysicists have learned how to detect these global free oscillations and analyze them to obtain information on the structure of the earth.

The value of free oscillations to the geophysicist arises from the fact that the total vibration of a body can be regarded as a superposition of independent harmonic motions called normal modes. Each mode can be excited by itself, but complex vibrations involve the superposition of large numbers of modes. The characteristic frequencies of these modes are determined solely by the nature of the vibrating body—not by the special circumstances that excite the vibration.

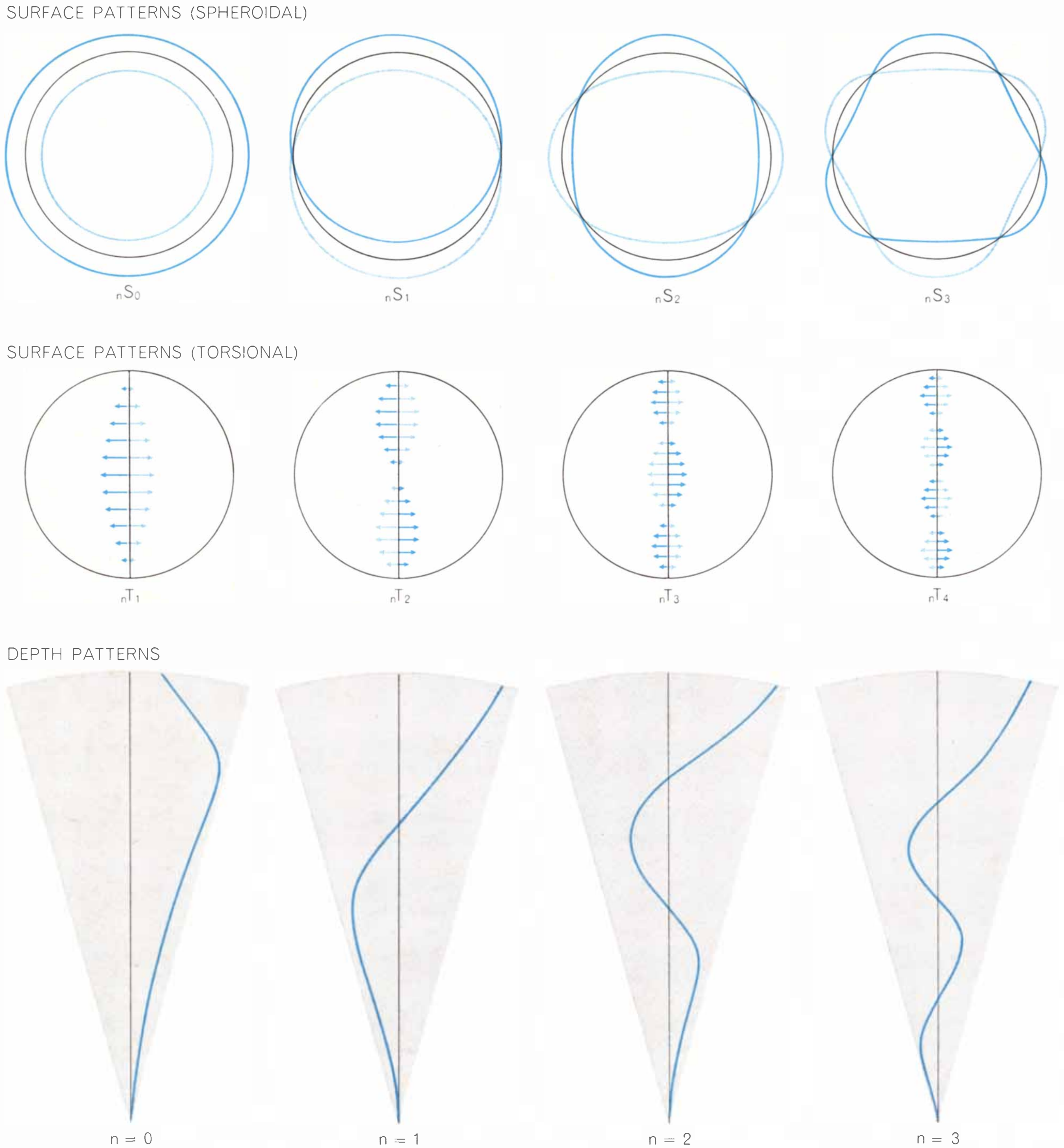


VIBRATION OF A STRING can be represented as a traveling wave (*left*) or as two standing waves (*right*). In this case the traveling wave is the result of superposition of the first two modes of vibration of the string, vibrating 90 degrees out of phase. Any wave motion, even the most complex, can be represented as the sum of a large number of modes.

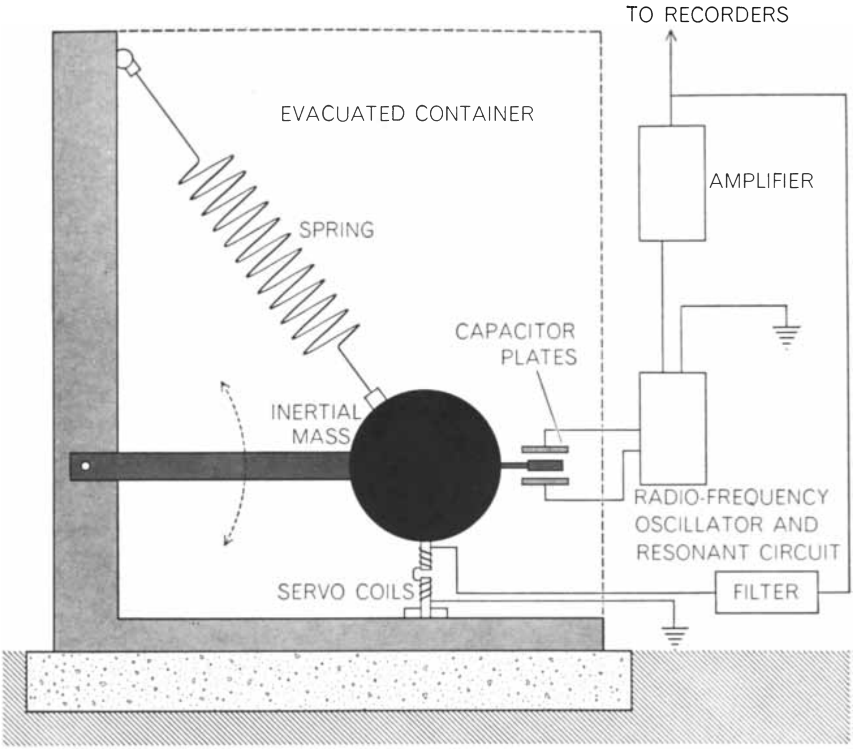
In the case of the earth all possible elastic motions of the planet can be represented by a superposition of free oscillations. Even the complex jumble of vibrations that emanates from an earthquake, which one usually thinks of as a series of different kinds of propagating waves, can be so represented. This follows from a dual aspect of waves: when a propagating wave interferes with itself, it is manifested as a "standing" wave. For example, the motion of a plucked violin string can be completely represented either by (1) a traveling wave that leaves the point at which the string is plucked and is reflected back and forth between the ends of the string or by (2) the modes, or standing waves, that are characteristic of the string [*see illustration at left*]. The wave motion by which seismic energy is transmitted is conventionally considered as a traveling disturbance affecting one part of the earth at a time; it can be considered just as correctly, and from a more general point of view, as belonging to some mode of vibration of the earth as a whole. This approach yields two dividends. It provides information on the structure and other characteristics of the earth as a whole, and it provides a "handle" with which to get at the information in certain very long seismic waves that are of special interest to geophysicists but that are



FIRST FOUR MODES of a vibrating string, the fundamental and first, second and third overtones, are illustrated. The string vibrates between the dark- and light-colored positions. The mode number is one less than the number of nodes, or points of zero displacement.



MODES OF A SPHERE are more complex. Here a few of the surface and depth displacement patterns are shown. In spheroidal (S) modes there is both radial and horizontal vibration; in torsional (T) modes, particles vibrate on a spherical surface. The subscript at the right of the designation of each surface pattern describes the pattern in terms of variation in latitude; in these examples the vibrations are assumed to be independent of longitude. The subscript n gives the depth pattern, or number of nodal surfaces. Any spheroidal or torsional mode can combine with any depth pattern; that is, it can be repeated at any number of levels.



VERTICAL PENDULUM SEISMOGRAPH designed by Ralph Gilman of the California Institute of Technology detects the vertical component of long earthquake waves. The mass tends to remain stationary as the earth moves. Relative motion at the capacitor plates generates an electrical signal that is fed to an analogue and a digital recorder. The filter feeds back spurious signals, representing motions other than those of the desired waves, to coils that keep the mass centered. The base of the instrument is two feet long.

particularly difficult to define and analyze as individual waves.

The normal modes of a sphere can be grouped in two classes: "spheroidal," or *S*, modes and "torsional," or *T*, modes. In the *T* modes each particle of a body vibrates back and forth on a spherical surface—on the outside of the body or on some interior "shell." The *S* modes involve not only this horizontal motion but also a radial motion in and out from the center. Now, in the case of a vibrating string only one integer is required to describe a mode of vibration: the "mode number" is one less than the number of nodes, or points of zero displacement [*see top illustration on preceding page*]. It takes two integers to describe the modes of a vibrating membrane such as a drumhead. In the case of a sphere, which has three dimensions, three integers are required; they are designated *l*, *m* and *n*.

The integers *l* and *m* define the pattern of surface displacements, or of lines of nodes, with regard to the source of the disturbance. One integer, *l*, fixes the variation with latitude: the angular distance (measured at the center of the sphere) from the source. The other, *m*, fixes the variation with longitude, or azimuth. When the oscillations are independent of longitude, there are *l* lines of nodal latitude in the surface pattern for spheroidal modes and $l-1$ lines for torsional modes. The index *n* specifies the pattern of displacements with depth: the number of nodal surfaces [*see bottom illustration on preceding page*].

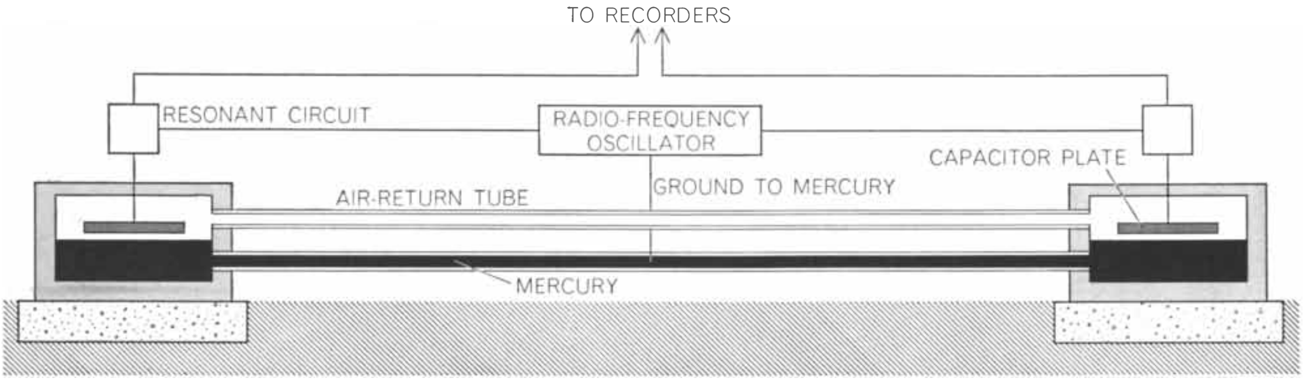
A mode of vibration can be completely described by either of the following two symbolic expressions: ${}_nS_l^m$ or ${}_nT_l^m$. A double infinity of modes and frequencies is possible. There are an infinite number of surface patterns as *l* varies from 0 to infinity and, for each *l*, there are a fundamental mode ($n=0$) and an infinite number of overtones as *n* varies. In a nonrotating sphere the frequencies are independent of *m*. In the illustration (in which *m* is held constant so as not to affect the patterns) it can be seen that the sphere expands and contracts radially in the ${}_nS_0$ mode, "shakes" in the ${}_nS_1$ mode and becomes football-shaped in the ${}_nS_2$ mode. In mode ${}_nT_2$ the hemispheres rotate in opposite directions around the same axis; in higher *T* modes the direction of rotation alternates with smaller changes in latitude.

The theory of elastic vibrations in spheres has been under development for a long time; it was discussed by the French mathematician Siméon Denis Poisson in 1829 and was worked out in detail and applied to the earth by several noted British mathematical physicists at the end of the 19th century and the beginning of this century; more than 50 years ago A. E. H. Love even made an estimate of one hour for the period of the earth's mode ${}_0S_2$, assuming a homogeneous earth with the mean elastic properties of steel. It was only recently, however, that a fortuitous combination of circumstances led to the observation and theoretical verification of the earth's free oscillations. Hugo Benioff at the California Institute of Technology, Lucien LaCoste of LaCoste & Romberg and Maurice W. Ewing and I at Columbia University's Lamont Geological Observatory developed instruments sensitive to long-period earth movements and these instruments were deployed around the world. Electronic digital computers became available, along with new techniques for the interpretation and numerical spectral analysis of seismic waves. And Chaim Pekeris and his colleagues at the Weizmann Institute of Science in Israel made advances in the theory of wave propagation, particularly for models of the real earth.

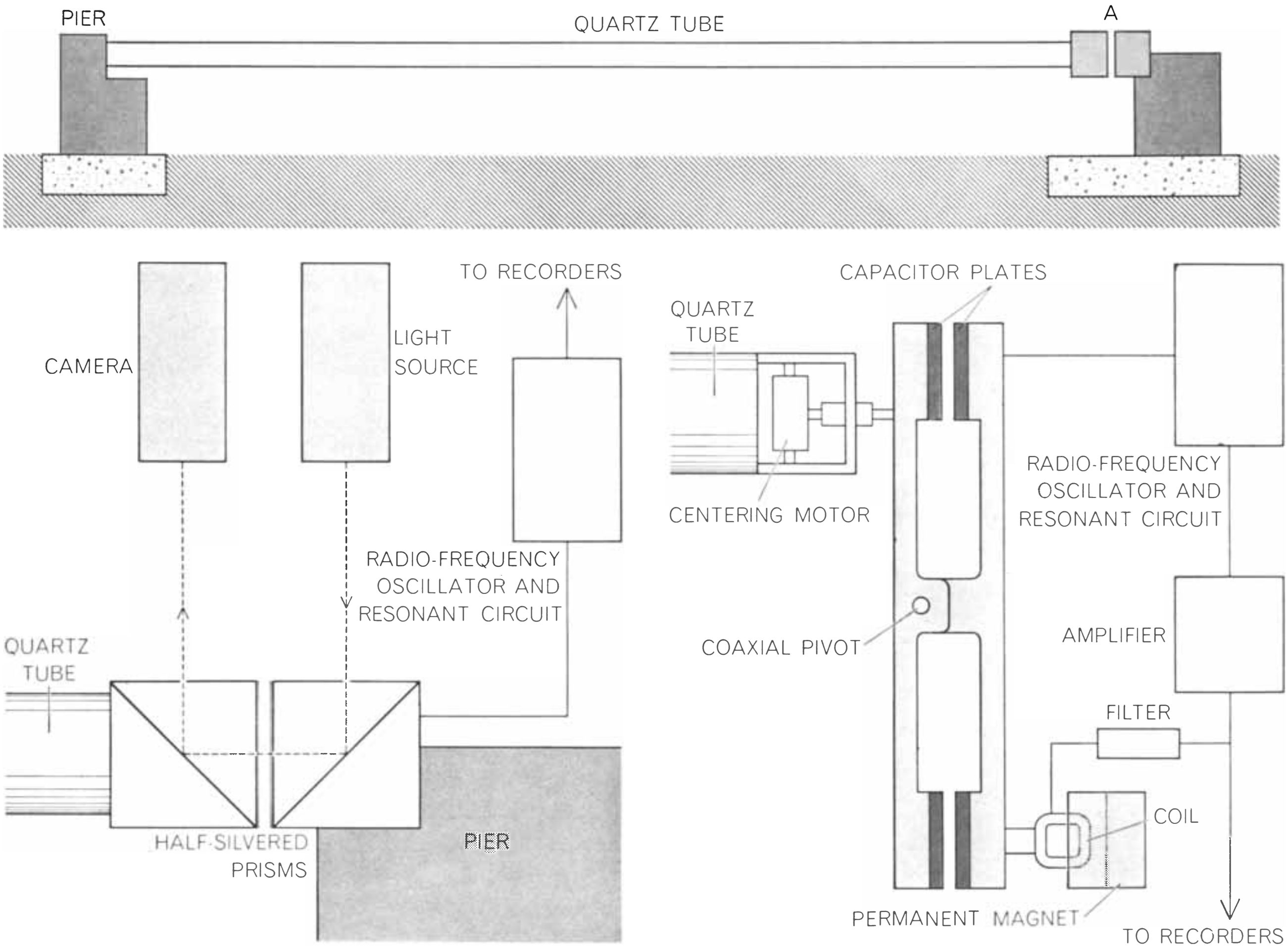
The major effort in instrumentation has been to improve the response to long-period, low-frequency waves [see "Long Earthquake Waves," by Jack Oliver; SCIENTIFIC AMERICAN, March, 1959]. This has required the development of electronic transducers that are selectively sensitive to very slow earth movements, with filters that minimize background noise and maximize the signal. Transducers that sense small changes in capacitance detect the movements of the inertial mass in a pendulum seismometer [*see illustration on this page*], the differential change in the level of mercury in a "tiltmeter" [*top illustration on opposite page*] and the changing distance between the piers of a "strainmeter" [*bottom illustration on opposite page*]. Optical interferometers and differential transformers also serve as transducers. The output from the transducer can be recorded not only as a wiggly line on a pen recorder or on photographic film but also in digital form, on magnetic tape that can be fed into a computer for subsequent analysis.

Modern seismographs are limited in sensitivity not by design considerations but by background noise. Microseisms, which originate in the transfer of energy from the wind or sea to the solid earth, can travel thousands of miles and register on an instrument. Industrial machinery is a source of noise; so is the diurnal heating and cooling of the outer few inches of the earth's crust. Even the periodic yielding of the solid earth under the influence of lunar tides can contaminate seismic signals. (One investigator's "noise" is of course another investigator's "signal"; earth tides are of particular interest to many geophysicists.)

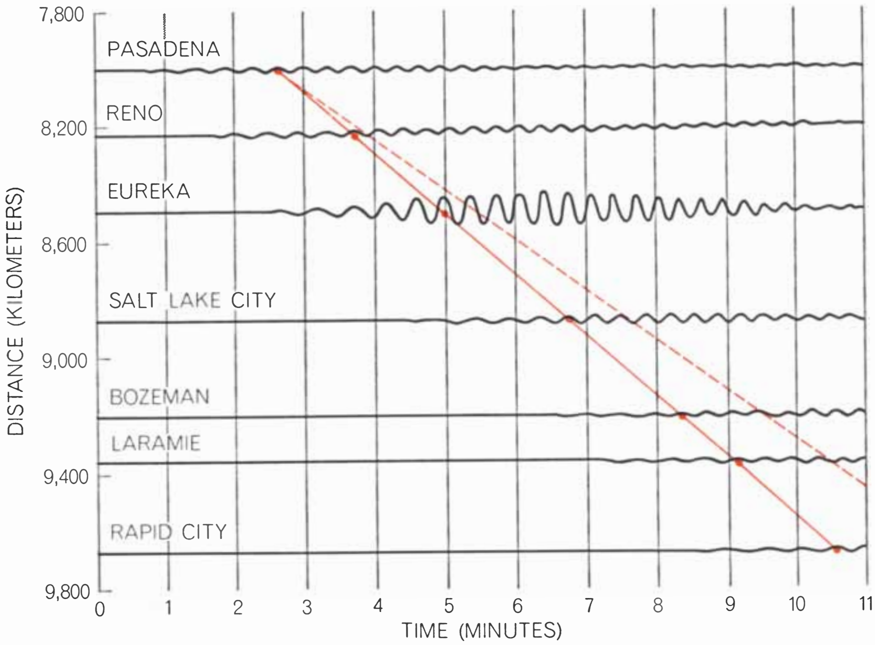
The most sensitive pendulum seismographs can detect displacements of one millimicron, or a millionth of a millimeter. In an array of such instruments the detection capability increases—roughly as the square root of the number of elements. A huge array is currently being installed in Montana for the purpose of detecting small earthquakes and nuclear explosions. Its 500 seismographs, arranged in patterns covering



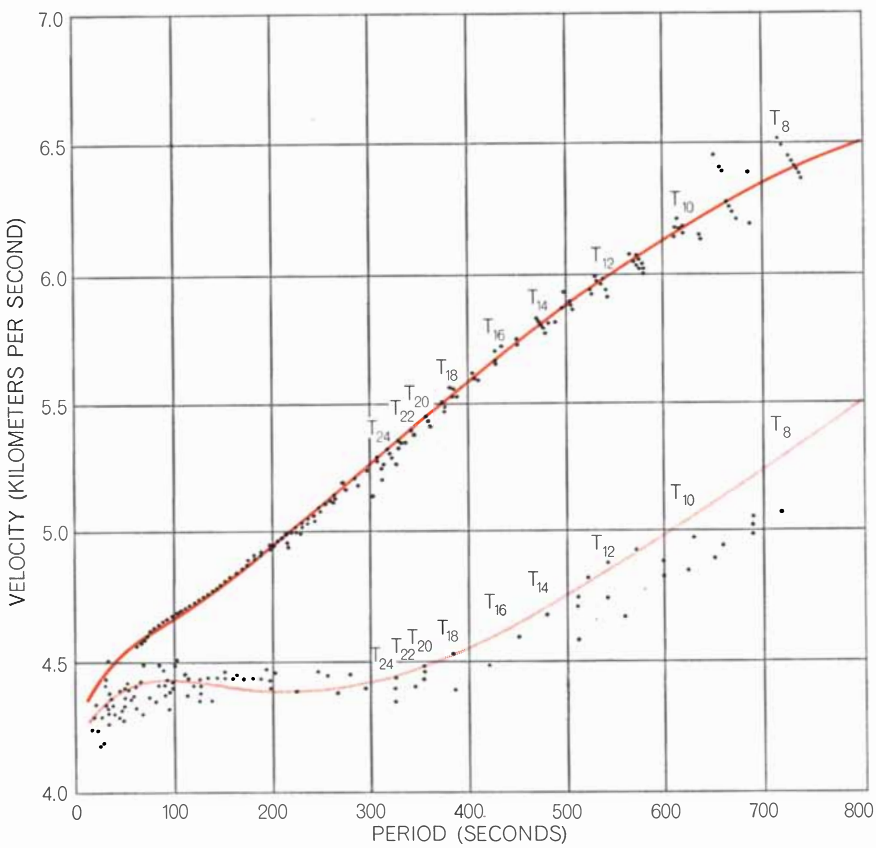
TILTMETER detects a tilt in the earth's surface by measuring the relative change in capacitance as the mercury level in two reservoirs changes. In this version designed by Hugo Benioff and William Gile of Cal Tech the reservoirs are three to 100 feet apart.



STRAINMETER designed by Benioff records strain, or a change in length over a given length, by measuring the changing distance between two piers. A quartz tube (*top*) extends from one pier almost to a second pier 10 to 100 feet away. A change in the small distance at *A* is measured by either of two transducers (*bottom*) designed with Leonard Blayney. In one (*left*) half-silvered prisms serve as capacitor plates and also constitute an interferometer that calibrates the instrument. In another transducer (*right*) the capacitor plates are pivoted and spurious signals are corrected for, as in the vertical pendulum seismograph, by a feedback system.



VELOCITY of Rayleigh waves is derived from seven seismograms recording the waves' arrival at instruments constituting a 2,000-kilometer array. The vertical scale shows distance from the epicenter. The solid line connects wave crests and indicates "phase velocity." The broken line connects wave groups of the same frequency and shows "group velocity."

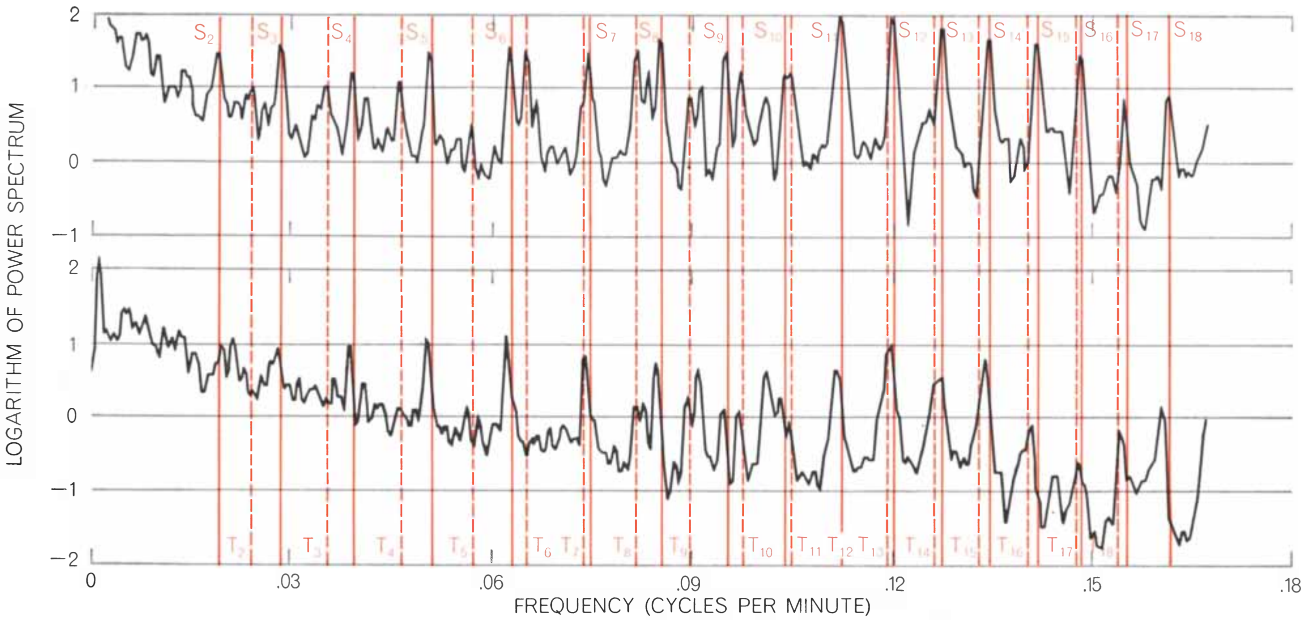


DISPERSION DATA, or phase and group velocities at various periods, were obtained experimentally from propagating Love waves for periods of less than about 300 seconds and from torsional free oscillations for longer periods. Data were plotted with theoretical curves of phase (*dark color*) and group (*light color*) velocity for a particular earth model.

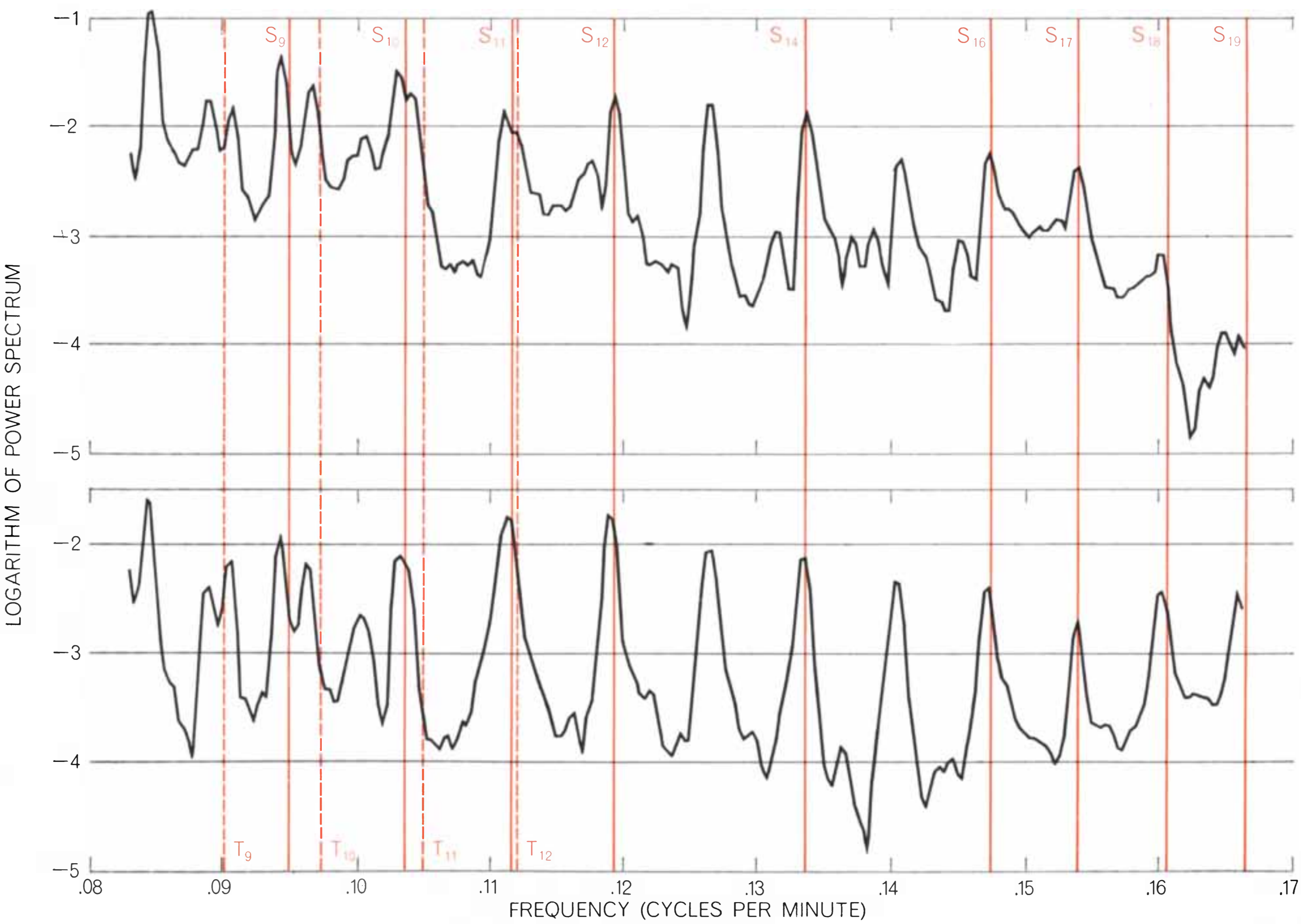
an area 200 kilometers on a side, may sense ground motions smaller than a ten-millionth of a millimeter! A strain seismograph, which is inherently more sensitive to very long waves, measures deformation in terms of the change in length over a certain length. Strainmeters are limited by noise to sensing strains of 10^{-9}—say one millimeter over 1,000 kilometers—in the case of permanent displacements and of 10^{-10} in the case of transient waves.

I mentioned earlier the dual aspect of waves represented by propagating waves and standing waves, or free oscillations. As a matter of fact, each of the two free-oscillation modes is related to a specific kind of propagating surface wave. The torsional modes are the interference patterns of Love waves (named for A. E. H. Love, who discovered them); the spheroidal modes are the standing-wave equivalents of Rayleigh waves (named for Lord Rayleigh, who described them in 1900). Love waves are transverse shear waves: the ground vibrates horizontally at right angles to the direction of the wave. Rayleigh waves are like water waves: particles in their path vibrate in ellipses that lie in the vertical plane along which the wave is being propagated.

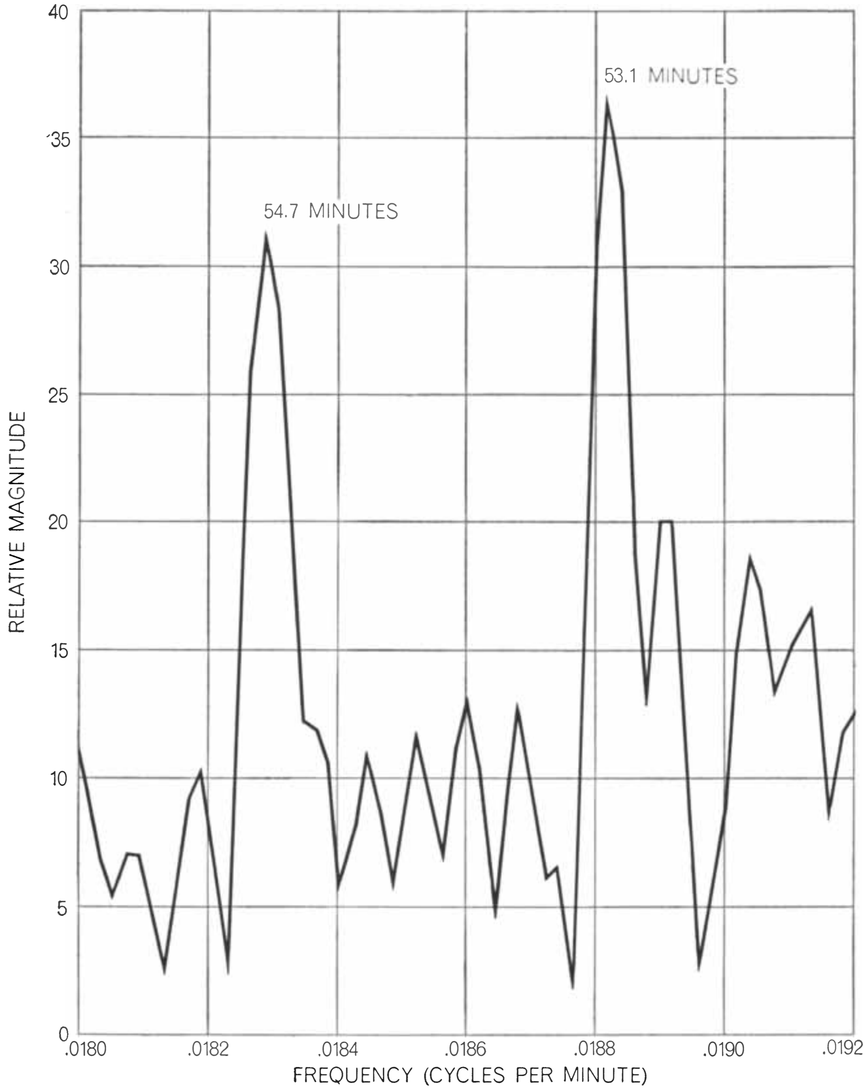
Free oscillations contain no information about the earth's interior that is not carried by the propagating surface waves. Whether one chooses to analyze a seismogram in terms of Love or Rayleigh waves or of free oscillations is therefore a matter of convenience. The length of the waves is the determining factor. Seismic waves radiate from a source and travel around the world repeatedly; a single wave arrives at a seismograph many times. In the case of waves with periods longer than about 1,000 seconds, with wavelengths of the order of the earth's radius, it is difficult to distinguish among these various arrivals, and such waves are best studied as free oscillations. Waves with periods shorter than 300 seconds or so are easily separated, however. Their lengths are shorter than about 1,500 kilometers and their speed is controlled by the properties of the earth's crust and upper mantle, properties that may differ below continents and ocean basins. By obtaining the propagation velocity of such waves in segments of their paths restricted to a single geological province, one can deduce crust and upper-mantle structure in detail. These shorter waves are therefore better studied as propagating waves than as global free oscilla-



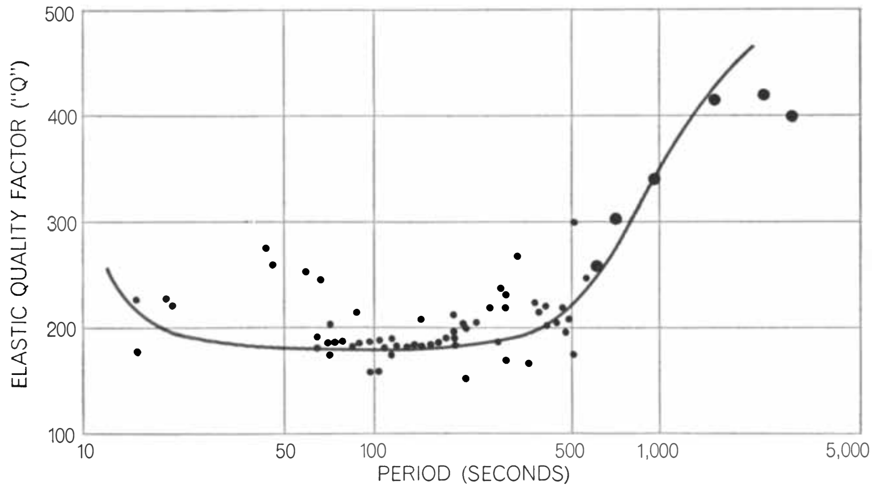
POWER SPECTRA of seismic waves from the Chilean earthquake of 1960 (*top*) and from the Alaskan earthquake of 1964 (*bottom*) are displayed together. The spectra were derived as explained in the text. Spectral peaks corresponding to spheroidal (*S*) and torsional (*T*) oscillations are labeled according to mode number. Peaks correspond in the two spectra; amplitudes differ.



SPECTRA obtained from strainmeters in Peru (*top*) and in California (*bottom*) for the Chilean earthquake also show peaks that coincide in frequency as predicted by theory. "Noise" between peaks in the spectra, on the other hand, shows no cross-correlation.



HIGH-RESOLUTION ANALYSIS of the earth's lowest-frequency mode of oscillation, the $_0S_2$ mode, revealed this double peak. Such multiplets are caused by the rotation of the earth, which affects the symmetry between waves traveling in opposite directions.



ELASTIC QUALITY, or the extent to which energy is retained in a system, is measured by the factor Q. Here Q is plotted as a function of wave period as determined from propagating-wave data (*small dots*) and free-oscillation data (*large dots*). The increasing Q at long periods implies that this factor increases with depth in the earth's mantle.

tions, which necessarily average out the geology of the entire world.

The propagation velocities of waves of various periods yield information on the structure of the earth because there is a correlation between the length of a wave and the depth it probes. Velocity data can be derived from the time at which waves arrive at a number of different stations [*see top illustration on page 32*], or arrive repeatedly at one station after circling the earth in both directions. The seismograms in the illustration record the arrival of Rayleigh waves from an earthquake in the Solomon Islands at seven stations in the U.S.; the seismograms are spaced according to the distance of the station from the epicenter and are aligned in time.

If a line is drawn connecting a point of constant phase in each seismogram, such as the crest of a certain wave, its slope gives the "phase velocity" of waves of a certain period. If, starting from the same point as the phase-velocity line, one connects instead the centers of groups of waves having about the same frequency, the slope of the line gives the "group velocity" for waves of the same period. Both kinds of velocity turn out to be greater for longer waves than for shorter waves; indeed, a glance at the seismograms shows that there are longer waves at the head of the wave train and shorter waves toward the rear. This dispersion, or sorting out, of the waves according to period—frequency modulation of the wave train, as it were—depends primarily on the variation of elastic velocity with depth in the earth: the long waves travel faster because they probe greater depths. Analysis of a seismogram for dispersion therefore tells one about the properties of various layers of the earth or of specific subcontinental or suboceanic regions, depending on the periods of the waves being studied.

Dispersion curves are built up from a large number of velocity observations [*see bottom illustration on page 32*]. One can also construct theoretical curves by working backward from assumptions about the earth's structure to the elastic velocities at various depths and thus to the speed with which waves of different lengths should propagate. There are theoretical curves that fit the observed data quite well. So far the fit is not unique because not enough data have yet been accumulated, but the available dispersion curves do at least limit the range of possible earth structures. Such constraints are important to the investigator; as constraints accumulate from different kinds of data they narrow the range of uncertainty, much as information from a number of senses converges to define an object.

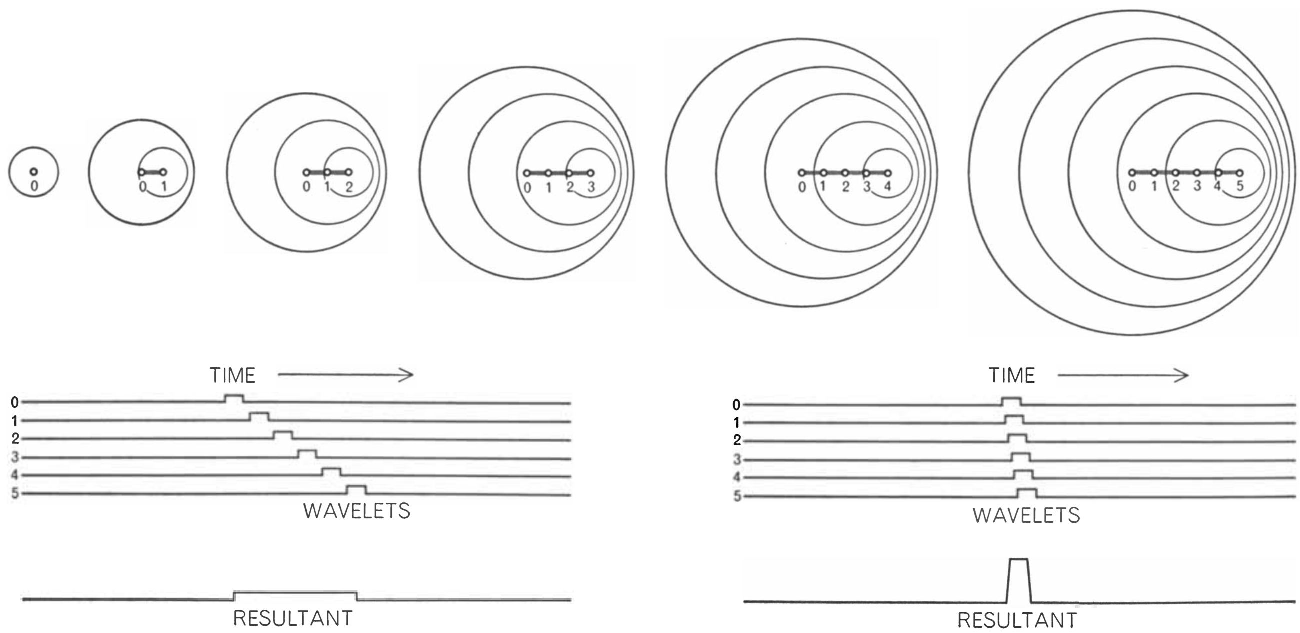
Measurements of the earth's free oscillations have extended the depth to which one can examine the earth's structure. In the bottom illustration on page 32, for example, the data for waves with periods of less than about 300 seconds were obtained from measurements of Love waves. The data for longer waves, which reflect the properties of deep layers of the earth's mantle, came from analysis of the earth's torsional modes.

Although long surface waves have been studied intensively for a decade, the necessary tools for observing free oscillations and a sufficiently large seismic source to excite strong oscillations were not available at the same time until the great Chilean earthquake of May, 1960. Within a few weeks after that event teams from Cal Tech, Columbia University and the University of California at Los Angeles reported observing some 40 fundamental spheroidal modes, 25 torsional modes and several spheroidal overtones.

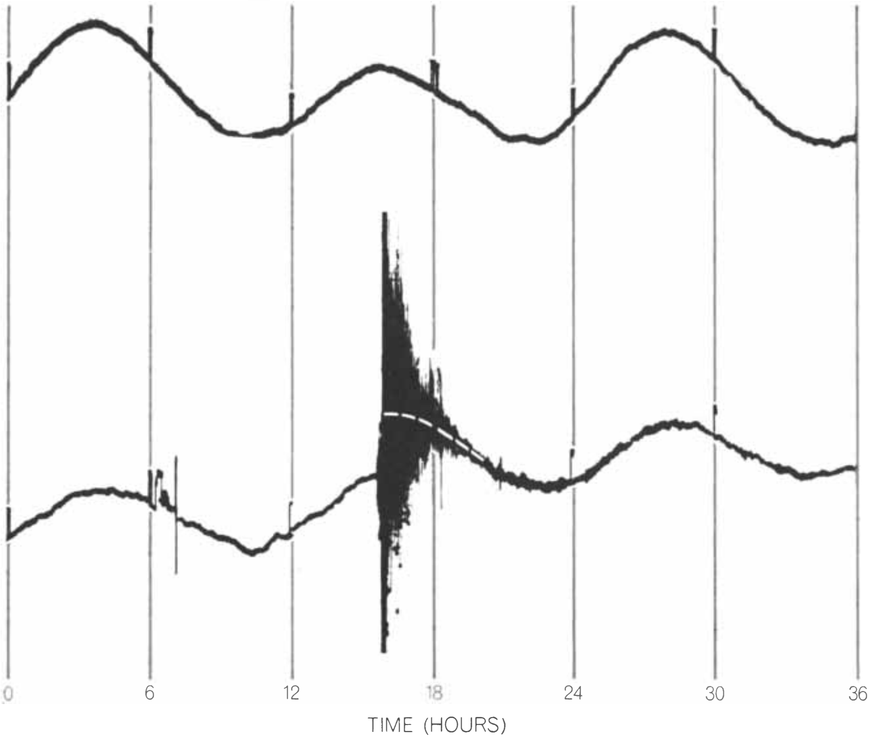
The experimental procedure for detecting free modes begins with a seismogram cast in the form of a time series—a record of the variation with time of the amount of strain or tilt or other motion of the earth. The output from the detecting instrument is quantified at discrete time intervals—say once every 10 seconds—and recorded on tape as a series of digits. The sequence of digits begins with the first signal from the earthquake and may last for a period of weeks or months, depending on how quickly the oscillations decay. (An analogue record is made simultaneously because it is easier to tell from a wiggly line than from a list of numbers whether or not the instruments are working.)

The problem of identifying free oscillations is simply one of decomposing the time series into its component modes. This is accomplished by the process of Fourier analysis. The numerical procedure, carried out in a computer, is to multiply the time series by a sine wave of a given frequency and to average the product over the entire series. The averaging procedure cancels components of all frequencies but the one being considered, and the average is proportional to the strength of that component in the series as a whole. The process is repeated at one frequency after another until the entire frequency band has been scanned. The result is a spectrum with peaks at the frequencies of the earth's normal modes of oscillation. The height of each peak is a measure of the power, or the degree of excitation, of the mode. One might liken Fourier analysis to the process of passing a complex electrical signal through a sharp filter. The filter can be adjusted to reject all frequencies but one, and its output is then proportional to the degree to which the harmonic component with that frequency is present in the original signal. The spectrum can be made cleaner by the process of cross-spectrum analysis. If two time series are derived from widely separated stations, and if the signal is correlated but the noise is not, the contamination of the spectrum by noise can be reduced significantly.

Stewart Smith of Cal Tech compared power spectra for the two great earthquakes of recent years, the one in Chile in 1960 and the one in Alaska last year. The earth's free-oscillation modes are plain to see from his data [*see top illustration on page* 33]. There is a sequence of spectral peaks, most of which are present in both spectra. As a result of the theoretical predictions by Pekeris and his colleagues it is possible to assign the appropriate *S* and *T* mode numbers to each peak. As theory requires, the modes reflect the properties of the earth, not the individual earthquake: the peaks fall at exactly the same periods whether they were excited by the Chilean or the Alaskan shock. The amount of energy in each mode, however, depends on the location and dimensions of the source, so that not all



ASYMMETRIC WAVE PATTERN is radiated by an earthquake as it propagates along a fault. The top diagrams show how the waves excited at the first instant (*0*) and at five equal time intervals thereafter are crowded together in the direction in which the earth is cracking and are spread out in the opposite direction. Such wavelets will be recorded as resultants of greater amplitude and higher frequency at a seismograph placed in the direction of fault progression (*bottom right*) than at an instrument on the opposite side of the epicenter (*bottom left*). The ratio of spectra from two such instruments yields fault length and rupture velocity.



PERMANENT STRAIN CHANGE of 10^{-8} is indicated on a strain seismogram made in Hawaii for the Alaskan earthquake of 1964. The sinusoidal motion with a 12-hour period is due to earth tides. Waves from the earthquake are bunched solidly because of the recorder's slow speed. Broken white line is added to delineate the permanent strain.

the peaks are of the same magnitude in both spectra. By way of analogy, a violin string can be bowed heavily or lightly; it will sound the same fundamental frequency but will do so loudly or softly.

Just as the peaks coincide in spectra derived from two earthquakes recorded at one site, so they coincide in the case of spectra from two widely separated strainmeters measuring the same earthquake [*see bottom illustration on page 33*]. In this case the two curves were analyzed for coherence, a measure of correlation. The coherence turned out to be high in the vicinity of the peaks but low between the peaks; that is, the frequencies of the modes coincided but those of the noise in the two records did not. Another check with theory is the fact that *T* modes, which have no vertical component, do not show on spectra derived from vertical pendulum instruments, whereas both *S* and *T* modes appear on spectra from horizontal pendulums and strainmeters.

The theoretical prediction and experimental verification of the earth's free oscillations constitute one of the most elegant experiments in geophysics. As the spectra indicate, the mode with the lowest frequency, or the longest period, is the "football" mode, ${}_0S_2$. Its mean observed period is 53.95 minutes. (In terms of what one might call the music of the spheres, that corresponds to *E* flat in the 20th octave below middle *C!*) This is amazingly close to the value of one hour Love predicted so long ago. As a matter of fact, the observed periods of all the *S* and *T* modes are extremely close to sets of theoretical values that had been worked out for four different earth models.

In the course of obtaining high-resolution spectra at Cal Tech we noted a curious phenomenon: many of the modes registered not as single peaks but as multiplets [*see top illustration on page 34*]. Pekeris in Israel and Freeman Gilbert and George Backus at the University of California at San Diego soon found that this was caused by the rotation of the earth, which makes the periods dependent—as they would not be in the case of a stationary earth—on the longitudinal index *m*. Rotation destroys the symmetry between waves traveling from east to west and those traveling from west to east. The excitation of the multiplets depends on the relative location of the source and the receiver: a seismograph at the South Pole would show no multiplets. Rotational splitting is of great theoretical interest but makes it harder to obtain the precise values for modal frequencies that are needed to explore the earth's interior. "Geographic filtering" with data from many stations or even a special installation at the South Pole may be required to eliminate the effect.

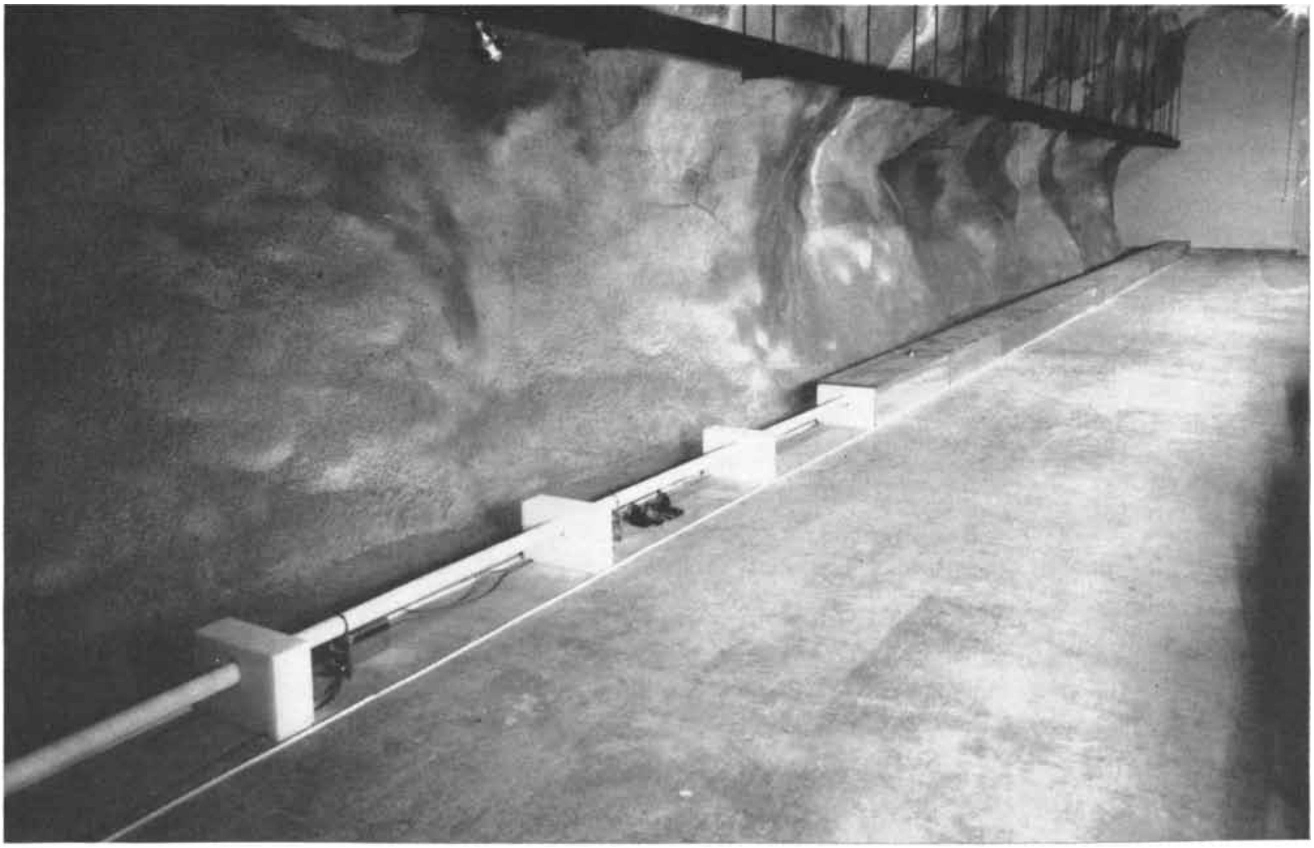
The investigation of long waves and of free oscillations has given geophysicists a new tool for deducing the structure of the deep interior of the earth and for studying the mechanism of earthquakes. One new aspect of earth structure that is currently being studied is the degree to which various layers tend to dissipate energy. The factor that electrical engineers and investigators of materials call *Q* is a measure of dissipation in energy-storing systems; it is proportional to the energy stored in the system divided by the energy dissipated during a cycle. Electrical engineers obtain *Q* from the sharpness of the resonance curve in a circuit; materials scientists measure *Q* in free elastic vibrations. Solids with high *Q* values "ring." Typical values are 100,000 for quartz, 1,000 for steel, 100 to 1,000 for crystalline rocks. *Q* can also be characterized as the degree of perfection of elasticity, and one measure of it in the earth is the width of spectral peaks in the free oscillations. The decay of Love and Rayleigh waves after repeated circling of the earth is an alternative measure.

Using both methods, Don L. Anderson and Charles Archambeau of Cal Tech showed that the increase in *Q* with period corresponds to an increase in *Q* with depth in the mantle [*see bottom illustration on page 34*]. The longer waves sample the deeper portions of the mantle, where the rocks are surprisingly less dissipative, or more perfectly elastic. The *Q* of rocks increases with pressure, decreases with temperature and depends on the rocks' physical state and composition. Since both pressure and temperature increase with depth, geophysicists are trying to decide if the low *Q* in the upper mantle indicates that temperature is more effective than pressure at these depths; in that case the reverse would have to be true at greater depths, where *Q* is of the order of 1,000. Alternatively, the mantle might be partially melted in the low-*Q* zone. Does a low *Q* correlate with low strength? The weak upper mantle this implies would account for the buoyancy by which mountains are supported. It would explain the large-scale horizontal movements of the earth's crust that seem to be indicated by studies of the directions in which ancient rocks were magnetized. The low-Q area, moreover, seems to coincide with a zone in the upper mantle of low shear velocity, indicated by recent dispersion data. The reason for the unexpected decrease in velocity could be that the rate at which velocity decreases with temperature is simply greater, at this point on the scales, than the rate at which it increases with pressure. On the other hand, it could imply that temperatures in the upper mantle are higher than had been thought and that a fraction of the mantle rock is melted. Geologists have speculated that there is a zone of molten basaltic rock at this level.

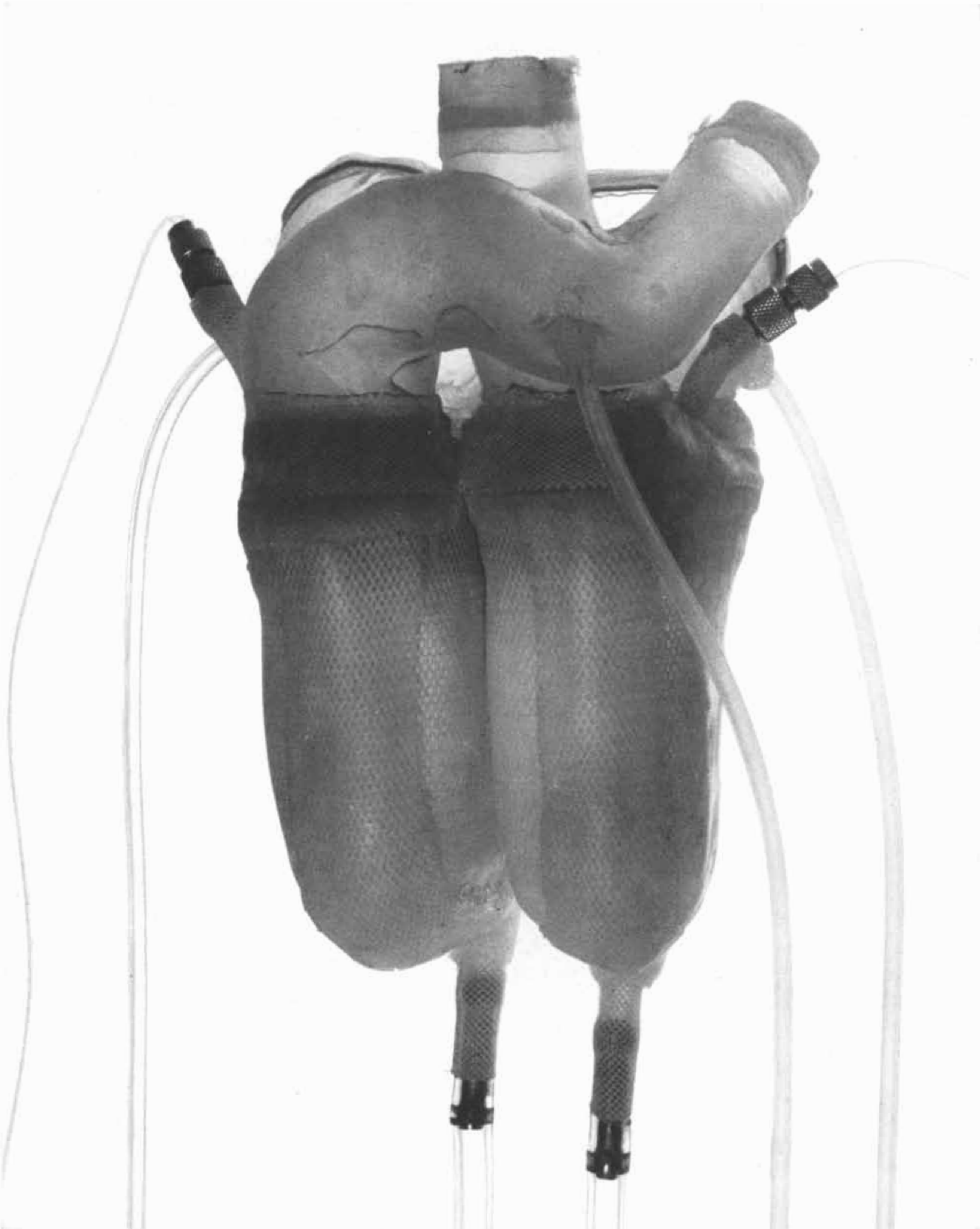
Mark Landisman and Anderson have suggested another application of free-oscillation data: the derivation of the density distribution of the earth. The present method for deducing densities requires arbitrary assumptions as to chemical composition and other factors. It appears that when the effect of velocity has been allowed for, the free oscillation periods are particularly sensitive to density, and studies are now under way in which the new techniques are combined with data on the overall velocity distribution of the earth and the earth's mass and inertia.

Seismologists would like to find out just what goes on at the source of an earthquake—how long the fault is, for example, and how quickly it propagates. Benioff and Ari Ben-Menahem of Cal Tech suggested recently that an earthquake could be considered as a traveling, radiating disturbance and that the resulting asymmetry of its radiation pattern could be a clue to the length of the fault and the velocity of rupture. Detectors on opposite sides of a fault receive different signals as the crack in the earth propagates [*see illustration on page 35*]. On one side the waves are crowded together; the pulse is larger and of higher frequency. On the other side the amplitude is less and the wave is longer. Ben-Menahem suggested dividing the free-oscillation spectrum of the waves on one side by the spectrum of the waves on the other side; the ratio should depend on the length of the fault and the velocity of rupture. Ben-Menahem went on to cast the idea in mathematical form, defining a "directivity function" by the application of which it has been possible to determine the length and rupture velocities of a number of earthquake faults. In the case of the Chilean earthquake, for example, the fault was about 750 kilometers long and the crack propagated at between three and a half and four and a half kilometers per second.

The longest possible elastic wave in the earth is the ${}_0S_2$ mode, with a period of about 54 minutes. (In anticipation of seismic measurements on the moon in the not too distant future, incidentally, Bruce A. Bolt of the University of California at Berkeley has calculated a 15-minute period for the same mode for one model of the moon.) There are actually "waves" of infinitely long period: permanent deformations of the earth. I found that the Alaskan earthquake, for example, caused a permanent strain change of 10^{-8} in Hawaii. The strain is small, but since it was detected several thousand kilometers from the source [*see illustration on opposite page*] it must represent a permanent displacement of the order of a centimeter. Such effects suggest a new field of study that has been dubbed "zero-frequency seismology." It holds real promise as a means of learning about the actual mechanism of an earthquake and defining the relation of earthquakes to mountain-building and continental drift.



QUARTZ ROD of a strain seismograph installed at the Cal Tech facility on Oahu, Hawaii, is shown in this photograph. The rod is about 100 feet long and has measured strains as small as 10^{-8}. The seismogram on the opposite page was recorded by this instrument.



ARTIFICIAL HEART designed to fit into a calf's chest is made of Silastic, a smooth silicone rubber. Its structure is closely analogous to that of a real heart. Deoxygenated blood from body enters heart through the vena cava and fills the right atrium (*chamber at top left of photograph, partly concealed by twisting tube*). It is passed on to the right ventricle (*bottom left*). Right ventricle pumps blood to the lungs via the pulmonary artery (*twisting tube at top*). In the lungs blood is oxygenated. It returns to the left atrium (*top of chamber at right*), then to the left ventricle (*bottom right*). Finally the left ventricle pumps blood into the aorta (*straight tube at top*) and thereby through the circulatory system. The two tubes with metal connectors at bottom are for input of air needed to squeeze the flexible sacs inside the rigid chambers. Other tubes are for gauging pressure and release of residual air at the time the heart is inserted in the body. Dacron mesh forms a framework for the chambers. It is covered by smooth Silastic.

An Artificial Heart inside the Body

An intensive effort is now being made to develop mechanical hearts that can be implanted in the chest. Such hearts have already been placed in animals, and the prospect of further progress is good

by Willem J. Kolff

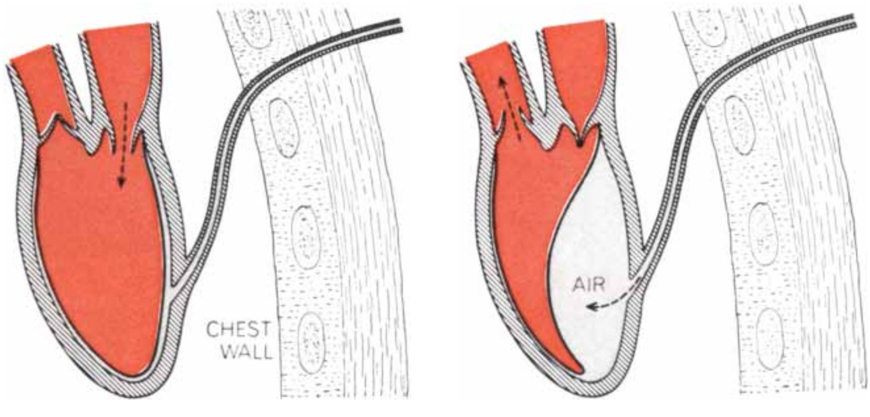
In the recent report to the President entitled "A National Program to Conquer Heart Disease, Cancer and Stroke" the distinguished commission that had made the study commented: "Perhaps the most dramatic of all the research efforts are now being directed toward the development of an artificial heart to replace a diseased heart. This challenge... as exciting as any across the entire range of science, is enormously complex, but the goal is feasible; the problems are not insuperable."

Coming from a panel broadly representative of the profession of medical science, this statement represented a decided change in point of view. Up to a very few years ago the goal of planting an artificial heart in the body was not recognized as a bona fide scientific effort worthy of support, and papers describing experiments in that endeavor were not accepted by scientific or medical societies. Within the past five years, however, all of that has changed. Experimental animals (dogs and calves) have been kept alive for many hours with an artificial pump substituted for the natural heart in the chest. Artificial hearts in various versions are now available to investigators in a number of laboratories. The National Heart Institute is supporting the work by giving contracts to industry for development of these devices.

The use of heart-lung machines outside the body to maintain temporary circulation of the blood during surgical operations is of course a familiar story. It allows a surgeon to operate on the heart for hours with the heart kept almost completely dry and yet without any interruption of the circulation. What we are concerned with here, however, is something quite different: the replacement of a dying patient's failing heart with a mechanical heart that is implanted in its place in his chest and will take over completely and permanently the function of the natural heart.

There is reason to hope that we shall eventually be able to transplant a living heart into the human body. Thanks to the development of methods of suppressing the immune reaction to transplants, it is now possible to transplant a healthy kidney from one person to another with considerable chance of success. In our own Department of Artificial Organs at the Cleveland Clinic we have successfully transplanted more than 20 kidneys, some of which have been functioning for more than two years, in human patients (none of them identical twins). Judging from certain experiments on dogs, transplanting the heart may be less difficult, from the standpoint of tissue reaction, than transplanting a kidney. Yet it is obvious that the transplantation of hearts could never offer a large-scale solution to the massive problem of heart disease and heart failure in the general population. The supply of available healthy human hearts (taken from the donors at death and kept functioning) would meet only a small fraction of the need. The heart of an animal comparable in size to man (a calf, pig or sheep) might serve a human recipient as a pump, but for the present and the near future the immunological barrier to transplants from one species to another is great.

The artificial heart therefore seems the most promising answer for wide application. Apparently the first experimenter to attempt to plant a mechanical heart inside the body was a Soviet investigator named V. P. Demikhov. In 1937 he performed three such experiments, implanting in animals a pumping contrivance that was driven by a rotating shaft powered from outside and inserted into the animal through a tube in the chest wall. Demikhov returned to this investigation with five more experiments in 1958, but as far as we can learn he has not pursued the work further.



ARTIFICIAL HEART IN CHEST is illustrated schematically. One ventricle is shown during diastole (*left*), the phase in which it is filled with blood, and during systole (*right*), the phase in which it contracts to expel blood. A flexible partition separates blood sac from air space within the rigid chamber. Source of compressed air is outside the body.

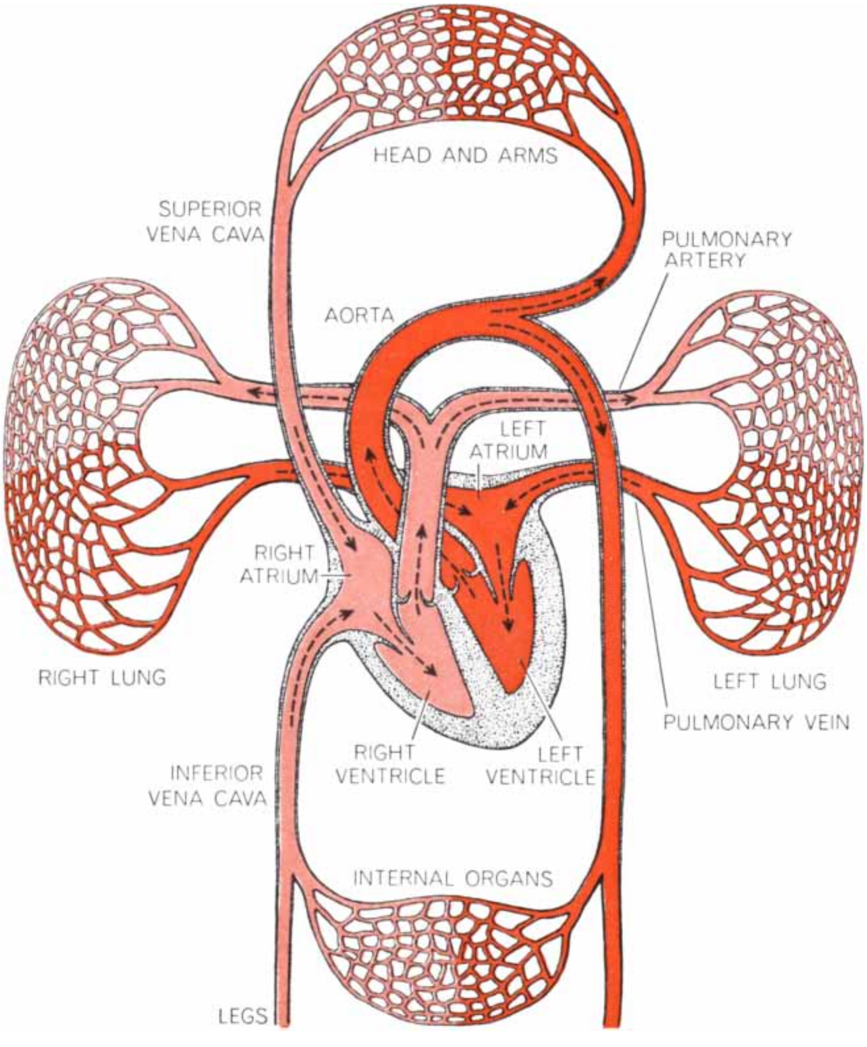
In the U.S. investigators interested in such problems have come together for discussions in an organization called the American Society for Artificial Internal Organs. At the annual meeting in 1957 the society's president-elect, Peter Salisbury, explicitly discussed the possibility of making an artificial heart that would be implanted inside the chest. On December 12 of that year our group at the Cleveland Clinic executed this experiment for the first time. We removed the heart from a dog, put an air-driven artificial heart in its place and closed up the chest. With the mechanical pump driving the blood through the dog's circulatory system, the animal lived for 90 minutes. This was the beginning of many experiments in our laboratory. Among the early investigators of the problem elsewhere are Selwyn McCabe of Washington, Bert K. Kusserow of the University of Vermont College of Medicine, F. W. Hastings of Harlan, Ky., William J. Fry and Francis J. Fry of the University of Illinois, Domingo Liotta of Argentina and Kazuhiko Atsumi of Japan. Recently still other workers have joined the effort. Here I shall confine myself to a summary of our own work over the past eight years.

Essentially the natural heart acts only as a pump [see "The Heart," by Carl J. Wiggers; SCIENTIFIC AMERICAN, May, 1957]. It is a double pump with two main working parts: the right ventricle, which pumps the body's spent venous blood to the lungs for aeration, and the left ventricle, which pumps the reoxygenated blood back into the general circulatory system. The two ventricles work in unison, both discharging their load of blood simultaneously into their respective outlets, or arteries. This phase of the heart cycle—the expulsion of the blood by contraction of the ventricles—is called systole. The phase in which the ventricles are filled with blood, each from its own atrium, or auricle, is called diastole.

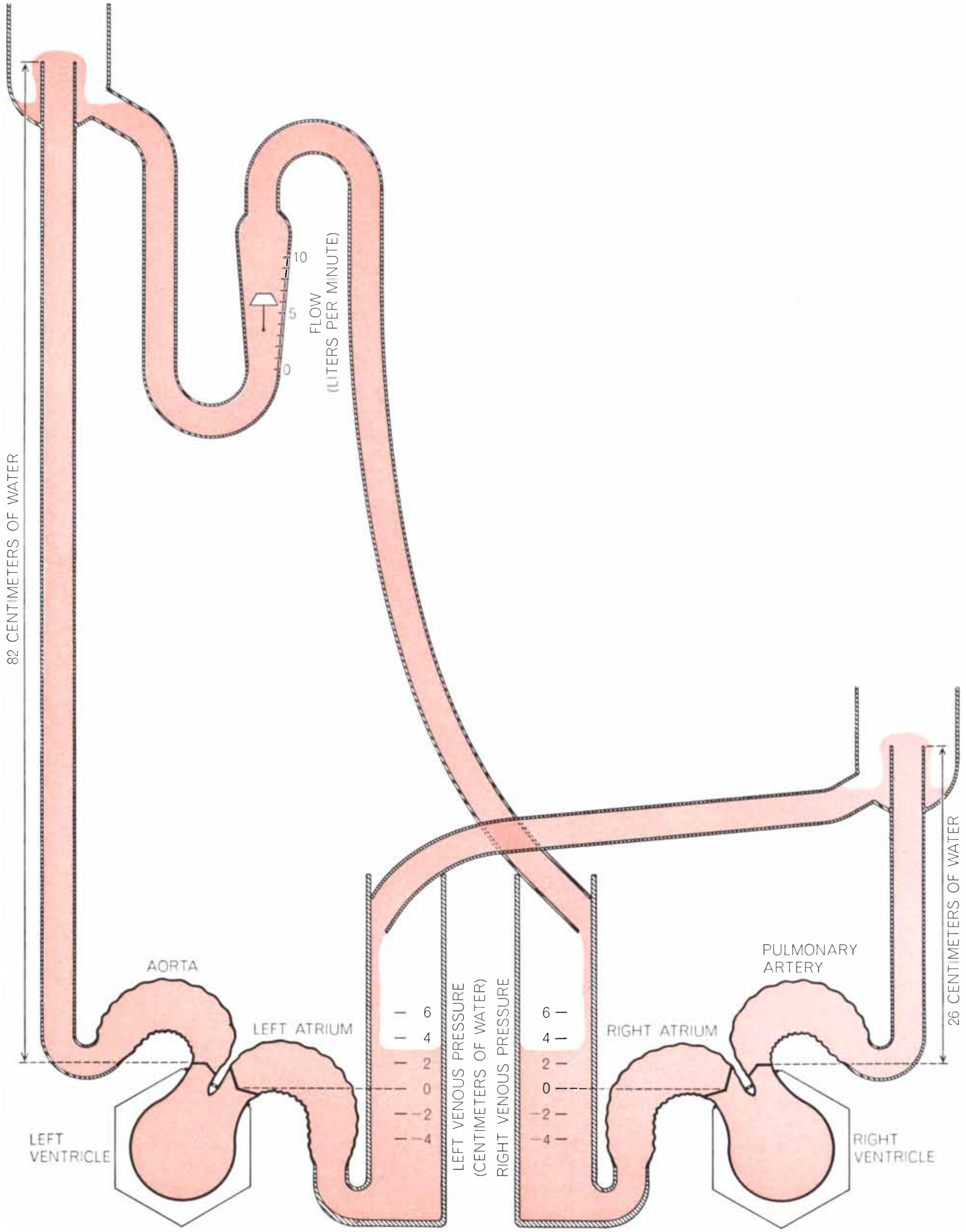
In the natural heart each atrium facilitates the filling of its ventricle (which takes only about half a second) by contracting to drive the blood in. This is not, however, absolutely necessary. The pressure in the filled atrium is sufficient to push blood into the relaxed, partly empty ventricle. Indeed, there are millions of people walking about and leading normal lives without effective contraction of their atria owing to the lack of heart-muscle coordination known as atrial fibrillation. This indicates that an artificial heart can dispense with atrial contraction, and its construction is thereby simplified. The one requirement is that the atrium must be collapsible, so that as the blood pours into the ventricle no vacuum is formed.

It is easy to see that there is another basic requirement for the artificial heart. The two ventricles must pump equal amounts of blood; that is, their outputs must be balanced. If they are not, either the blood vessels in the lungs or those in the rest of the body will become filled to bursting with an excessive accumulation of blood. In the natural heart the regulation of the ventricles' output is taken care of by the principle known as Starling's law. The principle is that the amount of blood pumped at each beat depends simply on the amount of stretching of the chamber muscles, which is determined by the degree to which the ventricle is filled. The output of each ventricle therefore depends on how much blood is pushed into it from its atrium. In the development of the artificial heart the problem has been solved by a means that produces the effect of Starling's law.

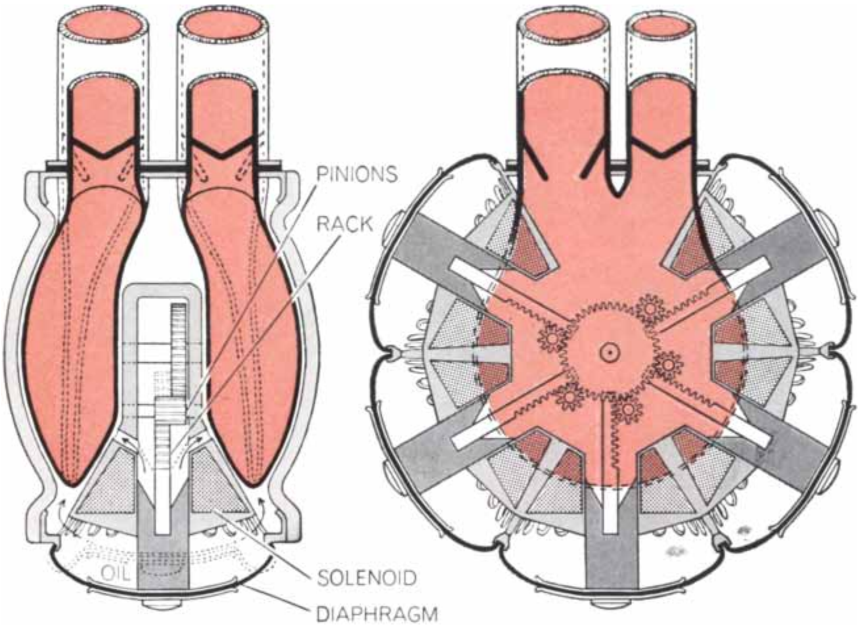
In detail the requirements for a mechanical heart can be specified as follows: It should be a double pump small enough to fit inside the chest. The right and left ventricles should have equal outputs (on the average). The atria should fill the ventricles with reasonable speed and should collapse like balloons as blood pours out of them. The pressure of their input should not be more than 16 millimeters of mercury, and at the low point the atrial pressure should not fall below a negative pressure of 10 millimeters with respect to the pressure of the atmosphere. The output pressure of the right ventricle should be at least 20 millimeters of mercury and capable of rising to 80 millimeters; that of the left ventricle should have a range between 120 and 180 millimeters. The ventricles' pumping rate should cover



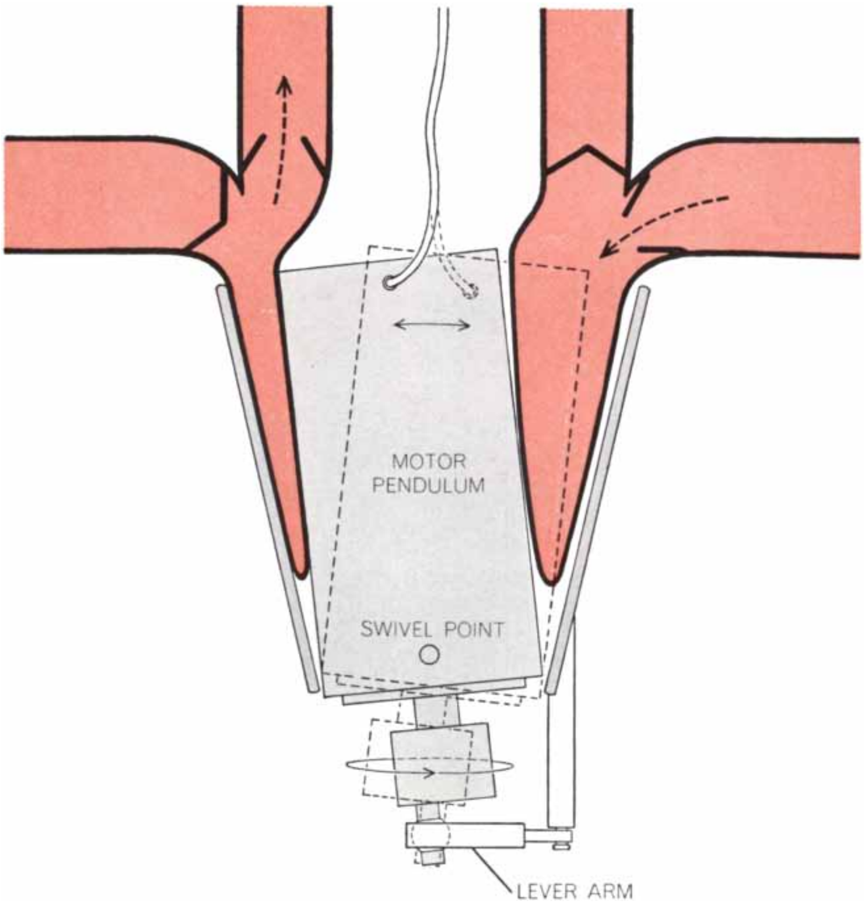
CIRCULATORY SYSTEM of a human being and its relation to the heart is outlined. Oxygenated blood is represented by a dark red; deoxygenated blood by a slightly paler red.



MOCK CIRCULATORY SYSTEM is designed for testing artificial hearts. Left ventricle of an artificial heart pumps blood or test fluid such as water through an analogue of the aorta (*left*), in which normal aortic pressure (*82 centimeters of water*) is simulated. Rate of flow is measured as blood goes to a receptacle called the right venous reservoir. Blood then goes through the right atrium and right ventricle. The ventricle pumps blood through the pulmonary artery (*right*), the normal pressure of which is simulated by a 26-centimeter column of water. The circulatory cycle is completed as blood is channeled to the left venous reservoir and then into the left ventricle. If the artificial heart is functioning properly, the two venous reservoirs should maintain the same blood level.



EARLY ARTIFICIAL HEART has pumping units run by electromagnetic power (*section at left*). Current in the solenoid (coil around cylinder) pushes diaphragm inward. Pressure transferred by hydraulic fluid forces ventricle sacs to contract and expel blood through tubes at top. Five solenoid pistons are coordinated (*section at right*) to exert equal pressure.



ANOTHER EARLY HEART uses the back-and-forth swing of a pendulum to expel blood from left and right ventricle sacs. The pendulum is the metal casing in which an electric motor is contained. An advantage of this scheme is that circulating blood cools the motor.

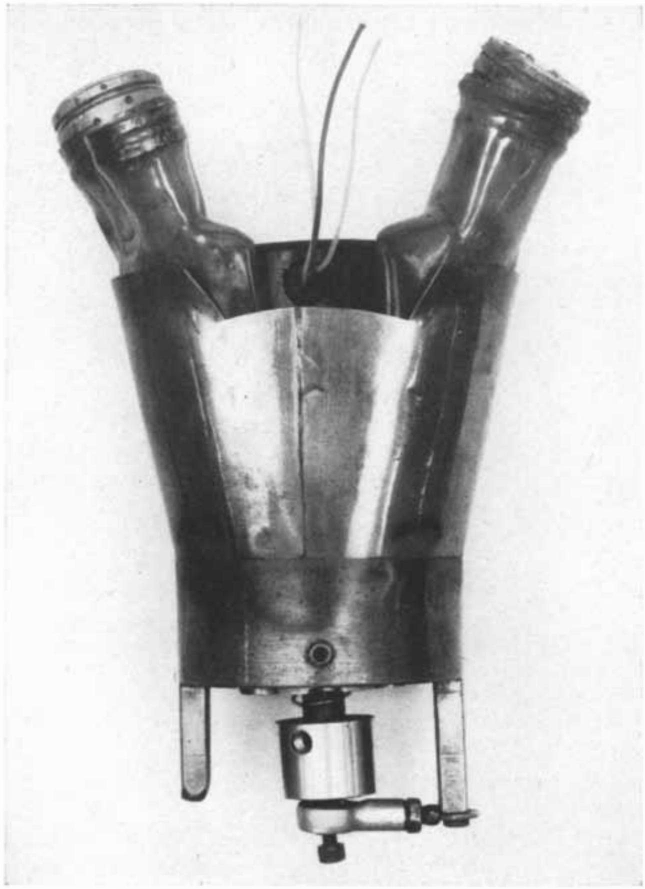
the range between 60 and 160 strokes per minute, and each should have a minimum output of 1.5 liters per minute and a maximum of more than eight liters per minute.

Of course it goes without saying that a mechanical heart to be planted in the body should be easy to insert and connect to the circulatory system and should require no maintenance. The operation itself presents no insurmountable problem. While the natural heart is removed and the artificial organ is being inserted the recipient's circulation can be maintained by a heart-lung machine, or the patient can be kept under hypothermia (deep cooling), which enables a man to survive for a period as long as 35 minutes even if the circulation is totally arrested.

I can best illustrate the mechanics of the heart-and-circulation system by describing a simple model we set up for testing the functioning of our artificial hearts before we inserted them in animals. One side of this apparatus simulates the activity of the right ventricle; the other, that of the left ventricle [*see illustration on preceding page*]. Each side draws its fluid (water) from a reservoir. The level of fluid in the reservoir represents the pressure in the venous system. Fluid from the right reservoir fills the right "atrium," which in turn fills the right "ventricle." When filled, the ventricle contracts and pumps its output into a "pulmonary artery"—a column of water whose height represents the pressure of the blood in that artery. This output passes by way of a tube to the left reservoir (after theoretically circulating through the lungs). The left reservoir supplies the left atrium and the left ventricle, which pumps its output into an "aorta" at a pressure considerably higher than that in the pulmonary artery on the right side.

The apparatus gives only a crude approximation of what the pressure relations would be in the living body, because the resistance of the column of water representing the aorta here is not the same as that of the elastic natural aorta. Nevertheless, the contrivance does indicate whether or not the artificial heart is functioning as a heart should. In particular it shows whether or not the pump is obeying Starling's law. The level of the water (or venous pressure) in the two "venous" reservoirs is supposed to regulate the degree of filling in the right and left ventricles. For instance, when the level rises in the left reservoir because of increased output by the right ventricle, this height-

ELECTROMAGNETIC HEART depicted in top illustration on opposite page was designed by S. Harry Norton. Ventricle sacs lie in hydraulic fluid in the main chamber. When solenoids press on the fluid, blood goes through tubes at top left to lungs and rest of body.



PENDULUM HEART was designed by the author with help from Globe Industries, Inc. Motor in the main chamber is connected by wires to an electric source outside the body. It swings back and forth, expelling blood from two ventricles through tubes at top.

ened pressure should cause an increase in the filling and output of the left ventricle, thus tending to equalize the two outputs. If the artificial heart is performing properly, the level in the two reservoirs should always be equal.

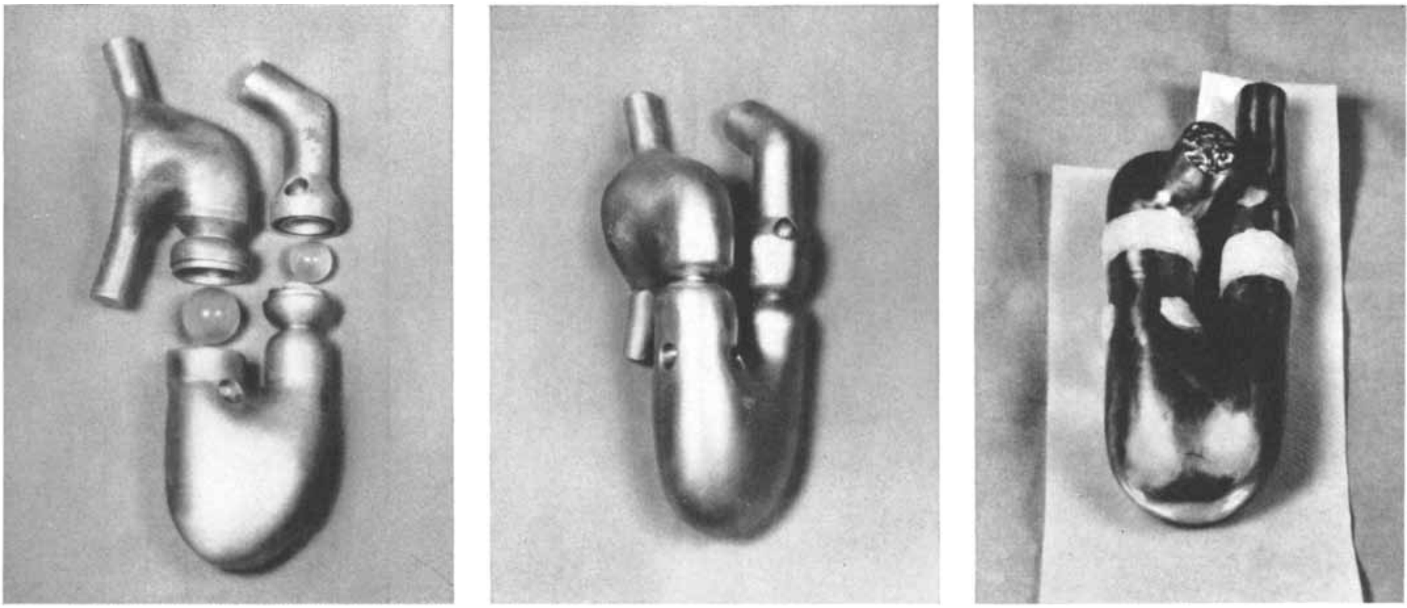
Let us now consider the various types of artificial heart with which we have been experimenting. They vary greatly in form and method of operation, but we can conveniently examine the basic problems and ideas in terms of four factors: the elementary components and material of which the artificial heart is to be made, the source of energy, the driving mechanism and the regulating devices.

The principal parts are of course the ventricles. They could be sacs made of an elastic material, which immediately suggests rubber. This rubber must, however, have very special properties. It must be impervious to attack by the body fluids and substances; it must be so inert and compatible with blood that it does not cause the blood to clot; it must not be injurious or stimulating to body cells or tissues (lest it induce cancerous growth); it should be strong and long-lived. It may be that natural rubber, or some synthetic version of natural rubber, can be purified so that it is inert enough to meet these specifications; that possibility has not yet been fully explored. The most inert and satisfactory material we have found so far is a silicone rubber called Silastic, made by the Dow Corning Corporation. This plastic product has proved suitable both for the chambers and for the valves of the artificial heart. In most of our artificial hearts we have used the ball type of valve, which heart surgeons often employ as a replacement for diseased or defective valves in human patients.

The delicacy of the foreign-body problem was vividly impressed on us early in our experiments. Casting about for an appropriate material for valves in our artificial hearts, we decided to try the woven plastics that were already being used successfully for artificial aortas replacing diseased ones in human patients. The choice turned out to be a monumental mistake. This rough-surfaced material, when placed inside the heart of a dog, soon became covered with a growth of fibrin, a fibrous product of the blood. The fibrin either chipped off, forming clots in the bloodstream, or grew until it completely plugged the valve orifice in the heart. By further experimentation we determined that any rubber or plastics used for an artificial heart or valves must be perfectly smooth, and that the surface is safe from the formation of growths only in locations where the blood flows over it rapidly.

We build our artificial hearts of Silastic around a mold [*see illustrations on next two pages*]. This mold is made of a metal with a low melting point (Cerrotru), so that it can be removed by melting at low heat after the heart has been formed over it. Sheets of Silastic are folded and pressed around the mold and then cured by heat. After the metal has been melted out, what remains is a completely plastic heart without seams and with the ball valves already positioned inside.

What kind of energy source might



STAGES OF MANUFACTURE of half of an artificial heart are shown in series of photographs. Two ball valves of Silastic are placed inside a mold of Cerrotru, a metal alloy with a low melting point (*photograph at left*). These go between atrium and ventricle (*left*) and between ventricle and aorta (*right*). Silastic is pressed into cups for the valve rings; it also forms prongs that hold the balls in place. The mold is put on Silastic (*third from left*) that will be folded and compressed around it. Electrical leads

be used to power this heart? Electricity comes to mind first. The ultimate aim is to make the energy available inside the body without having to transmit it from outside through a hole in the chest wall. Perhaps the energy will be supplied by means of a small radio transmitter worn on the chest or even a tiny steam engine inside the body driven by a well-shielded nuclear heat source. For the time being, however, we must be content in our experiments with delivering energy from an outside source to the artificial heart inside by way of wires or a tube passing through the chest wall.

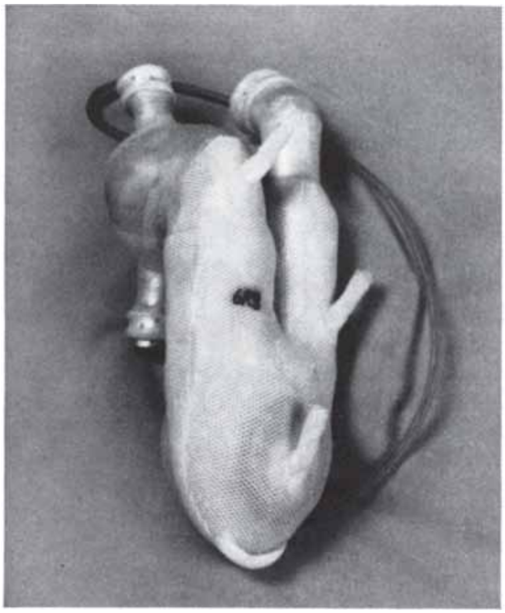
One of our early artificial hearts, built by S. Harry Norton of the Thompson-Ramo-Wooldridge Corporation in collaboration with our group, was driven by electromagnets. The "ventricle," made of the plastic polyurethane, lay in oil inside a rigid case. To drive the pump five solenoids pushed disks inward, compressing the oil and thereby squeezing the "ventricle" so that it discharged its fluid into an "artery." Unfortunately the commercial solenoids available today, and probably for some years to come, are low in efficiency. We therefore turned to small electric motors, which are more efficient, as the driving mechanism for the next models. One of these was called the "pendulum heart." The motor swung back and forth, alternately compressing the separated right and left ventricles. Since the two chambers did not pump simultaneously, this device minimized the size of the motor required. Another advantage was that the motor lay directly against the blood-containing chambers, so that the circulating blood carried off the heat generated by the motor. We also tried a "roller" type of artificial heart powered by a motor. In that model a roller passed over the ventricle, compressing it and driving the blood along as it rolled. It allowed a long diastole (filling of the ventricle); moreover, the device required no valve between the atrium and the ventricle, because when the roller reached the entrance to the ventricle it prevented any backflow of blood.

Our electrically driven hearts were disappointing in several respects. The electrical mechanisms were inefficient, too weak, too heavy and generated too much heat. While I was in this frame of mind I had an opportunity to discuss some of our problems with the leading engineers at the Lewis Research Center of the National Aeronautics and Space Administration in Cleveland. They responded with a startling suggestion: Why not use compressed air instead of electricity as the power source? I recoiled; that idea would commit us to a system in which the power supply would have to be outside the body. I had visions of the possessor of an artificial heart walking around with something like a garden hose sticking out of his chest! The engineers minimized that objection; they assured me that with compressed gas enough energy could be delivered to the mechanical heart through a fine tube no more than an eighth of an inch in diameter.

I was persuaded that, during the basic experimental stage in which we were trying to find out if an artificial heart would work at all for any appreciable length of time, our first concern must be to keep the heart pumping effectively, even if we had to resort temporarily to an apparently clumsy driving mechanism for that purpose. We began then (in 1960) to devise artificial hearts driven by compressed air. The ventricle now could be a simple sac inside a rigid housing; for the systole, air forced into the housing would compress the sac and drive its blood through an outlet valve [*see illustration on page 39*].

The change to the more efficient and powerful new type of drive had the hoped-for result. With an air-driven artificial heart in place of the natural heart dogs lived as long as 27 hours. They ate, drank and behaved normally in other respects. Their failure to survive longer than 27 hours was due not to any failure of the pumping mechanism but to the formation of blood clots; after a time the clots broke loose and formed emboli that lodged in various places in the body and blocked the circulation.

Kirby Hiller and his associates at the Lewis Research Center built us a sophisticated driving mechanism for the artificial heart that makes it possible to simulate the pumping pattern of a natural heart. The machine writes an elec-



are inserted. The Silastic is vulcanized and cured. When the assembly is heated, the inner mold melts and flows out, leaving the valves in position (*photograph at right*).

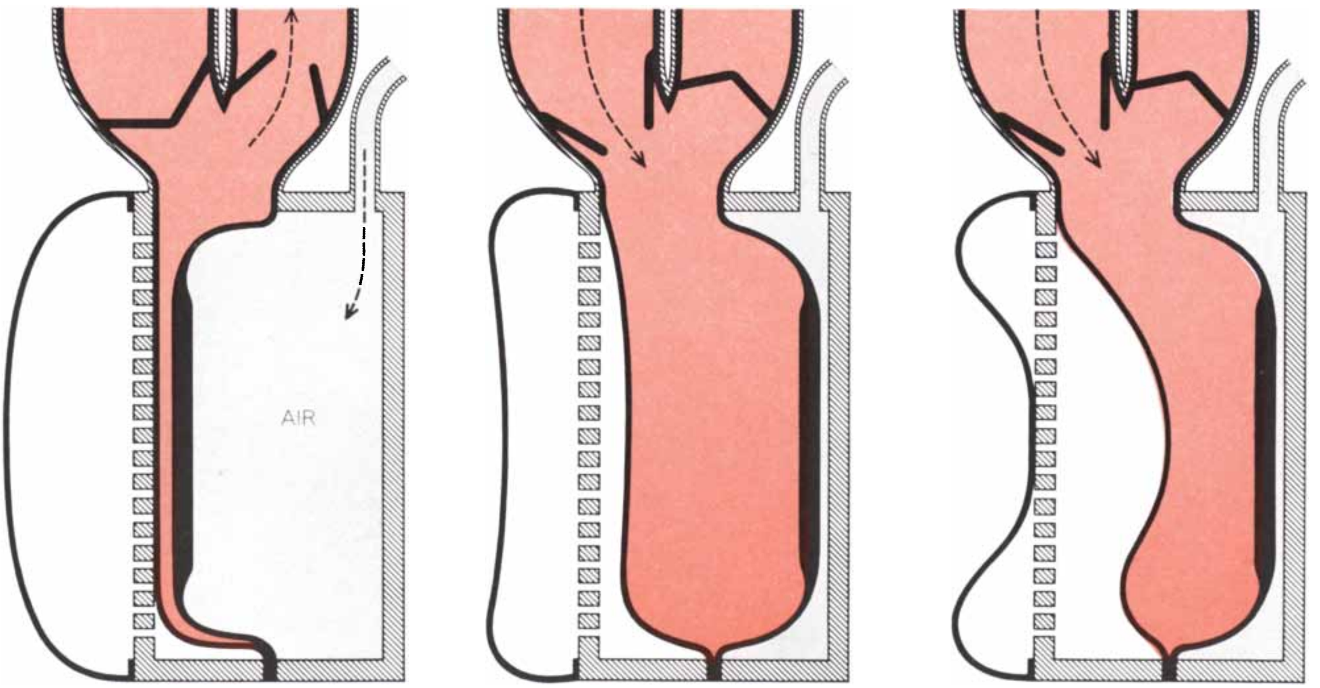
trical function in the form of a wave, and this wave form is then translated into a cycle of air pressure that has the same form [*see illustration at left at bottom of next page*]. The rise in the curve represents the increase in pressure; the shape of the wave top represents the pattern and duration of high pressure, and the descent of the curve represents the fall in pressure. The electrical instructions are written to command a given rate and pattern of pumping, and the obedience of the air input to these commands is controlled by three feedback mechanisms, one of which indicates whether or not the ventricle of the artificial heart is making the necessary movements.

It turns out that the effective cycle of the air pressure driving the ventricle of an artificial heart takes the form of a curve in the shape of the lowercase letter *h*. The quick initial jump in pressure (shown by the upright of the *h*) may be necessitated by the inertial resistance of the blood in the filled ventricle. In effect the pressure pattern in the chamber follows an almost square wave, the high-pressure level lasting until the ventricle has discharged its load. The entire cycle takes between half a second and a second.

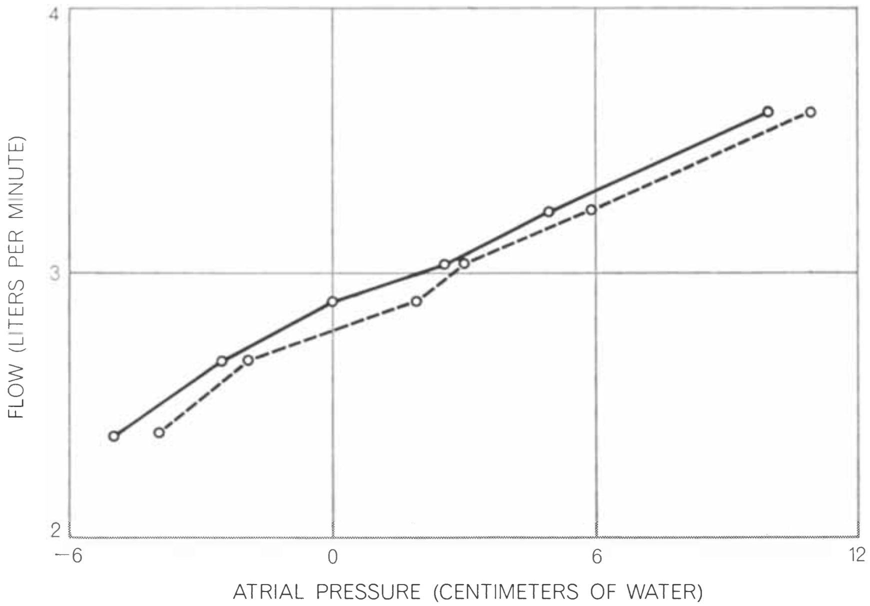
The paramount test of whether or not an artificial heart (or the natural heart, for that matter) is doing its job is the "cardiac output," or the volume of blood pumped per minute. The arterial blood pressure, usually taken to indicate this output, is actually an unreliable guide. This has been demonstrated by experiments in which we have given noradrenalin or some other drug that raises the blood pressure to a dog with an artificial heart. The drug produces sharp rises of the blood pressure in the aorta, the pulmonary artery and the left ventricle, but the cardiac output actually falls, presumably because of the resistance of the heightened pressure in the arteries. One concludes that although a pressor drug may be given to relieve the anxiety of the physician, it does not necessarily improve the circulation of the patient.

It is apparent, then, that the cardiac output of a patient with an artificial heart will have to be monitored very carefully. Fortunately this can be arranged. In our experimental setups we have placed in the artificial ventricles transducers that record the chambers' movements so that we can actually see the strokes, or beats, of the heart on an oscilloscope. From these beats, which can be followed from minute to minute, hour to hour and year to year, the heart output can be calibrated and measured at any time.

We have tested several different types of air-driven artificial heart. The principle lends itself to a wide variety of devices. For example, Kenneth Woodward and his co-workers at the U.S. Army's Harry Diamond Laboratories built an artificial heart based on the fluid-amplification technique. The fluid amplifier is a mechanical analogue of



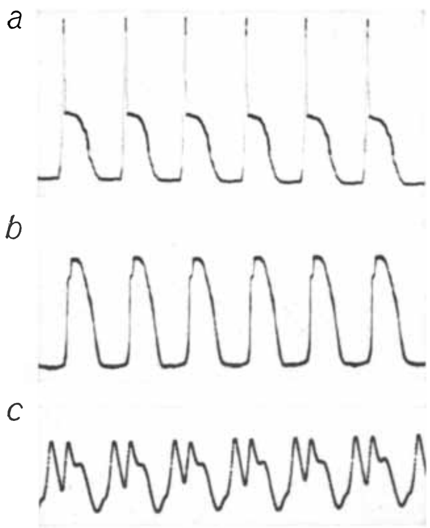
ANTISUCTION BALLOON prevents harm to blood vessels caused by excessive suction when there is insufficient blood pressure to fill the ventricle of an artificial heart. Artificial heart equipped with balloon is shown in cross section during three phases. Normal systole is depicted at left. Ventricle is compressed and blood is expelled as chamber fills with air from tube at top right. Normal diastole is depicted in center. Ventricle is entirely filled with blood from atrium at top left. When venous blood pressure is inadequate during diastole (*as in cross section at right*), the balloon is sucked inward, preventing the creation of a vacuum inside the chamber.



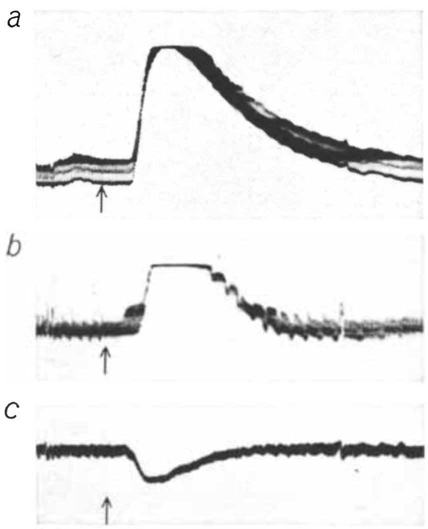
STARLING'S LAW that the output of each ventricle depends on the amount of blood pushed into it from its atrium applies, as this graph shows, to artificial as well as real hearts. The curve reveals an almost linear relation between blood flow (*in liters per minute on the vertical axis*) and atrial pressure (*in centimeters of water on horizontal axis*). It is based on data for flow from ventricle of an air-driven artificial heart tested in mock circulation.

the electronic tube: a stream of air or other fluid entering a system of channels is amplified or switched from one outlet to another by means of control jets from the sides [see "Fluid Control Devices," by Stanley W. Angrist; SCIENTIFIC AMERICAN, December, 1964]. It is basically a simple system that operates without any moving parts. Woodward's group applied the technique to drive an artificial heart with a stream of compressed air that is switched back and forth by the state of the ventricle. This heart has worked very well in our experiments.

Another design, invented by Norton of Thompson-Ramo-Wooldridge, employs the reciprocating-engine idea. A plunger moving back and forth like a piston compresses the air that drives the ventricle at systole and then moves back to let the ventricle fill again. Norton's device has the advantage that the volume, or size, of the stroke can be varied from one beat to the next, although the plunger always returns to the same starting position. In this system, if the venous pressure were too low to fill the ventricle during the diastolic (backward) stroke of the plunger, an excessive suction would produce a high negative pressure that might result in damage to the blood or blood vessels. To avoid that possibility we added an "antisuction" balloon that prevents excessive suction on the ventricle even when it is not filled to its potential capacity [*see bottom illustration on preceding page*]. Thus the venous pressure accurately controls the amount of expansion of the ventricle for each stroke, and the ventricles' output closely follows Starling's law [*see illustration at left*].



PUMPING PRESSURE in artificial heart is determined by a machine that translates electrical function in form of an *h*-shaped air-pressure wave (*a*) to desirable pattern of pressure for ventricle (*b*). Pressure curve for aorta (*c*) has second peak caused by rigid mock circulation in which it was tested.



EFFECT OF PRESSOR DRUG on circulation of a dog with an artificial heart in its chest is indicated. When the drug noradrenaline was administered (*arrow*), causing arteries to contract, pressure in aorta (*a*) and pulmonary artery (*b*) rose but the flow of blood from the heart decreased (*c*).

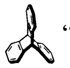
At the present stage of our explorations we are working on the problem of developing a compact artificial heart, bringing together the right and left ventricles, that will be small enough to fit inside the pericardial sac of a human-sized heart. The development of a pump that will be simple and reliable enough in construction and operation to substitute for the human heart is still a long way off. Nonetheless, the magnificent equipment built for us by the NASA laboratory and other collaborating groups has enabled us to carry on an intensive study of the physiological factors and requirements for an artificial heart. A calf with an artificial heart implanted in its chest has survived as long as 33 hours 30 minutes. The mechanical pump maintained the calf's blood circulation at a normal level and caused no formation of clots. The results of current experiments lead us to believe that the physiological problems are now well understood and that the achievement of a workable, permanent artificial heart depends only on the solution of certain technical problems that should be solvable.

Nearly a fourth of the adult population of the U.S. lives with at least the threat of heart disease hanging over it, and considerably more than half a million people die of coronary disease each year. It may be disenchanting to think of living with an artificial heart in one's chest, with life itself depending on the functioning of the machine. In the face of imminent death, however, most people will accept an artificial heart if it can promise them a comfortable, enjoyable existence.

Kodak reports on:

orthographical support for the Harvard team . . . carefree data-recording . . . sweetening the odds for radiography

A hydrocarbon of unnatural shape

The finest one of the freshest crop of organic textbooks calls  "tryptycene." This spelling ignores the suggestion from the Department of Classics at Harvard to the team of Harvard chemists who first prepared the rigid, 3-fold-symmetrical, propeller-like hydrocarbon in 1942. Classical scholars like triptychs better than propellers. We support the Harvard team orthographically and announce *Triptycene* (EASTMAN 9739) at the low, low price of $15.50 for 10 grams, which is about ⅛ what we have seen the compound advertised at a year ago.

The timing of this announcement is interesting. The generation that learned about triptycene in graduate school has now been out long enough to have made a small start toward paying off their mortgages, and their employers are daring to hope they will soon start thinking about practical matters. Here and there chemical thinking in three dimensions is being applied to such matters, whereupon the eminently non-planar triptycene comes to mind.

In medicinal chemistry, for example, studies have been published on the effect of non-planarity in the aromatic blocking group that constitutes one end of many different pharmacological agents. In the absence of evidence that triptycene occurs anywhere in nature, would there be sinister implications if this work should eventually lead to something taken internally to extend human life or comfort? Another school of chemists—those who work on colorants—take an obvious interest in how odd steric configuration might govern the behavior of their traditionally flat molecules toward light and substrates. Whatever excitement they may feel at being propelled in profitable directions by this hydrocarbon propeller, they remain outwardly calm.

Within the short time for this to reach print, we may also be offering derivatives of triptycene with a handle on the bridgehead for fastening to other moieties. Ask the source of all EASTMAN *Organic Chemicals for the laboratory, Distillation Products Industries, Rochester, N. Y. 14603 (Division of Eastman Kodak Company). The catalog of these wares has a new supplement, No. 43-4. We hope all who need it have it.*

Price subject to change without notice.

For haters of chemistry

Two new commercial realities await inquiry to Instrumentation Products, Eastman Kodak Company, Rochester, N. Y. 14650, by engineers who need the sensitivity of photography for data-recording but rarely derive pleasure from the details of photographic chemical technology.

- Certain late-model oscillographs are supposed to make their wiggle traces visible as fast as people can read. This they will actually do if loaded with KODAK LINAGRAPH Direct Print Paper. Records to be kept permanently or duplicated for distribution, however, had had to be treated in special image-preserving chemicals. Now, with the latest improvements in the LINAGRAPH Paper, you put the records to be treated through the same chemicals for *all* oscillographs, late-model or early-model.
- Data film for recording either real objects or indications from instruments can be processed in a minute at 90°F or half a minute at 105°F if the film happens to be KODAK 2490 RAR Film and the processing is done in KODAK 448 Monobath. This new solution neither requires a tense eye on clock or thermometer nor any interest in the difference between a developer and a fixer, being both. Once it has completed its work, nothing further happens. If you intend to keep the film, wash it later. A quick rinse in warm water several weeks later is adequate.

The writer shows his teeth

Only a very small minority of readers of these words will ever have occasion to specify a brand of x-ray film.* We have other ways of getting hot news to them while it is still hot. The x-ray film news has now cooled off enough to be properly digested among the general populace. A dentist in Lima, Ohio has written to our president suggesting that we allay the radiation fear by publicizing the news about our "fast film" and how it permits him now to take a complete series of 14 exposures with one-half the radiation he formerly needed for a single exposure.

Perhaps we should, but we are not wholly sure. We certainly don't want to be caught pooh-poohing. Philosophy and commerce have long irritated each other. Philosophical geneticists who irradiate insects and mice and then warn us against crippling our great-great-great-grandchildren irk some busy practitioners who just want to stay busy. So do patients who stray too far in their reading from the sports or society page.

There are also other practitioners. Time is well spent in cleverly hunting one of them down. Having found him, trust him. He recognizes the case and the means for gonadal protection during radiology no less than he recognizes the undeserved compliment that genetic considerations imply for patients past a certain age.

Between genetic peril and somatic peril lies a comfortably huge gap of many, many millirads. It comforts those practitioners who might otherwise be philosophically troubled in recommending radiography to lengthen the odds against false teeth and twisted limbs and backs and unarrested diseases in the chest, gastrointestinal tract, and kidneys.

Humanity, the physicians and dentists, and we in the radiation business owe a considerable debt to the alarmists for the wide use today of fast fluorescent screens that let the film be exposed 95% by excited light and only 5% by x-rays, of filtration techniques that block off radiation too long in wavelength anyway to help the visualization—and of fast film, if we are to be permitted candor.

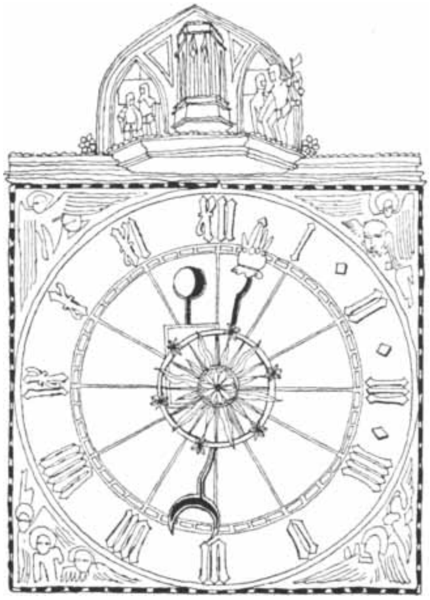
Don't send for a booklet. Don't march into a physician's or dentist's office and demand x-rays. Just stay reasonable on the subject.

Writer's right molars radiographed September 24, 1952 with about 5.5 roentgens.

Same writer's same molars radiographed April 6, 1965 with 0.21 roentgen.

*Note to the small minority: in the unlikely event that you do not already have a fresh catalog of KODAK X-ray Films, please notify Radiography Markets Division, Eastman Kodak Company, Rochester, N. Y. 14650.

This is another advertisement where Eastman Kodak Company probes at random for mutual interests and occasionally a little revenue from those whose work has something to do with science



SCIENCE AND

Equitable Immigration

After more than 80 years during which many potential immigrants to the U.S. were either barred or subjected to restrictive quotas because of their race or nationality, Congress has passed a law eliminating such considerations as criteria for entry. The new regulations, which go into effect in July, 1968, place an annual limit of 120,000 persons on immigration from the Western Hemisphere (hitherto not subject to any quota) and a limit of 170,000 on immigration from elsewhere. The yearly maximum for any single nation outside the Western Hemisphere is 20,000 persons. This will reduce the present immigration rate for only two nations: Great Britain (former quota 65,361; immigrants in 1964, 28,653) and West Germany (quota 25,814; immigrants in 1964, 22,628). Immigrants from previously less favored nations such as Italy (quota 5,666) and Greece (quota 308) will benefit proportionately, as will those from Asia, where most nations have been assigned nominal quotas of 100 a year.

The law's revised system of preferences gives primary consideration to family ties. More than half of the visas available each year are allocated either to the children or to the brothers and sisters of U.S. citizens; another 34,000 are allotted to the spouses and unmarried children of U.S. residents who are not citizens. Other preferences include the allocation of 10,200 visas to political refugees, 17,000 to people of exceptional ability in the professions, arts or sciences, and 17,000 to workers whom the Federal Government certifies as noncompetitive with U.S. labor. Surplus visas in any of these categories will be made available to other immigrants on a first-come, first-served basis. The law contains one further change: between now and 1968 the portions of existing national quotas in excess of demand (for example the 36,000 not used by Britain in 1964) will no longer go unused. Instead the excess will be made available to other nations with a waiting list of potential immigrants.

For Outstanding Contributions

The first Arches of Science Award—$25,000 and a gold medal for "outstanding contributions by an individual to the understanding in America of the meaning of science"—was bestowed on Warren Weaver last month. By far the most munificent for such contributions, the award was established this year by the Pacific Science Center in Seattle, Wash. Its name is intended to evoke the tall, freestanding arches that adorn the campus of the center, built originally to house the U.S. science exhibit at the Seattle World's Fair in 1962 and now operated as a museum of science.

Weaver, chosen for the award by a national jury of 12 scientists and laymen, is a mathematician who has played a central role for more than 30 years in the public affairs of science in the U.S. and in the interpretation of science to his fellow citizens. From 1932 to 1959 he was the Rockefeller Foundation's bursar for the natural sciences. On assuming that office he made the astute determination to spend the foundation's funds with "greatly increasing emphasis on biology and psychology and on those special developments in mathematics, physics and chemistry which are themselves fundamental to biology." Careers and programs of research fostered under this policy in the U.S. and abroad have culminated in the contemporary triumphs of molecular biology. During World War II, Weaver organized and headed the Applied Mathematics Panel of the Office of Scientific Research and Development, the principal U.S. agency for "operational research." As president of the American Association for the Advancement of Science in 1954, he helped to

THE CITIZEN

establish in that organization its present preoccupation with public policy and the popularization of science.

A willing and felicitous writer and lecturer, Weaver has an acute interest in problems of communication. He was quick to recognize the importance of Claude E. Shannon's fundamental contribution to communication theory. With Shannon he wrote *Mathematical Theory of Communication,* an exposition addressed to scientists that hastened the recognition and impact of this work in fields outside mathematics. More recently—in *Alice in Many Tongues*—he has explored the question of why Lewis Carroll's masterpiece casts the same semantic and logical spell in 40 different languages.

For such activities Weaver was also honored a second time last month. In Paris he received the Kalinga Prize of the United Nations Educational, Scientific and Cultural Organization.

The Moonlike Planet (Cont.)

New analyses of the pictures of Mars made by *Mariner IV* dispute the original interpretation that the Martian surface may have undergone little change, except for the formation of craters by meteorites, in the past two billion to five billion years. Three papers recently published as a group in *Science* maintain that the age of the Martian surface is only a fraction of the age first estimated and that erosion by water, dust storms or other processes could have been intense early in the planet's history.

The three papers argue, in brief, that the rate of crater formation on Mars should be about 25 times higher than on the moon. The reason is that Mars is much closer to the asteroid belt between Mars and Jupiter, which presumably supplied most of the crater-forming bodies. According to the first paper (by Edward Anders of the University of Chicago and James R. Arnold of the University of California at San Diego), the Martian surface observed by *Mariner IV* is pocked by only one-sixth as many craters as would be expected if it were as old as the maria ("seas") of the moon. Instead of 220 large craters (craters 20 kilometers or more in diameter) per million square kilometers Mars has only 37. This discrepancy implies that the Martian craters are only about a sixth as old as those found on the lunar maria, or between 300 million and 800 million years old. Anders and Arnold believe craters older than that have been obliterated by erosion. The only other way to account for the "missing" craters is to assume that multiple, overlapping impacts make the crater count unreliable. "In any event," they conclude, "the crater density on Mars no longer precludes the possibility that liquid water and a denser atmosphere were present on Mars during the first 3.5 billion years of its history."

One of the two papers supporting this general conclusion is by J. Witting, F. Narin and C. A. Stone of the Illinois Institute of Technology. The second is by Ralph B. Baldwin of the Oliver Machinery Company, who had predicted in 1949 that Mars would be found to have a moonlike surface.

Active RNA from a Test Tube

The synthetic replication of a fully functioning genetic molecule inside a test tube, long a goal of molecular biologists, has been announced by Sol Spiegelman, Ichiro Haruna and their co-workers at the University of Illinois. The genetic molecule synthesized is ribonucleic acid (RNA), which provides the complete hereditary message for certain viruses. The RNA used in the University of Illinois experiments was obtained from a virus called Q-beta, which normally replicates inside the colon bacterium *Escherichia coli*.

About 10 years ago biochemists first extracted a natural enzyme from living cells that was capable of synthesizing long-chain molecules of RNA from chemically pure building blocks. Although the RNA synthesized by this procedure had most of the chemical and physical properties of natural RNA, it lacked the biological activity of its natural counterpart. Subsequently many efforts were made to produce synthetic duplicates of natural RNA, both from bacterial cells and viruses, but without success.

Spiegelman and his co-workers succeeded by discovering an RNA-replicating enzyme (which they call replicase) in cells infected with the Q-beta virus. The replicase is not present in noninfected cells, nor is it present in the virus itself. The virus consists solely of a molecule of RNA encased in a protein jacket. The replicase, also a protein, is formed by the cell's using instructions coded in the viral RNA. It was found that the Q-beta replicase is an effective RNA-copying agent only when it is supplied with Q-beta RNA and that it will not work with RNA from other viruses.

The Illinois workers are able to produce infectious Q-beta RNA starting with nothing more than (1) Q-beta replicase, (2) a bit of Q-beta RNA to act as a template, (3) magnesium salts and (4) the chemically pure building blocks of RNA in the form of their triphosphates. To demonstrate that the infectivity is attributable to the synthetic RNA alone and not to traces of the original natural RNA, the following experiment was conducted. A few of the RNA molecules grown in one test tube are transferred to a second, where a fresh batch is grown. From the second test tube a few are transferred to a third test tube, and so on for 15 stages. In the 15th test tube the original RNA is so diluted that there is only one chance in 10 that a single molecule of the original RNA is present.

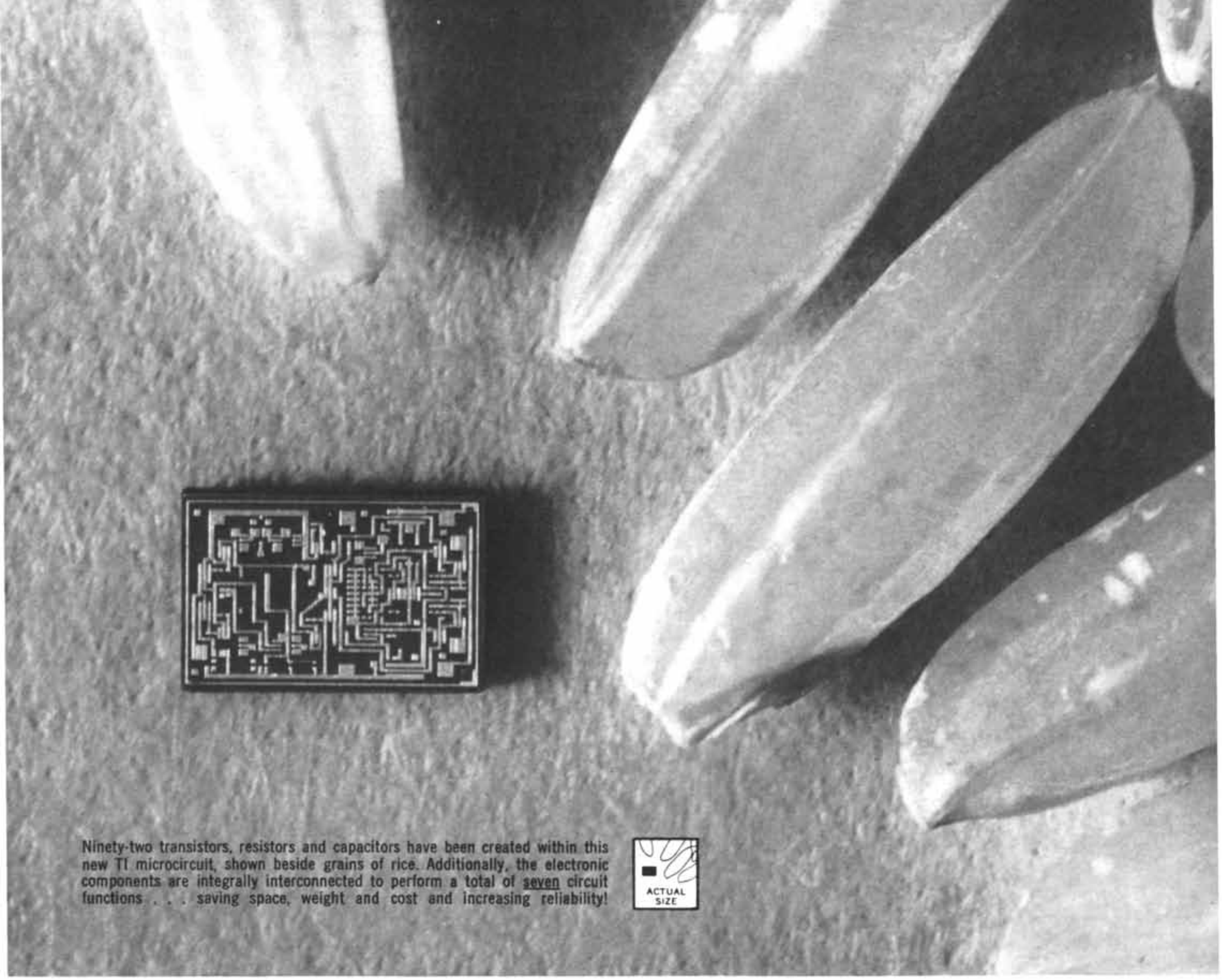
Working with Spiegelman and Haruna were George S. Beaudreau, Ian B. Holland and Donald R. Mills. The work is reported in *Proceedings of the National Academy of Sciences*.

Fallen Satellite?

A study of craters and meteorite fragments found in northern Argentina suggests that a large meteorite had a brief life as an orbiting satellite of the earth before plunging to the ground some 6,000 years ago. The area in which the craters are located is known as Campo del Cielo; it has been famous for its meteorites since Spanish explorers came on a 25-ton iron specimen in 1576. The results of a three-year study of the region has now been reported in *Science* by a joint U.S.-Argentine team of investigators.

William A. Cassidy of Columbia University, Luisa M. Villar of the University of Buenos Aires and their associates surveyed Campo del Cielo between 1960 and 1963; they located nine impact craters ranging from 65 to 380 feet in diameter and turned up more than 500 meteorite fragments weighing from one to 78 pounds. Inspired by their activity, a local farmer unearthed still another meteorite that weighed more than three tons. Under the rim of one crater Cassidy and Villar found charred wood that yielded a radiocarbon date of 3800 ± 200 B.C.

When the craters and meteorite locations were plotted on a map, they fell within an almost straight zone



Ninety-two transistors, resistors and capacitors have been created within this new TI microcircuit, shown beside grains of rice. Additionally, the electronic components are integrally interconnected to perform a total of seven circuit functions . . . saving space, weight and cost and increasing reliability!

it's smart to be dense!

Annual sales of semiconductor integrated circuits will exceed $100 million next year — only eight years following their invention – and Texas Instruments is the major manufacturer of these tiny, ultra-reliable devices! As "the next step beyond the transistor," they are the second semiconductor product to revolutionize the electronics industry in recent years.

A semiconductor integrated circuit – which modifies electrical signals to perform many tasks – contains scores of transistors, resistors and capacitors in a tiny sliver of silicon smaller than a grain of rice. This almost incredible component density gives several important advantages: increased reliability, reduced size, weight and – most important – lower cost.

Cost savings in a wide range of electronics equipment are possible because of drastic reductions in parts, packaging, design time, materials-handling, and assembly. As a result, most military electronics systems on the drawing boards today feature integrated circuits. And such significant cost advantages are rapidly opening up new industrial and consumer applications, many of which have not yet been penetrated by electronics.

As the world's largest semiconductor manufacturer, TI is uniquely prepared to serve this market. TI invented the semiconductor integrated circuit in 1958, introduced it commercially in 1959, and subsequently obtained patents. TI integrated circuits were first in space (IMP satellite), first in a major military program (Minuteman II), first in a consumer product (Zenith hearing aid), and even first to be shot from guns (artillery fuse)!

Dramatic as these advances have been, the revolution has just begun. In the laboratory, TI now has integrated circuits performing more than a hundred circuit functions! These advanced circuit arrays will be organized to perform complex logical decisions in small, inexpensive computers. The "home computer" to program and control all household functions is not far away!

Semiconductor integrated circuits are a prime example of TI's ability to synchronize multi-divisional technical effort, enabling TI to grow 30 per cent a year over the past decade. Write Corporate Marketing for brochure on the business and facilities of TI.

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nearly 50 miles long and a little more than a mile wide, running in a northeast-southwest direction. This linear array, together with mineralogical evidence that all the meteorite fragments are probably from a single parent body, suggests that a big meteorite entered the earth's atmosphere with a very flat trajectory. This, the investigators note, "might result either from a grazing approach to the earth from a solar orbit or from decay of a closed terrestrial orbit."

Protein from Coal

Coincident with programs for using microorganisms that grow on petroleum to make protein (see "Protein from Petroleum," by Alfred Champagnat; SCIENTIFIC AMERICAN, October) the U.S. Department of the Interior has announced that it is investigating the potential of coal as a raw material for producing proteins. A team of investigators from the department's Bureau of Mines discussed the project in a paper read at the 150th national meeting of the American Chemical Society. The investigators pointed to the similarity between certain chemicals from coal and chemicals from petroleum that already have proved capable of supporting the growth of the microorganisms that produce proteins. Already, the investigators said, some yeasts have been identified that thrive on chemicals obtained from coal tar.

As an example of the potentiality of coal as a source of protein, the Bureau of Mines workers noted that certain of the yeasts that grow on chemicals from coal produce protein 2,500 times faster than domestic meat animals. A cow weighing 1,100 pounds converts its food into proteins at a rate of 1.1 pounds a day, the bureau investigators said, whereas 1,100 pounds of microorganisms living on chemicals derived from coal can convert the paraffinic hydrocarbons of the chemicals into protein at a rate of 2,750 pounds a day.

Earthquake Forecasting

A panel of earth scientists has recommended a massive research program designed to develop methods of predicting earthquakes. In a report to the White House Office of Science and Technology the 13-member panel, headed by Frank Press of the Massachusetts Institute of Technology, outlined a 10-year program of theoretical, laboratory and field studies estimated to cost $137 million. Geophysicists still do not know what causes earthquakes, and part of the program is designed to help them find out. Prediction is sometimes possible, however, as in the case of weather forecasting, without complete understanding of a natural process. A major part of the program is designed to make prediction possible in this empirical sense by capitalizing on current evidence that a destructive earthquake may be preceded by small deformations of the earth's surface and an increase in the frequency of "microearthquakes" in the area.

To this end the report suggests a major effort to "instrument" the seismic regions of California and Alaska. Regional deformations would be monitored by sensitive surveying instruments, including lasers. Statistics on the numerous microearthquakes, local strains and tilts in the earth, changes in gravity and magnetic-field readings would be tested for coherence with one another and for possible correlation with a major earthquake. All this would require a "new generation" of instruments, but according to the report the necessary design principles are known. A central feature would be the installation of instruments in large arrays to reduce the effect of background noise.

Harvested Rain

A test recently completed by the U.S. Geological Survey has demonstrated the efficiency of a new technique for collecting the rainfall that otherwise goes to waste in semiarid and desert regions. Two similar nine-acre plots were selected on the White Sands Military Reservation in New Mexico; shallow pits were dug into which the rainfall running off from each plot would drain. One of the test plots was left undisturbed; the surface of the other was cleared of desert vegetation and was then given a thin coating of a special asphalt mix that had been developed by the Esso Research and Engineering Company. During a 12-month test period both plots received eight inches of rainfall. The runoff from the asphalt-coated plot totaled more than a million gallons, representing a collection efficiency of 60 percent. In contrast, normal evaporation and plant transpiration kept the collection efficiency of the untreated nine acres down to 3 percent.

Extrapolating from the test results, project engineers estimate that larger asphalt coatings could harvest runoff water at a cost of about 25 cents per 1,000 gallons. This is nearly 40 percent more costly than the average paid for city water and very much more costly than the price of irrigation water, where the rule of thumb is that 1,000 gallons of water is needed for every 10 cents' worth of crop. It nonetheless appears possible that large asphalted catchment basins could provide economically practical amounts of water in regions where neither well water nor desalinated ocean water is available.

The Bathtub Vortex (Cont.)

Strong support for the old hypothesis that water draining from a tank would swirl clockwise in the Southern Hemisphere if the influence of the earth's rotation were stronger than other influences is reported by five investigators at the University of Sydney. Three years ago Ascher H. Shapiro of the Massachusetts Institute of Technology conducted similar experiments that supported the parallel hypothesis that in the Northern Hemisphere the swirl would be counterclockwise ("Science and the Citizen," SCIENTIFIC AMERICAN, November, 1962). Each swirling effect can be expected, if the earth's rotation is the dominant influence, because of the conservation of angular momentum; seen from the Northern Hemisphere the earth's rotation is counterclockwise, whereas it is clockwise as seen from the Southern Hemisphere.

The Australian investigators (Lloyd M. Trefethen, R. W. Bilger, P. T. Fink, R. E. Luxton and R. I. Tanner) say in *Nature* that they modeled their experiments on Shapiro's, using a tank six feet in diameter and nine inches high with a central drain. They filled the tank to a depth of about seven inches, directing the filling hose so that the water swirled counterclockwise, and then they let the water settle for several hours. "Clockwise rotation was observed in all five of the later tests that had settling times of 18 hours or more," the Australians say. In each case it took about 11 minutes, which was approximately half the draining time, for any rotation to appear. Summing up, the investigators write: "One can never prove . . . that it was not some small air current which persistently maintained a circulation that gave the results we observed, and that a quantitatively comparable, but oppositely directed, air current caused Shapiro's results. . . . Nevertheless, we have acquired confidence in the hypothesis that carefully performed experiments on liquid drainage from a tank will show clockwise rotation, if done in the Southern Hemisphere."

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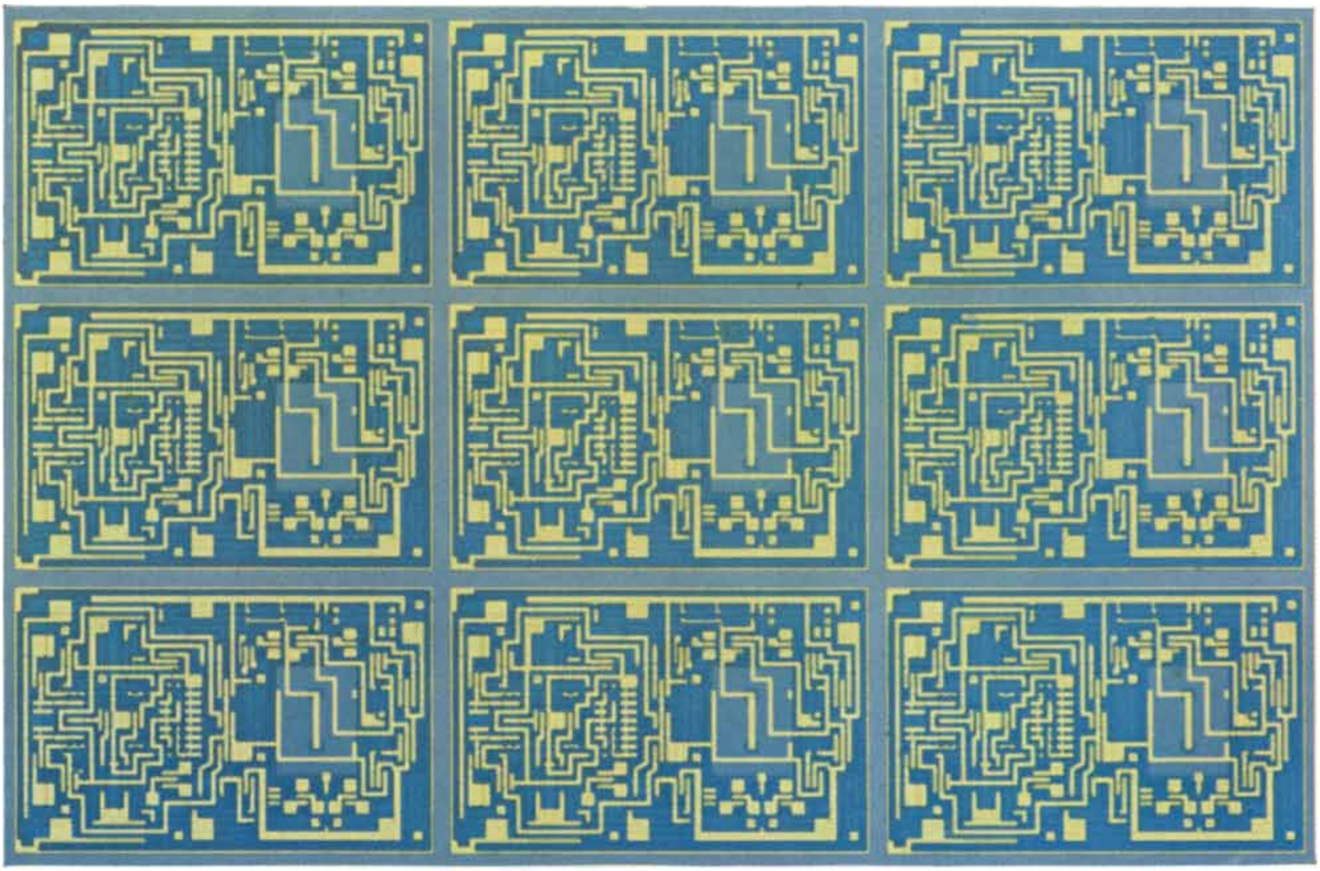
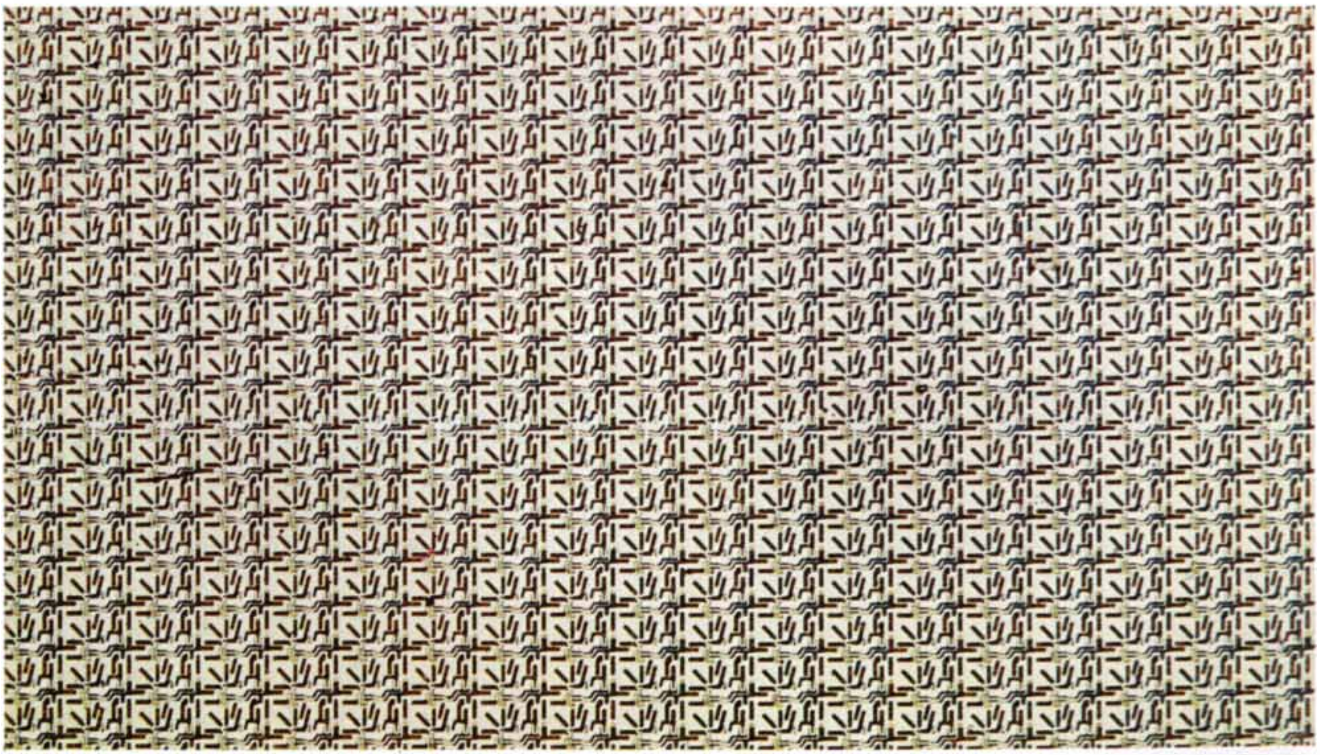


INTEGRATED CIRCUITS made by Texas Instruments Inc. are magnified about 20 diameters; actual circuits are a tenth of an inch long and a fifteenth of an inch wide. Each of these circuits, among the most complex in production, contains 16 transistors, 32 resistors and one capacitor. It receives the output from a computer memory, amplifies it and sends it into a computer logic unit.



BEAM-LEAD CIRCUITS developed by the Bell Telephone Laboratories contain gold circuit leads, or connections, strong enough to hold the circuit together when the underlying silicon is etched into islands, improving electrical performance. The picture, a 20-diameter enlargement, shows 323 (19 by 17) "logic gate" circuits, each equivalent to two transistors, four resistors and seven diodes.

MICROELECTRONICS

A new technology reduces entire electronic circuits to tiny modular "chips." Its importance lies less in making circuits smaller than in making them faster, cheaper and more reliable

by William C. Hittinger and Morgan Sparks

The intensive effort of the electronics industry to increase the reliability and performance of its products while reducing their size and cost has led to results that hardly anyone would have dared to predict as recently as 10 years ago. At that time the junction transistor, a basic improvement on the original point-contact transistor of 1947, was only four years old and just entering commercial production. The few junction transistors on the market cost from $5 to $20 each, depending on their quality, and even the best of them were somewhat unreliable and limited to use in circuits operating at fairly low frequency. As of 1955 no major item of military electronics had yet been transistorized; the commercial use of transistors was limited almost entirely to hearing aids. The first all-transistor radios appeared in that year. Delivery of the first "solid state," or transistorized, commercial computer was still three years in the future.

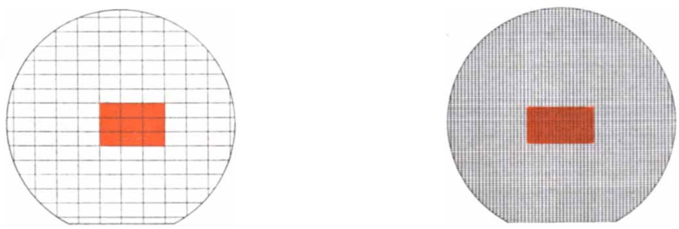
Between 1955 and 1965 the electronics industry developed and reduced to practice a remarkable microelectronic technology that has shrunk transistors and other circuit elements to dimensions almost invisible to the unaided eye. A complete circuit typically consisting of 10 to 20 transistors and 40 to 60 resistors can be built into a bit of silicon measuring only about a tenth or a twentieth of an inch on a side. Between 100 and 500 such "integrated" circuits can be manufactured simultaneously on a silicon wafer that is about an inch in diameter and less than a hundredth of an inch thick [*see illustrations on these two pages*].

The point of this extraordinary miniaturization is not so much to make circuits small per se as to make circuits that are rugged, long-lasting, low in cost and capable of performing electronic functions at extremely high speed. Except in a few specialized applications —such as in rockets, space vehicles and hearing aids—the size of these microelectronic circuits is usually of secondary importance.

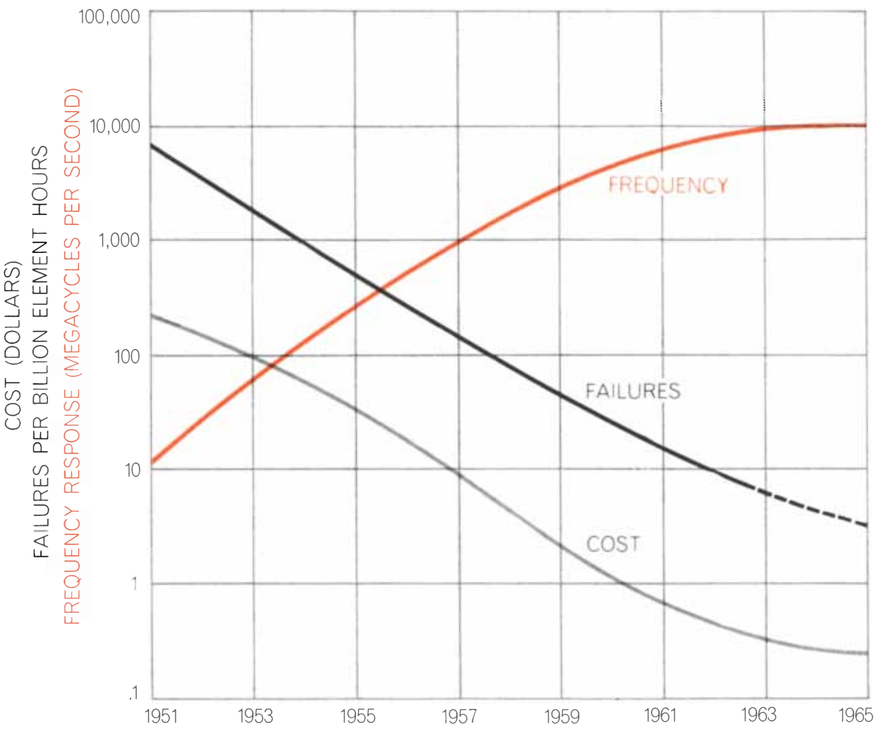
With the new microelectronic technology it is hardly more costly to put 100 circuit elements on a single chip of silicon than it is to put one, 10 or 50. Moreover, the 100 elements can then be handled as a unit when the final system is being assembled. Whereas a good transistor cost about $1 as an individual unit in 1960, an integrated circuit containing several dozen transistors and other elements can now be bought for about the same price.

The microscopic dimensions of the new circuits have improved performance in two ways. The basic function of a transistor is to regulate the flow of current in response to an input signal. The speed of response depends primarily on the size of the transistor: the smaller the transistor, the faster it is. Early transistors, which were often described as being the size of a pea to dramatize their smallness, were actually enormous on the scale at which electronic events take place, and therefore they were very slow. They could respond at a rate of a few million times a second; this was fast enough to serve in radio and hearing-aid circuits but far below the speed needed for high-speed computers or for microwave communication systems, such as those that relay messages from tower to tower across the country—and more recently from the earth to space and back. It was, in fact, the effort to reduce the size of transistors so that they could operate at higher speed that gave rise to the whole technology of microelectronics. Roughly between 1960 and 1963, spurred by military requirements (particularly the Minuteman solid-fuel intercontinental ballistic missile), the new circuit technology became a reality.

The second performance benefit resulting from microelectronics stems directly from the reduction of distances between circuit components. The ultimate factor limiting the speed at which a computer or any other electronic system can operate is the velocity of light, which also sets the upper limit for the flow of electric current through a wire. Light travels about a foot in a billionth



ACTUAL SIZE OF INTEGRATED CIRCUITS is represented in these schematic drawings of the silicon wafers on which the circuits are produced. The colored rectangles indicate the areas shown in the photographs on the opposite page. The Texas Instruments wafer is represented at the left; the wafer designed by Bell Laboratories is shown at the right.



TRANSISTOR PERFORMANCE AND COST are plotted for the period 1951–1965. Frequency response has gone up by three orders of magnitude; failure rate and cost have dropped by about three orders of magnitude. Costs pertain to individual transistors. Comparable devices incorporated in integrated circuits are now only a few cents each.

of a second. If a circuit is to operate a few billion times a second, the conductors that tie the circuit together must be measured in fractions of an inch. The microelectronic technology makes such close coupling attainable.

Types of Electronic Devices

Before we describe the new technology in greater detail, it may be helpful if we say a few words about four of the principal devices found in electronic circuits: resistors, capacitors, diodes and transistors. Each device has a particular role in controlling the flow of electrons so that the completed circuit performs some desired function. In a radio the function is to transform a weak electromagnetic signal of high frequency into a much amplified signal of lower frequency that can be used to actuate an electromechanical device such as a loudspeaker. In a television set more complicated circuitry is required to produce an electronic picture from a weak electromagnetic signal whose frequency is much higher than that of the ordinary radio signal.

Elements of a circuit are classed either as active or passive, depending on how they modify the signal energy in a circuit. Passive elements such as resistors and capacitors have the property of impeding the flow of signal energy or of storing it; they cannot, however, generate, modulate or amplify the signal. Diodes are also passive elements: when fed an alternating current, they allow only half of each cycle of current to pass, so that what emerges is a direct current. This is the process called rectification. Active elements such as vacuum tubes and transistors have the essential property of generating, amplifying or switching the signal energy. Without them electronics could not exist. The circuit designer, understanding the properties of such electronic devices and their interactions, combines them so that they can perform useful functions.

Prior to the invention of the transistor in 1947 its function in an electronic circuit could be performed only by a vacuum tube, a device that had absorbed vastly more engineering development than any other circuit component. Tubes came in so many shapes and sizes and performed so many functions so well that in 1947 it seemed audacious to think that the transistor would be able to compete except in limited applications. The first transistors had no striking advantage in size over the smallest tubes; they were—and remained for many years—more costly, and although they promised greater reliability and longer life, these attributes took years to demonstrate. The one great advantage the transistor had over the best vacuum tube was its exceedingly low power consumption. This advantage, combined with its inherent simplicity and potential for improvement, justified the immense international effort that was soon poured into its development.

With the invention of the transistor all essential circuit functions could be carried out inside solid bodies. The goal of creating electronic circuits entirely with solid-state components had finally been realized. This had been an explicit objective of electronic research at Bell Telephone Laboratories since the late 1930's.

The Tyranny of Numbers

In 1947, however, the future of electronics outside the entertainment industry was only dimly perceived. There was as yet no computer industry. The first electronic digital computer, the room-sized machine called ENIAC, was only two years old, but its 19,000 vacuum tubes far exceeded the number ever before built into a single electronic mechanism. They foreshadowed the "tyranny of numbers" that would soon be felt throughout the electronics industry as government and industry turned increasingly to electronics to cope with problems of mounting complexity.

Telephone engineers were probably among the first to recognize this particular tyranny. They had already designed and built central-office switching systems that contained hundreds of thousands of electromechanical relays; they knew the cost and difficulty of manufacturing devices that would function for 10 to 20 years with an exceedingly low failure rate [see "Telephone Switching," by H. S. Feder and A. E. Spencer; SCIENTIFIC AMERICAN, July, 1962]. Although telephone engineers recognized many advantages in replacing electromechanical systems with all-electronic ones, they could see no way to meet cost and reliability requirements with a technology based on vacuum tubes.

Transistor technology has in large measure hurdled the economic barrier to large systems that the vacuum tube presented. The performance, cost and reliability of the transistor have all improved dramatically during the past decade [*see illustration on this page*].

During that span the performance of electronic systems increased manyfold by the use of ever larger numbers of components as they continued to evolve. Modern scientific and business computers, for example, contain several hundred thousand components; the electronic switching systems now being built for telephone central offices contain more than a million components [*see illustration on this page*].

Although further improvement of the transistor can be expected, it will not be at the dramatic rate of the past; intrinsic limits of design and manufacture are being approached. At the same time the equipment builder is approaching a limit in the size of systems he can afford to assemble piece by piece from discrete devices.

This tyranny of numbers—the problem of handling many discrete electronic devices—began to concern the armed services as early as 1950. In that year the Navy asked the National Bureau of Standards to study the problem and recommend a solution. This led to the "Tinkertoy" project, in which standard combinations of devices—including tiny vacuum tubes—were designed to fit within compact, uniform circuit modules. These modules in turn could be variously combined and assembled by automatic machinery to provide almost any circuit function desired [see "Automatic Manufacture of Electronic Equipment," by Lawrence P. Lessing; SCIENTIFIC AMERICAN, August, 1955]. Project Tinkertoy attacked the size problem by providing a packing density of about eight electronic devices per cubic inch with the conventional devices available at that time. It did not, however, reduce the number of devices and interconnections.

A variety of similar programs, primarily concerned with size reduction and standardization of devices, were conceived and financed during the 1950's. The development of rockets and space vehicles toward the end of the decade provided the final impetus to such studies; added payload could be related directly to rocket cost at an average saving of about $20,000 per pound. Reducing the weight of portable ground equipment was also important, and to that end the Signal Corps sponsored the technique known as "Micromodule." This technique increased the packing density to about 400 parts per cubic inch by mounting miniature devices on uniform ceramic wafers, which could then be assembled in standard modules. Other assembly techniques were given such picturesque names as "cordwood," "Swiss cheese," "2-D" and "3-D." All shared the shortcoming of the original Tinkertoy concept: the number of devices and interconnections needed to do a certain job remained the same as in a conventional electronic circuit.

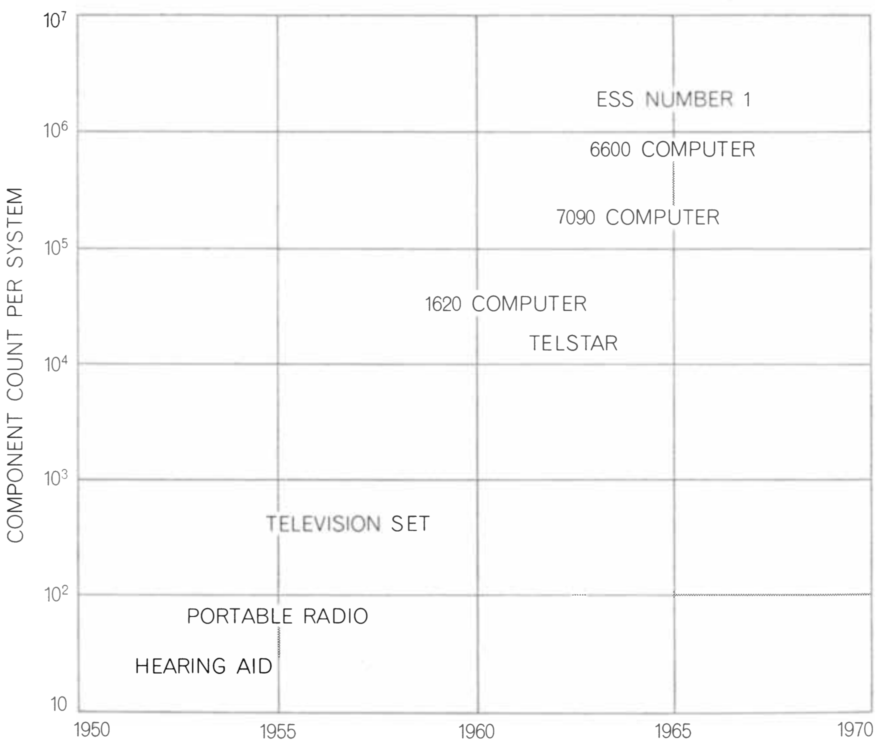
A more serious shortcoming was that the overall reliability of the electronic system was still inversely related to the number of individual circuit components: the more components and interconnections, the less reliable the system. Thus a crucial limitation to the size of useful systems remained. Fortunately the scientists and engineers engaged in the development of new and improved devices were developing skills that would lead to a solution.

Integrated Circuits

Two independent lines of development led to the microelectronic techniques that produced the present integrated circuits—so named because all the elements of the circuit are inseparably associated. One involves the semiconductor technology developed for making transistors and diodes; the other is the thin-film technology that can produce high-quality resistors and capacitors. The semiconductor technology can provide all four principal circuit elements, but its resistors and capacitors are not yet adequate for the most exacting circuit requirements. To meet such requirements one can fabricate a hybrid integrated circuit in which diodes and transistors produced by the semiconductor technology are combined with resistors and capacitors made by the thin-film technology. We shall describe the latter technology first.

Even before the invention of the transistor the electronics industry had studied the properties of thin films of metallic and insulating materials. Such films can range in thickness from a fraction of a micron, or less than a wavelength of light, to several microns. (A micron is a millionth of a meter; the wavelength of red light is about .7 micron.)

A typical thin-film resistor will consist of a fine metal line only a few thousandths of an inch wide and long enough to provide the desired value of resistance. If high values are desired,

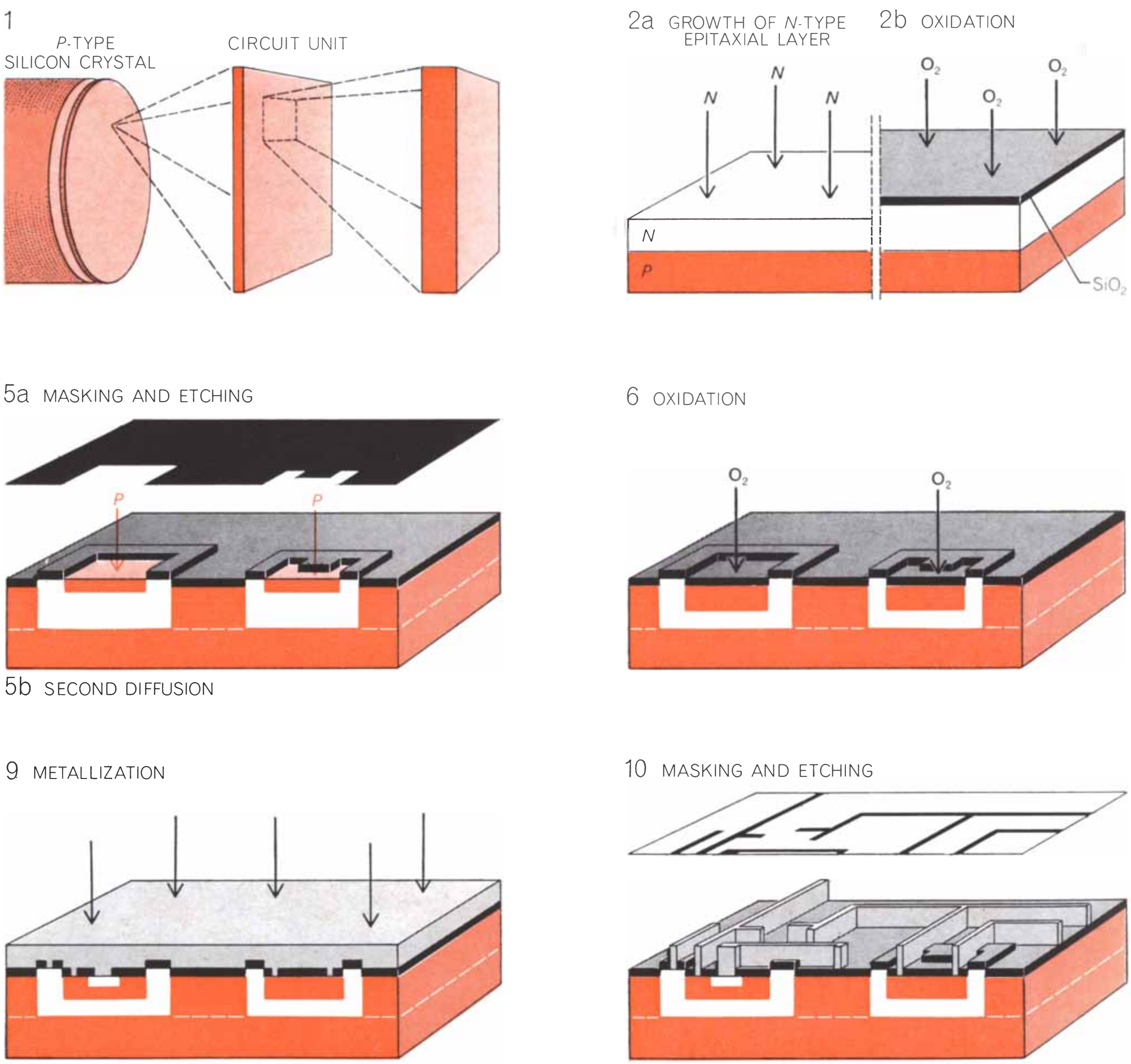


GROWTH IN ELECTRONIC-SYSTEM COMPLEXITY is indicated by the number of devices (such as resistors, diodes and transistors) required in representative electronic mechanisms developed since 1950. The 1620 and 7090 computers are those of International Business Machines Corporation. The 6600 computer, currently believed to be the most capable in the world, is built by Control Data Corporation. It contains about 100,000 diodes, 350,000 transistors and 500,000 resistors, all assembled individually. Telstar is the Bell System's communication satellite. "ESS" refers to Bell's "electronic switching system."

the line can be laid down in a zigzag pattern. To form a capacitor one can lay down a thin film of insulating material between two thin films of metal; the appropriate value of capacitance can be closely controlled by adjusting the surface area of the sandwich and the thickness of the insulating material.

Thin films are commonly deposited by evaporation or, if the film material is a refractory substance that does not readily vaporize, by "cathode sputtering." Evaporation is achieved by heating the metal above its boiling point inside a vacuum chamber that also contains plates of glass or ceramic on which the metal is to be deposited. Films of the desired thickness can be produced in a matter of minutes.

Cathode sputtering is a process in which positively charged ions of a gas are used to bombard a negatively charged target, or cathode, consisting of the refractory material that is to be deposited as a thin film. The gas particles act as high-speed projectiles that vaporize the target material by bombardment rather than by heat. The substrate becomes coated with the atoms driven from the cathode. Sputtering also pro-

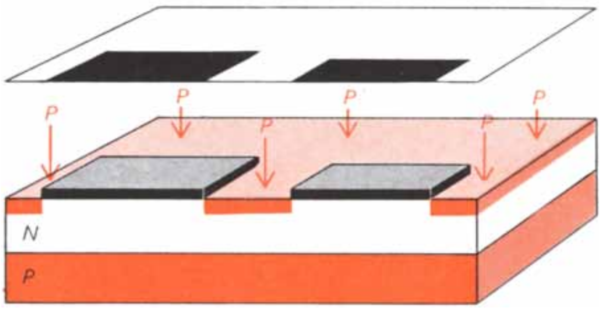


FABRICATION OF INTEGRATED CIRCUIT is an elaboration of the process used to make individual silicon transistors. The process begins (*1*) when a long single crystal of silicon about an inch in diameter is sawed into wafers a few thousandths of an inch thick. Each wafer will ultimately yield 100 to 500 individual circuits. This sequence will show how a transistor and a resistor are formed in one small portion of such a circuit. The original silicon wafer contains "dopants," or impurity atoms, that make it *p*-type (for "positive"). It is thus a good conductor of positive current. By epitaxial growth (*2a*) a thin layer of *n*-type (for "negative") silicon is deposited over the *p*-type substrate; oxidation (*2b*) forms a layer of silicon dioxide (SiO_2) that seals the silicon below. A photolithographic process involving extremely accurate masks and acid etching (*3a*) removes the silicon dioxide in certain areas to expose the *n*-type silicon. High-temperature diffusion in an atmosphere containing *p*-type dopants (*3b*) converts *n*-type silicon to *p*-type. Oxidation (*4*) again seals the entire surface. Another masking and etching step (*5a*) selectively exposes *n*-type regions, and a second diffusion (*5b*) converts these regions to *p*-type down to a carefully controlled depth. Oxidation (*6*) once more seals the duces useful films in very few minutes.

To form large numbers of passive devices, such as resistors or capacitors, one or more thin-film layers are deposited on a large sheet of glass or ceramic. This is followed by a shaping operation, such as etching, to form the required outlines. Alternatively, the film can be deposited through a mask onto the substrate to define the outlines directly. In this way many identical thin-film devices can be made on a single sheet of material, which is then cut apart to yield individual devices. One can easily see, however, that a group or network of devices can be tied together into a circuit merely by providing a pattern of interconnections leading from one device to another.

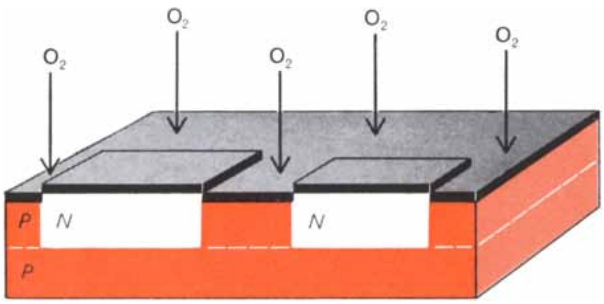
One system of thin-film circuitry that has particular interest because of its simplicity, high quality and durability employs the metal tantalum and some of its compounds. Resistors are formed by lines of tantalum nitride; capacitors are created by sandwiching a film of anodized, or oxidized, tantalum between two films of tantalum metal. Resistors are also anodized to adjust their values precisely and to provide a protective

3a MASKING AND ETCHING

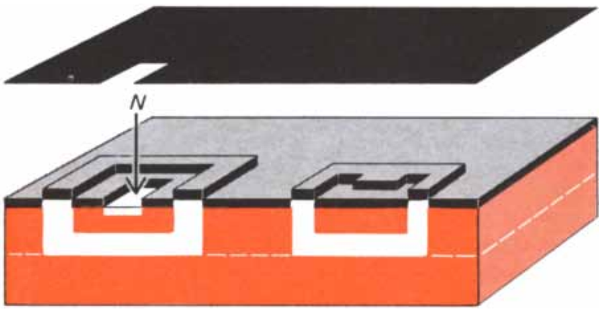


3b FIRST DIFFUSION

4 OXIDATION

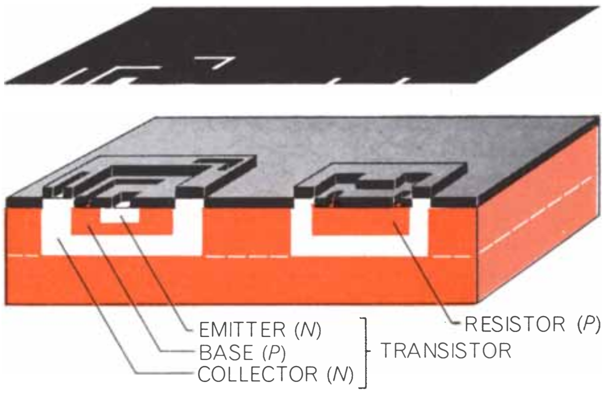


7a MASKING AND ETCHING

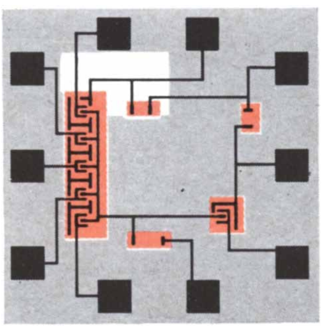


7b THIRD DIFFUSION

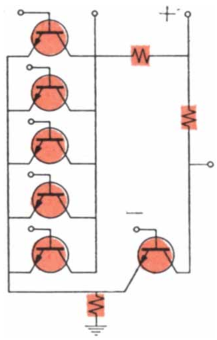
8 MASKING AND ETCHING



11a



11b



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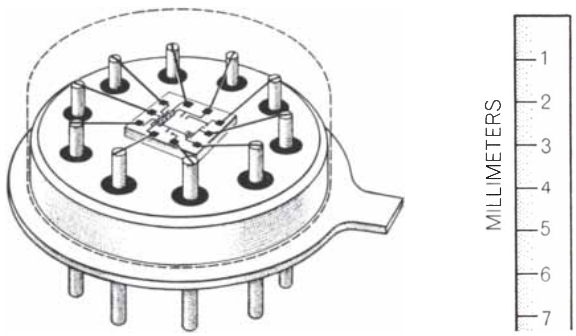


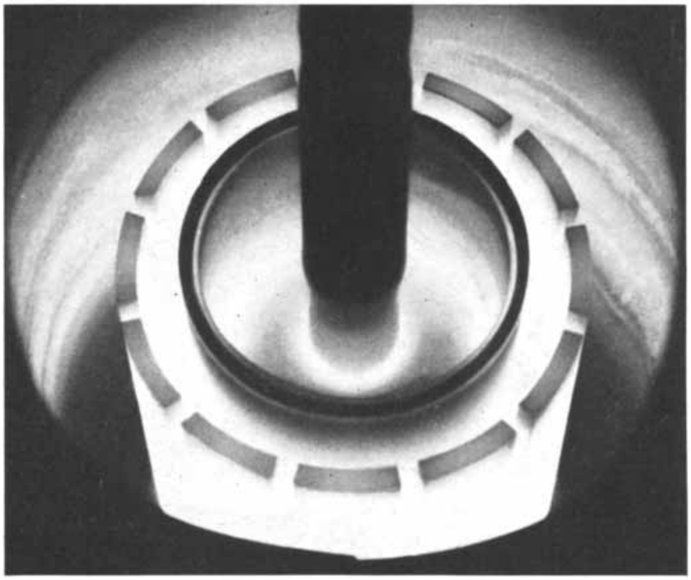
surface. Another masking and etching step (*7a*) and a third diffusion (*7b*), this time with *n*-type dopants, creates a tiny *n*-type region that will form the "emitter" of a transistor. Note that the U-shaped region to the right, which will become a resistor, remains sealed by silicon dioxide and thus is not affected by the third diffusion. Another masking and etching step (*8*) produces the pattern of windows that will enable metal to make contact with three regions on the transistor (emitter, base and collector) and two points on the resistor. These contacts are made (*9*) when metal is evaporated over the entire surface of the wafer. A final masking and etching (*10*) creates a network of conductors and "pads," or terminals, that makes the circuit accessible to the outside world. A top view of the complete circuit (*11a*) shows a network of six transistors and three resistors, which are connected as shown in the symbolic diagram of the circuit (*11b*). Fine gold wires are bonded to the terminals of the circuit and to posts on a 10-lead platform. This assembly is then sealed with a vacuum-tight cover (*12*). The circuit shown is an "input-gate circuit" manufactured for use in computers by Motorola Semiconductor Products Inc. Vertical dimensions are exaggerated for clarity.

layer of oxide. The various circuit components are connected by metallic tantalum. By close monitoring of the process at each step, circuits made up of thin-film resistors and capacitors can be held to within a fraction of a percent of the appropriate electrical values.

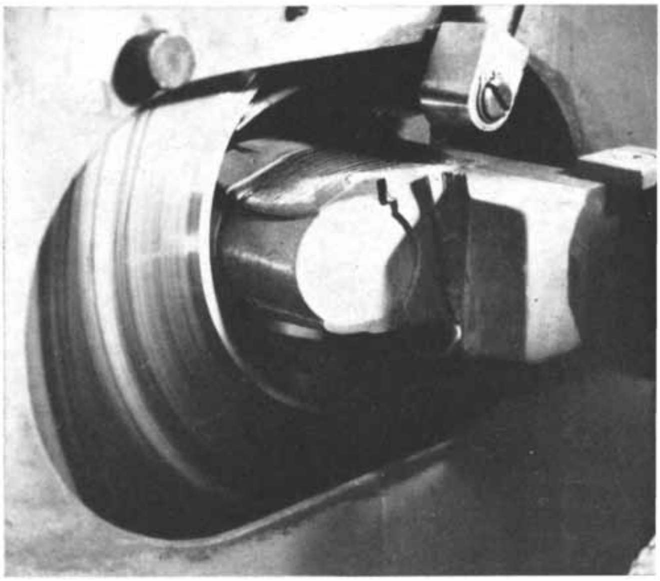
Semiconductor Technology

The second stream of microelectronic development, flowing from transistor technology, led to the most versatile circuit-building process of all. This activity has been more intensive and several times larger in scale than the thin-film program. It is based on carefully grown single crystals of silicon, a semiconducting material whose electrical properties stand midway between those of metals and non-metals. The electrical properties of silicon can be sensitively and precisely manipulated by adding minute amounts of "dopants," or impurities.

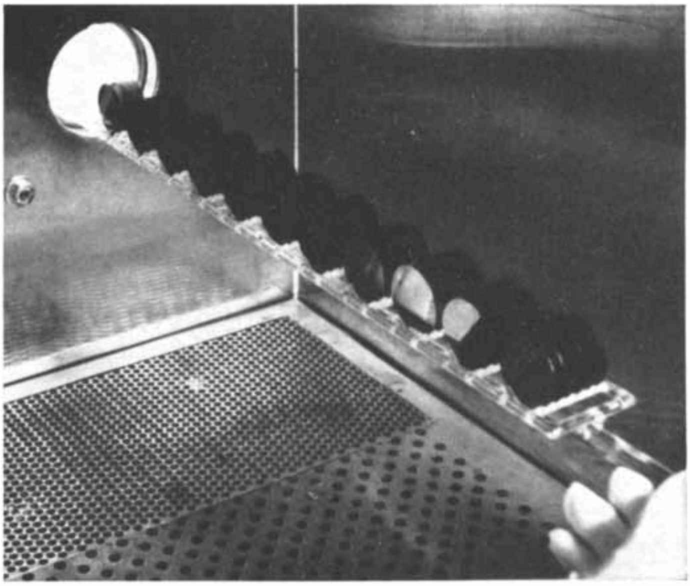
In the periodic table of elements silicon (and germanium) are found in the column labeled Group IV. The dopants are elements such as gallium and boron from the Group III column, or elements such as arsenic and phosphorus from the Group V column. When Group III dopants are added to silicon or germanium, they create a deficiency of conduction electrons in the semiconductor. As a result the doped region contains "holes"—sites that would otherwise be occupied by electrons. The holes act as positive charges and therefore can carry



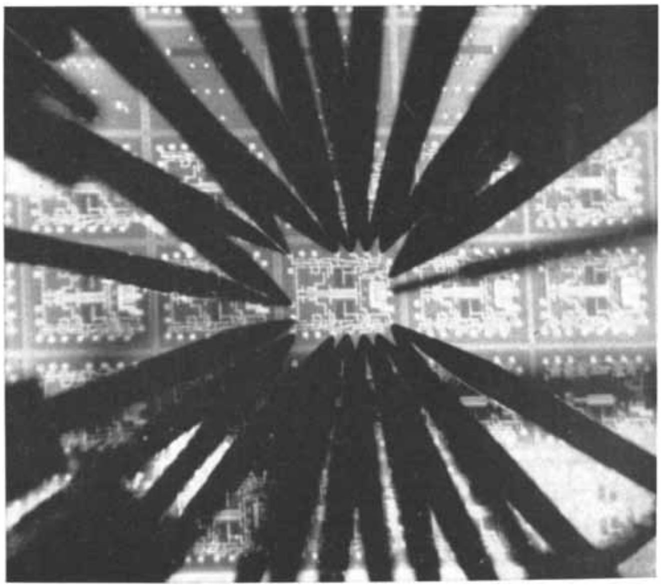
GROWING OF SILICON CRYSTAL starts the process of manufacturing an integrated circuit. Here a single crystal is being withdrawn slowly from a crucible of molten silicon. The scenes on these two pages were photographed at Texas Instruments and Western Electric.



SLICING OF CRYSTAL produces the wafers on which dozens to hundreds of complete circuits are fabricated. The crystal is cut by a circular saw whose diamond edge is on the inside of the blade. The wafers are held together after being cut.



VAPOR DIFFUSION introduces dopants and thereby alters the electrical properties of the epitaxial layer wherever it has been exposed by the previous etching step. This "boatload" of wafers is about to enter a diffusion furnace held between 900 and 1,200 degrees centigrade.



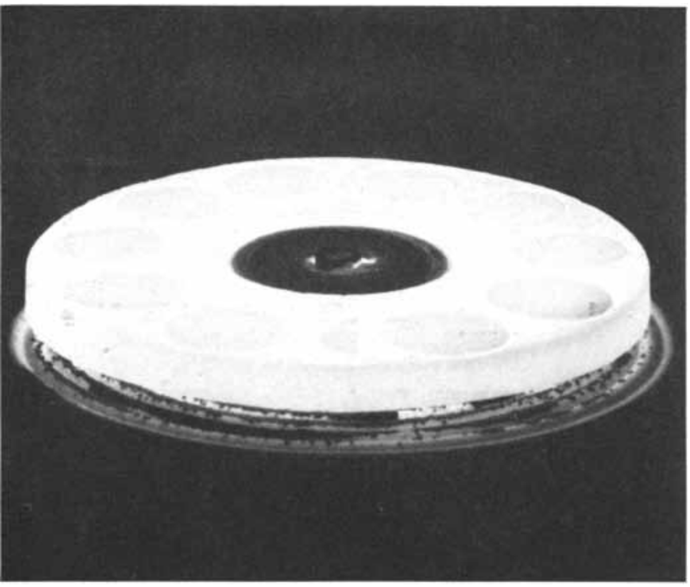
TESTING OF COMPLETED CIRCUIT is performed by a 14-point probe that makes contact with the various terminals. The circuit is one of Western Electric's, but it resembles in size the Texas Instruments circuit shown at the top of page 56.

a positive current; such a region is designated p-type. Group V dopants, on the other hand, create regions with an excess of conduction electrons; these electrons carry negative current and the regions are therefore designated n-type. The boundary between a p-type region and an n-type region within a single crystal is called a p-n junction.

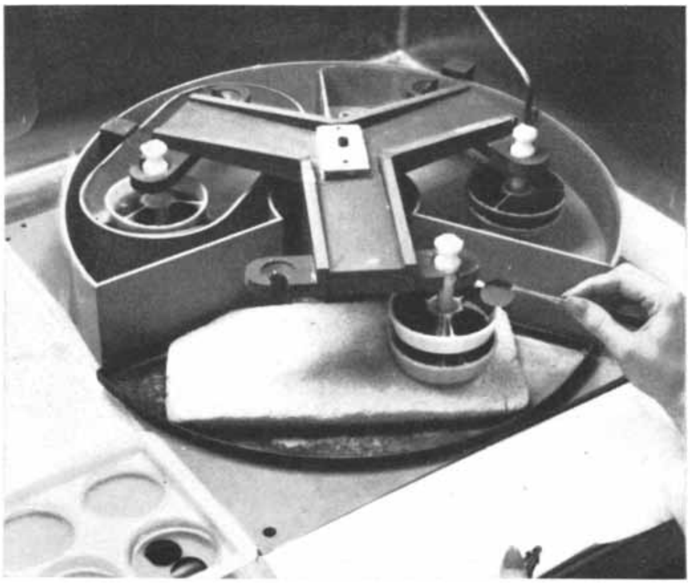
A structure with a single p-n junction can act as a diode: it has the ability to rectify alternating current or to function as a switch. The transistor is a two-junction device in which the junctions separate three regions that can be either p-n-p or n-p-n. An electrical contact is affixed to each of the three regions, which are called the emitter, the base and the collector.

Transistor performance was steadily improved as it became possible to bring these regions closer and closer together. This depended in turn on the ability to introduce Group III and Group V elements in extremely accurate amounts and in precise locations. It is commonplace today to control the concentration of dopants to parts per billion and the junction separations to a fraction of a wavelength of light. The dopants are diffused into the semiconductor crystal at high temperatures.

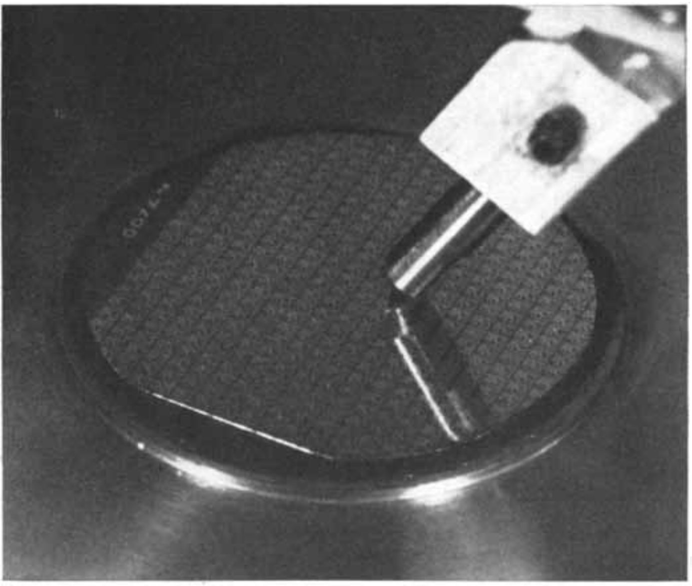
The diffusion process has been used since about 1955 to make high-performance diodes and transistors. In this process a "boatload" of semiconductor crystals, usually in the form of silicon wafers about an inch in diameter, is placed in a furnace held closely at a



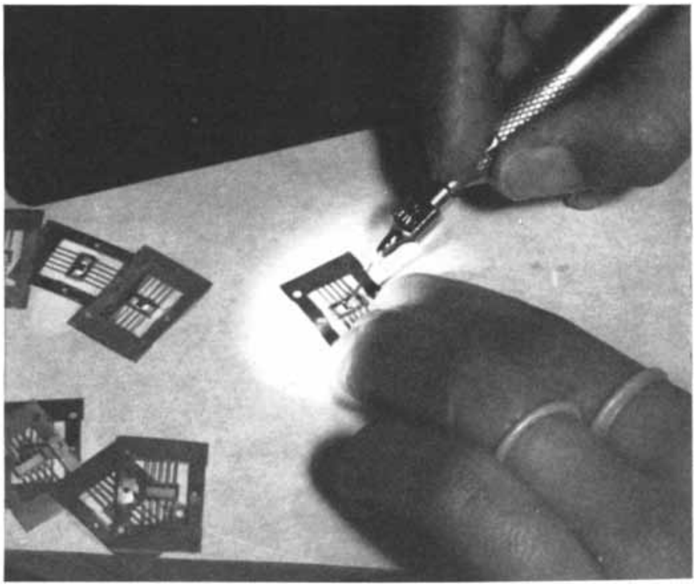
EPITAXIAL LAYERS are grown on silicon wafers inside a furnace. The furnace atmosphere contains silicon doped with tiny amounts of additives that will give the epitaxial layer different electrical properties from those of the substrate.



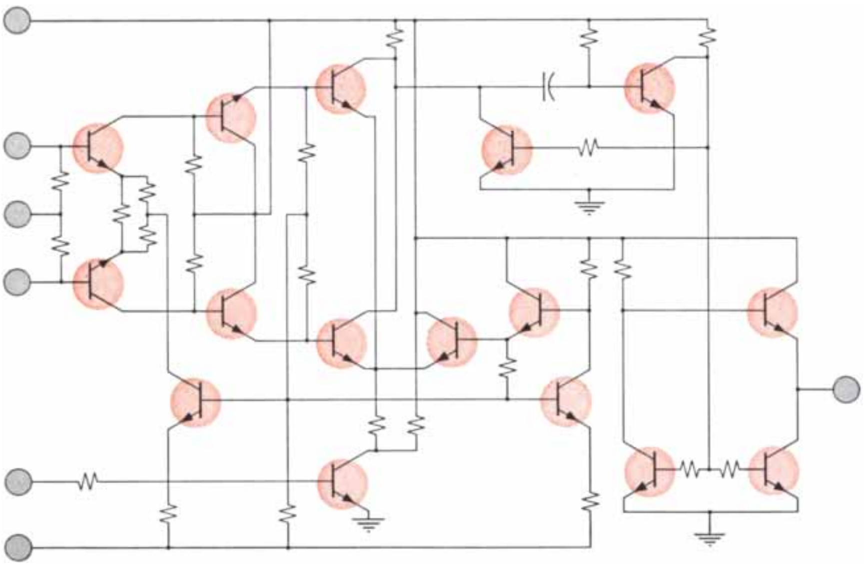
ACID ETCHING produces a minuscule pattern of windows in a protective layer of silicon dioxide that was formed on the wafer following the step shown at left. The windows delineate the tiny regions that will become transistors and other elements in the finished integrated circuit.



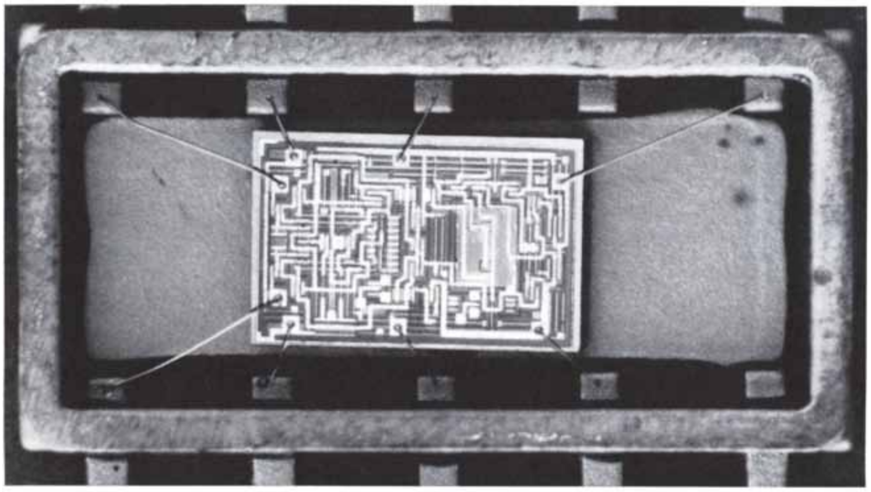
DIAMOND-TIPPED SCRIBER scratches a grid of fine lines between the rows and columns of circuits. After being jacketed in transparent plastic tape the wafer is drawn across a sharp straightedge, thus breaking the circuits into individual "chips."



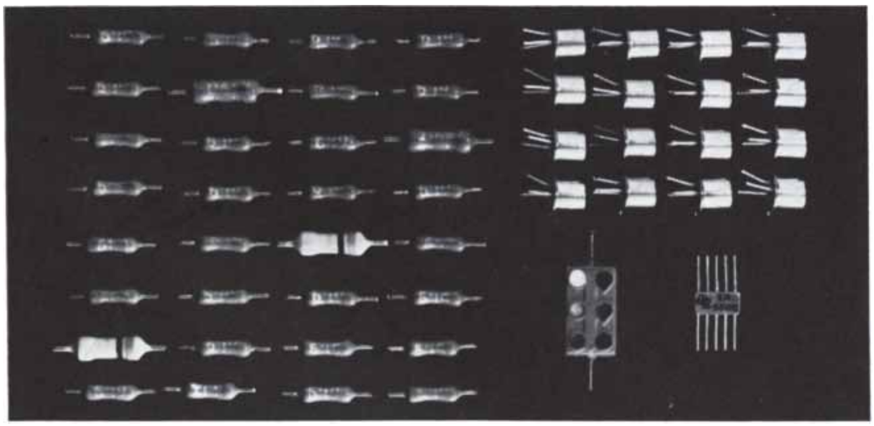
FINAL PACKAGING is a delicate operation; here a vacuum pencil is used to pick up the circuit and position it accurately in a metal case. After positioning, the circuit is cemented in place with a glass-frit adhesive. The rectangular frame around the package facilitates handling.



CIRCUIT DIAGRAM shows the complexity of the Texas Instruments circuit pictured at the top of page 56 and below. The 24 zigzag lines represent resistors; the 16 circles represent transistors. The short straight line facing a curved line is the circuit's single capacitor. In the actual circuit 32 resistors are needed to do the work of the 24 in the diagram.



CLOSEUP OF CIRCUIT shows details of packaging. The circuit chip actually contains a total of 23 transistors and 68 resistors, which can be used to form other kinds of circuits.



FORTY-NINE CONVENTIONAL COMPONENTS, the equivalent of those in the integrated circuit above, are shown actual size. The 16 transistors are in metal cans; the 32 resistors and one capacitor (*the rectangular object with dots*) are sealed in a plastic-like compound. The integrated circuit itself appears at bottom right in its hermetic package.

temperature in the range between 900 and 1,200 degrees centigrade. In the furnace the crystals are surrounded by a vapor containing atoms of the desired dopant. These atoms enter the crystal by substituting for the semiconductor atoms at regular sites in the crystal lattice and move into the interior of the crystal by jumping from one site to an adjacent vacancy.

At each diffusion step in which *n*-type or *p*-type regions are to be created in certain areas, the adjacent areas are protected by a surface layer of silicon dioxide, which effectively blocks the passage of impurity atoms. This protective layer is created very simply by exposing the silicon wafer at high temperature to an oxidizing atmosphere. The silicon dioxide is then etched away in conformity with a sequence of masks that accurately delineate a multiplicity of *n*-type and *p*-type regions.

To define the microscopic regions that are exposed to diffusion in various stages of the process, extremely precise photolithographic procedures have been developed. The surface of the silicon dioxide is coated with a photosensitive organic compound that polymerizes wherever it is struck by ultraviolet radiation and that can be dissolved and washed away everywhere else. By the use of a high-resolution photographic mask the desired configurations can thus be transferred to the coated wafer. In areas where the mask prevents the ultraviolet radiation from reaching the organic coating the coating is removed. An etching acid can then attack the silicon dioxide layer and leave the underlying silicon exposed to diffusion. The multiple pattern of tiny images that forms the mask for each step is reduced and replicated photographically from master drawings that are usually two or three feet square to minimize drafting irregularities [*see illustration on page 66*]. The copying lenses for the job must have exceptionally high resolution and low distortion.

Contributing greatly to the manufacturing technique is a unique crystal-forming method known as epitaxial growth. This is a term used by crystallographers to describe the growth on a crystal surface of a second material that preserves the crystalline structure of the original substrate. Electronic engineers have borrowed the term and applied it broadly to include the controlled deposition on a single semiconductor crystal of a layer of the same semiconductor. The new layer, which grows at the rate of about five microns a minute, can have almost any desired composition of

ITT Scientist awarded medal by Franklin Institute for being 25 years ahead of his time.

Twenty-five years ago Alec Reeves, ITT scientist, invented the system which allowed the recent Mariner IV spacecraft to transmit television pictures from Mars to Earth. It's called Pulse Code Modulation or PCM.

Only now, 25 years later, has science, with the introduction of transistor devices and other semiconductors, caught up with PCM's great potential.

PCM, of course, was never intended for outer space projects. It was a way to slice a telephone call, a television picture or other electric communication into pieces or "bits." These then could be transmitted long distances and reconstructed instantaneously at the receiving end.

Today PCM permits multiple telephone conversations to be sent simultaneously over a single line facility. It's already installed in England and widely used in the United States.

For his remarkable idea, Alec Reeves was awarded this year's Stuart Ballantine Medal of the Franklin Institute.

Helping people and nations communicate, that's a vital part of the work of all the people at ITT, world's largest international supplier of electronic and telecommunication equipment.

International Telephone and Telegraph Corporation, New York, N.Y. ITT

PRECISION MASK for laying down the pattern of elements in an integrated circuit is drawn on a large scale by a computer at Western Electric. By means of precision photographic lenses the mask is reduced to microscopic size and replicated as may be required to cover the surface of a silicon wafer. The overall reduction in scale is about 500 to one.

electronically active impurity atoms. It is the highly controlled epitaxial layer that is further altered locally by the diffusion process described earlier.

When this technology is used to make individual transistors, about 1,000 are diffused into a single one-inch wafer of silicon that is about .006 inch thick. The transistors are sometimes separated by sawing them apart, but closer spacing can be achieved if a diamond point is used to inscribe a grid of fine lines between the individual devices. If the inscribed wafer is drawn across a sharp edge—in two directions at right angles to each other—it will break cleanly into tiny square "chips." Fine wire leads are then bonded to the emitter and base regions on each chip and the chip is sealed in a vacuum-tight can to form a finished transistor. Last year about 100 million transistors were produced in the U.S. by this method.

Epitaxial growth in combination with oxide masking and diffusion have given the device designer extremely flexible tools for making an almost limitless variety of structures. The best of the transistors produced in this way are so reliable that in a billion device-hours of operation (for example 100,000 transistors tested for 10,000 hours) the failure rate ranges between one and 10.

Extension of the Technology

These processes for transistor fabrication were well established by 1960. Engineers at Texas Instruments Incorporated saw the possibility of producing complete circuits within a silicon chip by forming all the circuit elements by diffusion and connecting them by fine bonded wires. Fairchild Semiconductor made similar circuits in silicon chips but connected the elements by a planar, or essentially two-dimensional, pattern of aluminum evaporated as a thin film over the silicon dioxide layer used during the oxide masking operation [*see illustration on pages 60 and 61*].

Such assemblages, known as silicon integrated circuits, were rapidly developed in the preferred planar form between 1960 and 1963 to meet the requirements of the solid-fuel missile program. Designers of commercial computers and other complex nonmilitary equipment were quick to recognize that integrated circuits promised reliability, performance and economy unmatched

by any other technique. Today integrated circuits are produced commercially in great variety and large volume by such firms as Texas Instruments, Fairchild, Motorola Semiconductor Products Incorporated and the Westinghouse Electric Corporation. The Western Electric Company, the manufacturing arm of the Bell System, is building integrated circuits for military purposes and Bell Laboratories is exploring their application to commercial telecommunications. Meanwhile Western Electric is producing thin-film circuits combined with high-performance diodes and transistors for certain demanding tasks in the Bell System.

Almost certainly the integrated circuit will undergo many improvements before its potential is exhausted. About a year ago engineers at Bell Laboratories made one such improvement with the "beam lead" technique. Here the word "lead" (as in "lead into," not the metal lead) refers to the metallic conductors that connect the individual devices in an integrated circuit. Originally these leads were made of aluminum applied over the top surface of the integrated circuit chip and terminated near the edges of the chip in "pads" of relatively large area. Fine gold wires a quarter of the thickness of a human hair were then bonded to the pads by heat and pressure to make the circuit accessible to the external world. The cost of making the wire bonds, and also their low but finite failure rate, stimulated a search for an alternative scheme.

The remedy was to replace the aluminum intraconnections with intraconnections of gold. At the same time the size of the gold leads was increased, so that with respect to the mass of the tiny circuits they have the strength of structural beams. This makes it possible to etch through the back of the silicon substrate in which the circuit is embedded and thereby provide a strong overhanging lead that can be used to attach the circuit to the interconnection pattern of the electronic system. In addition, the back-etching makes it possible to isolate the various devices in the circuit, thus eliminating unwanted electrical interactions that tend to degrade circuit performance.

Packaging and Reliability

The first packages used for integrated circuits were a simple adaptation of the metal cans that had been used to house transistors. Whereas the transistor package has only three leads extending from its base, however, the integrated-circuit package has many more, typically eight to 12. These packages, which are vacuum-tight and rugged, can be assembled into complete systems by attaching them to printed circuit boards. Recently a new flat package has been designed specifically for integrated circuits. Extending from two edges of the package are ribbon leads that can be attached to printed circuit boards or three-dimensional wiring arrays. Circuits containing either the cylindrical or the flat package routinely withstand centrifugal tests that produce accelerations of 20,000 *g*'s, which is roughly the acceleration experienced by a well-hit golf ball as it leaves the tee. (One *g* is the acceleration due to gravity at the surface of the earth.)

These various forms of packaging add significantly to the cost of integrated circuits. Efforts are being made, therefore, to provide a stable, protective surface over the silicon chip so that cheaper packages, supplying only mechanical protection, can be used. Recently circuits "potted" in plastic have been developed for use in noncritical applications, and further improvements can be expected in the future.

The reliability of integrated circuits has not yet been established with as much certainty as the reliability of discrete devices, both because of the magnitude of the task and because of the insufficient period of time since the circuits were developed. It seems reasonably safe to say, however, that the reliability of the latest integrated circuits is at least equivalent to that of high-quality individual components. This implies that a given system made from such circuits should have a considerably higher level of reliability than one made from conventional devices because far fewer packaged units would be needed.

There are many variations of circuit design and assembly that might be placed under the heading of microelectronics, but the thin-film circuit and the semiconductor integrated circuit—and combinations of the two—represent the leading developments in the field. Together they should be able to meet the needs of the electronics industry for some years to come.

Future Directions

For the rather more distant future one may hope to find new conceptions that will drastically reduce the number of devices now needed to perform a given function. One has the feeling that present circuit theory, tied as it is to the familiar circuit elements, fails to provide system functions as directly and

simply as possible. It should be possible to develop a new class of functional devices that use basic properties of matter to obtain results now achieved by sheer multiplication of devices.

An example of a functional device that has been in use for many years is the piezoelectric quartz-crystal resonator. This is a device that provides an accurate frequency, or timing, impulse in many electronic systems. Its operation is based directly on the piezoelectric effect, in which a crystal produces a voltage when it is mechanically deformed or conversely is mechanically deformed when it is subjected to a voltage. Quartz not only exhibits this effect but also its crystal structure is highly elastic, so that it vibrates in selective modes with low internal friction. These two properties can be exploited to maintain a precise frequency in an electronic circuit. If one tries to duplicate such a resonant circuit with standard circuit elements, one needs many more components and the result is much less satisfactory. Moreover, one cannot point to anything in the quartz-crystal resonator and say this acts as a capacitor, this as a resistor and so on. One might say that it works out of internal necessity.

Several laboratories now have programs seeking to develop functional devices. Before such programs can be fully effective, however, new analytical tools will be needed to formulate the functions one wishes to perform in a way that suggests how the functions may be achieved. The functional-device approach is therefore a long-range program, but it is one that promises large returns if it succeeds.

Meanwhile the microelectronic technology we have described will continue to grow vigorously. Discrete components will be of decreasing importance for future systems, but like the vacuum tube they will remain available and useful for many tasks.

Within the electronics industry integrated circuits have upset the traditional division of effort between component suppliers and system designers. The component supplier is now capable of moving up one level in complexity by providing circuits in place of individual devices. Thus he can vie with the system designer and encroach on design territory once regarded as the system engineer's exclusive domain. System builders, in self-defense, are learning how to make integrated circuits. It is not at all clear how traditional roles will evolve with time, but then the electronics industry thrives on change.

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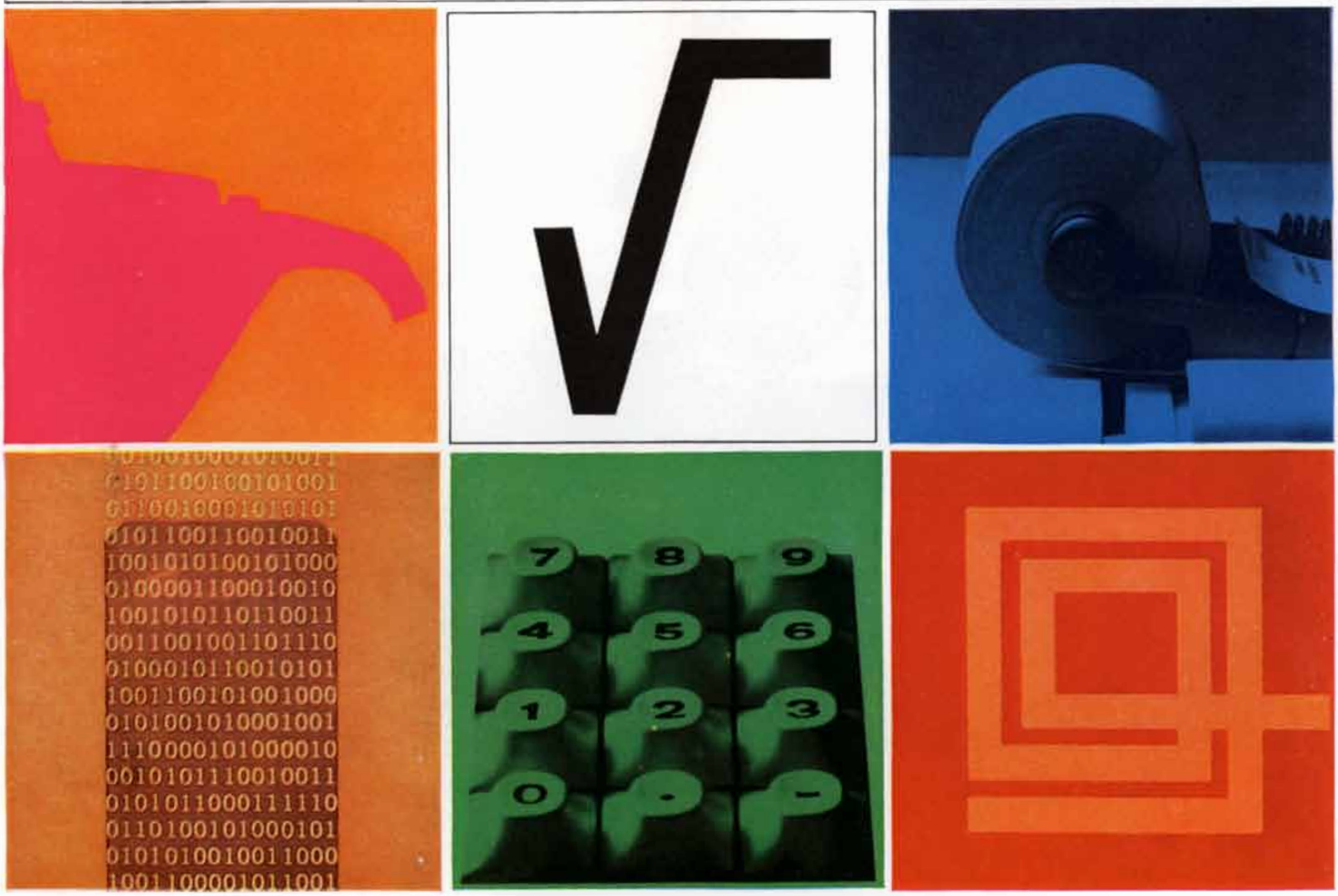

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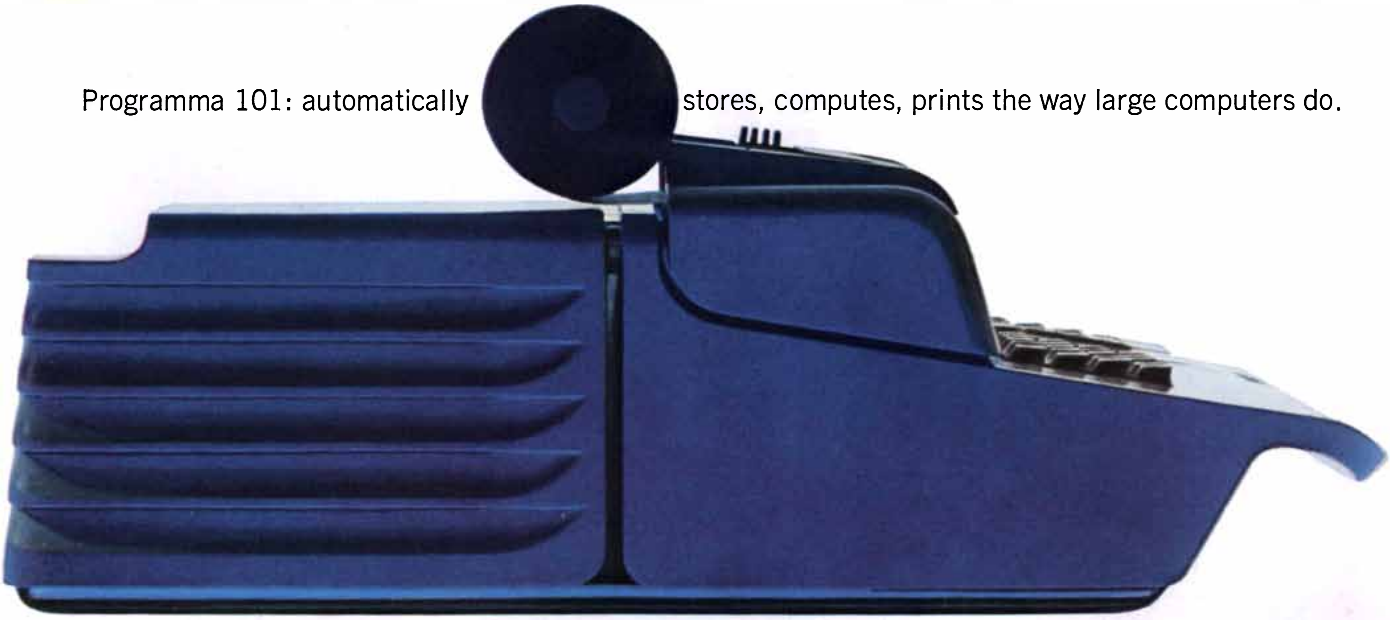

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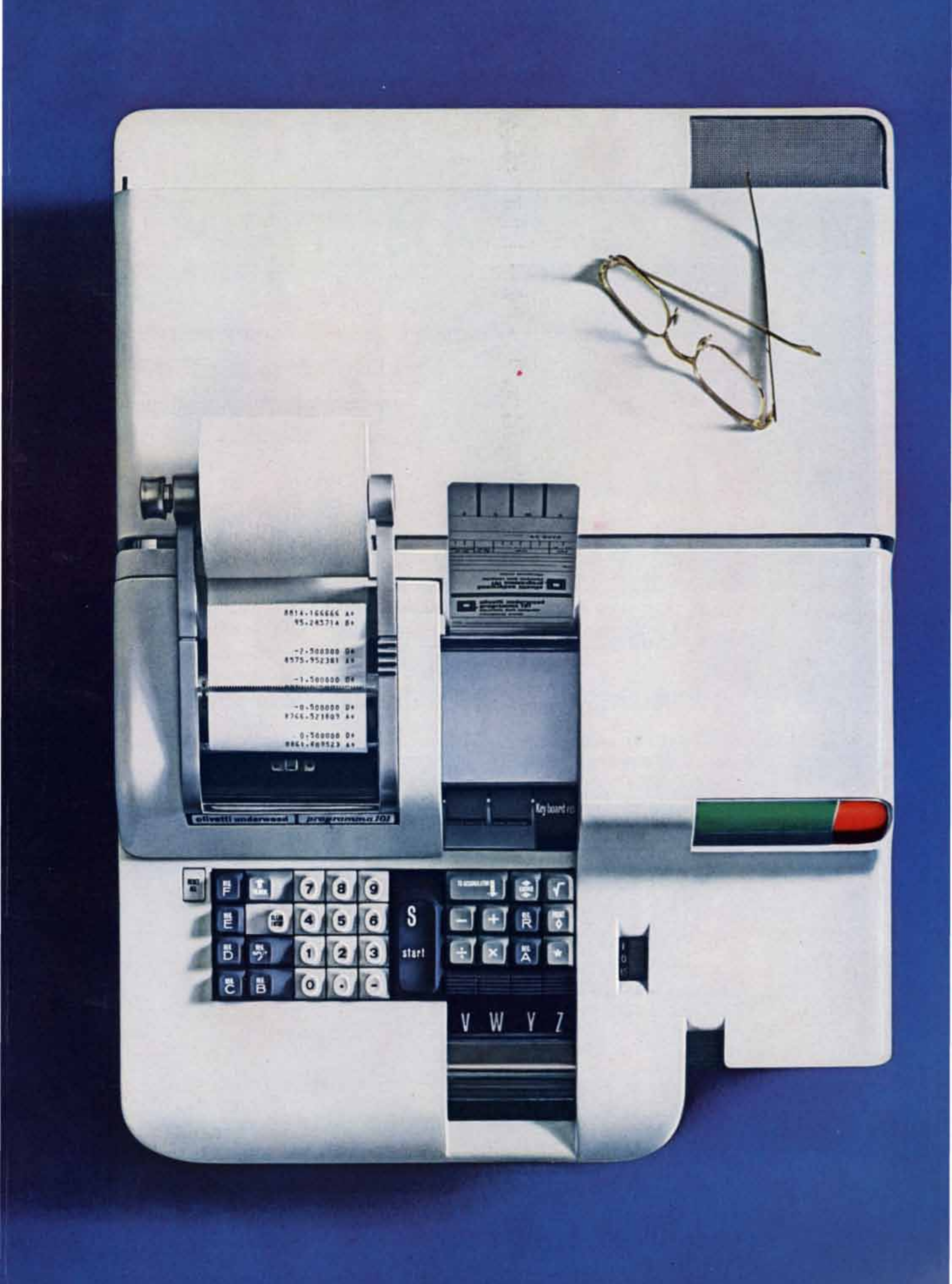
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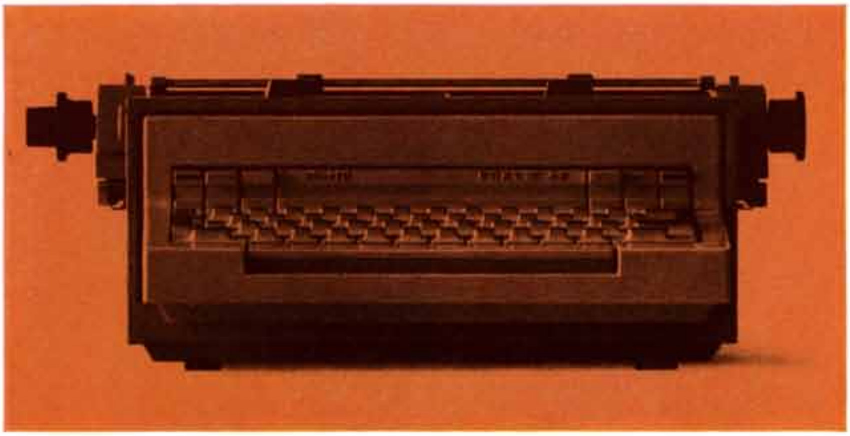

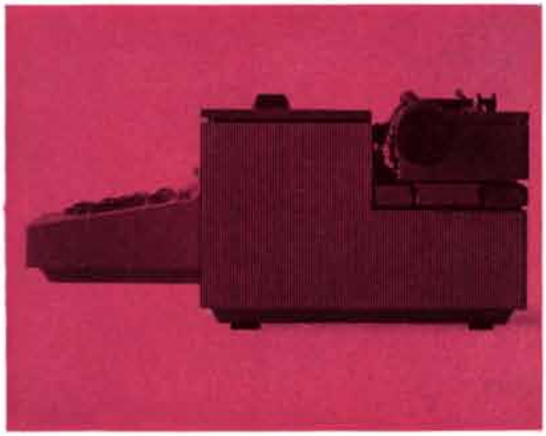

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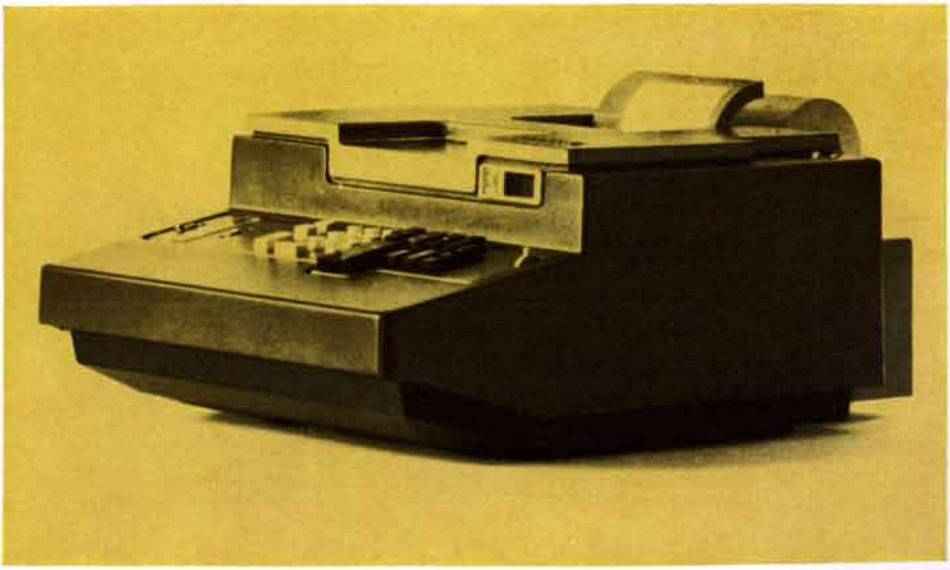

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The Reversal of Tumor Growth

The fact that cancers are usually irreversible is sometimes taken as showing that they are caused by mutation. Some "multipotential" cells in plants and animals, however, can change from malignant to normal

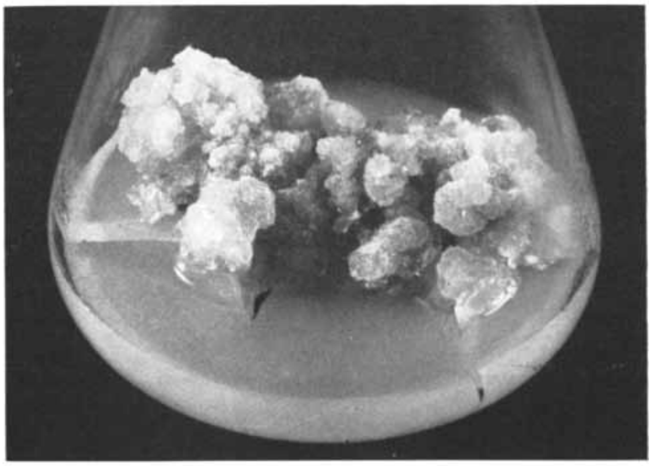
by Armin C. Braun

It is fashionable today to attempt to explain the abnormal growth characteristics of a tumor cell on the basis of the chemistry of the cell's genetic material: the nucleic acids. This seems reasonable because there can now be little doubt that the cellular change that gives rise to tumor cells is inheritable. Tumor cells, on dividing, produce tumor cells like themselves, and rarely do the descendants change back to normal cells. An interpretation of the nature of the inheritable cellular change that is often favored is that the malignant transformation involves a permanent alteration of the cell's genetic makeup—specifically of its deoxyribonucleic acid (DNA). Such changes in the DNA, which are known as mutations, could result from either the loss or the permanent rearrangement of some of the genetic material present in a cell. They could also result from the addition and integration of new genetic material into the cell's genome, or set of genes. There appears, nevertheless, to be another possible explanation to account for the abnormal growth behavior of a tumor cell. The inheritable cellular change that leads to abnormal growth may lie not in any alteration of the information carried by the genes but in an altered *expression* of their information.

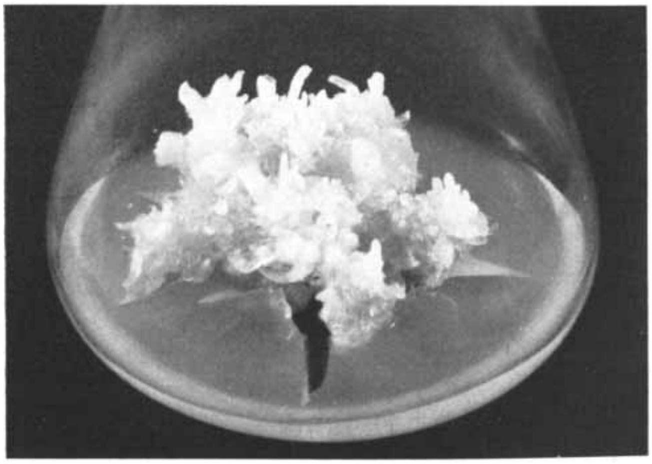
It is well known that in its ordinary chemical activities the normal, differentiated cell uses only part of its genetic information. Perhaps 10 to 20 percent of its genes are active at any one time; the rest are repressed and hence nonfunctional. It is also known that by changing the environment in which cells are grown an experimenter can sometimes repress certain genes and activate others. This results in new patterns of synthesis in a cell and may lead to striking differences in the behavior of a cell. It may be, therefore, that in some tumor cells the malignant pattern of behavior results from the fact that certain genes are activated and certain others are repressed.

There is an obvious test for this concept. Can a tumor cell be transformed back to the normal state, in which it exhibits normal behavior, by manipulating the conditions under which it is grown? It turns out that this can indeed be accomplished with certain types of tumor cell. They are called "multipotential" cells, because they are capable through intracellular regenerations of giving rise to a wide variety of different cell types. The most spectacular experiment has been achieved with tumor cells from certain plants; in this experiment an entire plant, consisting of fully differentiated cells and tissues, has been grown from a single multipotential tumor cell!

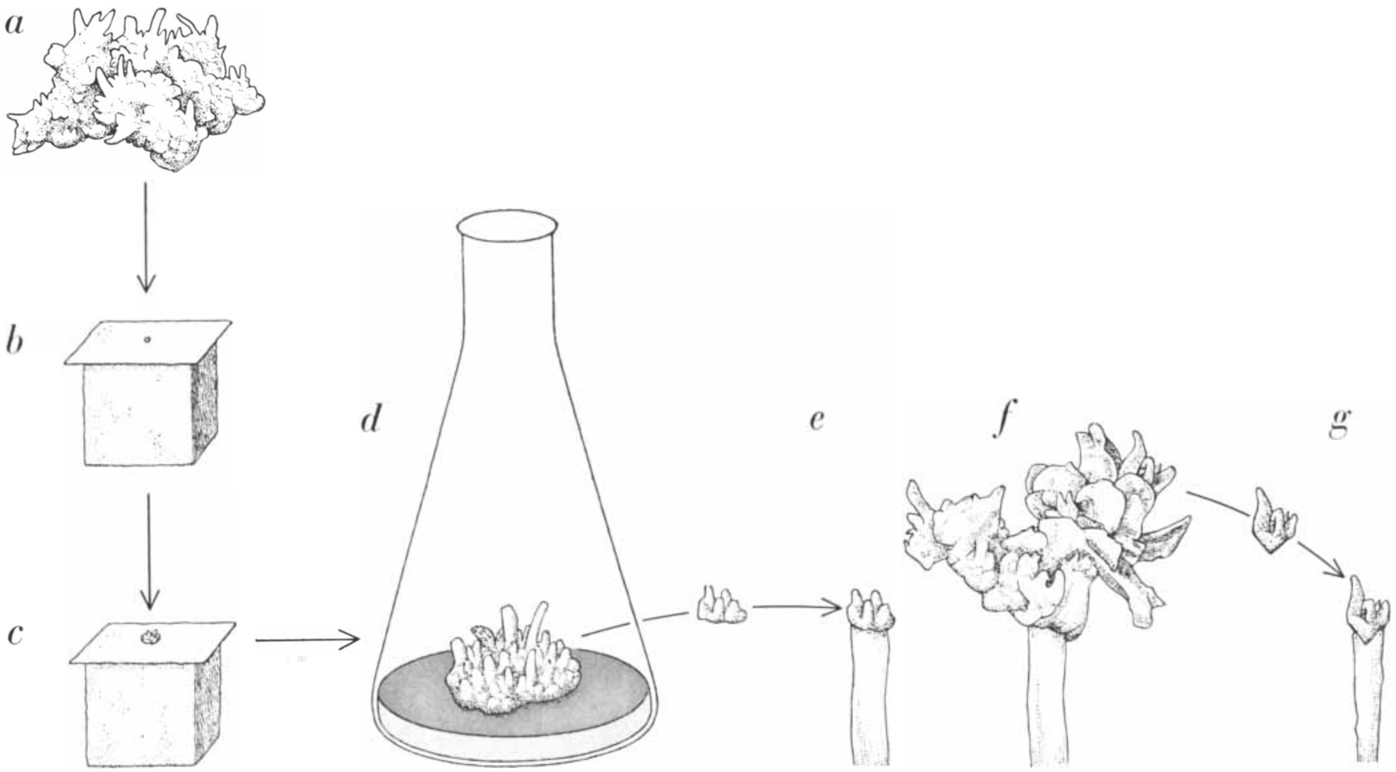
I shall discuss four examples of multipotential tumor cells—two from plants



CROWN GALL TUMOR cut from a tobacco plant continues its profuse growth in a laboratory flask, nourished by a basic culture medium solidified with agar. The crown gall disease begins when a wounded plant is infected by a bacterium; the tumor cells will then flourish even if the parent plant and bacterium are removed.



SLOWER-GROWING TUMOR, although abnormal, still retains a significant remnant of the normal plant's capacity to form differentiated tissues in that it can form tissues that resemble leaves and buds. Called a teratoma, such a growth can be forced into changing from abnormal to normal (*see illustration on next two pages*).



REVERSAL PROCESS is demonstrated in this sequence of drawings. First, a tobacco teratoma (*a*) provides a single tumor cell that is moved to filter paper resting on "nurse" tissue (*b*). The cell multiplies (*c*); it is moved (*d*) to a basic culture medium in a flask, where it grows into an array of abnormal teratoma buds and leaves. One bud is then grafted onto the cut stem of a normal

and two from animals—that have shown this capacity to heal themselves and recover completely from the tumorous state. They are special cases; most other types of cancerous cell have not so far given evidence that they can recover from the tumorous condition and revert to normal cell types. These four cases, however, indicate clearly that at least in some tumors it is possible for the cells to regain the normal state.

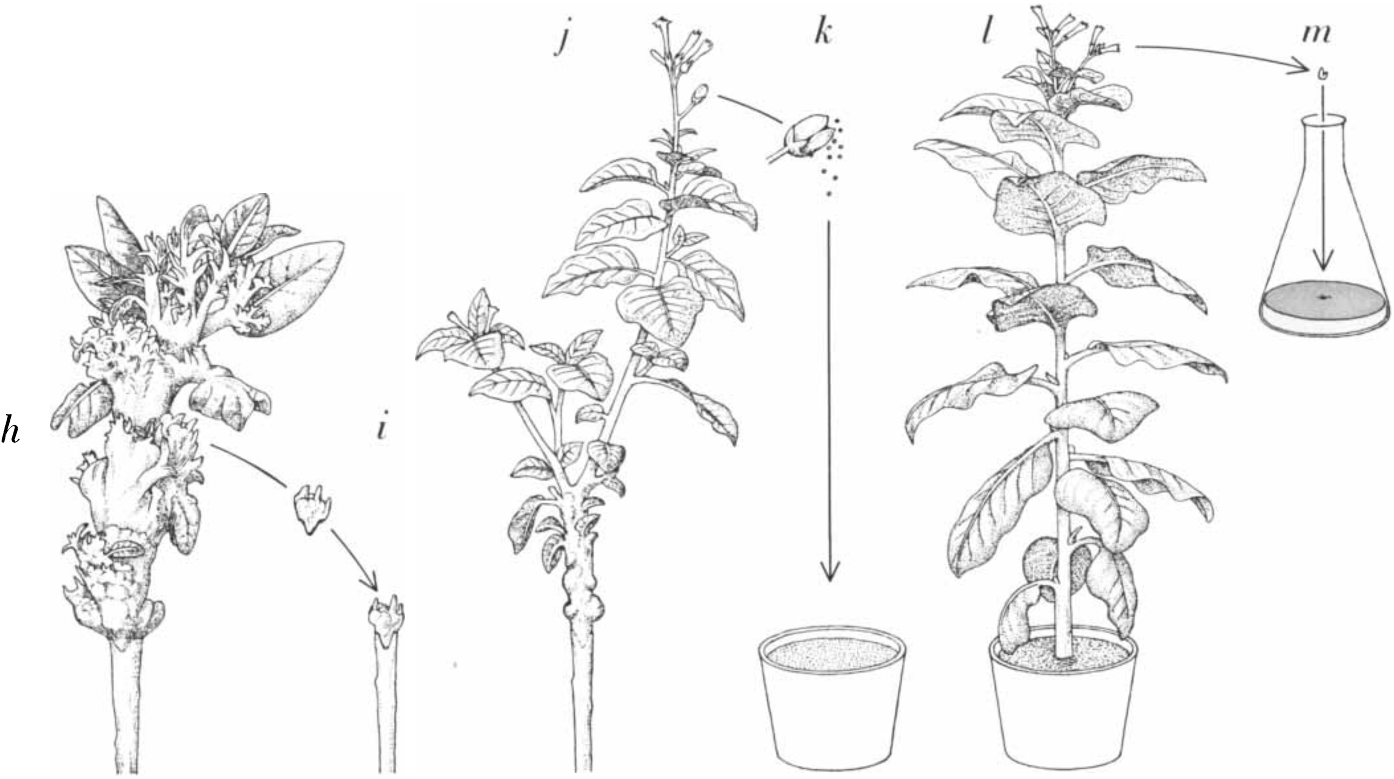
The first example deals with a tumorous disease of plants known as the crown gall disease. This disease has been studied thoroughly and therefore can be described in greater detail than the others [see "Plant Cancer," by Armin C. Braun; SCIENTIFIC AMERICAN, June, 1952]. Let us note to begin with that the cancers of plants are in many respects strikingly similar to those of animals. They can be initiated by many of the same kinds of agents; the transformed cells grow autonomously without control by the host plant; they reproduce true to their tumor type; they lack the structure and functions of normal cells. In short, they show the essential biological characteristics of malignant animal cells.

The crown gall disease is caused by a tumor-inducing principle (TIP) produced by infection of the plant with a certain bacterium. This principle can transform normal cells of the plant into tumor cells within a matter of hours. Once transformed, the changed cells will proliferate of their own accord, independently of the growth-restraining influences of the plant or the bacterium that originally gave rise to them. Cells taken from a crown gall tumor in which all bacteria have been killed will grow profusely and indefinitely on a simple culture medium on which normal cells cannot grow at all. A small fragment of crown gall tissue completely free of bacteria will grow into a typical tumor when it is transplanted from the culture or the diseased plant into a healthy plant of the same kind. These studies show that the cells transformed to the tumorous state have undergone a profound and inheritable change.

The way the change comes about does not, however, suggest a sudden genetic mutation; rather, it seems more consistent with the assumption that some alteration in the cell that affects the activity of the genes has occurred. Studies show that the change to the tumorous state varies in degree and that it depends on the physiological state of the cell at the time that the transformation of a normal cell to a tumor cell takes place. The mere presence of the bacterium and the tumor-inducing principle will not transform normal cells unless the plant has been conditioned—that is, made susceptible—by means of a wound inflicted on its tissues. In other words, the principle takes effect only if the cells have been subjected to the irritation accompanying a wound.

Moreover, the effect is not a one-step process but takes place gradually and progressively over a period of about three days. Cells transformed to the tumorous state about 34 hours after the wound has been inflicted on the plant are benign and grow only slowly. If the transformation takes place about 50 hours after the wound, the tumor cells grow somewhat faster. In contrast, cells that are transformed in the period between 60 and 72 hours after wounding grow very rapidly and are fully autonomous. Detailed examination has disclosed that this drastic transformation occurs if the change is induced at the stage in the wound-healing cycle just before the normal plant cells begin to divide most actively in the process of repairing the wound.

The degree of transformation is transmitted to the offspring of the changed cells. Slow-growing tumor cells have



tobacco plant (*e*) and allowed to develop (*f*). A bud from this less abnormal growth is grafted to a second normal plant (*g*) and allowed to develop again (*h*). When a bud from this second plant is grafted onto a third host (*i*), the new growth gradually becomes normal; it flowers (*j*) and sets seed (*k*). A plant raised from this seed (*l*) is completely normal; its cells will not grow on the medium (*m*).

slow-growing descendants; moderately fast-growing cells reproduce their own kind, and fully malignant, autonomous cells give rise to fast-growing tumors. Here, then, is a case of transformation of cells to three different degrees of the tumorous condition, with the degree of change controllable at will.

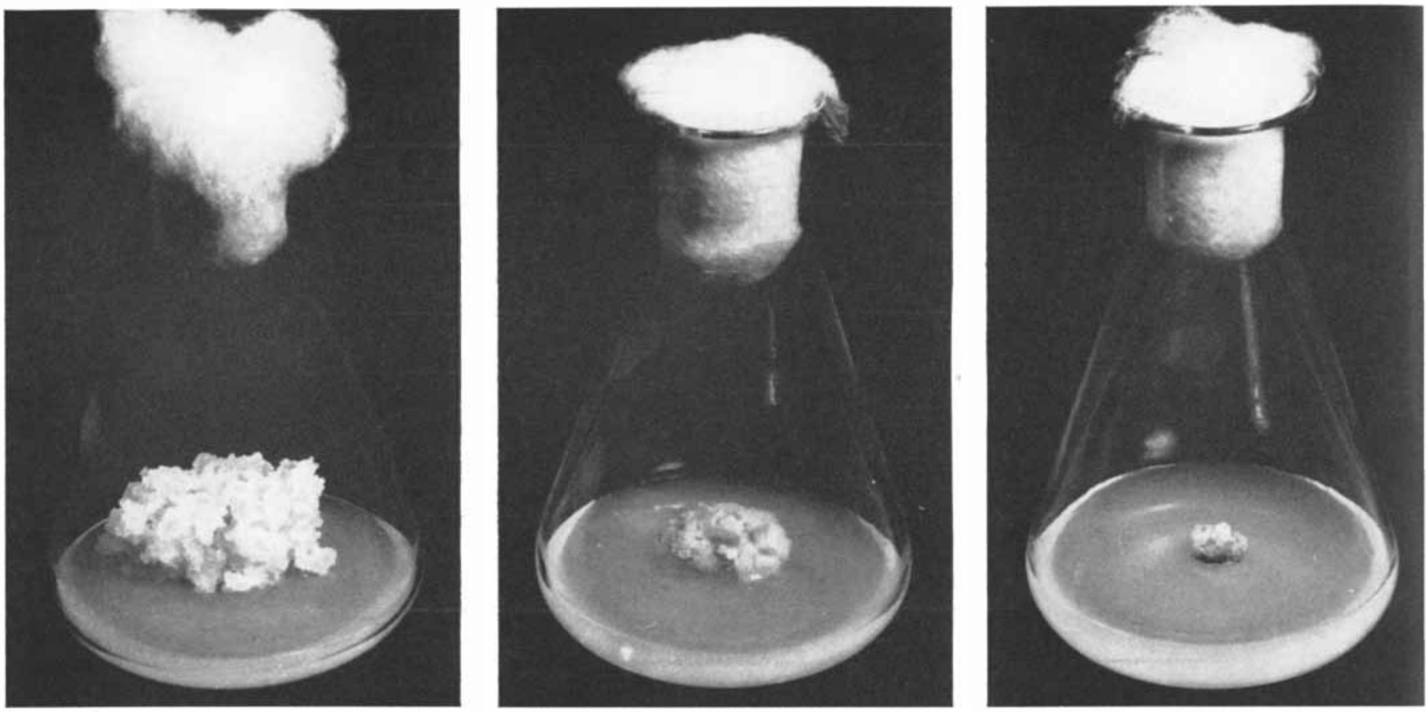
What cellular factors might be responsible for bringing about such alterations in behavior? To find the answer to that question we must look to the factors that regulate the normal growth and development of cells. These factors, in general, are hormones. In plants the hormones that regulate cell growth and division are of two kinds: the auxins, which control the cell's growth in size, and the cytokinins, which act together with the auxins to trigger cell division. Because of the fundamental role these two hormones play in regulating cell growth and cell division it is likely that they play a central role in establishing the abnormal pattern of growth that is characteristic of plant tumor cells.

Experimental studies have now clearly demonstrated that tumor cells do, in fact, produce these hormones. Mature, differentiated plant cells do not, but when they are transformed into the tumor cells of the crown gall disease, they manufacture both hormones in copious quantities. This production not only can account in large part for their abnormal growth but also throws light on a specific difference between the normal cell and a tumor cell. A comparison of the three types of tumor cell I have described above—slow-growing, moderately fast-growing and rapidly growing—provides a clue to this difference.

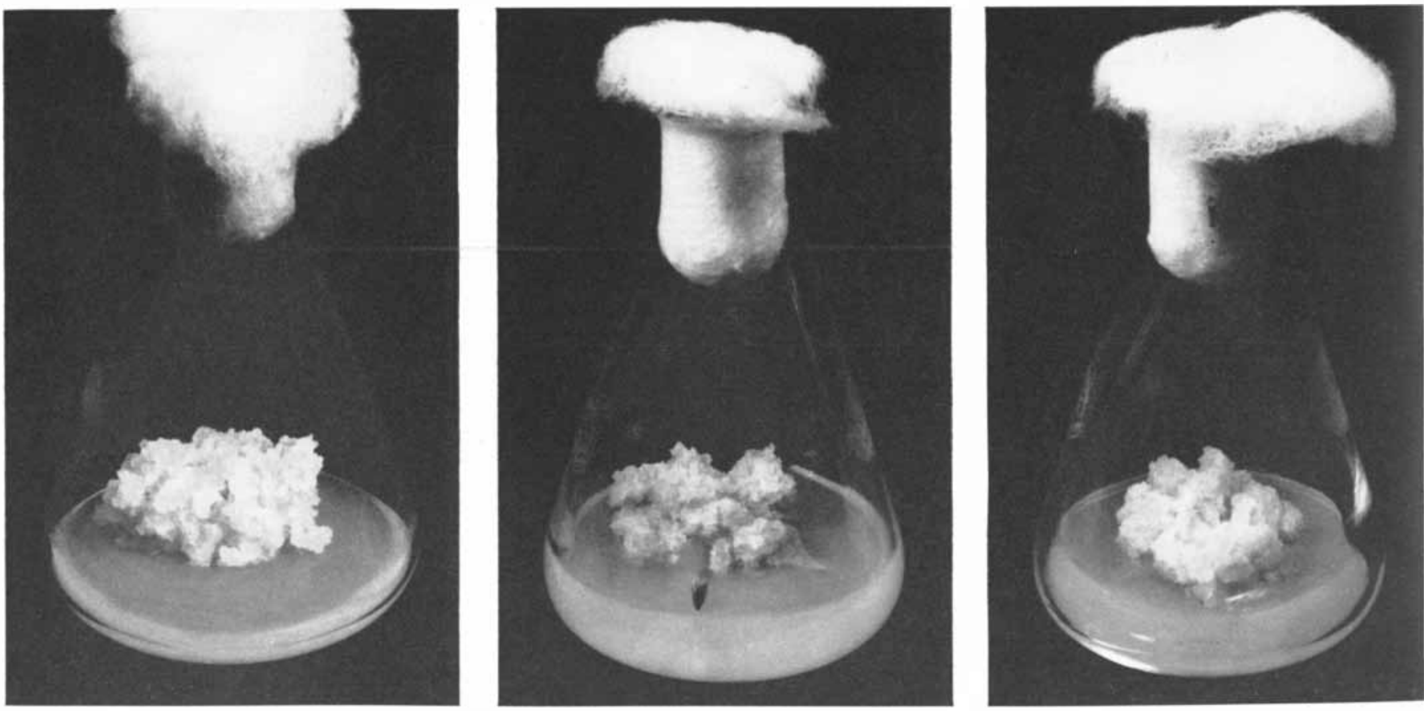
Tumor cells of the type that grow very rapidly can synthesize all the hormones and other essential growth factors they need for their continued rapid growth from a minimal culture medium consisting only of mineral salts, sugar and three vitamins. They are therefore fully autonomous. The moderately fast-growing tumor cells can also produce all those essential substances but not in amounts required for their rapid growth. The growth of such cells can be speeded up to the high rate of the fully transformed cells by adding the hormone auxin, plus glutamine (an amino acid) and inositol (a component of the *B*-vitamin complex), to the basic culture medium. The very slow-growing tumor cells, in turn, can be boosted to the same growth rate by adding to the medium not only these three substances but also aspartic acid (an amino acid) and cytidylic and guanylic acids (building blocks for nucleic acid). The difference between the three types of tumor cell is thus a quantitative matter. All three can grow continuously, although at different rates, on the basic culture medium, and the slower two can be speeded up to the maximum rate by being supplied with certain additional ingredients.

Normal cells, on the other hand, cannot grow at all on the basic medium. This represents a qualitative difference between them and the tumor cells. Indeed, the difference can be pinpointed more specifically. Like the slow-growing tumor cell, a normal cell can be forced into rapid growth on a culture medium supplemented with the ingredients necessary for the rapid growth of the slowest-growing types of tumor cell. In addition, however, the normal cells must be supplied with one added ingredient the tumor cells do not require: cytokinin, the hormone that triggers cell division. The normal differentiated cell does not synthesize the hormone. All three types of tumor cell do produce it, and this distinction sets them apart from the normal cell.

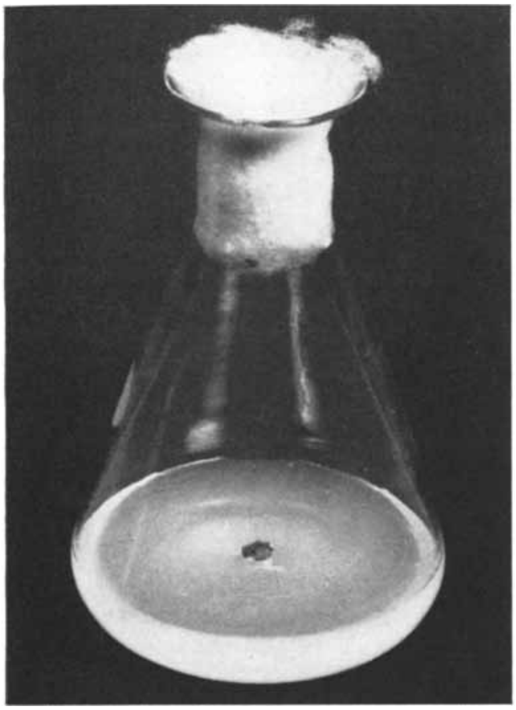
The experiments indicate, then, that the transformation from the normal cell to the fully autonomous tumor cell entails a series of changes in metabolism. In the normal cell the systems that synthesize the factors required for growth and division of the cell are inactive; in the tumor cell all these systems are activated, and the degree of activation of these systems in a tumor cell determines the rate at which the tumor cell will grow. The substances that must be supplied to normal cells to stimulate their growth in a culture are just those specifically required by dividing cells, that is, the basic materials for making nucleic acids, certain special proteins involved in cell division and certain structures needed by the new cells, including membranes (for which inositol is required). The fully autonomous tumor cell, released from the restraints that regulate metabolism in the normal cell, becomes capable of synthesizing all these substances from simple food elements. In other words,



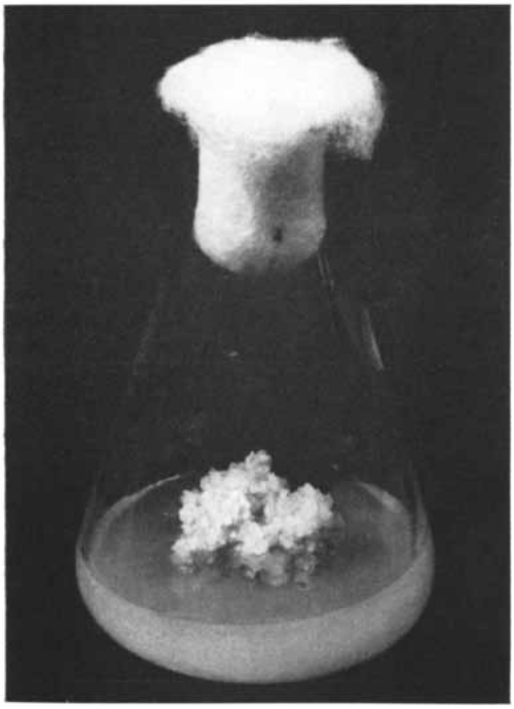
VARYING GROWTH RATES among tumor cells demonstrate their various abilities to synthesize hormones and other essential substances from basic nutrients. A fully malignant tumor (*first*) grows best, a moderate one (*second*) less rapidly and a weak tumor (*third*)



IDENTICAL GROWTH RATES are achieved by adding nutrients. None are needed by the malignant tumor (*first*). Growth of the moderate tumor (*second*) has been speeded by adding auxin, an amino acid and a *B*-vitamin component. The weak tumor (*third*) requires in the tumor cell a new pattern of synthesis is turned on. In this turning on the preliminary wounding and irritation of the cells play a crucial role. Once normal plant cells have been subjected to that triggering irritation they can be transformed into tumor cells not only by the tumor-inducing principle of bacteria but also by various other tumorigenic agents.



even less than that. A clump of normal cells (*fourth*) shows no signs of growth at all.



six extra nutrients; the normal plant cells (*fourth*) need six and hormone cytokinin.

The fully transformed crown gall tumor cell gives every sign of being permanently changed in character. In our laboratory at the Rockefeller Institute (now Rockefeller University) we have been growing such cells for more than 10 years without their showing the slightest tendency to revert to the properties or behavior of a normal plant cell. If, however, the multipotential cells of certain plant species are transformed only to a moderate degree, the tumor cells retain a significant remnant of normal behavior. These cells do not produce the characteristic unorganized crown gall tumor in a plant; instead they form a growth consisting of a chaotic mixture of partly developed plant tissues and organs. This type of growth, called a teratoma, shows some organization, but it is of an abnormal kind. The cells are clearly tumorous: they will grow profusely and indefinitely on a simple culture medium that does not support the growth of normal cells. Yet they retain in the culture a pronounced capacity for forming organized structures recognizable as leaves and buds, although these are highly abnormal. The tissues are not a mixture of normal and tumorous cells; we were able to demonstrate that they are composed only of tumor cells by growing teratoma tissue from single multipotential tumor cells.

Suppose the abnormal tumor buds in such tissue were grafted to a normal plant. Might they, by being forced into rapid and organized growth, develop into normal shoots? If the tumor cells were actually mutants, irreversibly altered by mutations of their genes, such an outcome would be highly improbable. If, however, the cells' abnormal behavior was merely the result of a change in the expression of the genes' activity, perhaps the experiment might bring about a recovery of the cells.

The experiments to explore this hypothesis began with the grafting of fragments of teratoma tissue, grown from single cells, to the tips of the cut stems of tobacco plants. The teratoma tissues grew rapidly and organized highly abnormal leaves and buds. Tumor buds were removed and grafted to the cut stem tips of tobacco plants; the grafted buds grew slowly into highly abnormal shoots. Cells taken from all parts of these shoots grew well on a simple artificial medium, indicating that they were still tumorous. On the tobacco plant the abnormal shoots were allowed to grow to a length of four to six inches; then their tips were removed and grafted to another plant. This time the shoots grew somewhat more rapidly and were closer to normal in appearance. When this procedure was pursued a third time, the grafted tip usually grew into a normal shoot. It flowered and set fertile seed, which when planted gave rise to normal tobacco plants.

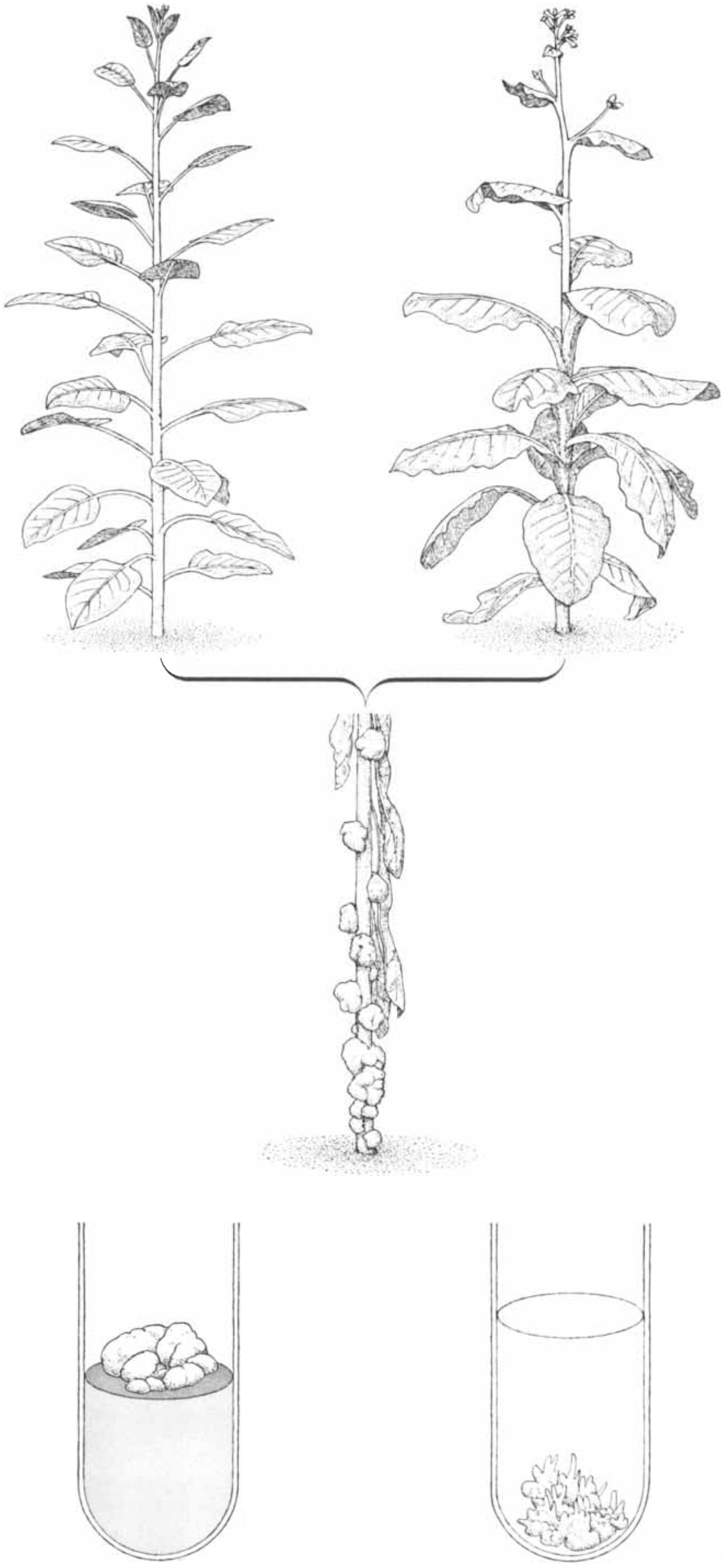
The transformed tumor cells had made a complete recovery. The recovery, and the gradual process by which it took place, seem to rule out any likelihood that the change to the tumorous state was the result of mutation at the level of genes in the cell nucleus. The evidence suggests rather that there was only a change in the expression of the cells' genetic potentialities. In their tumorous condition the crown gall tumor cells retained all the factors, genetic and nongenetic, that had been present in the normal state; nothing was lost or permanently rearranged. The cells were made tumorous simply by activation of some of the ordinarily inactive genes; the cells returned to the normal state when those genes were again repressed and rendered nonfunctional.

The second example I shall cite, but discuss only briefly, has to do with a tumor disease of plants that is inborn, not induced by an outside agent. Hybrid plants grown from a cross of two tobacco species (*Nicotiana glauca* and *Nicotiana langsdorffii*) invariably develop many tumors after they have reached maturity. The tumor cells of these plants confirm their tumorous state by the classic test: by their ability to grow profusely on a simple medium that will not support the growth of normal cells and by the fact that they can be successfully transplanted. Some years ago Philip R. White (now at the Jackson Memorial Laboratory in Bar Harbor, Me.) found evidence that these cells could be switched back to organized growth simply by changing the physical environment in which they were cultured. When they were grown on a medium solidified by agar, they developed in the unorganized way typical of tumor cells; when, on the other hand, they were immersed in the same medium in the liquid state, the cells formed organized tissues possessing the normal appearance of leaves and shoots. White believed at the time that their recovery from the tumorous state was due to the reduced amount of oxygen in their submerged growing environment. Studies by Folke Skoog and his colleagues at the University of

Wisconsin later showed, however, that the difference between the normal and the tumorous cells lay largely in their relative production of the auxin and cytokinin hormones. A high ratio of auxin to cytokinin in the cells led to unorganized growth; the reverse, to organized growth. Apparently the environmental conditions affect the growth patterns of the tissues' proportionate production of the two hormones.

Let us now consider two examples in the animal world showing that the recovery of cells from the tumorous condition is not by any means confined to plant life. A few years ago two Austrian investigators, Friedrich Seilern-Aspang and K. Kratochwil, reported remarkable findings in studies of the newt, an animal well known for its ability to regenerate injured or lost tissues. They injected methylcholanthrene and other cancer-producing substances under the skin of the experimental animals; the animals rapidly developed massive malignant growths that infiltrated and destroyed normal tissues and metastasized freely to other parts. Many of the newts died from the complications. In many instances, however, after the tumor had grown to a large size its cells stopped dividing and reverted to perfectly normal, differentiated cells; the animals then recovered completely from the disease. The Austrian investigators found that they could demonstrate such recovery most readily by inducing the tumor at a site close to the base of the tail and removing part of the tail to stimulate the regenerative processes in the animal.

It can be argued that the newt, like a plant, is a rather low form of life and therefore gives little indication of what may happen in higher animals. Very recently, however, the journal *Cancer Research* reported a striking case of similar recovery in a mammal. In this

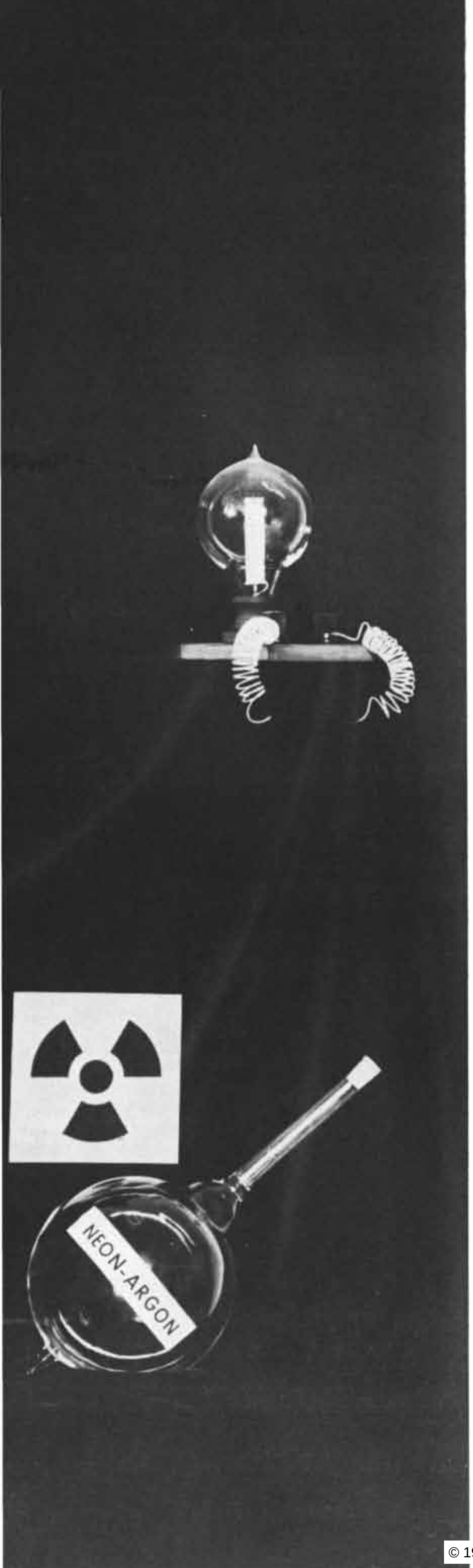


INNATE TUMOR DISEASE arises when the tobacco species *Nicotiana glauca* (*top left in illustration at left*) is crossbred with *Nicotiana langsdorffii* (*top right*). As the hybrid offspring matures (*center*) the abnormal growths develop spontaneously. A cell from such a tumor, placed on a culture medium solidified with agar, multiplies in typically unorganized fashion (*bottom left*). If the cell is placed in a liquid medium (*bottom right*), however, its growth shows organization. This is because cells on a solid medium synthesize more growth-promoting auxin than cytokinin, which promotes cell division; in the case of cells growing in the liquid medium, the ratio is reversed.

instance, reported by Lewis J. Kleinsmith and G. Barry Pierce, Jr., of the University of Michigan, the experimental animal was the mouse and the growth involved was a highly malignant teratocarcinoma (a type of tumor that occurs in man as well as in the mouse). Typically the growth contains cells of bone, cartilage, nerve tissue, tooth buds, hair follicles and many other well-differentiated cell types. The differentiated cells are mixed in a completely disorganized array in the tumor, and interspersed among them are many embryonal cancer cells. During serial transfer of such a tumor from mouse to mouse the broad spectrum of cell types is reproduced indefinitely.

Kleinsmith and Pierce were interested in the origin of this great variety of different cells in the tumor. Did the various types of cell arise and proliferate independently or did they perhaps come from a common precursor or stem cell? To test the latter hypothesis the investigators implanted single embryonal cancer cells in the peritoneal cavities of mice. They found that these single cancer cells developed into malignant tumors that killed the animals in two to three weeks. The tumors consisted, however, of the typical mixture of different cell types. That is to say, the single cancer cells had given rise not only to embryonal cancer cells like themselves but also to as many as 14 well-differentiated cell types that were completely benign. These studies clearly show, then, that a cancer cell in a mammal can produce benign, or normal, offspring. Moreover, it also seems likely from earlier studies in Pierce's laboratory that embryonal cancer cells themselves may often develop into benign, differentiated cells. In other words, they are multipotential cells, highly malignant in the undifferentiated state but capable of giving rise to cells of various types that have lost their malignant properties.

We are thus confronted with the basic question: Why is it that multipotential cells recover from the cancerous state whereas other tumor cells do not? The answer to that question would appear to rest in the fact that multipotential cells are endowed with broad morphogenetic, or regenerative, capacities. Such cell types can very effectively remodel metabolic patterns, as is clearly evident from the results described in this article. The apparent irreversibility of the tumorous state in the great majority of instances may simply reflect an inability of most differentiated body cells to undergo intracellular regenera-



One of a series briefly describing GM's research in depth

A Noble Approach to an Old Problem

Edison was first.

He converted heat to electricity in a vacuum tube back in '83. But there was a barrier. We're knocking it down.

In a gas-filled thermionic tube, electrons can be boiled off of an emitter and directed to a collector, giving current flow. But only briefly. Then a cloud of electrons forms in the path . . . a space charge inhibiting further flow.

One way to get rid of this barrier is to neutralize it with positive ions, charged atoms of some gas. Many experimenters use vaporized cesium. But its atoms impede electron flow, requiring close interelectrode spacing. So GM Research physicists chose some of the noble gases—argon, neon, and xenon. They offer less impedance.

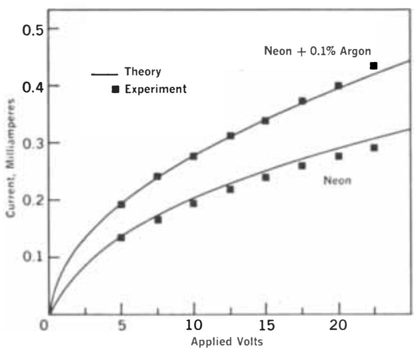
Our experimental emitter is a mixture of fissionable material and good electron-emitting material. Exposed to a neutron barrage in a reactor, the emitter gets hot from its own nuclear fission, sending electrons toward the collector. This same fission produces fragments that bombard the noble gas, generating ions to counteract the space charge.

We have developed a theory to predict the ion generation rate and have experimental data that backs it up. We think we understand why and how things happen.

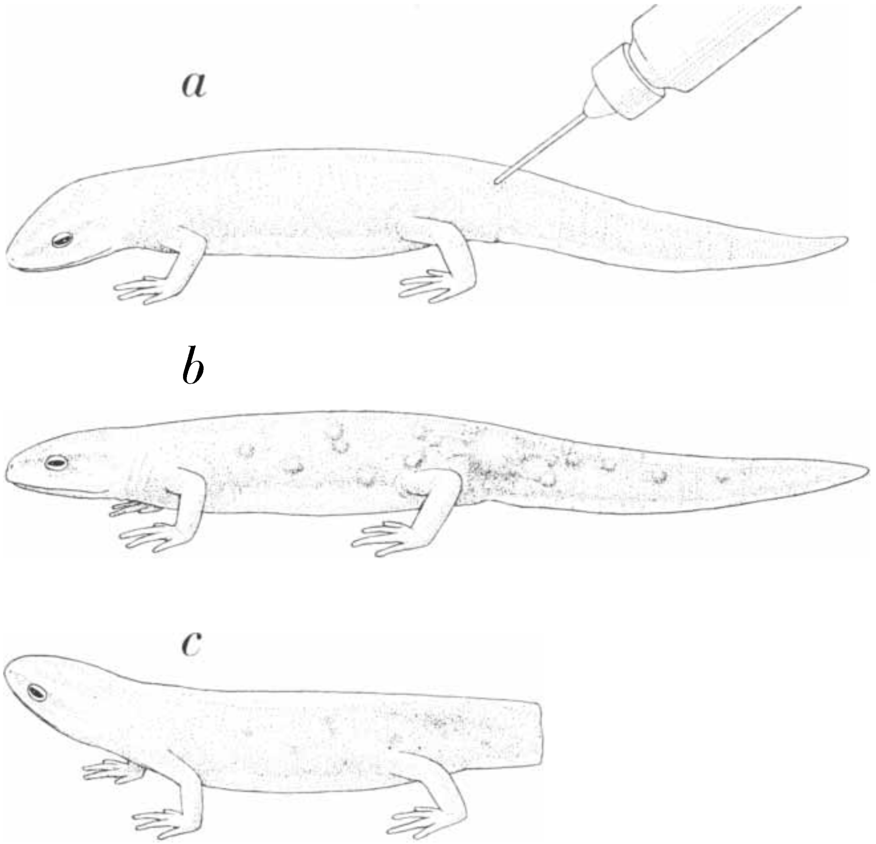
General Motors is in the energy conversion business. The direct conversion of heat to electricity, with a device having no moving parts, interests us.

General Motors Research Laboratories

Warren, Michigan



Characteristics of tubes filled with gases ionized by fission fragments. Resulting current is a function of ion generation rate, which is increased greatly (from 1.8 to 2.6 x 10^{16} ions per cm^3 per sec) by small addition of argon.



REVERSAL OF MALIGNANCY in the case of a newt that has been injected with cancer-producing compounds (*a*) is a frequent occurrence even after the tumors have grown to a considerable size (*b*). The rate of recovery is markedly enhanced when the site of the malignancy is near the base of the tail the newt is regenerating after removal (*c*).

tions of the kind that are characteristic of a multipotential cell.

It is likely that in some instances the malignant properties of tumor cells can be attributed to alterations of the genetic material itself. A well-documented example of this is found in chronic myelocytic leukemia, a disease of humans, where the loss of part of one of the chromosomes, the so-called Philadelphia chromosome, is correlated with the abnormal growth behavior of the cell. In cases such as this the transformed cell is rendered permanently incapable of recovering the normal pattern of chemical synthesis and regulation. It is nevertheless quite conceivable that if one understood the function in cellular metabolism of the genes that had been lost from the cell in chronic myelocytic leukemia, it would be possible to cause those cells to behave as normal cell types do by continually supplying them with the metabolic products normally produced by the activity of those genes. Such cells might, moreover, be permanently converted into normal cell types by reintroducing in the proper form and place the genetic information the cells have lost.

Although the basic mechanism for tumorous growth in the case of chronic myelocytic leukemia is different from that found in the examples given earlier, the end result is the same; in all instances the genetic information required for continued production of the nucleic acids, the specialized proteins and other substances that are specifically needed for continued cell growth and division is functional in the tumor cells.

It appears, therefore, that a long step forward in understanding the tumor problem may be achieved by discovering how the genes in a cell are selectively turned on and off. This is a very fundamental problem, certain aspects of which are now just beginning to be understood. It offers the attractive possibility that we may one day learn, as the multipotential cell has learned, how to switch the pattern of synthesis in a cell from one that makes it grow as a malignant cell to the pattern that will restore it to normal behavior.

PLASTICITY IN SENSORY-MOTOR SYSTEMS

An animal's own movements change what it sees and hears. Laboratory experiments that tamper with this feedback loop show that it is a key to developing and maintaining spatial orientation in advanced mammals

by Richard Held

Anyone who has worn eyeglasses is likely to have experienced distorted vision the first time he put them on. The distortion may have been severe enough to cause him trouble in motor coordination, as in reaching out to touch something or in being sure of where he stepped. Such a person will also recall, however, that in a day or two the distortion disappeared. Evidently his central nervous system had made some adjustment so that the things he saw through the glasses looked normal again and he could have renewed confidence in his touch and step.

This process of adjustment, particularly as it operates in recovery from radical transformations of vision (as when the world is made to appear upside down or greatly shifted to one side by special goggles), has attracted the attention of scientists at least since the time of the great 19th-century investigator Hermann von Helmholtz. What has intrigued us all is the finding that correct perception of space and accurate visually guided action in space are in the long run not dependent on unique and permanently fixed optical properties of the paths taken by light rays traveling from object to eye. This finding, however, must be squared with the normally high order of precision in spatial vision and its stability over a period of time. How can the visual control of spatially coordinated action be stable under normal circumstances and yet sufficiently modifiable to allow recovery from transformation? Recovery takes time and renewed contact with the environment. Adaptation must result from information drawn from this contact with the environment. If the end product of adaptation is recovery of the former stability of perception, then the information on which that recovery is based must be as reliable and unvarying as its end product. The investigations my colleagues and I have undertaken (first at Brandeis University and more recently at the Massachusetts Institute of Technology) have been directed toward discovering this source of information and elucidating the mechanism of its use by the perceiving organism. A useful tool in our work has been deliberate distortion of visual and auditory signals, a technique we call rearrangement.

Visual rearrangement can be produced experimentally with prisms [see "Experiments with Goggles," by Ivo Kohler; Scientific American, May, 1962]. Similarly, the apparent direction of sounds can be distorted in the laboratory by suitable apparatus. We have used such devices to show that in many cases the viewer or the listener subjected to these distortions soon adapts to them, provided that during the experiment he has been allowed to make voluntary use of his muscles in a more or less normal way.

The proviso suggests that there is more to the mechanism of perceptual adaptation than a change in the way the sensory parts of the central nervous system process data from the eyes and ears. The muscles and motor parts of the nervous system are evidently involved in the adaptation too—a revelation that has been very important in our efforts to discover the responsible source of information. The concept of a relation between sensory and motor activities in the adaptive process is reinforced by what happens when humans and certain other mammals undergo sensory deprivation through prolonged isolation in monotonous environments, or motor deprivation through prolonged immobilization. Their performance on perceptual and motor tasks declines. By the same token, the young of higher mammals fail to develop normal behavior if they undergo sensory or motor deprivation.

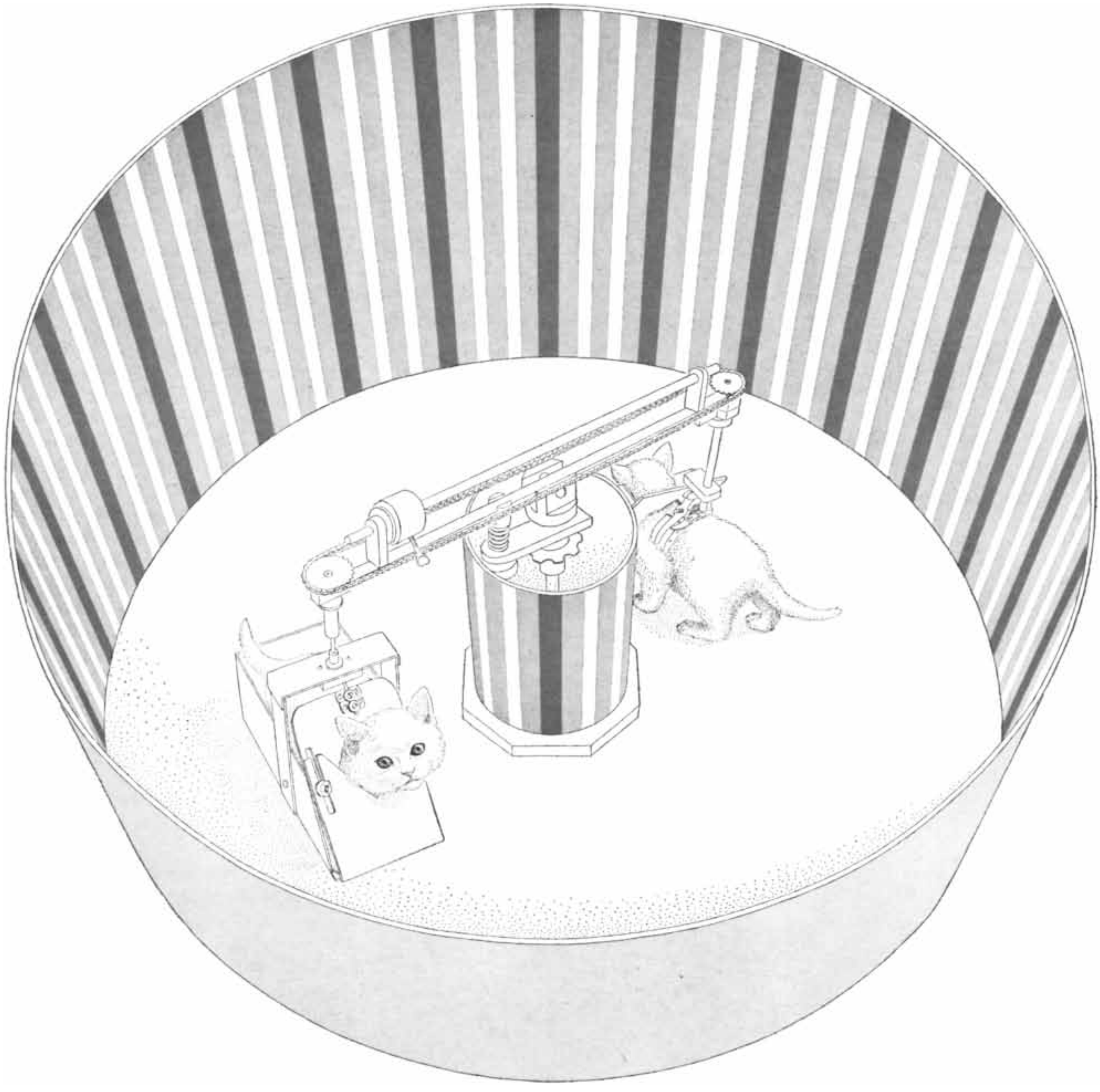
Taken together, these findings by various experimenters suggested to us that a single mechanism is involved in three processes: (1) the development of normal sensory-motor control in the young, (2) the maintenance of that control once it has developed and (3) the adaptation to changes or apparent changes in the data reported by the senses of sight and hearing. A demonstration that such a mechanism exists would be of value in understanding these processes. Moreover, it would help to explain a phenomenon that otherwise could be accounted for only by the existence of enormous amounts of genetically coded information. That phenomenon is the adjustment of the central nervous system to the growth of the body—on the sensory side to the fact that the afferent, or input, signals must change with the increasing separation between the eyes and between the ears, and on the motor side to the fact that the growth of bone and muscle must call for a gradual modification of the efferent, or output, signals required to accomplish a particular movement. This problem is especially critical for animals that grow slowly and have many jointed bones. The possibility that the need for genetically coded information has been reduced by some such mechanism is of course contingent on the assumption that the animal's environment is fairly stable. For these reasons it is not surprising that clear evidence for adaptation to rearrangement and for dependence of the young on environmental contact in developing coordination has been found only in primates and in cats.

Such, in brief, is the background of

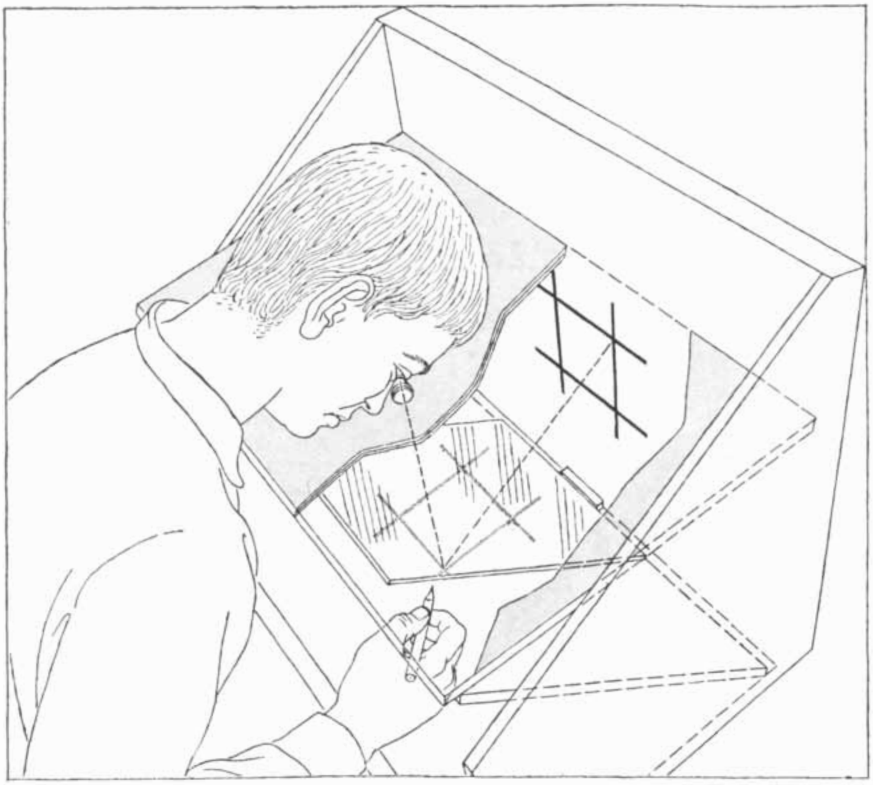
our effort to discover the operating conditions of the suspected mechanism. Our conclusion has been that a key to its operation is the availability of "reafference." This word was coined by the German physiologists Erich von Holst and Horst Mittelstädt to describe neural excitation following sensory stimulation that is systematically dependent on movements initiated by the sensing animal; von Holst and Mittelstädt also used the word "exafference" to describe the result of stimulation that is independent of self-produced movement. "Afference" alone refers to any excitation of afferent nerves. These concepts should become clearer to the reader from the remainder of this article.

Among the contributions von Helmholtz made to science were many that were later incorporated into psychology. His experiments included work on the displacement of visual images by prisms. He was the first to report that the misreaching caused by such a displacement is progressively reduced during repeated efforts and that on removal of the prism the subject who has succeeded in adapting to this displacement will at first misreach in the opposite direction.

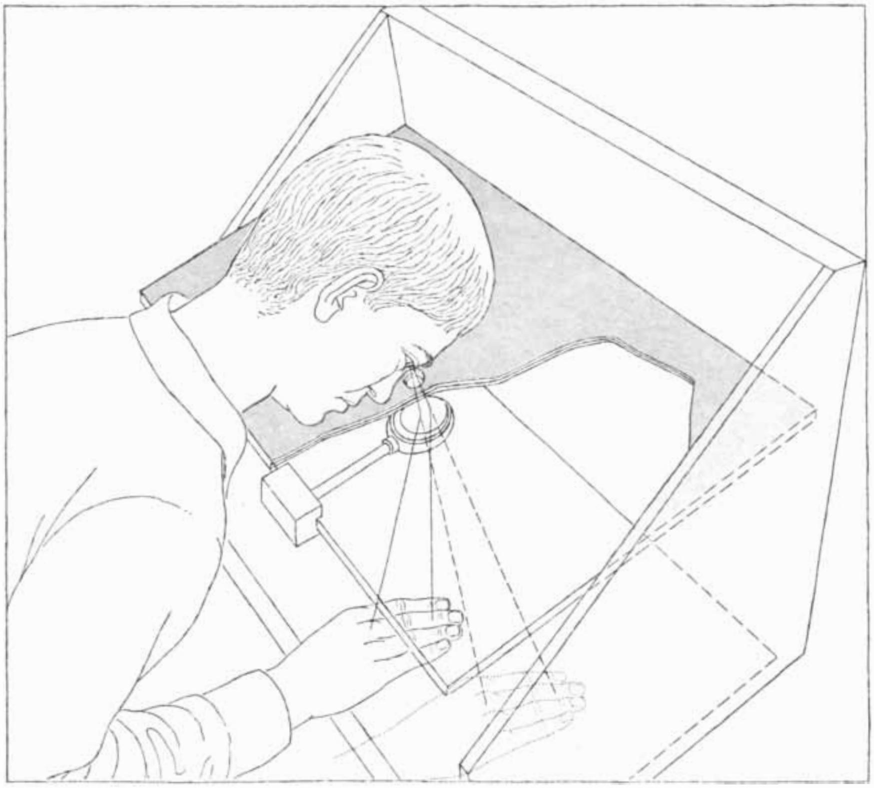
Helmholtz' findings and those of similar experiments by many other workers have often been interpreted as resulting from recognition of error and consequent correction. We doubted this interpretation because of our conviction that a single mechanism underlies both



ACTIVE AND PASSIVE MOVEMENTS of kittens were compared in this apparatus. The active kitten walked about more or less freely; its gross movements were transmitted to the passive kitten by the chain and bar. The passive kitten, carried in a gondola, received essentially the same visual stimulation as the active kitten because of the unvarying pattern on the wall and on the center post. Active kittens developed normal sensory-motor coordination; passive kittens failed to do so until after being freed for several days.



MIRROR APPARATUS tests subject's ability to guide his unseen hand to a visible target. Subject first marks under the mirror the apparent location of the corners of the square as he sees them in the mirror. He then looks through a prism, as depicted in the illustration below, after which he makes more marks. They show his adaptation to the prism effect.



VIEW THROUGH PRISM displaces a visual image. Some subjects looked at their motionless hand, some moved the arm back and forth in a left-right arc, and some had the arm moved passively in a similar arc. They then made marks under the mirror as shown in the illustration at the top of the page. Typical results appear in illustrations on opposite page.

adaptation to rearrangement in the adult and the development of the young. An error-correcting process could hardly explain the original acquisition of coordination. If an infant initially has no sense of the spatial relation between his efforts to move his hand and their visual consequences, he cannot recognize a visible error in reaching. Yet infants do acquire eye-hand coordination in their earliest months. Hence we suspected that error recognition was no more necessary for adaptation in the adult than it was in the development of the infant's coordination. To test this assumption we designed an experiment that prevented the subject from recognizing his error. If he still managed to correct his reach to allow for a displaced image, it would be evident that there was more to the matter of adaptation than the simple fact that the subject could see his error directly.

With this objective in mind we designed the apparatus shown in the top illustration at the left. In this apparatus the subject saw the image of a square target reflected by a mirror and was asked to mark on a piece of paper under the mirror the apparent position of the corners of the square. Because of the mirror, he could see neither the marks nor his hand. After he had marked each point 10 times, withdrawing his hand between markings so that he would have to position it anew each time, the mirror and marking sheet were removed and a prism was substituted. Looking through the prism, the subject then spent several minutes moving his hand in various ways, none of which involved deliberate reaching for a target. Thereafter the original situation was restored and the subject made more marks under the mirror. These marks revealed that each of the subjects was making some correction for the displacement of image that had been caused by the prism.

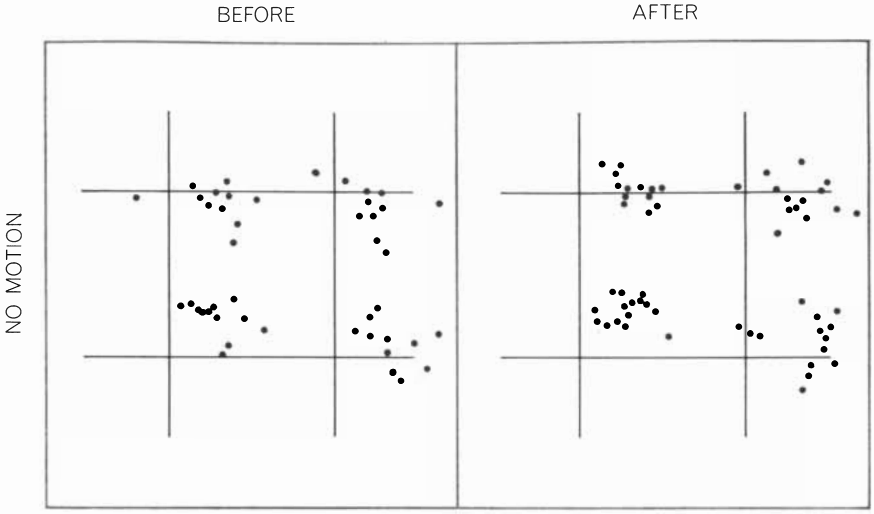
Having thus established that at least partial adaptation can occur in the absence of direct recognition of error, we used the apparatus to test the role of motor-sensory feedback in adaptation. Our main purpose was to see what degree of adaptation would occur under the respective conditions of active and passive movement—in other words, under conditions of reafference and exafference in which the afference was equivalent. In these experiments the subject's writing arm was strapped to a board pivoted at his elbow to allow left and right movement. He then looked at his hand through a prism under three conditions: (1) no movement, (2) active movement, in which he moved the arm back and forth himself, and (3) passive movement, in which he kept his arm limp and it was moved back and forth by the experimenter. In each case he marked the apparent location of points under the mirror before and after looking through the prism.

Comparison of these marks showed that a few minutes of active movement produced substantial compensatory shifts [*see illustrations at right*]. Indeed, many of the subjects showed full adaptation, meaning exact compensation for the displacement caused by the prism, within half an hour. In contrast, the subjects in the condition of passive movement showed no adaptation. Even though the eye received the same information from both active and passive conditions, the evidently crucial connection between motor output and sensory input was lacking in the passive condition. These experiments showed that movement alone, in the absence of the opportunity for recognition of error, does not suffice to produce adaptation; it must be self-produced movement. From the point of view of our approach this kind of movement, with its contingent reafferent stimulation, is the critical factor in compensating for displaced visual images.

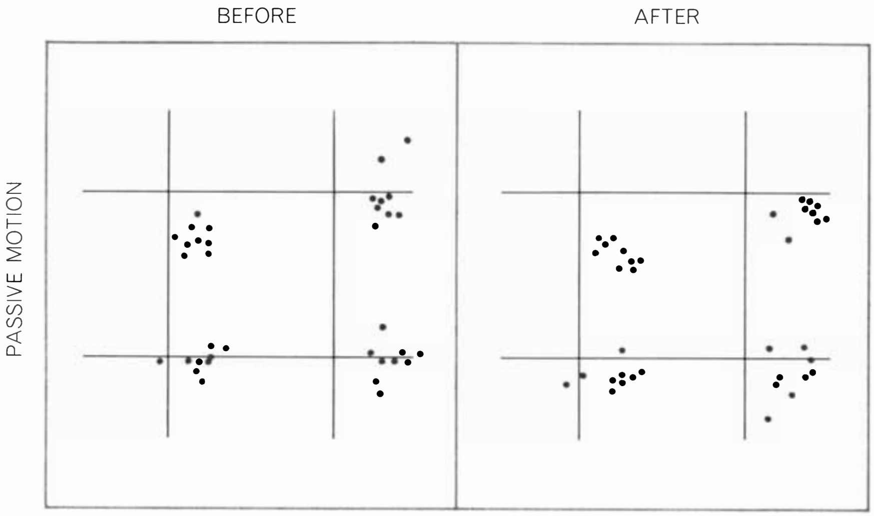
What about an adaptive situation involving movements of the entire body rather than just the arm and hand? We explored this situation in two ways, using an apparatus in which the subject judged the direction of a target only in reference to himself and not to other visible objects [*see top illustration on next page*]. This kind of direction-finding is sometimes called egocentric localization.

The apparatus consisted initially of a drum that could be rotated by the experimenter, after which the subject, sitting in a chair that he could rotate, was asked to position himself so that a target appeared directly in front of him. Later we dispensed with the drum and merely put the subject in a rotatable chair in a small room. After the experimenter had randomly positioned the target, which was a dimly illuminated slit, the subject rotated himself to find the target.

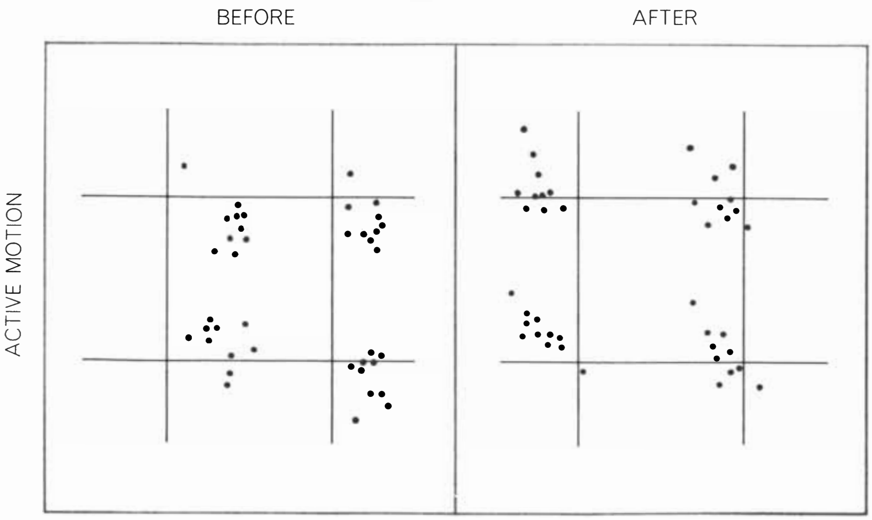
The first of the two ways in which we tested the role of reafferent stimulation involving movement of the whole body was an experiment in adaptation to short-term exposure to prisms. After several trials at locating the target, the subject put on prism goggles. He then



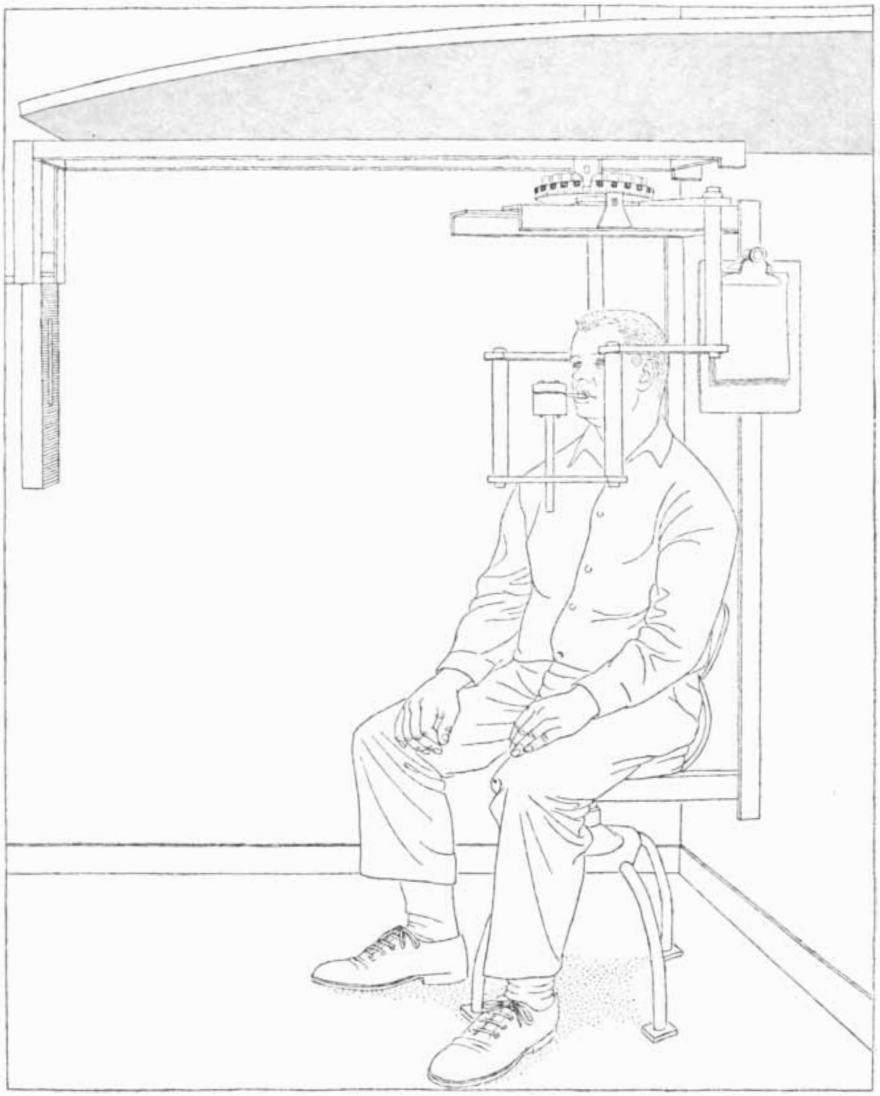
MARKINGS made by a subject before and after looking through a prism as described in illustrations on opposite page are shown. He kept hand still while viewing it through prism.



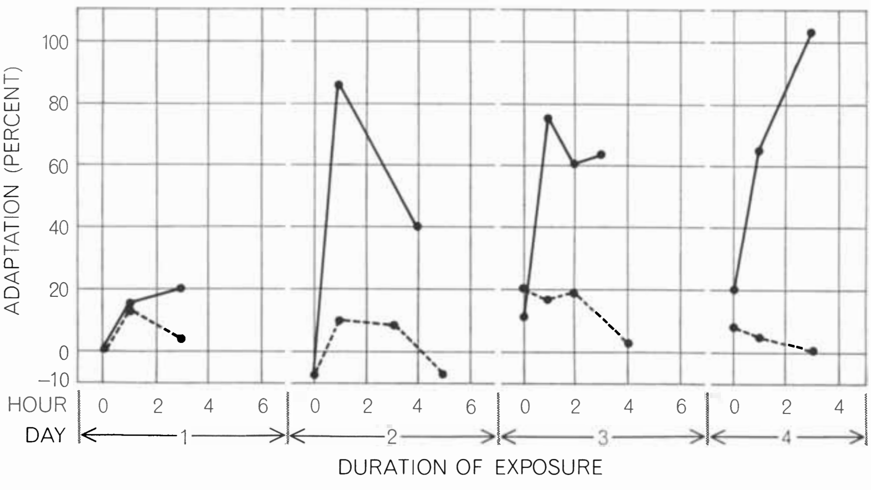
PASSIVE MOVEMENT of subject's hand as he viewed it through prism produced these marks. They show no adaptation to horizontal displacement of images caused by the prism.



ACTIVE MOVEMENT of subject's hand produced a clear adaptation to displacement of images by prism. Tests showed importance of such movement in sensorimotor coordination.



DIRECTION-FINDING by egocentric localization, in which a subject judges the direction of a target only in relation to himself and not to other visual cues, uses this apparatus. Target is randomly positioned at subject's eye level; he then rotates himself so that the target is directly in front of him. He does this before and after wearing prism goggles with which he either walks on an outdoor path or is pushed along the same path in a wheelchair. Change in direction-finding after wearing prisms measures adaptation to the prisms.



PROLONGED EXPOSURE to prisms produced varying degrees of adaptation to them depending on whether a subject's movement was active (*solid lines*) or passive (*broken lines*).

walked for an hour along an outdoor path or sat in a wheelchair that was pushed along the same path for the same length of time. Thereupon he removed the goggles and went back to the target-finding apparatus for more tests. Any error in target-finding after wearing the prism goggles would be a measure of the adaptation the subject had made to the visual displacements produced by the prisms.

Again the degree of adaptation achieved by the subjects who had been involved in active movement was far greater than that of the subjects who had been carried in the wheelchair. This was true both when one subject had been exposed to the active condition and another to the passive and when a single subject had been exposed successively to each condition. Even more striking contrasts appeared in our second test, which involved wearing prisms for several hours at a time under conditions of active and passive movement. In these circumstances several of the subjects who were able to move voluntarily achieved full adaptation, whereas subjects whose movements were passive achieved virtually no adaptation.

In this connection it will be useful to mention an experiment we conducted on directional hearing. The sound emanating from a localized source reaches the listener's nearer ear a fraction of a second sooner than it reaches his farther ear. This small difference in the time of arrival of the sound at the two ears is the first stage in ascertaining the direction from which the sound comes. If, then, a subject's ears could be in effect displaced around the vertical axis of his head by a small angle, he would err by an equivalent angle in his location of the sound. This effect can be produced artificially by a device called the pseudophone, in which microphones substitute for the external ears. Subjects who have worn a pseudophone for several hours in a normally noisy environment show compensatory shifts in locating sounds, provided that they have been able to move voluntarily. In addition they occasionally report that they hear two sources of sound when only one is present. When measurements are made of the two apparent directions of the source, they differ by approximately the angle at which the ears were displaced around the center of the head during the exposure period. I have called the effect diplophonia.

The reports of doubled localization

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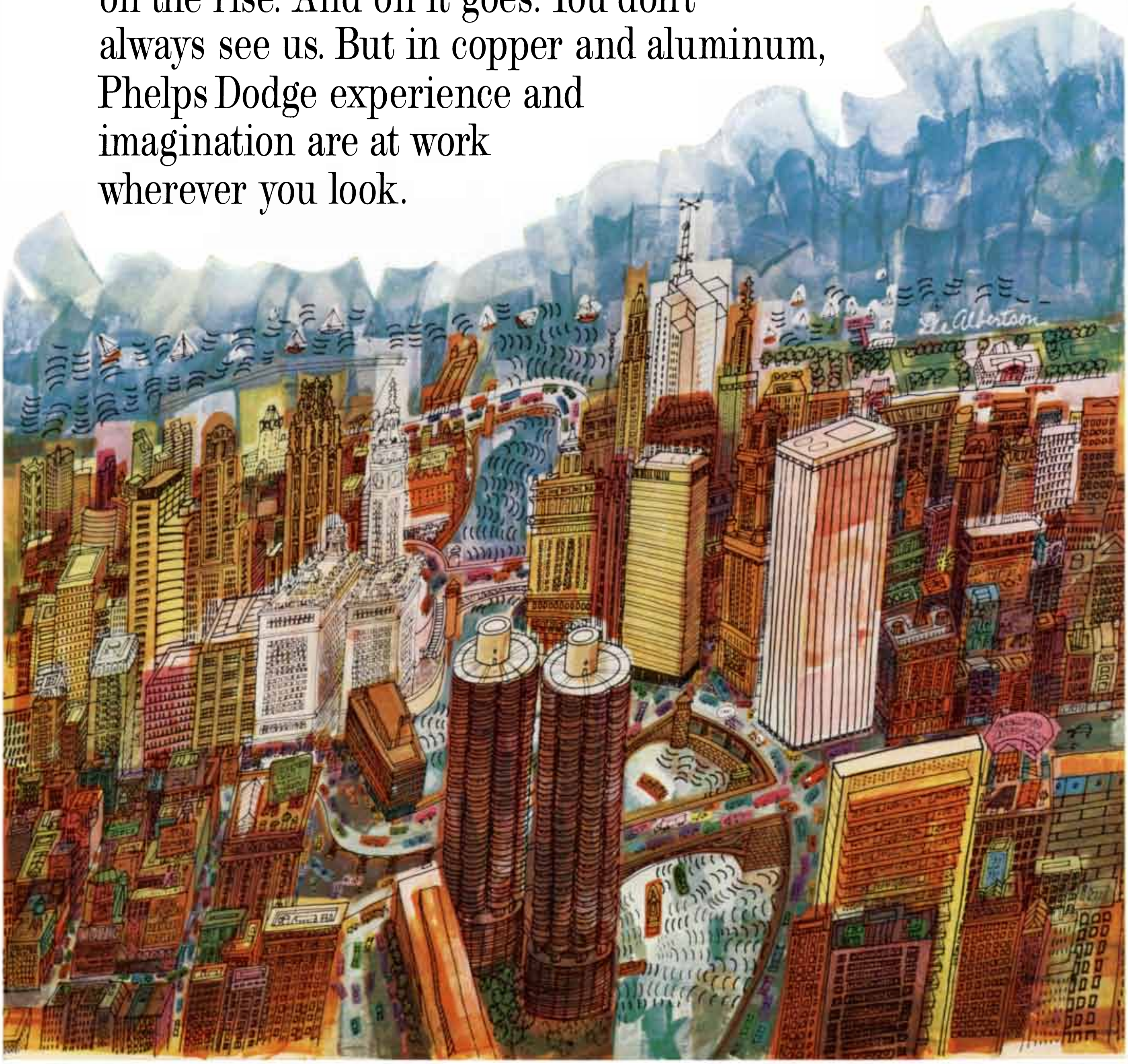
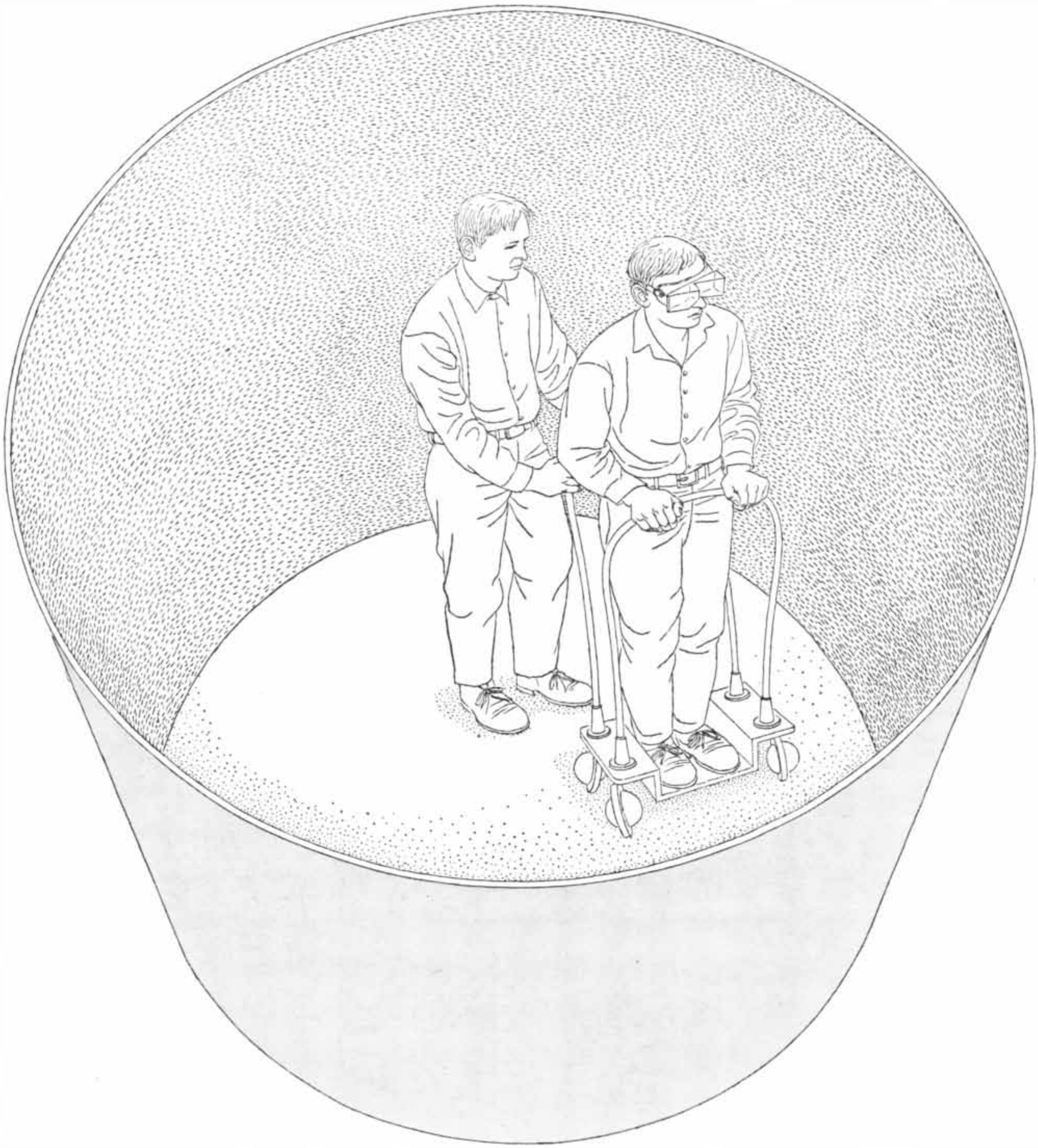
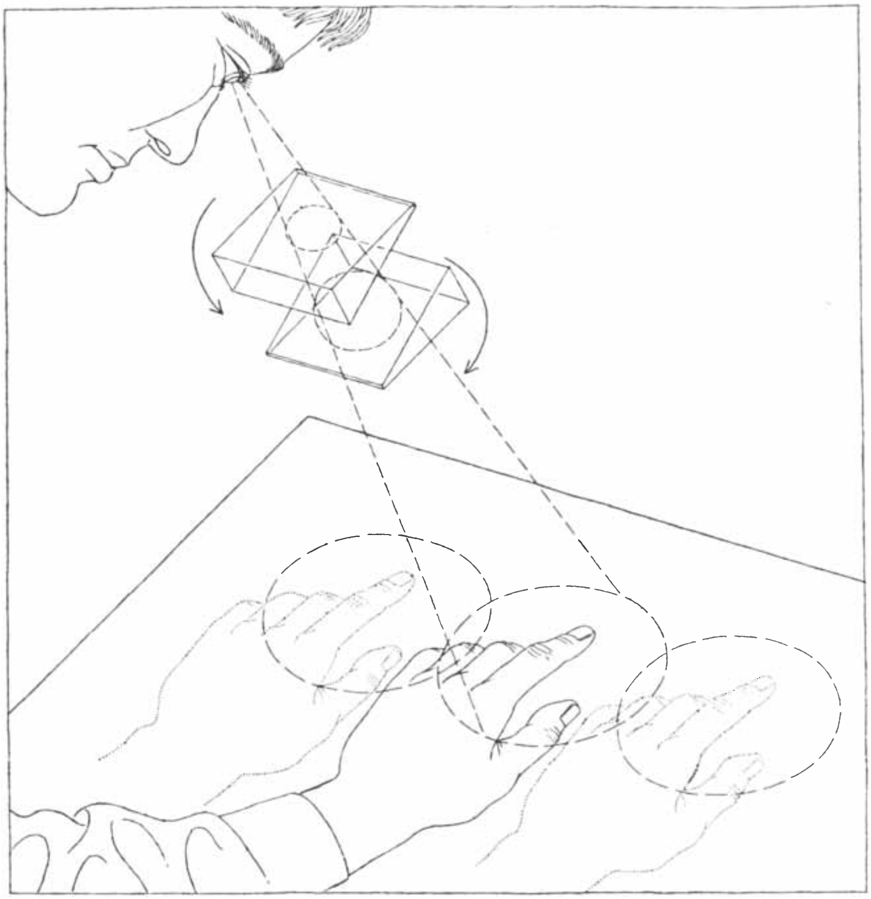


following adaptation suggest that compensation for rearrangement consists in the acquisition of a new mode of coordination that is objectively accurate for the condition of rearrangement but that coexists along with the older and more habitual mode. If this is true, the gradual and progressive course of adaptation usually found in experiments must be considered the result of a slow shift by the subject from the older direction of localization to the newer direction.

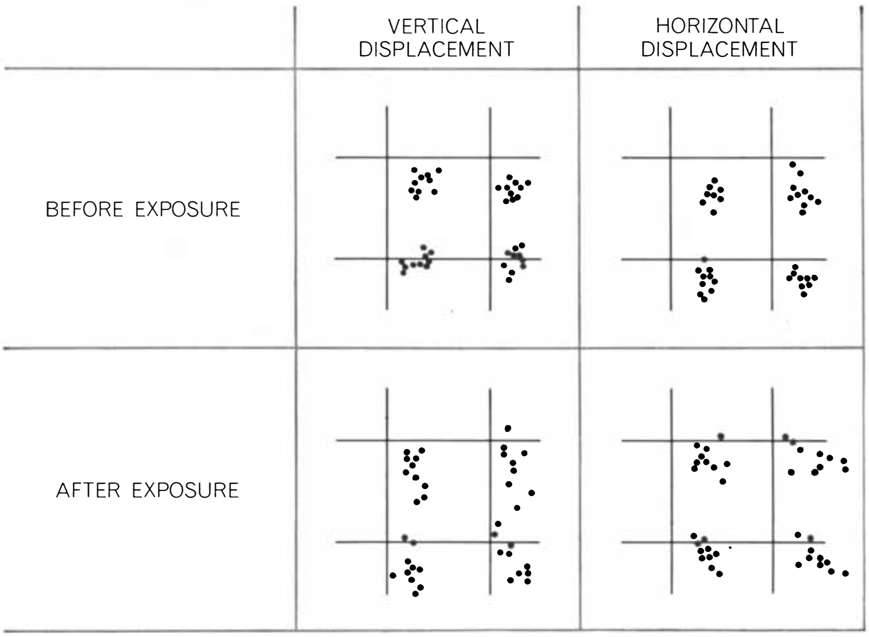
All these experiments strongly suggested the role in adaptation of the close correlation between signals from the motor nervous system, producing aetive physical movement, and the consequent sensory feedback. This correlation results from the fact that the feedback signals are causally related to movement and that in a stable environ-



PASSIVE TRANSPORT of a subject wearing prism goggles while viewing a random scene is depicted. Purpose of the apparatus was to test the hypothesis that subjects moving actively through such a scene, which looks the same with or without prisms, would show a degree of adaptation to the prisms whereas subjects moved passively would not. That is what happened. Tests showed a link between visual and motor processes in the central nervous system by altering the correlation between motor outflow and visual feedback.



VERIFICATION EXPERIMENT sought to show role of correlation of sensory feedback and active physical movement by impairing it. Means of decorrelation was the rotating-prism apparatus shown here. It produces apparently continuous movement of subject's hand in one dimension, thus breaking the link between actual movement and visual feedback.



RESULTS OF DECORRELATION are shown in markings made by a subject before and after looking through rotating prism. In one condition (*left*) prisms displaced images vertically; in another (*right*), horizontally. Markings after long exposure are spread out in the direction of displacement, showing a loss of precision in visual-motor coordination.

ment there is a unique feedback signal for any particular movement. The correlation is reduced by environmental instability: the presence either of objects that themselves move or of passive movements of the body that are produced by external forces. Under these conditions more than one feedback signal may accompany any particular movement.

From a theoretical point of view the importance of body movement and particularly of self-produced movement derives from the fact that only an organism that can take account of the output signals to its own musculature is in a position to detect and factor out the decorrelating effects of both moving objects and externally imposed body movement. One way to verify the importance of the correlation would be to set up an experimental situation in which the correlation was impaired or deliberately decorrelated. If the consequence was a loss of coordination, evidence for the role of normally correlated reafference in maintaining normal coordination would be strengthened.

We conducted such an experiment in visual perception by means of an apparatus that provided a prism effect of continually varying power [*see top illustration at left*]. In such an apparatus an object such as the hand seems to move constantly, and the movement perceived is wholly independent of whatever actual motion may be taking place. The same arm movement made at different times will produce different retinal feedbacks. Since the subject does not control the continual changes in his visual input that are produced by the prism, his nervous system has no means of distinguishing these changes in the input from those that are self-initiated.

With this apparatus we conducted various experiments, again including active and passive arm movements of the type described previously. We found that the coordination between eye and hand was significantly degraded under conditions of active movement but not under conditions of passive movement. Similar results appeared in tests made by Sanford Freedman of Tufts University of the effect of decorrelation on hearing. Again the performance of subjects who were allowed to move actively during decorrelation deteriorated badly, whereas the performance of subjects whose bodily movements were restricted did not deteriorate. Both the visual and the auditory experiments confirmed the importance of the correlation between movement and sensory feedback in maintaining accurate coordination.

In another test of our hypothesis about reafference we undertook to see what would happen when subjects looked through prisms at a random scene, lacking in the lines and curves that provide normal visual cues. The straight lines characteristic of normal scenes look curved when viewed through a prism. When the prism is removed, such lines seem to curve in the opposite direction. What if straight lines looked curved after a subject had removed prism goggles through which he had viewed a random scene?

Our hypothesis was that such an effect would be produced in subjects who moved actively while viewing the random field but not in those whose movements were passive. If such a result occurred, we would have shown that the subjective geometry of the visual field can be altered by reafference. This finding would have the surprising implication that a motor factor is involved in a process traditionally regarded as purely visual. We would have demonstrated in another way the close, one-to-one correlation between movement and visual feedback and would have further evidence of a link between motor and visual mechanisms in the central nervous system.

Our apparatus for testing this hypothesis consisted of a large drum that had on its inside surface an irregular array of small spots [*see illustration on page 91*]. These spots looked the same whether viewed with a prism or not. Each subject, before putting on prism goggles and entering the drum, was tested for his perception of a vertical line; we did this by having him indicate when a grating of bars given varying curvatures by prisms appeared straight. Thereafter, entering the drum with the goggles on, the subject either walked around in the drum or was transported on a cart. He stayed in the drum for half an hour and then, after removing the goggles, again took the test with the grating of bars. Without exception the active subjects perceived curvature when looking at lines that were actually straight, whereas the passive subjects perceived little or none.

Having established by these various means the role of reafference in adaptation to changed sensory inputs, we decided to examine its role in the development of visually controlled coordination in the newborn. The contribution of experience to the development of perceived space and of spatially oriented behavior has been debated for some centuries. During the past few decades a number of experimental approaches to the issue have been made. The technique most often used involves depriving very young animals of sensory contact with the environment. It has been hoped that the procedure would decide whether or not sensory experience, as opposed to maturation alone in the absence of such experience. is required for the development of spatial discrimination.

In certain species of higher mammals, including man, various forms of visual deprivation ranging from total absence of light to mere absence of gross movement in a normally illuminated environment have all resulted in deficiencies in visually guided behavior. Unfortunately these deficiencies are not easily interpreted. They can be attributed, at least in part, to several alternative causes, including pathological changes in the anatomy of the retina and its projections to the brain. Since our findings implicated movement-produced stimulation, they enabled us to test this factor without depriving animals of normal visual stimulation.

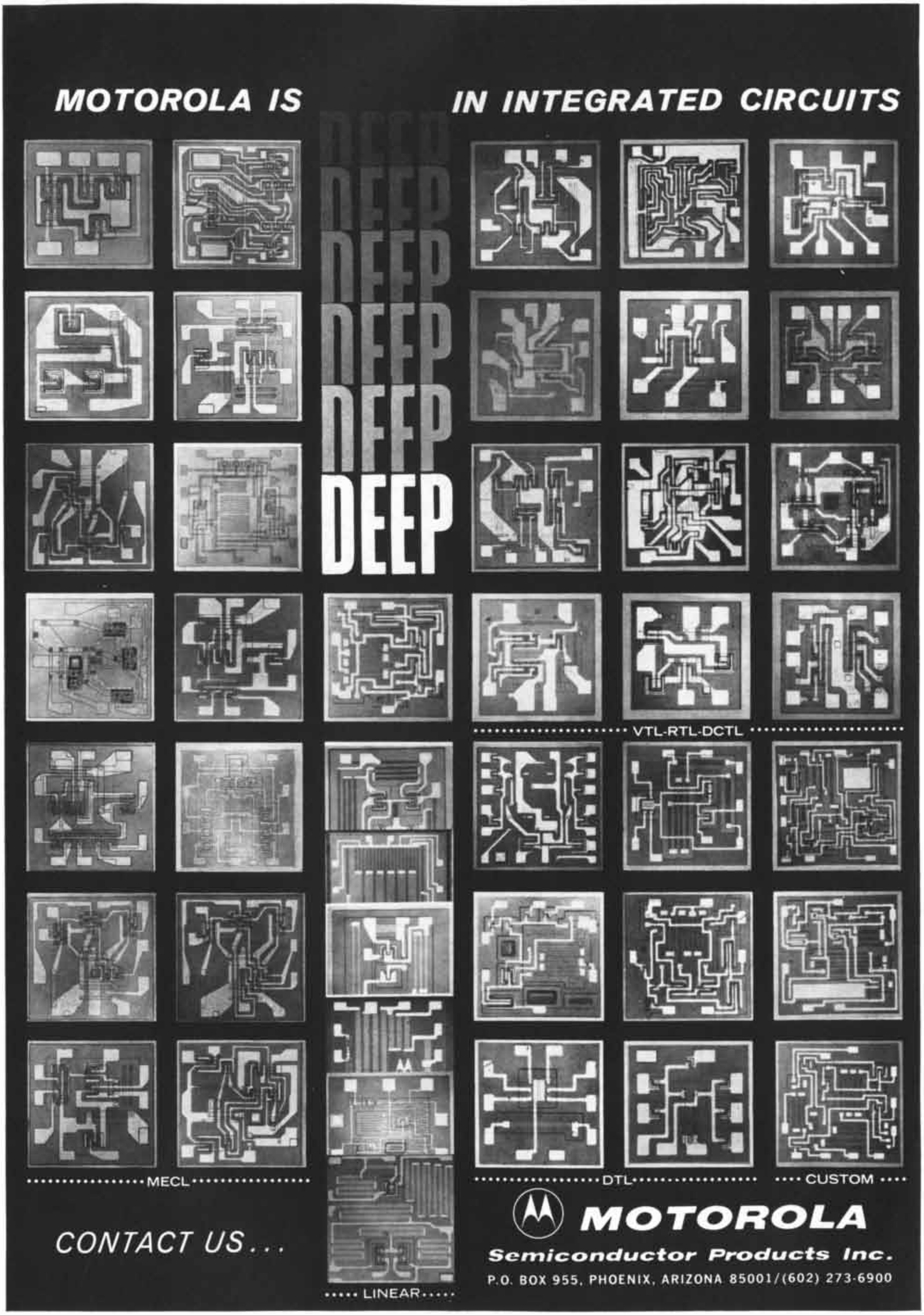
The experiments my colleague Alan Hein and I have performed to study the earliest development of vision originated from observations made by Austin H. Riesen of the University of California at Riverside and his collaborators. Riesen's research demonstrated that kittens restrained from walking from the time of their earliest exposure to light develop marked deficiencies in the visual control of behavior compared with unrestrained animals reared normally. The deficiencies of Riesen's animals may have resulted either from the lack of variation in visual stimulation, which was the explanation he preferred, or from the lack of visual stimulation correlated with movement, which was our own hypothesis.

To decide between these alternatives we devised an apparatus in which the gross movements of a kitten moving more or less normally were transmitted to a second kitten that was carried in a gondola [*see illustration on page 85*]. These gross movements included turns to left and right, circular progress around the center post of the apparatus and any up-and-down motions made by the first kitten. The second kitten was allowed to move its head, since prior experimenters had reported that head movement alone was not sufficient to produce normal behavior in kittens, and it could also move its legs inside the gondola. Both kittens received essentially the same visual stimulation because the pattern on the walls and the center post of the apparatus was unvarying.

Eight pairs of kittens were reared in darkness until the active member of each pair had enough strength and coordination to move the other kitten in the apparatus; the ages at which that state was attained ranged from eight to 12 weeks. Two other pairs were exposed to patterned light for three hours a day between the ages of two and 10 weeks; during exposure they were in a holder that prevented locomotion. Thereafter all 10 pairs spent three hours a day in the apparatus under the experimental condition; when they were not in the apparatus, they were kept with their mothers and littermates in unlighted cages.

After an average of about 30 hours in the apparatus the active member of each pair showed normal behavior in several visually guided tasks. It blinked at an approaching object; it put out its forepaws as if to ward off collision when gently carried downward toward a surface, and it avoided the deep side of a visual cliff—an apparatus in which two depths, one shallow and the other a sharp drop, appear beneath a sheet of glass [see "The 'Visual Cliff,'" by Eleanor J. Gibson and Richard D. Walk; SCIENTIFIC AMERICAN, April, 1960]. After the same period of exposure each of the passive kittens failed to show these types of behavior. The passive kittens did, however, develop such types of behavior within days after they were allowed to run about in a normal environment.

In sum, the experiments I have described have led us to conclude that the correlation entailed in the sensory feedback accompanying movement—reafference—plays a vital role in perceptual adaptation. It helps the newborn to develop motor coordination; it figures in the adjustment to the changed relation between afferent and efferent signals resulting from growth; it operates in the maintenance of normal coordination, and it is of major importance in coping with altered visual and auditory inputs. The importance of the correlation in all these functions has been revealed by experiments that tamper with its normal operation. In the process these experiments have uncovered a fundamental role of the motor-sensory feedback loop.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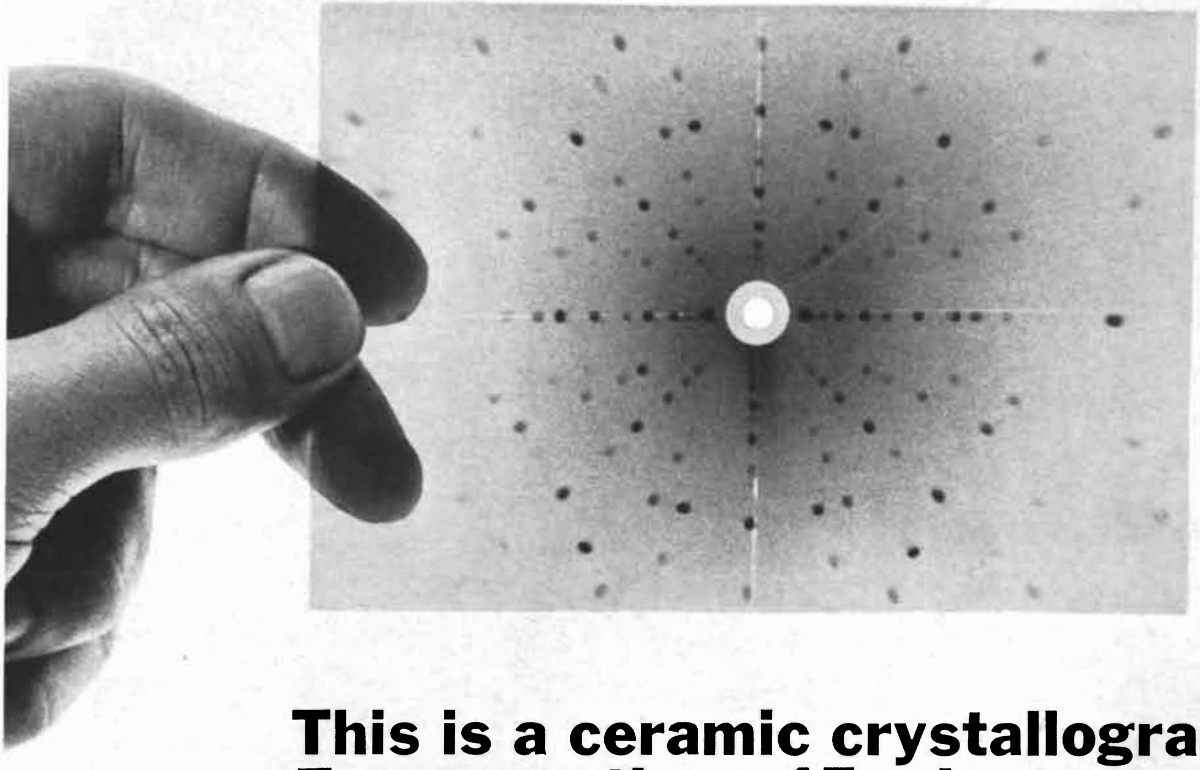


This is a ceramic crystallogram. Exposure time: 45 minutes Development time: 30 minutes

Polaroid announces the XR-7 system for x-ray crystallography.

Every crystal has its atoms arranged in a network around several intersecting axes. Just how this network is structured will determine the crystal's properties. How the crystal will conduct heat or light or electricity, for example.

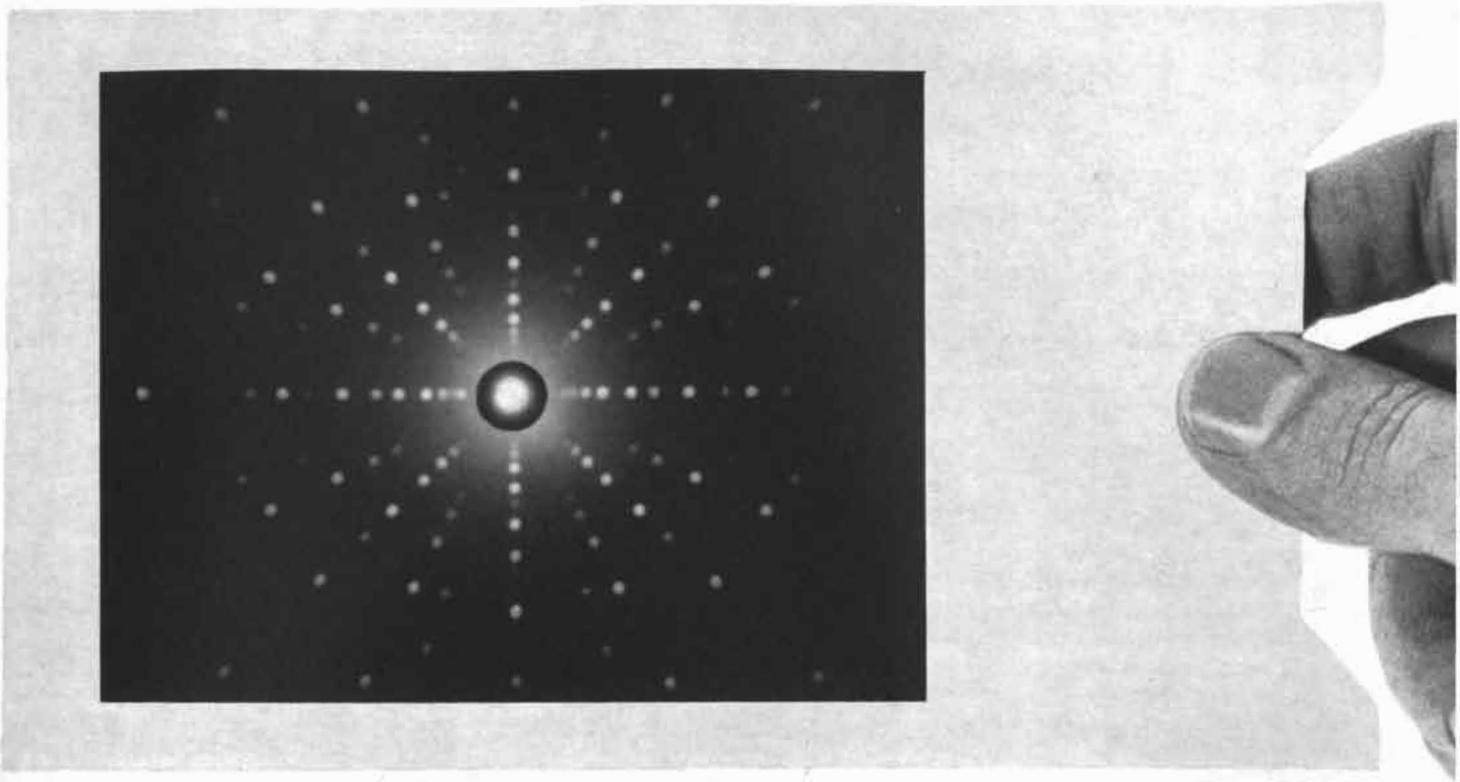
This atomic structure can be photographed. It's done by sending a beam of x-rays through the crystal (where they bounce off the atoms) and recording the pattern that emerges on film. The resulting picture is called a crystallogram.

Until now, crystallograms have been made with conventional x-ray film. The film has to be loaded in a darkroom. It needs very long exposures (hours in many cases). And it has to go through conventional darkroom developing and drying. That's a long time for one picture. When you consider that the first few crystallograms serve only to orient the crystal properly, you can see why it sometimes takes a whole day or more to analyze just one crystal.

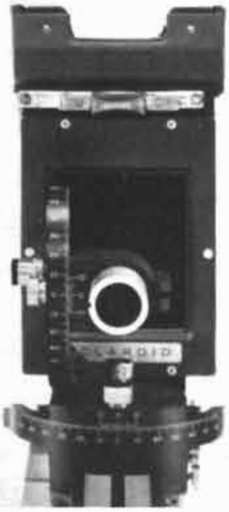
With the XR-7 system, Polaroid has come up with a dramatic shortcut. A crystallogram can now be made in 5 minutes, for instance, instead of an hour. In 45 seconds instead of 30 minutes. And so on.

The system, which is actually quite simple, has been designed for operation with most x-ray diffraction units and cameras. It is built around the capabilities of exceptionally sensitive (3000-speed) Polaroid Type 57 4x5 Land film.

The main part of the system is the Polaroid XR-7 cassette—essentially, a device to hold and expose the film. (The 4x5 film packet slides right into it.) When loaded, the inside of the cassette is a three-layer sandwich consisting of a lead-backed intensi-



This is a ceramic crystallogram. Exposure time: 4 minutes Development time: 10 seconds



fying screen with a special phosphor coating, the 4x5 film negative, and a unique air-filled pillow.

During exposure, the x-rays strike the intensifying screen which fluoresces and converts the x-ray information into visible light. This, in turn, exposes the 4x5 negative which the pillow holds in perfect contact with the screen.

After exposure, the packet is pulled out and the finished picture is peeled apart 10 seconds later. All darkroom time is completely eliminated. And because the film is so sensitive, exposures can be measured in minutes and seconds rather than hours and half hours. This unparalleled speed of the XR-7 system is, of course, its primary advantage. But that's not all.

With on-the-spot pictures, the crystallographer can make changes in crystal orientation right away. And can go on taking pictures in one continuous operation until he gets the alignment he wants.

The extreme sensitivity of the film offers still two more advantages. One, it permits using relatively low operating voltages. And two, it permits using greater distances between the crystal and the film plane (this produces an easier-to-read picture with larger and more widely separated diffraction spots). Because increased distances require longer exposures, nothing over 3 cm has ever been practical before. The XR-7 system can be used at 5 cm as well and a 5 cm extension comes with it.

What will this remarkable system mean to the people who work with it? Field tests have given us a good idea. They've already shown it can increase overall productivity anywhere from 2 to 8 times. Which amounts to a virtual revolution in x-ray crystallography.

Polaroid Corporation

Games, Logic and Computers

A close kinship among them is demonstrated by a game of solitaire played with colored "dominoes." Whether or not the game can be won is analogous to whether or not a problem can be solved by computer

by Hao Wang

Today much of the work once done by human muscles and brains is being delegated to machines, and people in all walks of life are asking: What human abilities are irreplaceable? What can machines not do? It may surprise the reader to learn that, whereas the first question has no definite answer, the second has a straightforward mathematical solution.

Even before the first modern computing machine was built the late British logician Alan Turing asked the question: What can computers not do? In his attempt to create a theory of what can be computed and what cannot, Turing devised a slow and simple imaginary computer that he proved to be theoretically capable of performing all the operations of *any* computer. He used his machine to demonstrate the close kinship of computer theory and logic, branches of mathematics that are both concerned with mathematical proof and with notations that can present our thoughts in exact form. This article will undertake to illustrate some fundamental concepts in the area of overlap between computer theory and logic by means of games.

The human mind can grasp only relatively small numbers and quantities. The discipline of mathematics, on the other hand, is primarily concerned with infinity. Finite mathematical operations and infinite mathematical entities present a significant and fascinating contrast. The smooth transition from intuitively comprehensible individual cases to unrestricted general situations is a remarkable achievement of the human intellect. Abstract considerations concerning games can introduce us to this phenomenon quite naturally.

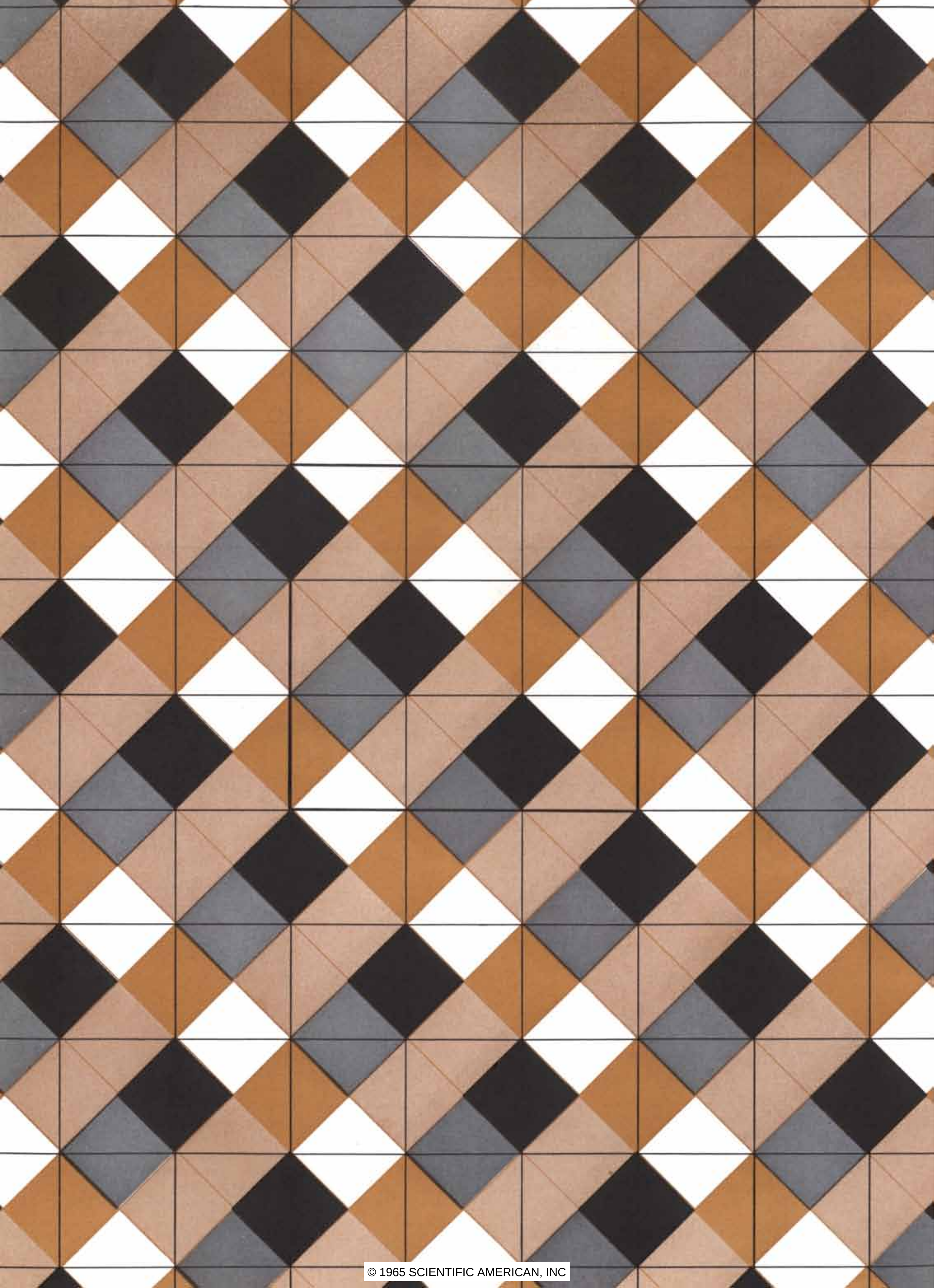
Finding the sequence of moves most likely to lead to victory in a game such as ticktacktoe presents a logical problem precisely analogous to finding the series of steps that will yield a solution to any mathematical problem of a given class. In certain games there is no optimum strategy that will guarantee victory; in certain classes of problems there is no algorithm—no general method of supplying a series of steps leading to a solution. Since a computer program is simply an algorithm designed for execution by machine, this means that there are classes of problems that computers cannot solve. Before considering the difficulties of constructing algorithms for solving problems (also of devising programs for arriving at solutions and of working out optimum strategies for winning games), let us examine why it is that their construction not only is useful but also represents an ultimate goal of mathematics.

Obviously it would take infinite time and energy to memorize the multiplication table if, instead of just including the products of all single-digit numbers taken two at a time, the table included the products of all multidigit numbers taken in this way. Man has made this infinite multiplication table unnecessary by memorizing, along with the multiplication table for single-digit numbers, a list of steps involving "carrying" and the addition of partial products that will yield the product of any two multidigit numbers.

We know that the operations of elementary arithmetic involve formal rules, and most of us recall that certain other operations, such as the extraction of a square root, can be done according to a fixed list of sequential steps. As we get to problems of greater complexity it becomes less clear that they can be solved by algorithm. Consider the following problem: "Given the two positive integers 6 and 9, find their largest common divisor." The reader will immediately see the answer: 3. If the two numbers were 68 and 153, readers who are inclined to try various possibilities might still find the answer (17). If it could be shown, however, that the general problem "Given two positive integers a and b, find their greatest common divisor" can be solved by algorithm, then anyone or any machine capable of performing the specified operations could solve it for any a and b. Such an algorithm exists; it was devised by Euclid [*see illustrations at top of page 100*].

The usefulness of algorithms is equal-

DOMINO PROBLEM involves assembling three colored tiles called domino types to form a block that can be infinitely extended with colors matching on all adjacent edges (*opposite page*). It is assumed that the player has an infinite quantity of each domino type and that no domino can be rotated in two dimensions. The problem is solved by finding a rectangular block in which the color sequence on the top edge is the same as that on the bottom edge and the sequence on the left edge is the same as that on the right. Such a unit (*heavy outline on opposite page*) can be repeated in all directions to fill an infinite plane.



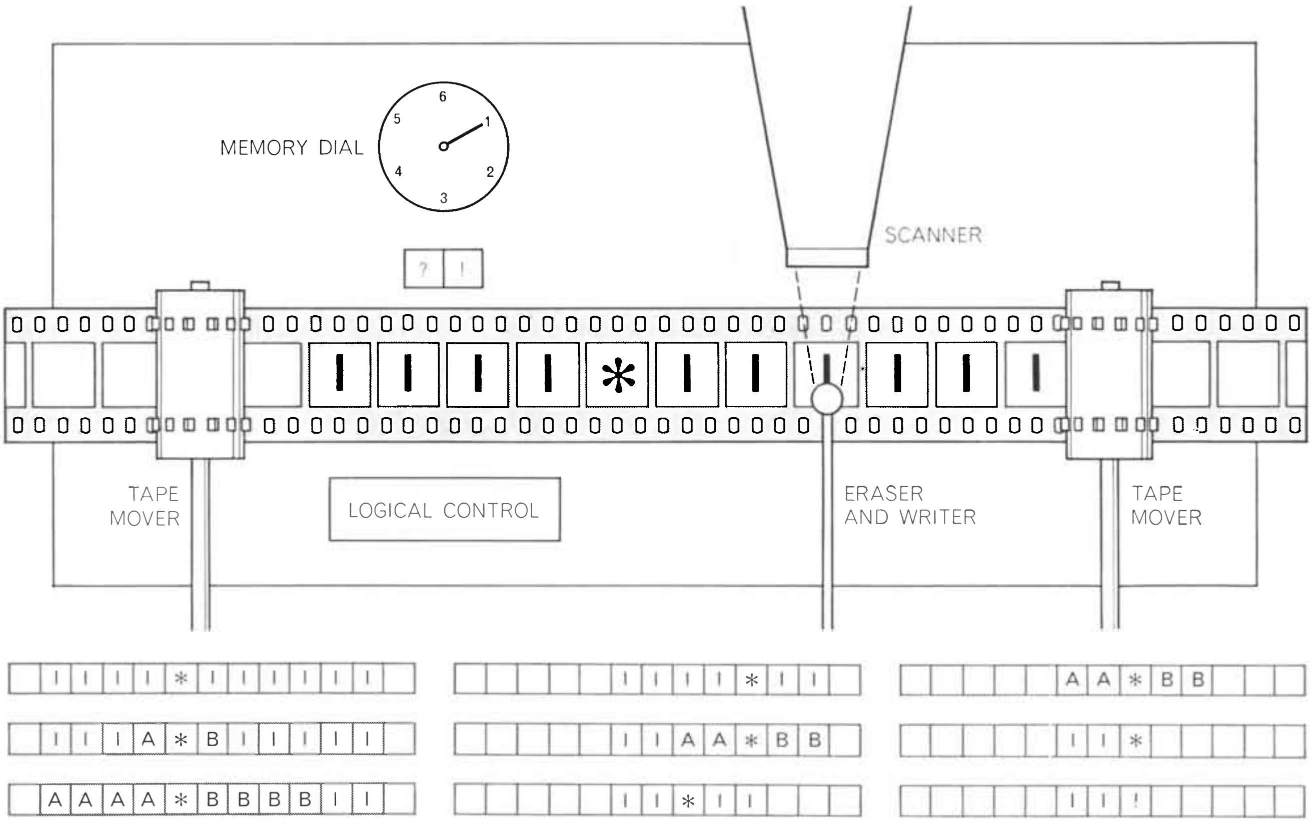
```
      :R
GCD   :R      THIS RØUTINE CØMPUTES THE GREATEST CØMMØN
      :R      DIVISØR ØF TWØ INTEGERS A AND B.
      :R
      EXTERNAL FUNCTIØN (A,B)
      NØRMAL MØDE IS INTEGER
      ENTRY TØ GCD.
LØØP  REMAIN = B - A*(B/A)
      WHENEVER REMAIN.E.0,FUNCTIØN RETURN .ABS.(A)
      B = A
      A = REMAIN
      TRANSFER TØ LØØP
      END ØF FUNCTIØN


      TYPE INPUT                  TYPE INPUT
      A=8,B=12*                   A=12345678,B=87654321*
      THE GCD ØF A AND B IS       THE GCD ØF A AND B IS
            4                            9
```

1. Consider two positive integers, *a* and *b*. Proceed to next instruction.
2. Compare the two numbers under consideration (determine if they are equal, and if not, which is larger). Proceed to next instruction.
3. If the numbers are equal, each is the answer; stop. If not, proceed to next instruction.
4. Subtract the smaller number from the larger one and replace the two numbers under consideration by the subtrahend and the remainder. Proceed to instruction *2*.

ALGORITHM IN COMPUTER LANGUAGE provides a series of steps by which the largest common divisor of any two numbers can be found. At bottom are computed solutions for two pairs of numbers. Procedure is in the language called MAD (for Michigan algorithm decoder). Letter *O* is printed with a line through it to distinguish it from zero.

SAME ALGORITHM is stated in ordinary language. The process of division is rendered as repeated subtraction. The series of steps is known as the Euclidean algorithm.



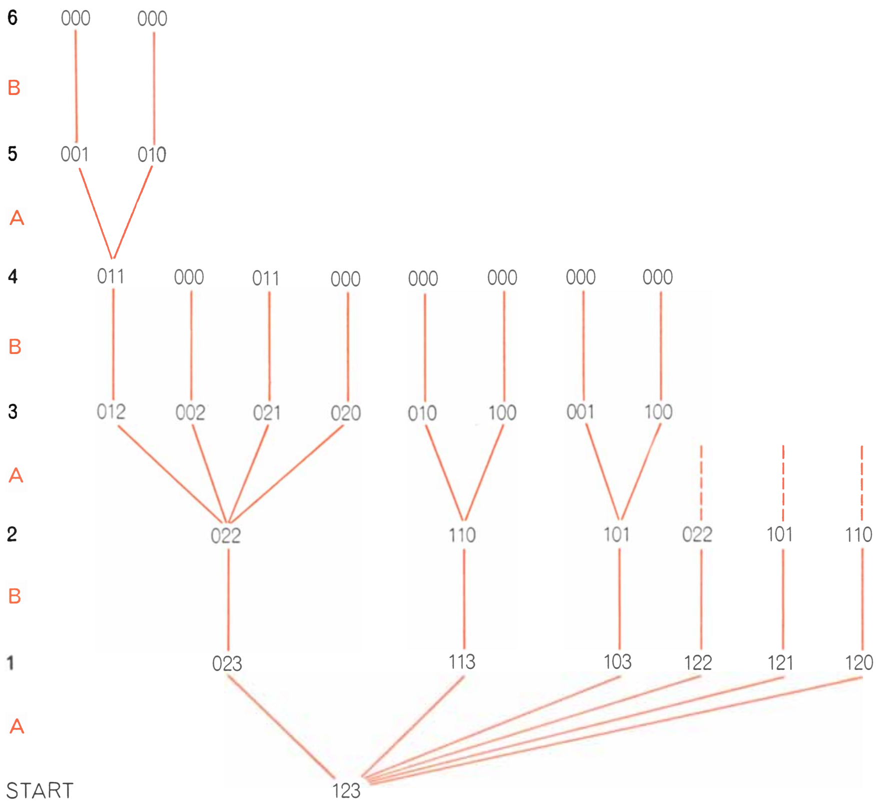
TURING MACHINE designed to perform steps of the Euclidean algorithm displays the numbers 4 and 6 on its tape in this schematic illustration. (Each digit is represented by a stroke; asterisk signals separation of numbers.) The logical control of the machine consists of instructions determined by a mark on the square of tape being scanned and the position of the memory dial. Steps of the Euclidean algorithm lead to changes on the tape illustrated in sequence at bottom. The machine first determines which number is larger by a "comparison loop" in which it replaces strokes to right and left of asterisk with symbols (*"A" at left and "B" at right*). When one set of strokes is exhausted, the machine begins a "subtraction loop," erasing the symbols of the smaller number and converting the symbols of the larger number back into strokes. These are separated from the two strokes representing the remainder of the subtraction by an asterisk. The process of comparison and subtraction is repeated with 4 and 2 on tape, and then with 2 and 2; finally, 2 and 0 appear on tape. As comparison loop begins, blank tape on one side of asterisk evokes a halt signal (!) from logical control, and the machine stops with the answer (2) on its tape. Machine is idealized because its tape is potentially infinite.

ly apparent in the realm of games, where they provide instructions for the most advantageous moves. The mathematician, of course, is less interested in winning a game than in understanding the abstract structure of that class of games. By considering the existence or nonexistence of a winning strategy, he gains insight into the abstract structure of the game and those of the same kind.

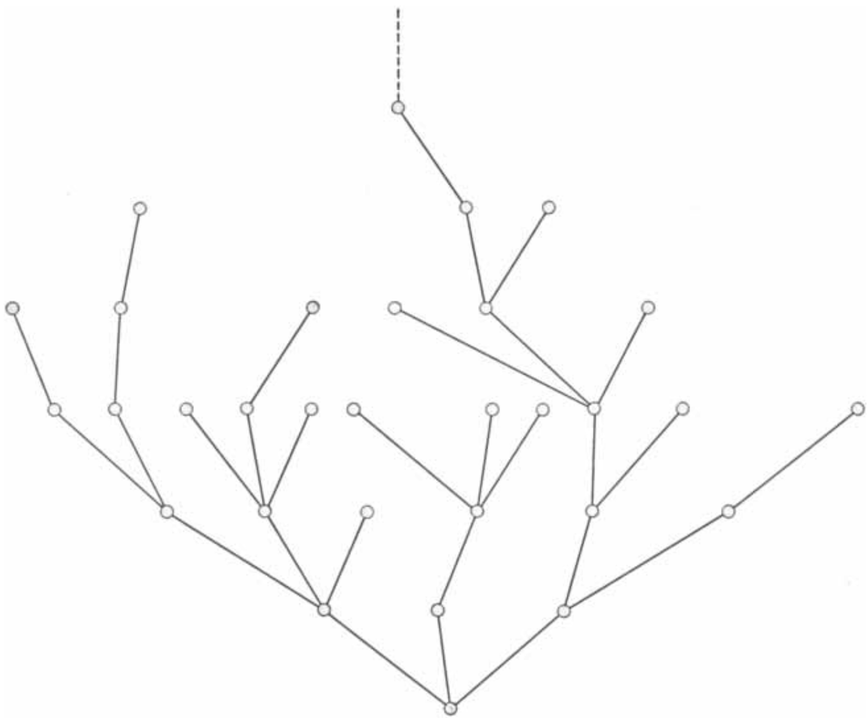
Take, for example, the game known as nim. Any number of objects, say six matches, are arranged in three piles. Two players, *A* and *B*, draw in turn, each taking any number of matches from any one pile. Whoever takes the last match is the winner. Since the finite quantity of matches will in the end be exhausted, it is obvious that the game allows no draw. It is significant that only one of the two players has a winning strategy, depending on the size of the initial three piles and who moves first. In the particular game defined by piles of one, two and three matches the winning strategy belongs to *B*, the player who moves second. This can be proved by means of a schematic tree with the node of each set of branches representing a situation at a stage of the game, and the branches from each node the possible moves a player can make in that situation [*see top illustration at right*].

Suppose we are to play this game with three piles containing 10 million, 234 and 2,729 matches. It is theoretically feasible to tabulate all the possible sequences of moves with these three piles and then to tell by inspection whether *A* or *B* has a winning strategy. No one, however, would be willing or able to undertake such a tabulation. The mathematician would undertake a systematic search for shortcuts to make the operations easier and to achieve economy of thought. A search of this kind has in fact been made for the game of nim, and a simple recipe has been worked out for determining which player has the winning strategy. The recipe states that *A* can always win if, when the numbers of objects in the three piles are expressed in binary notation, they add up to a figure that contains an odd number. Such a recipe can represent a dazzling but unimportant stunt or a way of achieving significant mathematical insight, depending on the nature of the game and the directness of its relation to major mathematical and logical problems.

A game such as nim is said to be "unfair," because one player always has a winning strategy. A game such as



TREE FOR GAME OF NIM indicates that the player who moves second, *B*, has a winning strategy. At beginning of game (*bottom*) there are piles of one, two and three matches (*digits at each node of tree give number of matches remaining in piles*). Players remove one or more matches from a single pile until someone wins by removing the last match. Branches show all the possible moves for *A* and the unanswerable response of *B* to each of them.

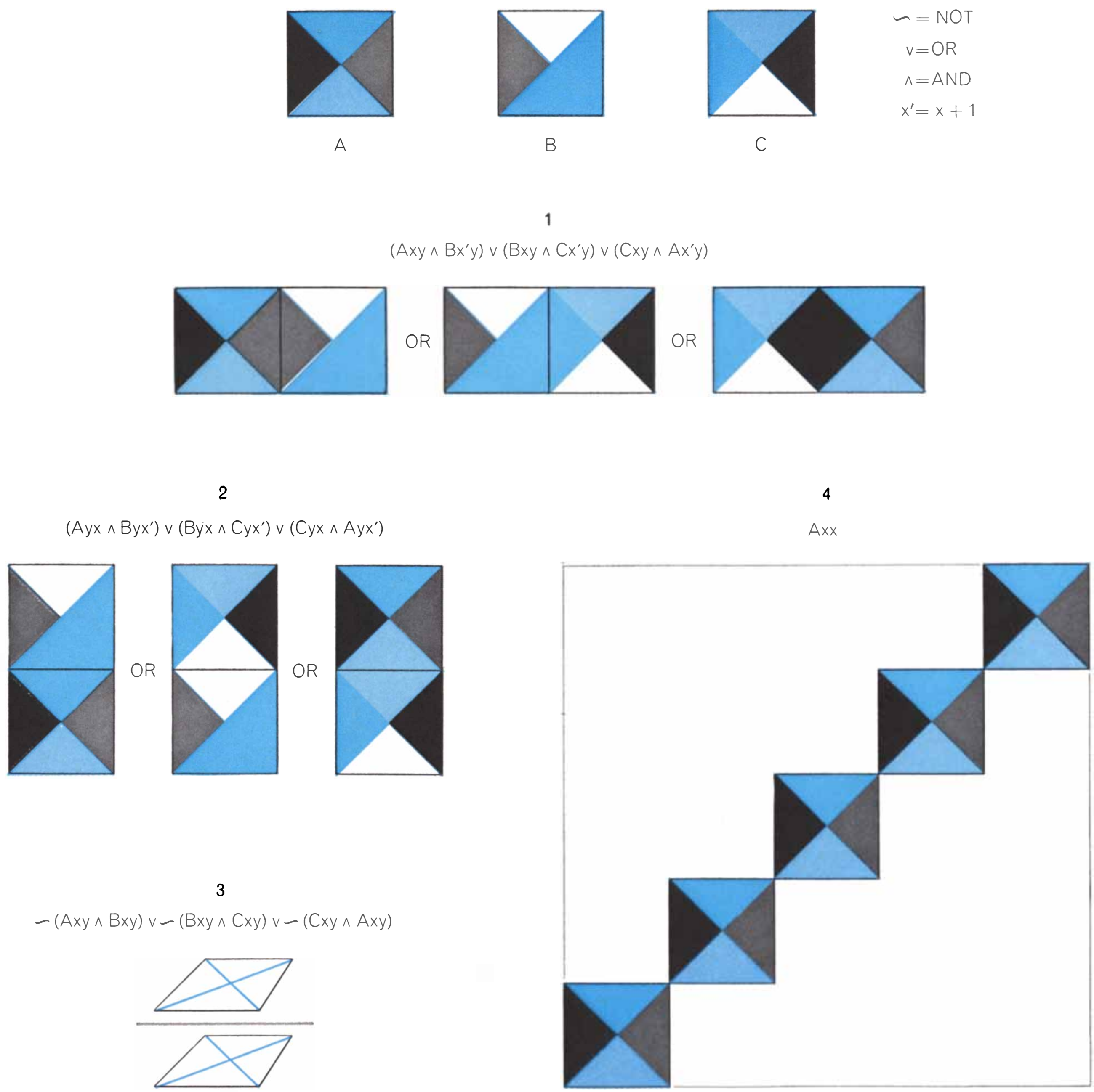


INFINITY LEMMA is suggested by a tree that continues at top. The lemma is a proposition to the effect that if there are infinitely many connected branches in a tree, and only finitely many branches from each of its nodes, then there must be one node at every level from which branches extend indefinitely upward; these, taken together, form an infinite path through the tree. The lemma can be paraphrased: "If the human species never disappears, there exists today someone who will at any future time have a living descendant."

ticktacktoe is said to be "futile," because each player has a nonlosing strategy that eliminates the possibility of a winner. These characterizations can be restated as a theorem: Every game is either futile or unfair if there is a fixed, finite upper boundary to the length of each path on its tree and only finitely many branches come directly from each node. The theorem holds because if there are no endless games and only finitely many legal moves at each stage, then the total number of possible sequences of moves is finite. If we represent all the permissible plays by a tree, we see that if neither player has a winning strategy, then each player has a nonlosing strategy.

The theorem does not apply directly to the game of chess, because there are no precise rules to prevent endless matches. Let us assume, however, that we could introduce rules to exclude endless chess matches, without imposing a limit on the absolute number of moves allowed in a complete match. We would then be able to apply to chess a proposition known as the infinity lemma, which states that if there are infinitely many connected branches in the tree of a game and only finitely many branches from each node, then there is an infinite path.

Given the infinity lemma and the assumption that new rules have excluded endless matches, it follows that the



RULES FOR DOMINO PROBLEMS are set forth in the formal shorthand used by students of mathematical logic (*glossary is at top right*). At top center is a set of dominoes: *A*, *B* and *C*. The first expression states that colors must match on left and right edges, second that colors must match on top and bottom edges. The third rule is that dominoes must not be placed one atop another.

The fourth expression, a constraint typical of those used to complicate games in approximating difficult problems of computation, states that only *A* can lie on the main diagonal of the plane. The positions on the plane are described by Cartesian coordinates. In designation such as "*Ayx*" domino's position on horizontal axis is given by the first variable, *y*, and vertical position by the second.

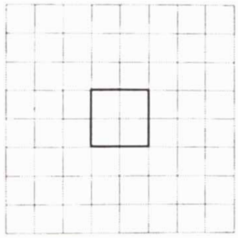
tree representing the game of chess has only finitely many branches. Otherwise, in view of the fact that there are only finitely many branches from each node, there would be an infinite path (an endless game). Hence there are only finitely many possible sequences of moves and, as we showed earlier, chess is either unfair or futile.

The proof of the infinity lemma is fairly straightforward. Take the node at the very bottom of the tree. Since we are assuming infinitely many branches but only finitely many branches directly from any one node, at least one of the nodes on the next level must be the bottom of a subtree with infinitely many branches. Let us call this node *X*. Our hypothesis states, however, that there are only finitely many branches directly from *X*. Therefore one of the nodes on the next level above *X* must be the root of an infinite subtree. By repeating this argument we see that on every level there is at least one node that is the root of an infinite subtree and that these roots together determine an infinite path through the tree. An anthropomorphic way of applying the infinity lemma would be to state that if the human species never disappears, there exists today someone who will at any future time have a living descendant.

One chooses to examine a game, of course, according to the importance of the mathematical questions it raises. In 1960, while I was studying certain problems in logic at the Bell Telephone Laboratories, I devised a new game of solitaire played with "dominoes" that are actually colored tiles. More recently my colleagues and I at the Harvard Computation Laboratory have found some surprising and significant applications of this game. Several problems that arise in the domino game are exact analogues of problems that Turing machines are designed to solve. The conditions under which a domino game is played can be made to correspond to the computations of Turing machines, so that working with dominoes grants us another view—sometimes a particularly revealing one—of certain mathematical problems.

In a domino game we are given a finite set of square tiles (the dominoes); the tiles are all the same size but each edge of a tile has a stipulated color and the colors are combined in several specified ways. We assume that we have infinitely many copies of each type of domino, and that we are not permitted to rotate a domino in two dimensions. The object of the game is to cover

Cover a section of the Cartesian plane with black and white tiles so that no block (of the size outlined at right or larger) has edges at left and right and top and bottom that match. Is there a method of filling an infinite plane in this way?



FOUR PROBLEMS are presented by the author to the resolute reader. Only this problem and the problem at bottom have known solutions. Solution to this problem is on next page.

We can make a string of 0's and 1's yield "progeny" by these rules:
1. If the string has fewer than three symbols, stop.
2. If the string begins with 0, delete the first three symbols and append 00 to the end.
3. If the string begins with 1, delete the first three symbols and append 1101 to the end.

Is there an algorithm to determine whether one of two given strings is a progeny of the other?

011010001001	101110110011
01000100100	1101100111101
0010010000	11001111011101
001000000	011110111011101
00000000	11011101110100
0000000	111011101001101
000000	0111010011011101
00000	101001101110100
0000	0011011101001101
000	10110100110100
00	1101001101001101
(stop)	(progeny continue)

SECOND PROBLEM is to find an algorithm that shows whether two strings of 0's and 1's are related. The problem is complicated by the fact that certain strings may give rise to infinite progeny. An alternative solution would be to prove that no such algorithm can exist.

Is there an algorithm to decide if a polynomial equation with integral coefficients has roots that are integers?

Equations of this type include

$$x^2 - 4x + 3 = 0$$

and

$$a^2 + b^2 - c^2 = 0.$$

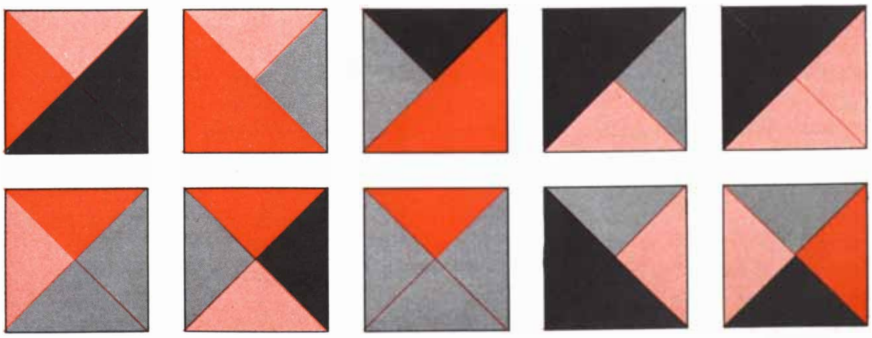
The first equation has only one unknown, *x*. It thus has the form

$$a_n x^n + a_{n-1} x^{n-1} + \dots + a_1 x + a_0 = 0$$

and for such equations the desired algorithm is known:
1. Find all the divisors of a_0.
2. Substitute each for *x* and calculate the resulting values for the left side of the equation.
3. If any yields the value 0, it is a root. If none do, the equation has no roots that are integers.

The problem is to devise such an algorithm for equations, such as the second, that contain more than one unknown.

THIRD PROBLEM has been known as "Hilbert's 10th problem" since the German mathematician David Hilbert listed it in 1900 as an outstanding problem confronting mathematics.



TEN-DOMINO PROBLEM calls for arranging these tiles in a block in which the color scheme is the same for top and bottom and left and right edges. Solution is on page 106.

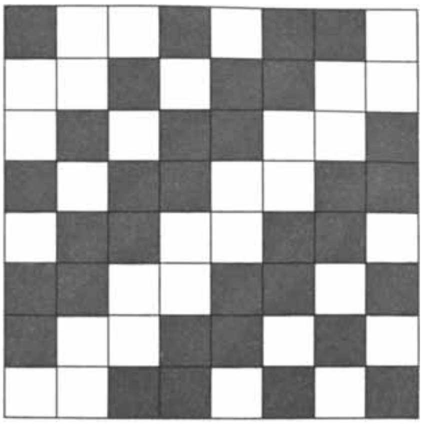
a

a b

a b b a

a b b a b a a b

a b b a b a a b b a a b a b b a ...



SOLUTION TO FIRST PROBLEM on preceding page is illustrated. To repeat its construction, let *a* represent a black tile, *b* a white one (*left*). Write *a* and replace it with *ab*. Replace *b* with *ba* and continue to replace *a* and *b* in this way. Transcribe this sequence onto top row of plane and copy each symbol along diagonal from top right toward bottom left.

an infinite plane with dominoes in such a way that adjoining edges have the same color. If the plane can be covered with a given set of dominoes, the set is said to be solvable.

Consider the set of three dominoes in the illustration on page 98. The set is solvable because it can be assembled into a nine-domino block that satisfies the rule with respect to edges and can be repeated in every direction. Given a solution for the whole plane, we can obviously chop off three quadrants, or quarters, to get a solution over one quadrant. The converse is less obvious, but it can be established with the help of the infinity lemma. Since there exists a solution over an infinite quadrant, there exist partial solutions of *its* quadrants—solutions of any area n by n. We can make an infinite tree out of such partial solutions and show by the infinity lemma that there is an infinite path in the tree that yields a solution over the whole plane. Thus if it is possible to fill a quadrant of the infinite plane, it is possible to fill the whole plane.

We can use dominoes to simulate various Turing machines and to create an equivalent of Turing's important "halting problem." This is more easily done if we specify what domino goes at the origin of the plane—what domino we put down first. With greater effort we can accomplish the same thing either by specifying that certain dominoes occur on the main diagonal or by omitting any restriction other than those mentioned earlier. Let us consider this equivalence between the halting problem and the domino game in greater detail.

Turing devised his simple computer to emulate a human calculator. A man solving a mathematical problem is likely to use pencil and paper for writing and erasing numbers; he may also have a collection of mathematical facts in the form of a book of tables and, contained in his mind or in the book, a set of instructions for performing the proper steps in the proper sequence. The imaginary Turing machine also has a marking device and an eraser for writing numbers according to instructions from a logical control unit that follows a prepared table of commands. The numbers are written in the form of single strokes on square cells of an infinitely long tape serving as the memory unit. (Since no actual machine can have an infinite memory, the Turing machine is idealized.)

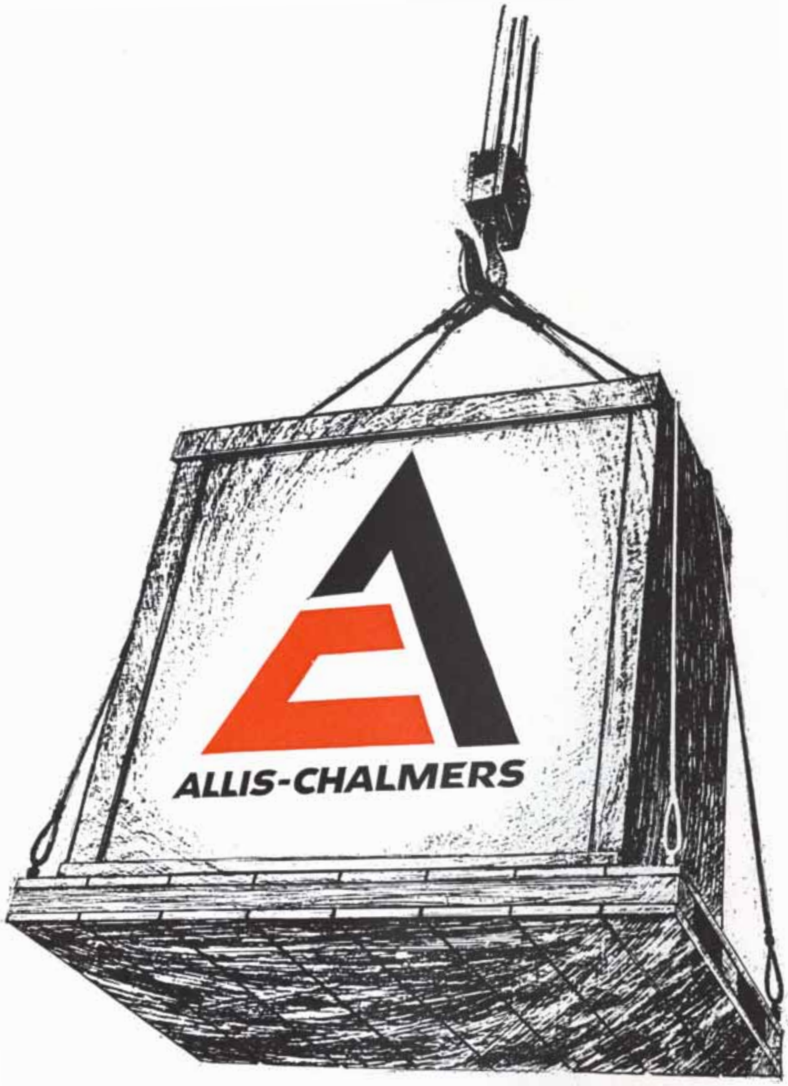
One square of the tape at a time is considered by a scanner that relays the symbol on the square to the control [*see bottom illustration on page 100*]. The control then consults its internal instructions by means of a dial that points to a location designated "Current instruction." Depending on the symbol at hand, the instruction specifies one of four commands: (1) Print a mark on the square, erasing it if necessary, (2) Move the tape one square to the right, (3) Move the tape one square to the left, (4) Halt! Then the instruction indicates the next instruction location. A Turing machine can be endowed with the requisite number of instruction locations and commands, as well as a tape with infinitely many squares, to solve any specified mathematical problem (if that problem is in a class solvable by algorithm).

Turing devised the halting problem to exemplify a problem for which no program could yield all the correct solutions. He surpassed the power of any possible single machine by formulating a question about all Turing machines. He was able to show that although each machine, depending on its tape, would either halt or continue operating indefinitely, there is no general algorithm to determine this behavior, no recipe equivalent to the one for determining the invariable winner of a given game of nim. Now, it is possible to find for each Turing machine a set of dominoes such that the machine will eventually halt if and only if the set of dominoes does not have a solution. It is then a direct consequence that the domino problem is unsolvable. If we could solve the domino problem, we could solve the halting problem; we cannot solve the halting problem and so we cannot solve the domino problem. In other words, there is no general method for deciding if any given set of dominoes has a solution.

The domino problem is an example of an infinite decision problem of the kind that frequently turns up in logic, in computer theory and in mathematics in general. It is an infinite problem in the following sense. Any solution to the domino problem must be a single method that provides the correct yes or no answer to an infinite number of questions in the form: "Does a certain set of dominoes cover the plane?" Whereas any specified set of domino types is finite, there is of course an infinite set of such sets, and therefore an infinite number of questions.

We have thus reduced problems about sets of dominoes to problems about machines, and we have established results about dominoes by appealing to known results about machines. The next step is to reduce the question of interpreting a formula in logic to the problem of solving a set of dominoes. Since the condition that a set of dominoes has a solution can be expressed by a simple formula in logic, this reduction yields an answer to a long-outstanding decision problem in logic.

If we wish to express the condition that a set of three domino types has a solution in the first quadrant of our infinite plane, we think of the familiar Cartesian coordinates for the positions of dominoes in the quadrant and represent each domino by a predicate: Axy, for example, indicates that domino A occurs at position (x,y). If we use x' for $x + 1$, the required condition can be



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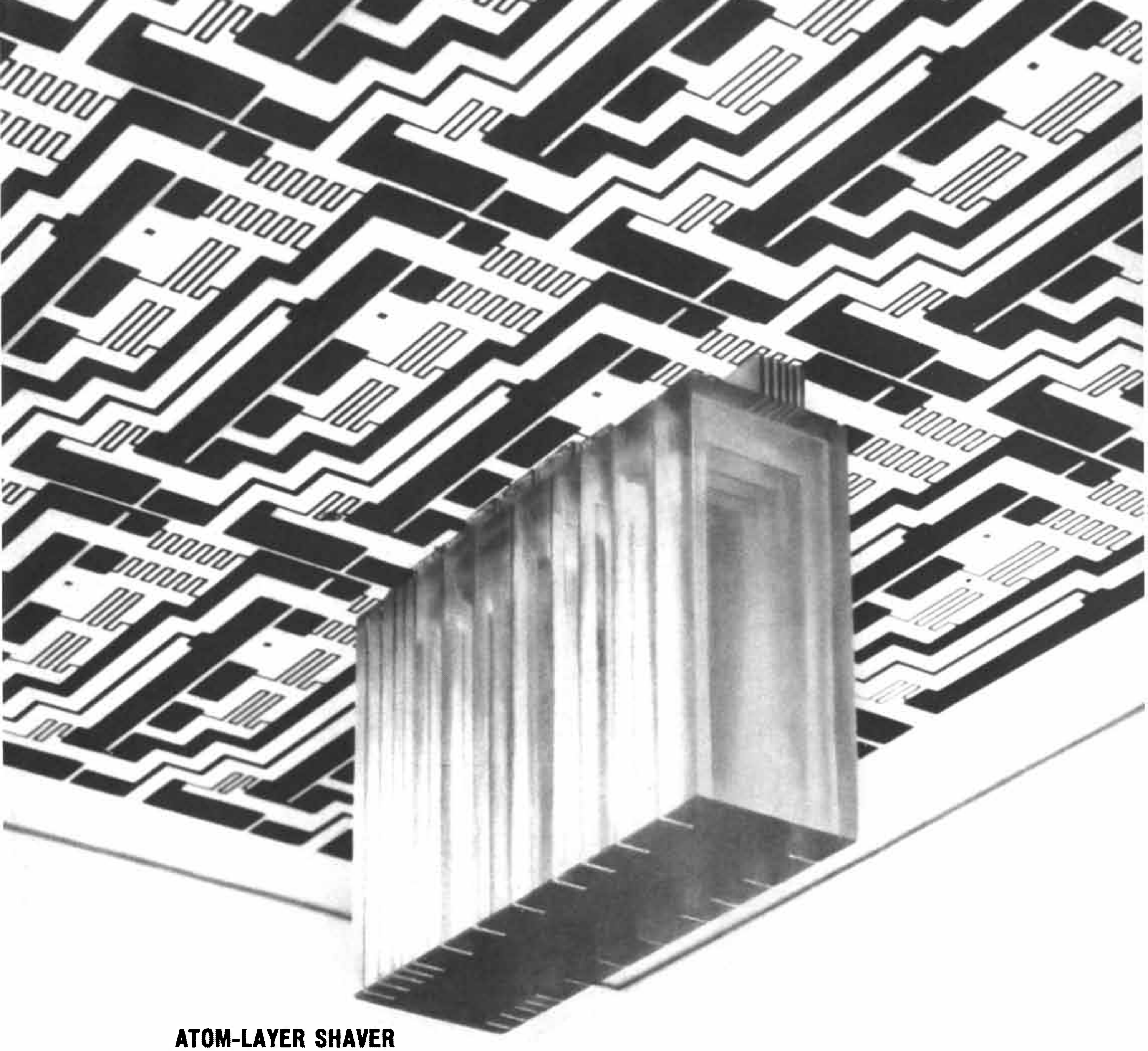
SOLUTION TO 10-DOMINO PROBLEM is a rectangular block of 36 dominoes, two of which are separated by heavy black line through center of illustration. The solution is not unique, that is, other configurations of the 10 dominoes are possible and equally acceptable.

given by a number of clauses that require very few quantifiers (constructions with "for all" and "there is"). We are generous only with such finite operations of formal logic as "not," "and" and "or" [*see illustration on page 102*]. We can conclude that for any given set of dominoes we can find a corresponding "*AEA* formula" (a sentence beginning "For all *x* there is a *y* such that for all *z*...," followed by a logical combination of predicates without quantifiers) such that the set has a solution if and only if the formula is not self-contradictory. In other words, we can translate a domino question into a logical formula by specifying certain constraints and then determine if the domino set is solvable by seeing if the formula is or is not self-contradictory. Therefore, since the general domino problem is unsolvable, there is no general method for deciding if an arbitrary *AEA* formula is self-contradictory.

The result is useful because the complexity of formulas in logic is to a large extent measured by the number and order of quantifiers, and the formulas of logic are often put into different classes according to the structure of quantifiers. It is surprising that as simple a class as that of *AEA* formulas (with three quantifiers only) is undecidable. In fact, with this result the decision problems for all quantifier classes are answered. Given any string of quantifiers we can now tell if the class of formulas determined by it is decidable.

The decision problem of logic is significant because all mathematical theories can be formulated in the framework of elementary logic. The question of whether or not a formula (*F*) can be derived from a set of axioms (*A*) is reduced to deciding if the logical formula "*A* but not *F*" is not self-contradictory. In this sense all mathematics is reducible to logic. Indeed, one measure of the complexity of a mathematical problem is given by the structure of its corresponding formula in logic. It is therefore an important enterprise to determine the complexity of various classes of logical formulas.

We can justifiably say that all mathematics can be reduced, by means of Turing machines, to a game of solitaire with dominoes. In most instances the reduction does not make a mathematical problem any easier to handle. Nevertheless, proving certain problems to be unsolvable by computer can be facilitated by reducing them to domino problems.



ATOM-LAYER SHAVER

How do you trim a resistor only 400 atom layers thick? Western Electric faced this problem in thin film circuits being manufactured for use in advanced communications equipment for the Bell telephone network.

Resistance values in such circuits are determined by pattern geometry, since film thickness is approximately uniform throughout. Resistance can be increased by decreasing the thickness of the film.

With film this thin, physical grinding or polishing is out of the question; but the same effect can be achieved by converting part of the film to nonconducting tantalum pentoxide. And this can be done by anodizing the film in an electrolytic bath.

The problem here, however, is how to anodize only those portions of the circuit requiring adjustment. No masking procedure proved satisfactory. Western Electric engineers solved the problem with a lucite block having a raised area that is a precise mirror image of those parts of the circuit requiring adjustment.

Slots 10 mils in diameter are machined into the block which is then placed in the anodizing bath. Capillary action pulls the liquid up through the slots and into the raised area. When lowered onto the block, the circuit touches only the raised portions. Hence the liquid can reach only the desired sections of the circuit.

Manufacturing ingenuity of this order is Western Electric's job within the Bell System. It is one of the reasons Bell System communications are the world's best.

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THE ICE FISH

This oddly shaped and nearly transparent denizen of antarctic waters lacks two characteristics once thought to be present in all vertebrates: it has no red blood cells and no hemoglobin

by Johan T. Ruud

Shortly after I received my undergraduate degree in zoology I spent a season in the Antarctic aboard the whaling factory ship *Vikingen*. One day in October, 1929, as the ship lay at anchor in a fjord of the South Atlantic island of South Georgia, I walked along the deck and stopped to watch some members of the crew get ready for a fishing trip in the fjord. One of them, an old whale-flenser who had spent several seasons around South Georgia, said to me: "Do you know there are fishes here that have no blood?" Certain that he was trying to pull a greenhorn's leg, I answered: "Oh, yes? Please bring some back with you."

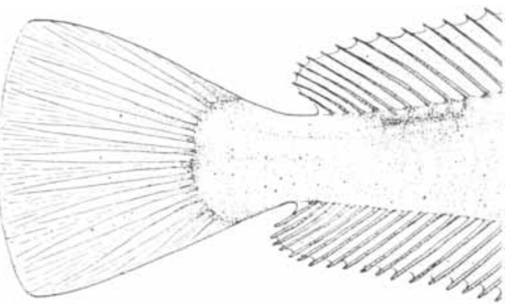
Knowing my animal physiology, I was perfectly sure that such a fish could not exist; in fact, many textbooks firmly state that all vertebrates possess red blood corpuscles containing the respiratory pigment hemoglobin. There are a few trivial exceptions to this rule. The larvae of the common eel do not develop red blood corpuscles until they metamorphose into young adults. The lamprey, the primitive eellike fish that feeds by sucking the blood of other fishes, has a respiratory pigment that is slightly different from hemoglobin.

When the flenser and his friends returned from their day's fishing, I asked them: "Where are your bloodless fish?" As I expected, they replied that they had not caught any. Then, after my return home in 1930, I happened to mention the episode to a fellow student, Ditlef Rustad. Two years earlier Rustad had spent a season in the Antarctic as the biologist on a Norwegian expedition, and much to my surprise he said: "I have seen such a fish." He produced photographs of what he called a "white crocodile fish," which he had examined at Bouvet Island in the South Atlantic.

The seemingly bloodless fish proved to be a member of the chaenichthyid family; the family is one of many in the order Perciformes, or perchlike fishes, the largest and most diverse group of bony fishes. Within this enormous order the chaenichthyids belong to the suborder Notothenioidei, a group of fishes found exclusively in the Antarctic or waters adjacent to it. On the basis of Rustad's photographs the Swedish ichthyologist Orvar Nybelin later declared that the crocodile fish from Bouvet Island was a new species, which he named *Chaenocephalus bouvetensis*. This species was distinct from another species of the same genus: *C. aceratus*, which had been known from South Georgia and other islands in the region. In his description of the new species, published in 1947, Nybelin quoted Rustad to the effect that the blood of the fish was colorless and noted that *C. aceratus* was also said to have colorless blood. So it was that 20 years after Rustad's visit to Bouvet Island the relevant ichthyological literature mentioned for the first time a fact of which whalers in the Antarctic had been aware for half a century. Only one earlier reference to an antarctic fish with colorless blood is known: in 1931 L. Harrison Matthews, now scientific director of the Zoological Society of London, mentioned in his book *South Georgia* that such fishes were found there and also that their gills were white instead of the usual red. The whalers had called the fishes crocodile fish because of the shape of their jaws or ice fish because of their transparency.

In 1948 my attention was directed to the ice fish for a second time. One of my students, Fredrik Beyer, returned that year from the Antarctic, where he had served as the biologist accompanying the "Brattegg" expedition. He brought back with him some specimens of a third chaenichthyid species—*Champsocephalus esox;* they had been caught with hook and line in the harbor of Punta Arenas, the subantarctic port in the Straits of Magellan. Beyer reported that when the fish were alive they had had creamy white gills and colorless blood.

A further opportunity to look into the riddle of the ice fish came in 1950, when a whaling company operating around South Georgia asked our group at the University of Oslo to undertake



ANTARCTIC ICE FISH caught off the island of South Georgia is a member of the

a survey of the South Georgia "cod"—actually a species of the nototheniid family, which, like the chaenichthyids, belongs to the Notothenioidei. This fish was so common in those waters that the development of a commercial fishery was being considered. Another of my students, Steinar Olsen, undertook the survey; he also promised to keep his eyes open for any species of ice fish he might run into. In 1951 Olsen returned with preserved specimens of three separate species of ice fish—and samples of their blood. The blood was nearly transparent, with a slightly yellowish cast. Under the microscope a few cells could be recognized as white corpuscles, but neither red corpuscles nor any blood pigment could be found.

So far, so good: we had some facts to go on. The ice fish evidently lacked both red blood corpuscles and hemoglobin. But vertebrates ought to have some means of storing oxygen in their blood. On what kind of mechanism did the ice fish rely? The first step toward answering the question would be to determine the oxygen-storage capacity of a freshly drawn sample of blood, and to do this it would be necessary to go to the Antarctic equipped with the appropriate apparatus. My chance came in 1953, when I volunteered as leader of an international whale-marking expedition.

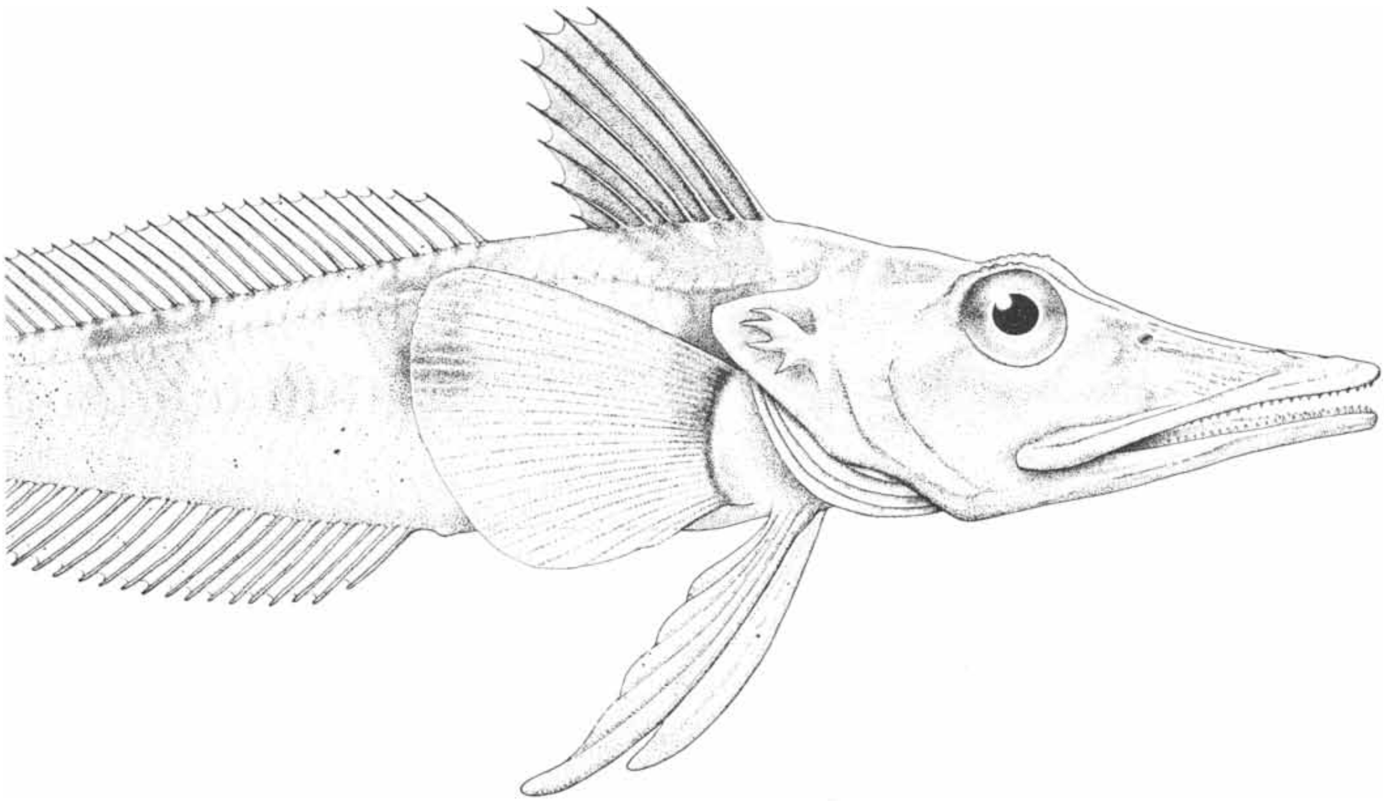
Our plan was to cruise in antarctic waters for six or seven weeks before the 1953–1954 whaling season began, marking as many whales as possible; our marking party would then be landed at Husvik Harbor on South Georgia just before Christmas to await a vessel due to sail back to Europe sometime in January. This schedule would give me two or three weeks on South Georgia during which I might have an opportunity to catch and study some ice fish.

Everything went as planned; we landed at South Georgia a few days before Christmas and three ice fish—all of them belonging to the local species *C. aceratus*—were brought to me on the first and second day of my visit. This was before I had been able to set up my little laboratory and test my apparatus. The obvious thing to do was to draw the blood from the specimens and store it in a refrigerator until I had everything under control; at the same time I assumed that additional ice fish could be obtained more or less at will.

The gills of *C. aceratus* were indeed creamy white, and the freshly drawn blood was nearly transparent. I found that, if the blood was left undisturbed, it clotted to the consistency of jelly in two or three minutes. When the blood was spun in a centrifuge, a sediment of white corpuscles settled out of it. This sediment constituted less than 1 percent of the blood by volume; the fluid above it was as clear as water.

After the blood samples had been adequately aerated, I determined their oxygen content; it was .67 percent by volume. This was a surprisingly low value. Ice fish are not small; some are two feet long or longer. It is generally assumed that a good-sized animal must have some reasonably efficient means of storing oxygen in its blood, so that its circulatory system can carry this vital element from the respiratory membranes to the tissues in the body most distant from them. Therefore my first conclusion was that something was wrong either with my apparatus or with the stored blood samples.

To check the apparatus I ran an analysis of the oxygen content of my own blood and the blood of some red-blooded nototheniid fishes; everything came out correct. Since there was no experimental error, the next check required another ice fish. Then my wait for more specimens of ice fish began. They seemed to have disappeared completely from the vicinity of Husvik Harbor; no ice fish entered our fish traps,



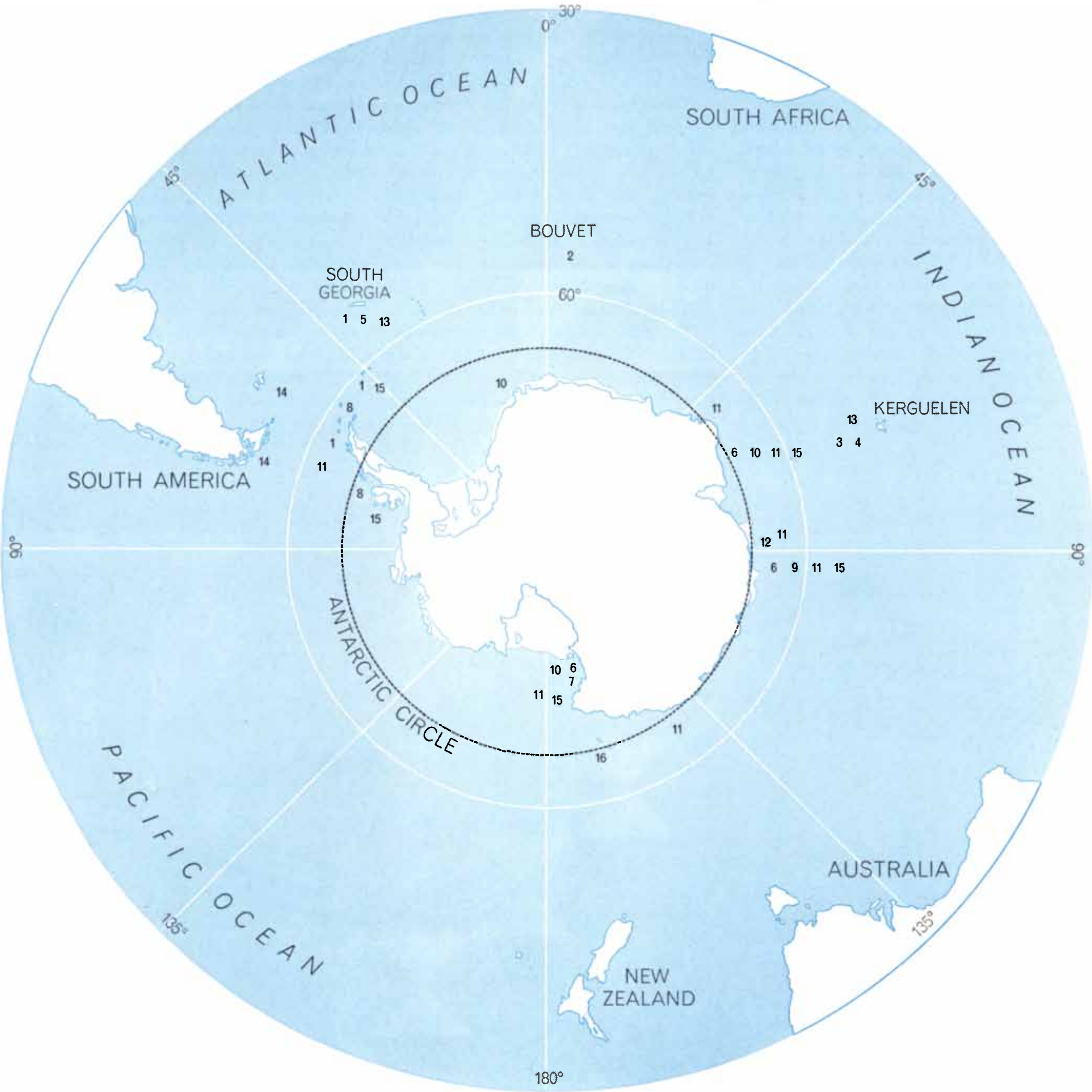
species *Chaenocephalus aceratus*. It has the large mouth and slim body characteristic of all 16 species in the family Chaenichthyidae (*see illustration on next two pages*). This species lives on the bottom. It is not a small fish; it grows to a length of about two feet.

and none took my baited hooks. As the day of our marking party's departure for Europe drew near I sent out an appeal to all the other whaling stations on South Georgia. Success! Felix Richards, the physician at the Leith Harbor station, appeared one afternoon in a motorboat carrying a live ice fish in a barrel of seawater.

I went to work immediately with some freshly drawn blood. The average of eight analyses was .72 percent of oxygen by volume—a result essentially the same as the earlier one. It was evident that the oxygen in saturated ice fish blood is no more than the amount the blood plasma can take up in solution; no other mechanism for the storage of oxygen could possibly be present.

This conclusion raised two related questions. First, how is it possible for a vertebrate of this size to survive in spite of what amounted to a complete anemia? Second, how did this lack of red blood corpuscles and hemoglobin evolve? The questions can be asked about all 16 species of chaenichthyid fishes. So far, however, the only species for which the oxygen capacity of the blood has been determined is *C. aceratus*. Let us examine what is known of the ecology of this species to see what light it may cast on our two questions.

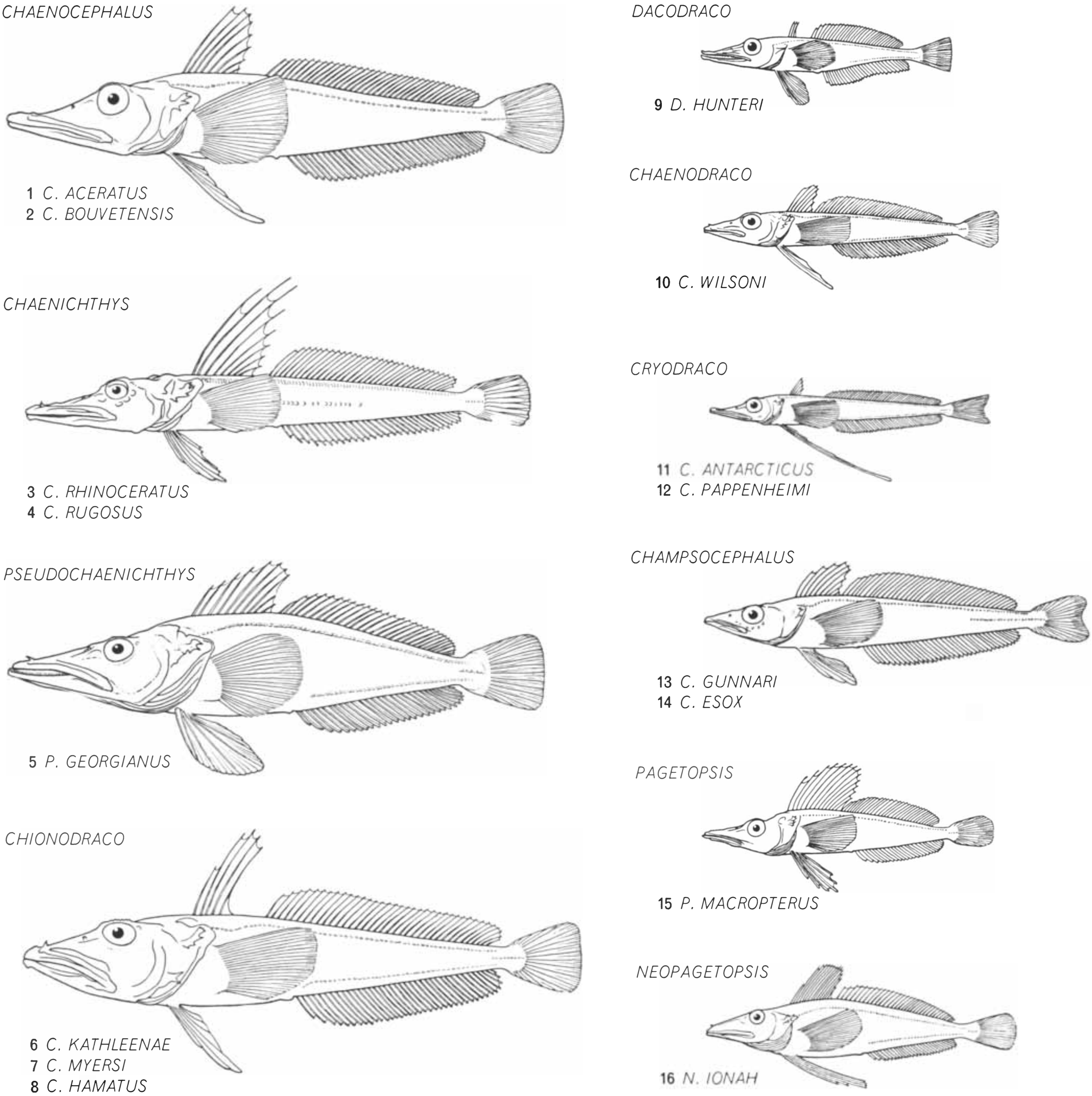
First, Olsen's studies of 1950 and 1951 on South Georgia showed that although the adults of two other local chaenichthyid species live in the open ocean, feeding on the same shoals of



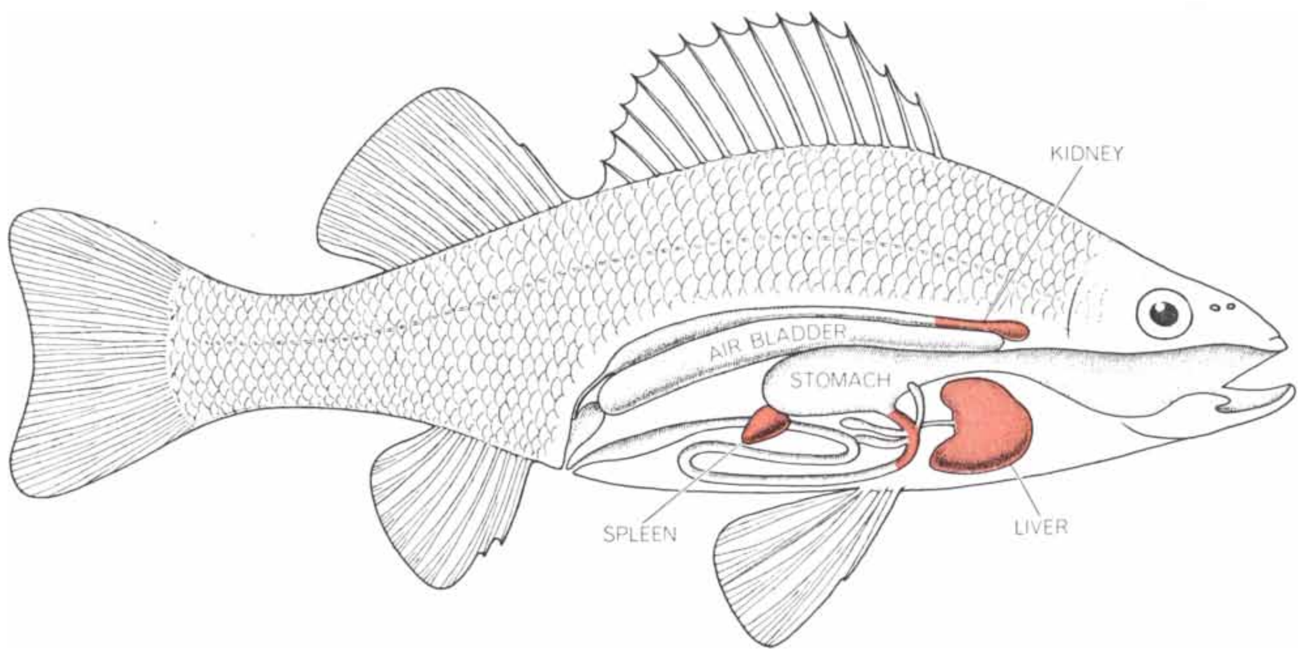
DISTRIBUTION of the various species of ice fish in antarctic and adjacent waters is plotted on this map. The first specimen of this family was taken near Kerguelen Island early in the 19th century and described in 1844 by Sir John Richardson, who placed it in a new genus, *Chaenichthys*. The newest family member is *Chionodraco myersi*, described in 1960 by Hugh H. DeWitt and

shrimplike krill that are the staple food of the baleen whales in antarctic waters, the young of these species and both the young and the adults of *C. aceratus* live near the bottom in deep fjords and along the continental shelf. This means that these particular ice fishes have a quite stable cnvironment; these deep waters are well aerated, rich in food and vary in temperature only a few degrees throughout the year (from 2 or 3 degrees above zero centigrade to 1.7 degrees below zero). This steady low temperature is significant because in cold-blooded animals such as fishes the consumption of oxygen roughly doubles with a rise in temperature of 10 degrees C. It appears that even during the cool antarctic summer *C. aceratus* moves from offshore waters to deeper ones, and so avoids the increase in metabolic rate that would result from an increase in the water temperature.

Next, the shape of the ice fish's body —the big head and mouth and the rather narrow body and tail—suggests a sluggish way of life. These antarctic fishes resemble the angler fish, the sculpin or the sea robin of warmer waters; can we assume that their existence is somewhat similar? Imagine an ice fish resting on the bottom waiting for prey—mostly smaller fishes—to come within reach of a quick, snapping movement. The lurking ice fish is nearly invisible; except for a few dark spots arranged in vertical bands its body is transparent, merging almost perfectly with the stems of the surrounding kelp.



James C. Tyler. This species and *Cryodraco pappenheimi* are the only two ice fish that are not surely known to have white gills or colorless blood. The outline drawings show the conformation and the relative size of representative species among the 10 genera that comprise the ice fish family; each is shown at one-sixth of natural size. Where several species are named only the first is illustrated.



BLOOD-PRODUCING ORGANS of the spiny-rayed fishes are shown in this drawing of a sectioned yellow perch. They are the front portion of the kidney, the front portion of the alimentary tract, the spleen and, to a lesser extent, the liver. A microscopic examination of 18 spleens taken from specimens of *C. aceratus* revealed no evidence of the development of red blood corpuscles.

The size of its mouth means that quite large prey can be taken with a single bite; thereafter the ice fish can take a long rest while it digests the food that came its way.

What, in terms of oxygen demand, must the ice fish accomplish in the course of a quick meal of this kind? For the first stage of muscular activity no oxygen is required; the dominant chemical event is the production of the waste product lactic acid. It is only later that oxygen is needed, partly for the combustion of the lactic acid and partly for the regeneration of other substances involved in the first stage. This oxygen debt is paid off by drawing on the store of oxygen held in solution in the blood plasma. Thus far in the sequence, at least, the anemic ice fish is no worse off than any other vertebrate.

In vertebrates that have red blood corpuscles the oxygen removed from the blood plasma is readily replenished by drawing on the oxygenated hemoglobin in the red cells. Moreover, the amount of oxygen stored in the oxygenated hemoglobin is usually much greater than the amount dissolved in the plasma. For example, the blood of two specimens of red-blooded nototheniid fishes I examined on South Georgia respectively contained oxygen at the volume levels of 5.99 percent and 6.24 percent. This is an oxygen capacity of the same order of magnitude as that possessed by fishes that live under similar circumstances in arctic waters; in both cases about 90 percent of the available oxygen is bound to the hemoglobin molecules in the red cells.

What can the anemic ice fish substitute for this second store of oxygen on which most vertebrates draw? What alternative mechanism exists for paying the oxygen debt built up in muscles and other tissues? The oxygen removed from the blood plasma can only be replaced by means of a quicker intake of oxygen from the environment, together with a quicker or greater transport of oxygen from the site of intake to the site of consumption. These two generalized mechanisms are exactly the ones on which I believe the ice fish relies.

To consider oxygen transport first, I am fairly confident that compared with other fishes the ice fish has a larger volume of body fluid and blood. The heart of the ice fish is unusually well developed, and the only red muscle to be found in the fish is the dilated part of the aorta called the bulbus arteriosus. This suggests that the circulation of the blood through the ice fish's gills and body is strong and persistent.

As for the intake of oxygen from the surrounding medium, two anatomical facts must be considered. First, the gill chamber of the ice fish appears quite large, but measurements reveal that the gill surface area is not exceptional in size. Moreover, studies soon to be published by Jon Steen and Trom Berg disclose that the epidermal membrane covering the gills is fairly thick; this does not favor a quick exchange of gases.

What may be significant is the second fact: the ice fish is almost completely without scales, which means that respiration can occur through the naked skin over most of its body. A former student, Finn Walvig, has examined the skin's microscopic structure and found the skin richly supplied with blood vessels. The space between these vessels and the surrounding water is so large, however, that the ice fish's skin is also not particularly well suited to the exchange of gases.

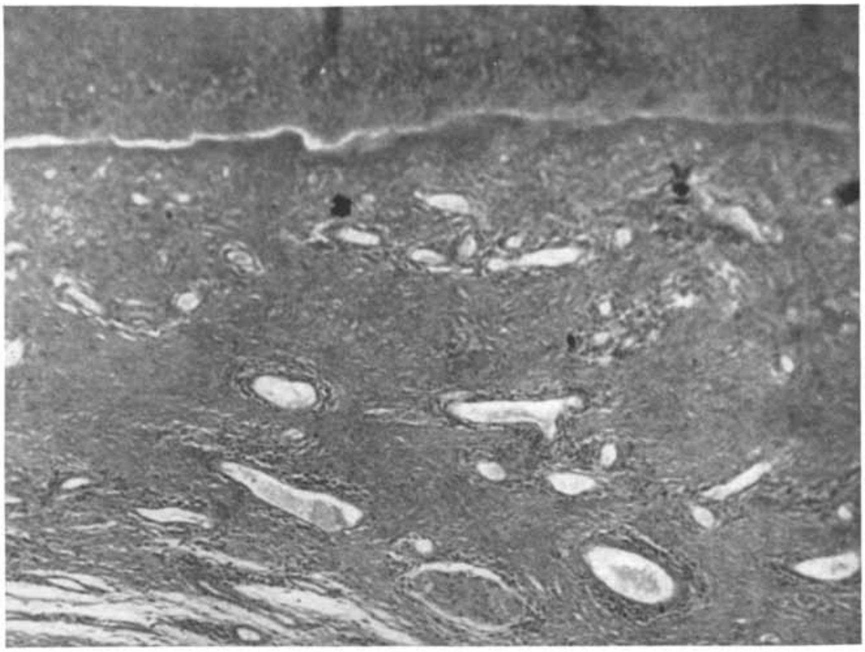
We must therefore assume that the ice fish's respiratory exchange of gases is not unusually effective. It remains possible that the ice fish overcomes its oxygen handicap to some extent by circulating an unusually large volume of body fluid; this is known to be the case in other fishes under emergency oxygen conditions. What remains to be determined is to what extent, if any, the ice fish may be dependent on anaerobic (oxygenless) metabolism for its survival.

Thus far I had learned that five of the 16 species of chaenichthyid fishes had white gills and colorless blood. Was this true of the family as a whole? The reader may have already wondered why early descriptions of the various species belonging to this family make no mention of gill color. The explanation is simple. Almost without exception the fish collections brought back from the Antarctic by explorers were preserved in alcohol; this bleaches the specimen's gills and sometimes further discolors them because the alcohol extracts pigments from the body of the specimen. The ichthyologist whose eventual task it is to describe such preserved fishes cannot possibly give any verdict about the original coloration of the gills; indeed, he can be expected to assume that in life they were the usual red color. Only if the man who actually collected the fish and saw it alive has made a note of the gill color—as Rustad did for *C. bouvetensis*—will the describer have the benefit of this information.

Fortunately there are other ways to overcome this absence of data, and I believe I have done so for 11 of the 16 chaenichthyid species. In the course of my work on *C. aceratus* I observed that the clot of blood remaining in the bulbus arteriosus of the fish after death had a consistency and appearance quite different from clots found in the bulbus of red-blooded fishes. The clot in a red-blooded fish is soft and opaque; under the pressure of a needle it disintegrates easily into individual corpuscles, the majority of which can be recognized as red blood cells. A clot removed from the bulbus of an ice fish, on the other hand, is nearly transparent and has a rubber-like consistency; it resists any attempt to break it down into smaller particles. This is exactly what one would expect of clotted blood plasma containing no cells apart from a minute number of white corpuscles.

Through the courtesy of F. C. Fraser, keeper of zoology at the British Museum (Natural History), I was able to remove and examine the clots from the bulbus of 11 separate species of chaenichthyid fishes in the museum's collection. All the clots appeared to be much the same as those I had found in *C. aceratus*. Although such an observation is not conclusive, I felt it was safe to assume that 12 species of chaenichthyid fishes, and probably all the other chaenichthyid species, have in common an almost complete lack of red corpuscles.

Our second basic question—how this anemia arose—must now be examined. Are the chaenichthyid fishes completely unable to produce red corpuscles? Or is the formation of red cells only suppressed and are the few cells that form nonetheless then destroyed so rapidly that they are extremely scarce or totally missing? In a normal bony fish the blood-forming tissues are the kidney, the spleen, the upper end of the alimentary tract and, to a lesser extent, the liver. Because the spleen is easy



SKIN SECTION from the forward edge of an ice fish's pelvic fin reveals the layer just below the epidermis (*top*) that is richly supplied with capillaries and larger blood vessels. Although the number of blood vessels elsewhere in the skin of *C. aceratus* varies, the overall vascular system is well developed. The author suggests that the blood vessels of the skin constitute a second respiratory surface supplementing the ice fish's inefficient gills.

both to dissect out and to preserve, Walvig and I decided to enlist the cooperation of the shore party at Husvig Harbor on South Georgia in collecting a number of ice fish spleens. Walvig analyzed the collection and published his results in 1958; in summary, no cells could be found that appeared to be red corpuscles in the making. This finding reinforced my opinion that the red-cell deficiency is total, at least in the case of *C. aceratus*.

Other findings cast doubt on whether this is true of all chaenichthyid species. The Soviet biologist L. D. Marcinkevic examined seven chaenichthyid species during an Antarctic expedition in 1957. His conclusions were published in 1958; he states that he has found red corpuscles in limited numbers in the fishes' blood vessels and also that he has found evidence of red-cell formation in the liver. Although the scarcity of red cells in Marcinkevic's specimens—they are about half as abundant as white cells—means that they could play no significant part in oxygen transport, the possibility remains that what I have assumed to be a total deficiency may instead be only partial. If such is the case, further investigation may reveal varying degrees of reduction in the number of red corpuscles and the amount of hemoglobin in the separate species of chaenichthyid fishes.

With this theoretical consideration in mind, James C. Tyler of the Academy of Natural Sciences in Philadelphia has proposed that there may exist "white-blooded," or hemoglobin-deficient, species of fish among several other antarctic fish families. In fact, two nototheniid species he collected in 1958 and 1959 proved to possess fewer red cells and lower amounts of hemoglobin than is normal among bony fishes. The deficiencies, however, were far from being in a class with those of *C. aceratus* and the other species of the chaenichthyid family I have examined.

Without attempting to guess what future studies will show, I believe that the answer to the question of how these anemic fishes have managed to evolve is to be found in their unique ecological setting. In the case of the ice fish, for example, its major physiological asset—an unusually large volume of blood circulation—by itself would probably not be enough to keep the animal alive in temperate waters. Only when this characteristic is combined with the Antarctic's low and stable water temperature and that environment's abundant supply of food and oxygen is the survival of these peculiar animals possible. In fact, it is hard to imagine any other marine or freshwater environment that would offer a similar chance of survival should another family of anemic fishes begin to evolve elsewhere in the world.

MATHEMATICAL GAMES

A selection of elementary word and number problems

by Martin Gardner

This month I present one of my occasional collections of short problems. As usual, only elementary mathematical skills are called for, and the problems are purposely varied in difficulty and in the type of mathematics involved. The first problem, as a matter of fact, is not mathematical but linguistic; whenever word puzzles have appeared in the department, readers have seemed to enjoy them. The answers to the problems will be given next month.

1.

Dmitri A. Borgmann, the distinguished expert on wordplay, has written a book called *Language on Vacation* (just published by Scribners) that can best be described by borrowing an adjective from the movie *Mary Poppins*—supercalifragilisticexpialidocious. It is the best, most comprehensive book ever written on what Borgmann likes to call "recreational linguistics." Borgmann's first objective is "to elevate recreational linguistics to the same high level of esteem now enjoyed by recreational mathematics." Readers with appetites "jaded by the ubiquitous crossword puzzle," as Borgmann puts it, will find the book an almost bottomless mine of problems involving palindromes, reversals, anagrams, antigrams, pangrams, geometric word forms, curious letter patterns, numerological aspects of words and hundreds of other oddities previously known only to a small circle of logophiles.

To honor the appearance of this remarkable compendium, here are some unusual word problems that arise in connection with a suggestion made last year by Nicholas Temperley, a student at the University of Cambridge. Temperley proposed that devotees of wordplay produce, as a working tool, an anagram dictionary. Every word in English is first converted to its "alphabetical anagram," in which its letters appear in alphabetical order. SCIENTIFIC, for example, becomes CCEFIIINST. These alphabetical anagrams are then arranged in alphabetical sequence to form the dictionary. Each entry in the volume is an alphabetical anagram, and under it are listed all the English words that can be formed with those letters. Thus BDEMOOR will be followed by BEDROOM, BOREDOM and all other words formed by those letters. AEIMNNOST will be followed by MINNESOTA and NOMINATES. Some entries even have mathematical interest. AEGILNRT, for instance, will be followed by such mathematical terms as INTEGRAL, RELATING and TRIANGLE as well as other words such as ALTERING. EIINNSTXY will be followed by both NINETY-SIX and SIXTY-NINE. AGHILMORT will have among its anagrams both ALGORITHM and LOGARITHM. If a crossword puzzle gives the clue BEAN SOUP and an indication that this is an anagram, someone armed with the anagram dictionary need only alphabetize its letters and look up ABENOPSU to find SUBPOENA. If the clue is THE CLASSROOM, it takes only a moment to discover SCHOOLMASTER.

Most of the entries will begin with letters near the front of the alphabet. Temperley estimates that more than half will start with *A*, which is to say that more than half of all English words contain *A*. (This is not true of common words, but rarer words tend to be longer and are more likely to have an *A*.) After *I* the number of entries will drop sharply. Beyond *O* the list is extremely short.

Can the reader answer these questions?

1. What will be the dictionary's last entry? (Place names, such as Uz, the home of Job, are not included.)
2. What will be the first and second entries?
3. What will be the last entry starting with *A*?
4. What will be the first entry starting with *B*?
5. An entry, ABCDEFLO, begins with the first six letters of the alphabet. What is the word?
6. What will be the longest entry that is itself a word? (Short examples include ADDER, AGLOW, BEEFY, BEST, DIPS, FORT.)
7. What will be the longest entry that does not repeat any letter?

2.

A young lady was vacationing on Circle Lake, a large artificial body of water named for its precisely circular shape. To escape from a man who was pursuing her, she got into a rowboat and rowed to the center of the lake, where a raft was anchored. The man decided to wait it out on shore. He knew she would have to come ashore eventually; since he could run four times faster than she could row, he assumed that it would be a simple matter to catch her as soon as her boat touched the lake's edge.

But the girl—a mathematics major at Radcliffe—gave some thought to her predicament. She knew that on foot she could outrun the man; it was only necessary to devise a rowing strategy that would get her to a point on shore before *he* could get there. She soon hit on a simple plan, and her applied mathematics applied successfully.

What was the girl's strategy? (For puzzle purposes it is assumed that she knows at all times her exact position on the lake.)

3.

This frustrating topological puzzle calls for a door key and a piece of heavy cord at least a few yards long. Double the cord, push the loop through the keyhole of a door as shown in the top drawing in the illustration on the opposite page, then put both ends of the cord through the projecting loop as in the middle drawing. Now separate the ends, one to the left, the other to the right [*bottom drawing*]. Thread the key on the left cord and slide it near the door, and secure the cord's ends by tying them to something—the backs of two chairs, for example. Allow plenty of slack.

The problem is to manipulate the key and rope so that the key is moved from spot *P* on the left cord to spot *Q* on the right cord. After the transfer the rope must be looped through the door in exactly the same way as before.

4.

This harmless-looking little problem

in combinatorial geometry, taken from an old, forgotten puzzle book, has more to it than first meets the eye. Forty toothpicks are arranged as shown at the top of the next page to form the skeleton of an order-four checkerboard. The problem is to remove the smallest number of toothpicks that will break the perimeter of every square. "Every square" means not just the 16 small ones but also the nine order-two squares, the four order-three squares and the one large order-four square that is the outside border—30 squares in all.

(On any square checkerboard with n^2 cells the total number of different rectangles is

$$\frac{(n^2 + n)^2}{4},$$

of which

$$\frac{n(n + 1)(2n + 1)}{6}$$

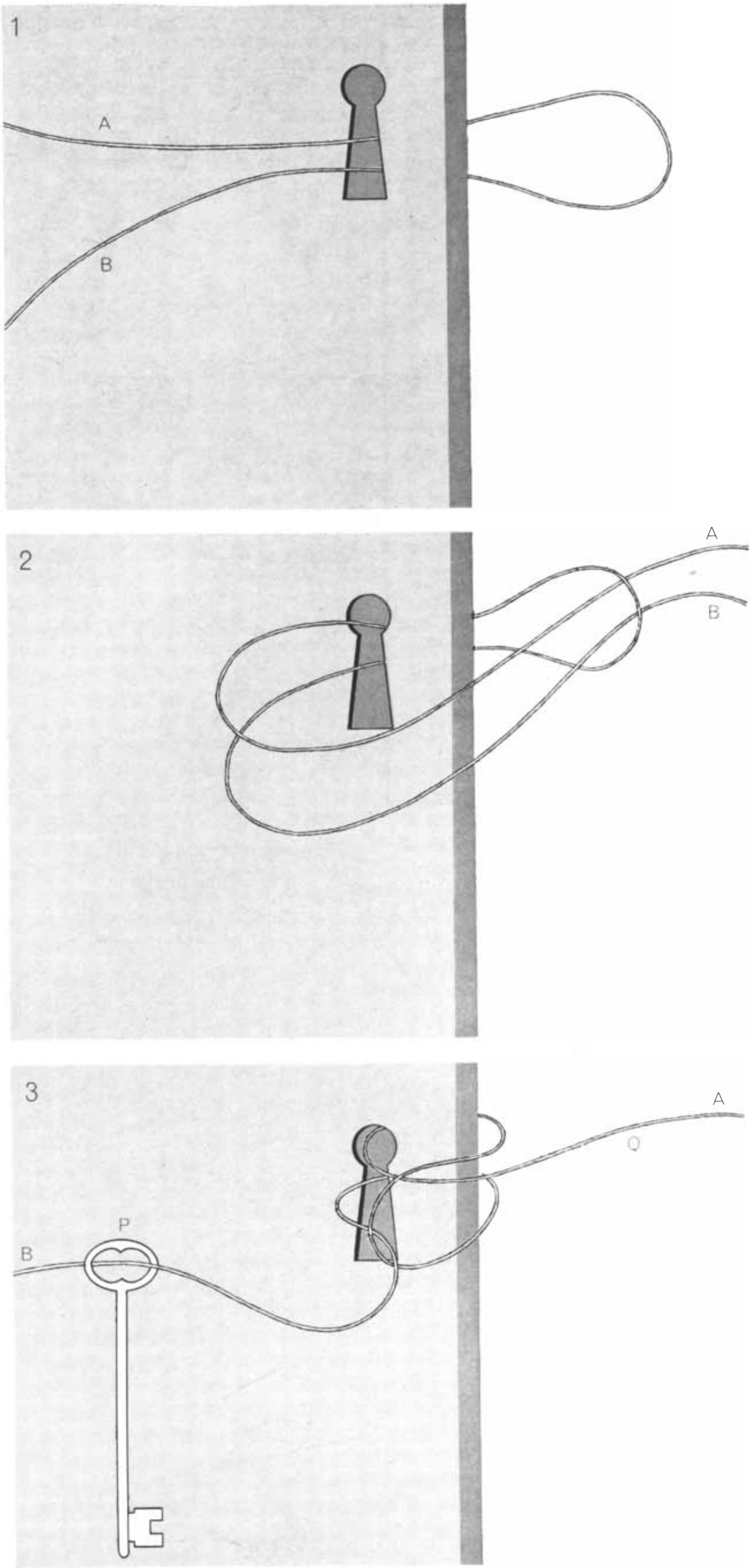
are squares. "It is curious and interesting," wrote Henry Ernest Dudeney, the noted British puzzle expert, "that the total number of rectangles is always the square of the triangular number whose side is n.")

The answer given in the old book was correct, and the reader should have little difficulty finding it. But can he go a step further and state a simple proof that the answer is indeed minimum?

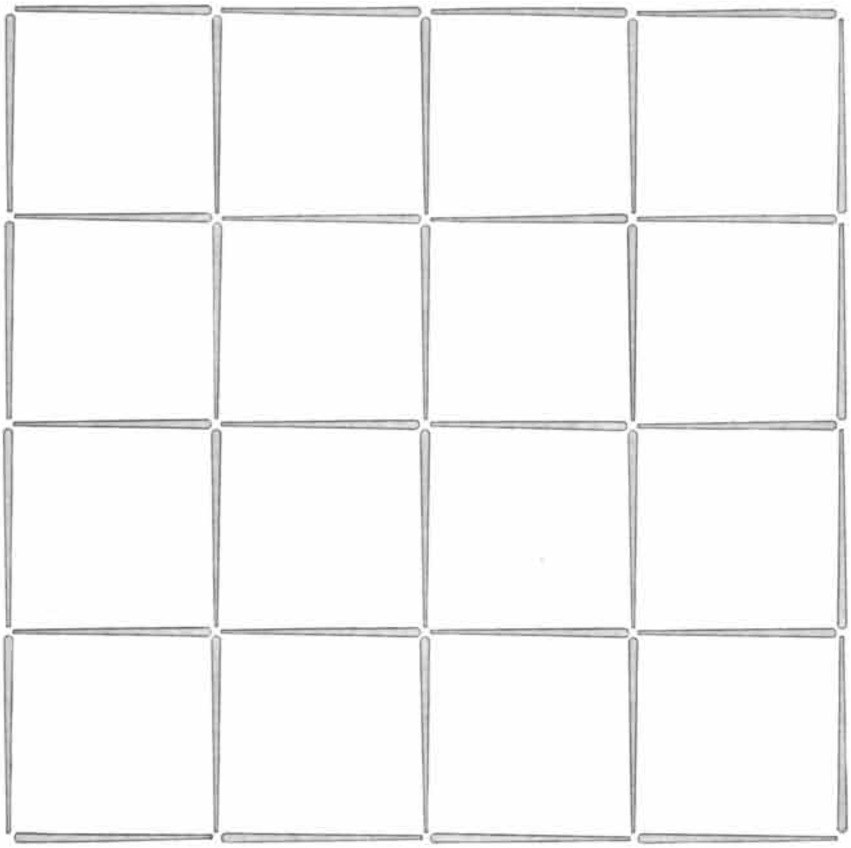
This far from exhausts the puzzle's depth. The obvious next step is to investigate square boards of other sizes. The order-one case is trivial. It is easy to show that three toothpicks must be removed from the order-two board to destroy all squares, and six from the order-three. The order-four situation is difficult enough to be interesting; beyond that the difficulty seems to increase rapidly.

The combinatorial mathematician is not likely to be content until he has a formula that gives the minimum number of toothpicks as a function of the board's order and also a method for producing at least one solution for any given order. The problem can then be extended to rectangular boards and to the removal of a minimum number of unit lines to kill all *rectangles,* including the squares. I know of no work that has been done on any of these questions.

The reader is invited to try his skill on squares with sides from four through eight; I shall present the best available solutions next month. A minimal solution for order-eight, the standard checkerboard (it has 204 different squares), is



Move the key from P *to* Q



A toothpick puzzle

not easy to find, and it will be disclosed next month for the first time.

5.

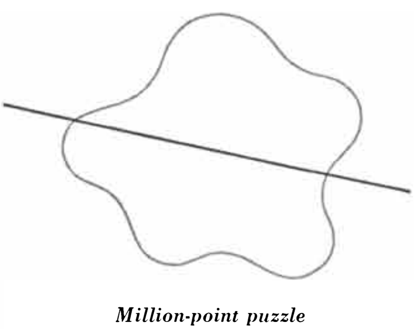
An infinity of points lie inside the closed curve shown below. Assume that a million of those points are selected at random. Will it always be possible to place a straight line on the plane so that it cuts across the curve, misses every point in the set of a million and divides the set exactly in half so that 500,000 points lie on each side of the line? The answer is yes; prove it.

6.

Gerald L. Kaufman, a New York City architect and the author of several puzzle books, devised this clever logic problem.

Three playing cards, removed from an ordinary bridge deck, lie face down in a horizontal row. To the right of a King there's a Queen or two. To the left of a Queen there's a Queen or two. To the left of a Heart there's a Spade or two. To the right of a Spade there's a Spade or two.

Name the three cards.



Million-point puzzle

7.

Five paper rectangles (one with a corner torn off) and six paper disks have been tossed on a table. They fall as shown in the illustration on page 120. Each corner of a rectangle and each spot where edges are seen to intersect marks a point. The problem is to find three sets of four "cocircular" points: four points that can be shown to lie on a circle.

For example, the corners of the isolated rectangle [*bottom right in illustration*] constitute such a set, because the corners of any rectangle obviously lie on a circle. What are the other two sets? This problem and the next are recent inventions of Stephen Barr, au-

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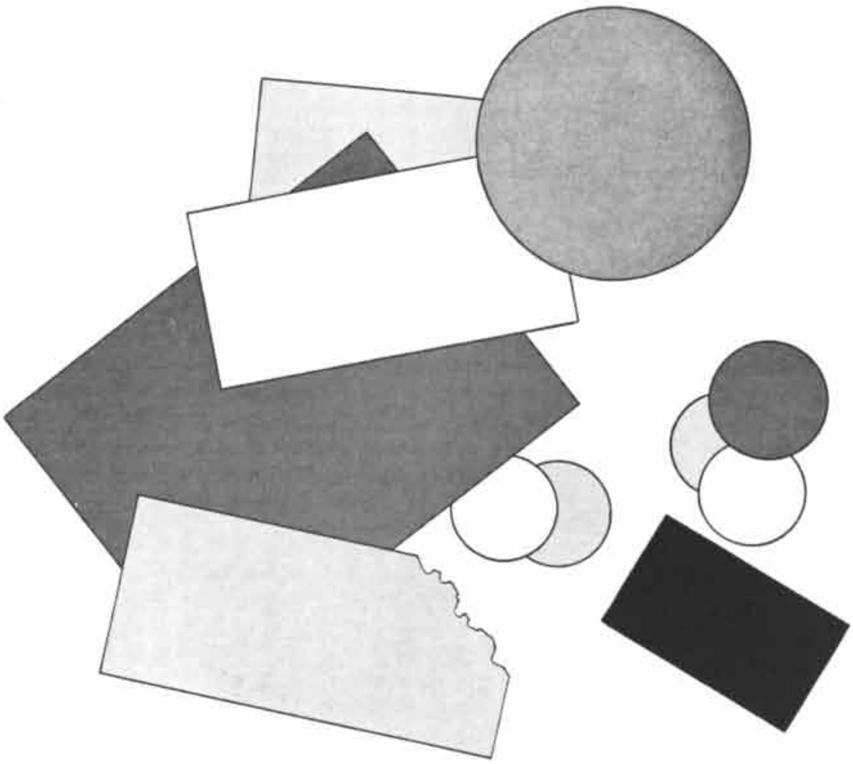

Find three sets of four cocircular points

thor of *Experiments in Topology* and *A Miscellany of Puzzles: Mathematical and Otherwise,* both published by Crowell. They will appear in a new puzzle book on which he is working.

8.

"Mathematicians are curious birds," the police commissioner said to his wife. "You see, we had all those partly filled glasses lined up in rows on a table in the hotel kitchen. Only one contained poison, and we wanted to know which one before searching that glass for fingerprints. Our laboratory could test the liquid in each glass, but the tests take time and money, so we wanted to make as few of them as possible. We phoned the university and they sent over a mathematics professor to help us. He counted the glasses, smiled and said:

" 'Pick any glass you want, Commissioner. We'll test it first.'

" 'But won't that waste a test?' I asked.

" 'No,' he said, 'it's part of the best procedure. We can test one glass first. It doesn't matter which one.' "

"How many glasses were there to start with?" the commissioner's wife asked.

"I don't remember. Somewhere between 100 and 200."*

What was the exact number of glasses? (It is assumed that any group of glasses can be tested simultaneously by taking a small sample of liquid from each, mixing the samples and making a single test of the mixture.)

9.

Recreational mathematicians have devoted much attention in the past to chessboard "tours" in which a chess piece is moved over the board to visit each square once and only once, in compliance with various constraints. Last year John Harris of Santa Barbara, Calif., devised a fascinating new kind of tour—the "cube-rolling tour"—that opens up a wealth of possibilities.

To work on two of Harris' best problems, obtain a small wooden cube from a set of children's blocks or make one of cardboard. Its sides should be about the same size as the squares of your chessboard or checkerboard. Paint one side red. The cube is moved from one square to an adjacent one by being tipped over an edge, the edge resting on the line dividing the two cells. During each move, therefore, the cube makes one quarter-turn in a north, south, east or west direction.

Problem 1. Place the cube on the northwest corner of the board, red side up. Tour the board, resting once only on every cell and ending with the cube

RECENT findings

RESEARCH LABORATORIES

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FERROELECTRICS

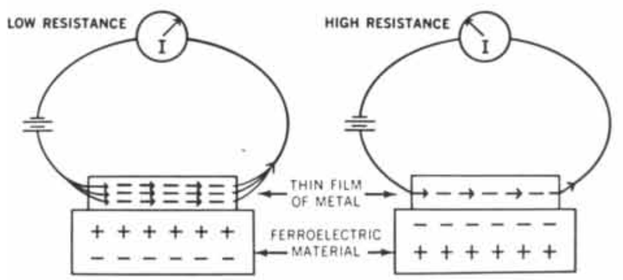
Ford scientists change certain properties of metals by applying polarized ferroelectric materials

It is well known that many of the physical properties of solids depend upon the number of free charge carriers (usually electrons) per unit volume. This number, and hence the properties, can be changed by placing the solid in an electric field so that more free charges are attracted to or repelled from a given unit volume. Previous attempts to accomplish control over the properties have used direct application of the highest attainable electric fields (approximately 10^7 volts/cm), and the observable effects have always been very small.

Ford Motor Company scientists have developed a method of changing the number of charge carriers in a solid by wedding a thin film of the solid to a crystal of polarized ferroelectric material (barium titanate, triglycine sulfate, and potassium dihydrogen phosphate, for example). Common ferroelectrics, in a polarized state, carry opposite electrical charges on opposite surfaces of the material, and the surface charge densities correspond to electric fields of 10^9 volts/cm. When a solid connected to a charging source is brought in contact with the charged surface of a polarized ferroelectric, the number of charge carriers per unit volume in the solid will change to cancel the surface charge of the ferroelectric (see diagram). The properties of the solid which depend upon charge carrier density can thus be modified.

This new method of changing the density of charge carriers in a solid is about 100 times more effective and much safer than the method utilizing the direct application of a high voltage electric field. In addition, the studies point the way to several new and useful devices such as computer memory elements, optical display devices and sensitive amplifiers.

Shown here is a diagram of how the resistivity of a thin metal film deposited on a ferroelectric material is modified by the polarization of the ferroelectric substrate. The ferroelectric is shown in a polarized state, i.e. with all its atomic cells or electric dipoles aligned parallel and opposite surfaces carrying opposite surface charges. (Since ferroelectrics are insulators, there is no way for these surface charges to flow together and cancel.) In the left-hand drawing, the charge on the surface adjoining the metal film is positive, thus attracting more negative free charges into the conductor and effectively decreasing its resistance. In the right-hand drawing, the polarization of the ferroelectric has been changed and the surface adjoining the metal film is negatively charged. Negative free charges thus are repelled from the conductor and its resistance is effectively increased.



PROBING DEEPER TO SERVE BETTER

Ford

red side up in the northeast corner. At no time *during* the tour, however, is the cube allowed to rest with the red side up. (NOTE: It is not possible to make such a tour from corner to diagonally opposite corner.)

Problem 2. Place the cube on any cell, an uncolored side up. Make a "reentrant tour" of the board (one that visits every cell once and returns the cube to its starting square) in such a way that at no time during the tour, including at the finish, will the cube's red side be up.

Both problems have unique solutions, not counting rotations and reflections of the path.

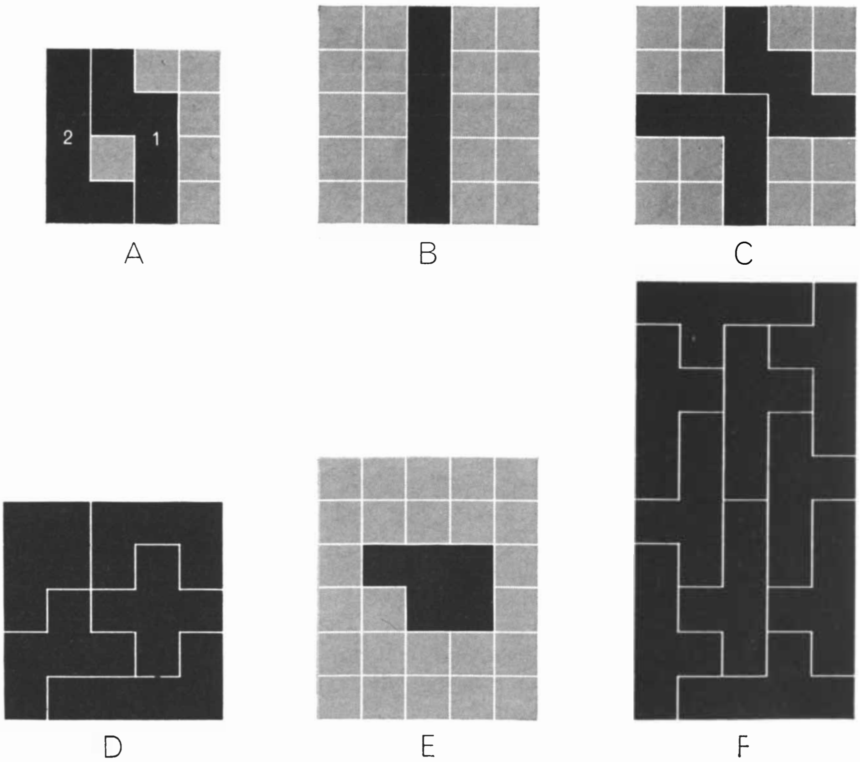
The first of last month's pentomino problems was to pick, from among the 33 different two-move pentomino games on the four-by-four board, the game that has only one winning reply by the second player. It is the game that was numbered 26 and is shown again at *A* in the illustration below. The first play leaves a space on the right that can be filled only by the *L*-pentomino. But if the *L* is placed in that space, the first player can win by playing on the left. If, on the other hand, the second player puts any piece except the *L* on the left, the first player can win by playing the *L* on the right. To win, therefore, the second player must place the *L* on the left as shown.

On the five-by-five board the first player has an obvious win by playing the *I*-pentomino in the center, as shown at *B* below. His opponent must play on one side and the first player then wins by playing on the other side. The shortest possible game on this board has two moves [*C*] and the longest has five [*D*]. The short-game pattern is unique, but there are many solutions to the long game.

The first player can win on the five-by-six board only if his first move is the one shown at *E*. There is no simple proof, and space does not allow showing correct responses to all possible second moves.

The *Y*-pentomino is rectifiable. The drawing at *F* shows the smallest rectangle that can be formed with replicas of this piece. The pattern illustrated is one of four possible rectangles.

I hope readers will understand that it was not possible to reply to some 100 correspondents who sent correct solutions to the interplanetary-code message in this department for August. More than half of these solutions included a correct interpretation of the final statement, identifying the earth as the source of the message.



Answers to pentomino problems

THE AMATEUR SCIENTIST

How to isolate from samples of topsoil microorganisms that secrete antibiotics

Conducted by C. L. Stong

Any pinch of topsoil taken from the ground in any part of the world could contain among its teeming millions of microorganisms a few that secrete antibiotic substances capable of being used in the treatment of such serious diseases as diphtheria, tuberculosis and leprosy. Do such organisms actually exist? No one knows, but the success more than a quarter of a century ago of the first effort to treat a patient with a secretion of the mold *Penicillium notatum* was an event of sufficient promise to have sent an army of biological prospectors into the field and to have kept them there ever since.

No precise count has been made of how many soil specimens these workers have examined. Estimates put the figure at close to a million. As in the case of mineral prospectors on the old Western frontier, however, few of these modern hunters have made lucky strikes. The million or so samples analyzed to date have yielded fewer than 500 organisms secreting substances that are poisonous to other organisms. Fewer than a dozen of the 500 can be used in the treatment of human disease, and the secretions of only five are routinely prescribed by physicians. All the others are either too weak or too toxic to human beings or are effective only in the test tube. Yet in spite of its many disappointments the quest continues.

Last year the quest was joined by Bill Hulett, a high school student in Charleston, Miss. He reports that the thrill of rediscovering penicillin and two other known antibiotics more than rewarded his many failures. "Anyone who likes to combine the joys of the open country with the fascinations of the laboratory," Hulett writes, "should make a hobby of hunting antibiotics. Soil organisms are fun to collect and interesting to grow. The analytical procedures are simple, inexpensive and full of surprises because the experimenter can never predict their outcome.

"My project began in 1963 when I came across a paper by the noted microbiologist Selman A. Waksman. In it he pointed out that although disease-producing organisms have been finding their way into the soil for millions of years, they have not crowded out all other organisms. Waksman suggested that, in the continuing struggle for survival, disease organisms in the soil must be destroyed by substances that are manufactured by other organisms.

"I wondered if such organisms inhabited our local soil. For background information I consulted my father, who is a physician, and borrowed some of his textbooks on bacteriology. Information on analytical procedures and culturing techniques was solicited from several manufacturers of antibiotics.

"During this preliminary phase I learned that the destruction of microorganisms is not difficult. Even bacteria that produce the most deadly diseases in man can be killed by fairly mild treatment with heat, acid, alkali and other chemical compounds. The trick is to kill the offending microorganism without harming the human host. The most widely and frequently used drug for accomplishing this is penicillin, the antibiotic discovered in 1928 by Alexander Fleming. Unfortunately penicillin is not effective against all diseases; neither is any combination of the other widely used antibiotics, which include streptomycin, Chloromycetin, Aureomycin and Terramycin. I learned too that all groups of microorganisms must be regarded as potential sources of useful antibiotic drugs and that the amateur has as good a chance as anyone of discovering them.

"With that background and encouragement I set up my experiment. My soil specimens were collected from a variety of nearby locations: at the base of an oak tree, from a pine woods, a pecan grove, a sumac thicket and so on. The culture that produced the most organisms came from a meadow. The one that produced the fewest—one—was collected near my house. Yet the organism in this specimen secreted an antibiotic! The specimen that produced the most antibiotics—three—was collected near a fishpond. In all, antibiotic activity was found in six out of 23 specimens—a good batting average in spite of the fact that the six represented only three antibiotics, all of which are well known.

"The soil organisms were cultured on several media to encourage growth of the maximum variety. Organisms that grow as colonies were then isolated and subcultured in nutrient broth. The broth was tested for antibiotic activity by saturating a small disk of blotting paper with the solution and placing it on a test culture of bacteria. Activity was indicated by a circular zone surrounding the paper disk in which the growth of the bacteria was inhibited. The width of the zone varies in proportion to the strength of the antibiotic activity.

"For test bacteria I used *Sarcina lutea*, the harmless organism adopted by the National Bureau of Standards for the control of commercial penicillin production. It is easily grown and responds uniformly to the presence of antibiotics. The zone of inhibition appears to the unaided eye as a clear circle surrounded by the bright yellow of the normal culture [*see bottom illustration on page 129*].

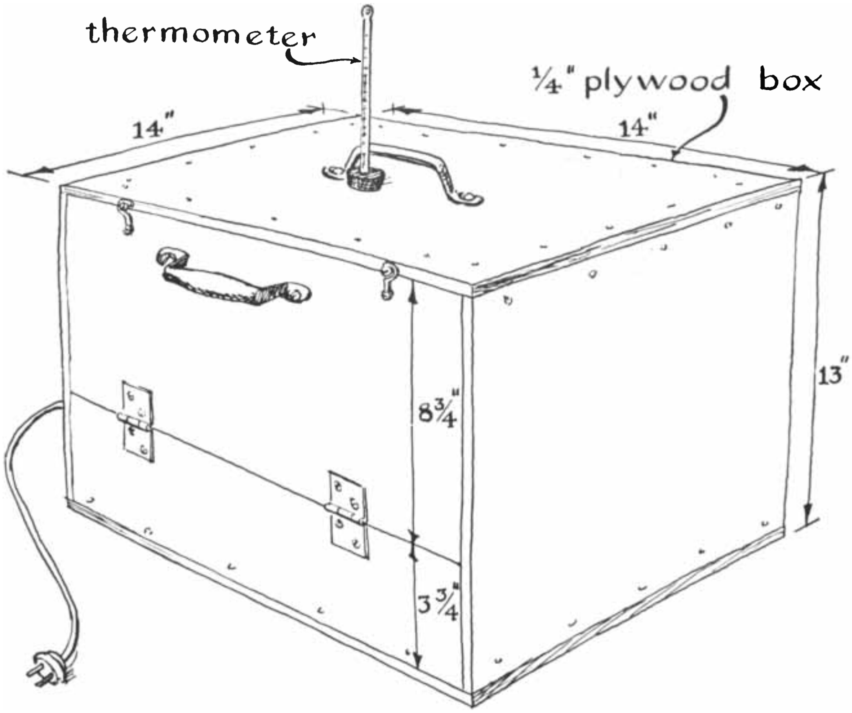
"To familiarize myself with the procedure I first made up a culture of *Sarcina lutea* and exposed it to several commercially prepared antibiotics. Small disks of blotting paper cut with a paper punch were moistened with drug solutions and placed on the plates of agar nutrient that had been freshly inoculated with *Sarcina lutea*. I had procured a culture of pure *Penicillium notatum* and cultivated it on nutrient broth under the same conditions I planned to use for culturing soil organisms. Blotting paper saturated with this broth was also tested on a nutrient agar plate of the *Sarcina lutea*. The resulting zones of inhibition varied from one to eight millimeters in width; the average was three millimeters.

"Some of the required apparatus, such as an incubator, can be constructed at home. I built an incubator of 1/4-inch plywood. It is essentially a box with a hinged door and an electric heater. The dimensions are not critical—any well-constructed cabinet of ample size will do. I joined the plywood rectangles by means of soft-pine corner strips that were fastened by brads and glue. The hinged door opened downward and was held shut by hooks or a magnetic latch of the kind used in kitchen cabinets. The latches, hinges, handles and other cabinet hardware were obtained from one of the large mail-order houses. The incubator was fitted with shelves cut from perforated aluminum of the do-it-yourself type stocked by most hardware dealers. One could substitute 1/4-inch-square wire mesh of the kind known as hardware cloth if perforated aluminum were not available.

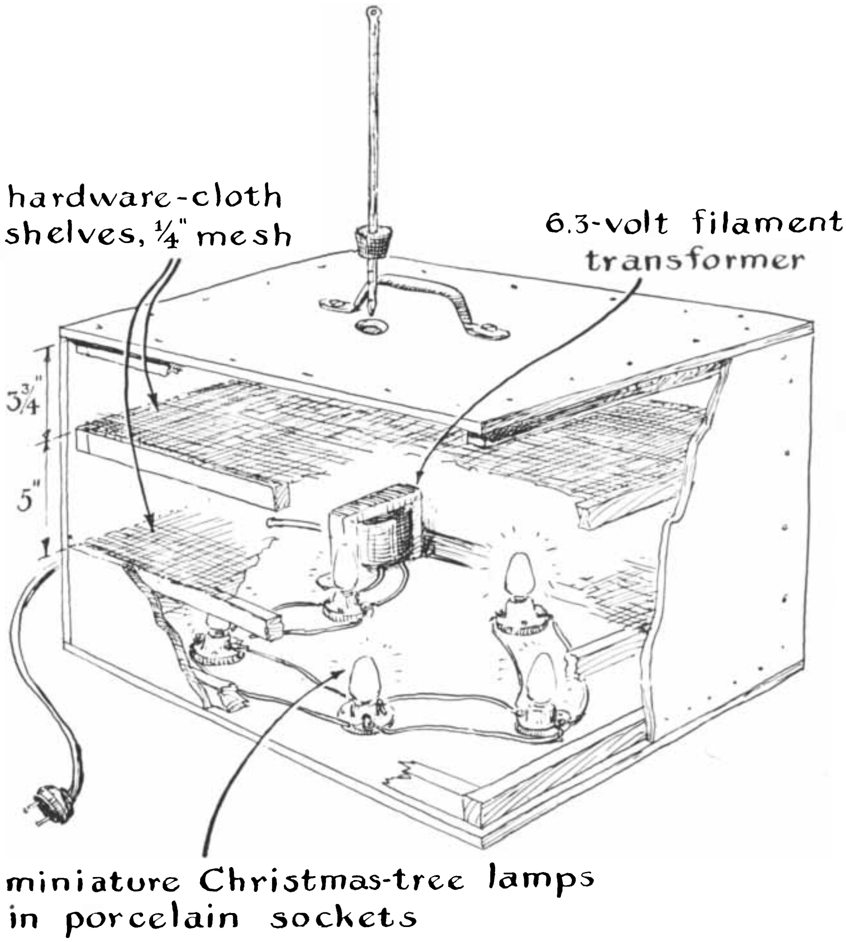
"The incubator was heated by five Christmas-tree lamp bulbs of Type No. 46. I installed miniature porcelain sockets for six bulbs but found that five heated the unit adequately. These lamps operate on 6.3 volts and are powered by the filament transformer of an old radio set. The heater assembly was installed in the bottom of the box, as shown in the accompanying illustration [*right*]. Room temperature did not vary widely, so that I did not equip the incubator with automatic temperature control. If automatic control were needed, it should be easy to improvise. One could substitute a single 60-watt lamp bulb for the miniature lamps and control it by a small thermostat of the kind used in chicken brooders. Such thermostats are listed in farm catalogues of the large mail-order houses for about $5.

"When it is used in locations where the temperature varies widely, the incubator should doubtless be insulated. Good insulation would be provided by an inch or so of rock wool in the space between a pair of nested boxes. Alternatively, the incubator could be made of slabs of foam plastic. My completed unit was sanded, painted with enamel and equipped with a door handle and a carrying handle.

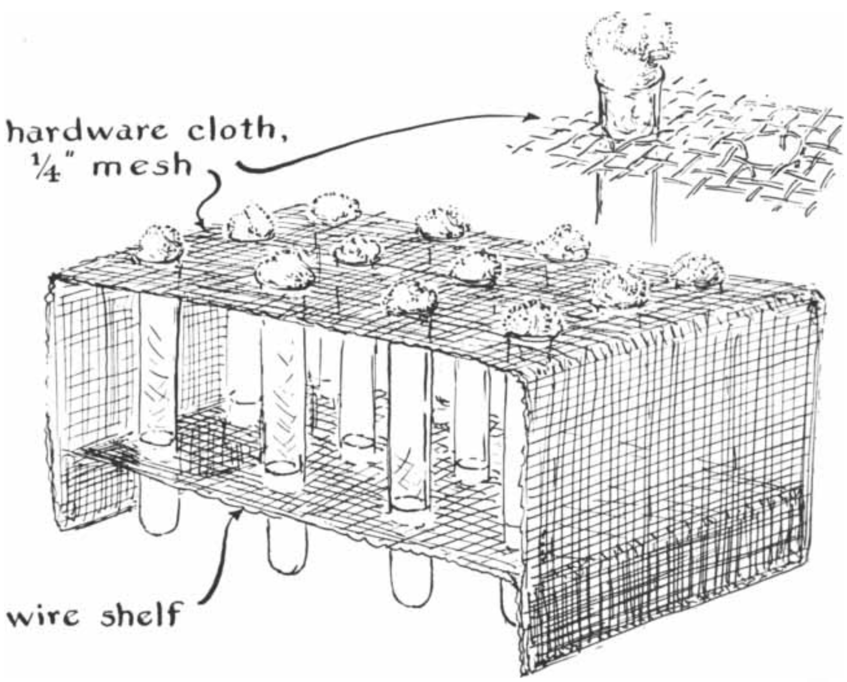
"I also made several other pieces of apparatus: an alcohol lamp (used for sterilizing test tubes), inoculating needles, wire loops for manipulating solutions and a test-tube rack. The lamp



Incubator for culturing soil organisms



Details of the incubator



Hardware cloth used to make a rack for test tubes

consists of a small glass bottle, the neck of which makes a snug fit with a wick of sack cord 3/8 inch in diameter. I have also made lamps out of bottles with larger necks. These were fitted with a perforated cork that in turn fit the wicking. The cork was protected from the flame by a metal washer made of aluminum foil. Incidentally, holes of any desired size can easily be burned through corks by means of a red-hot file tine.

"My inoculation needles and wire loops were made of straightened paper clips. The end of each wire was inserted in a six-inch length of six-millimeter soft-glass tubing and the joint was heated in the flame of a Bunsen burner until the materials sealed. Wooden handles would have been as good but they were not as easy to make. A loop about an eighth of an inch in diameter was made at the outer end of some of the wires; this provided a handy device for picking up and transferring a large drop of culture solution.

"I was surprised at the number of shallow containers one requires for making these experiments. Initially I bought four Pyrex Petri dishes for 65 cents each. When the project got under way, it became apparent that I would need dozens of them, so I hunted for alternate vessels. Finally I found a source of presterilized Petri dishes made of plastic. They are priced at $7.50 per 100 and are shipped in five sealed packages of 20 each. Eventually I used 250.

"Also required are three dozen test tubes approximately half an inch in diameter and five inches long. A rack for holding the test tubes can be made of hardware cloth. Mine measures six inches wide, eight inches long and four inches high. The mesh can be spread enough to accept the tubes. The top and ends of the rack consist of a single piece of mesh six inches wide and 16 inches long. Square bends made four inches from the ends serve as supports for the top. A second piece of mesh of the same width but only 10 inches long forms the bottom shelf of the holder. This nests inside the larger piece when square bends are made one inch from the ends [*see illustration above*]. Test tubes, stoppered by plugs of absorbent cotton, can be sterilized by being baked for 20 minutes at 300 degrees Fahrenheit in a kitchen oven.

"In general, I sterilized glassware in an autoclave—an old pressure cooker my mother had discarded. Six ounces of water was placed in the cooker along with the glassware and heated on the kitchen stove. A steam pressure of 15 pounds per square inch was maintained for 15 minutes to complete the sterilization. Because the pressure cooker was not large enough to take conventional half-liter flasks I used a variety of covered containers—peanut butter jars, fruit jars, jelly jars and so on—for agar preparations and other solutions.

"Harmless bacteria and penicillium cultures can be obtained from the American Type Culture Collection, 2112 M Street NW, Washington, D.C. 20036. (Pathogenic bacteria are not distributed to amateurs.) Substantial discounts are given on orders accompanied by documentary proof that the buyer is a student. Agar and related preparations can be procured from distributors such as Difco Laboratories, Detroit, Mich. 48201, and General Biological Supply House, 8200 South Hoyne Avenue, Chicago, Ill. 60620.

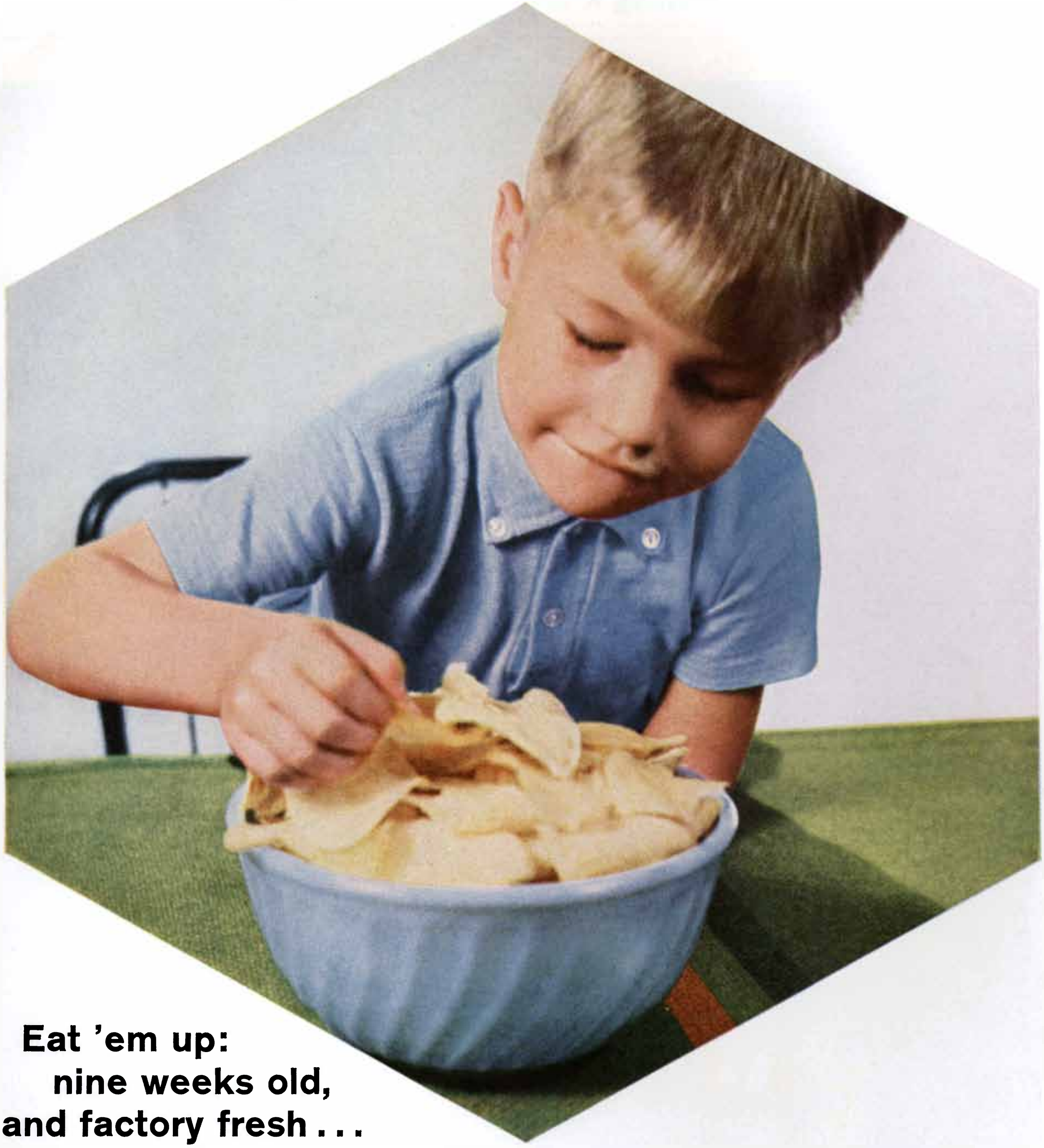
"In general, I maintained sterile conditions by means of techniques described in this department for March, 1958. I did not use a sterile transfer chamber, however, when manipulating the cultures. If Fleming had used a transfer chamber he might not have discovered penicillin, because the organism appeared on one of his cultures as a contamination. On the other hand, I did not deliberately encourage contamination. Only one culture was spoiled by what appeared to be an airborne organism.

"Five types of agar nutrient were tested initially. The first consisted of six grams of Difco nutrient agar added to 250 milliliters of water. Incidentally, distilled water was used for all preparations. The mixture was heated to approximately 150 degrees F. and stirred until the agar dissolved. It was then sterilized by autoclaving at a pressure of 15 pounds for 15 minutes.

"Agar medium of the second type consisted of 16 grams of BBL Sabouraud Dextrose agar; the third contained 14 grams of Difco Littman Oxgall agar. These nutrients were prepared in precisely the same way as the first type. The fourth type was specially compounded for the culture of actinomycetes. To 250 milliliters of distilled water I added five grams of Difco agar, .01 gram of ferrous sulfate, .1 gram of potassium chloride, .1 gram of magnesium sulfate, 2.5 grams of powdered skim milk and 2.5 milliliters of glycerine. The ingredients were heated to 150 degrees F., constantly stirred until dissolved and then autoclaved.

"The fifth type consisted of potato agar. Twenty-five grams of cubed potato was boiled for 10 minutes in 50 milliliters of water. The fluid was strained and to the clear solution was added 10 grams of glucose and eight grams of plain agar. Distilled water was then added to make a total volume of 250 milliliters, after which the preparation was autoclaved.

"The nutrient broth required for subculturing was prepared by boiling 10 grams of lean fresh chopped beef for 10 minutes in 50 milliliters of water. When



Moving air is easy . . . controlling it takes an expert

Overlooked by time, the aborigine of Australia's Arnhem Land lives today exactly as his ancestors did in the bleak wastes of the outback. Occasionally the monotony of his life is broken by a corroboree, the primitive rite which elevates boys to young manhood. One of the celebrants in this ritual is the didjeridoo man who, from a tapered wooden tube, "pulls" a song whose melancholy sound accompanies the balnooknook drum man and the songman as they conduct the ceremony. Primitive as the man who plays it, the didjeridoo proves to be a complete puzzle to outsiders. In Torrington's business of making air moving equipment, we concentrate on solving puzzles and converting outsiders into friends.
The Torrington Manufacturing Company, specialists in fans, blower wheels and blower units.

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TORRINGTON, CONN.   VAN NUYS, CALIF.   ROCHESTER, IND.   OAKVILLE, CANADA   NIVELLES, BELGIUM   SWINDON, ENGLAND   SYDNEY, AUSTRALIA it had cooled, the solution was filtered. Ten milliliters of unsulfured molasses, five grams of glucose and enough distilled water were then added to make up 250 milliliters. The resulting broth was autoclaved at a pressure of 15 pounds for 20 minutes.

"Each agar medium was poured while warm into previously sterilized plastic Petri dishes. On cooling, the material jelled. Approximately 20 milliliters was placed in each dish. Five milliliters of nutrient broth was placed in each test tube. All test tubes, after being plugged with a loose tuft of cotton, were then resterilized by autoclaving at 15 pounds for 20 minutes.

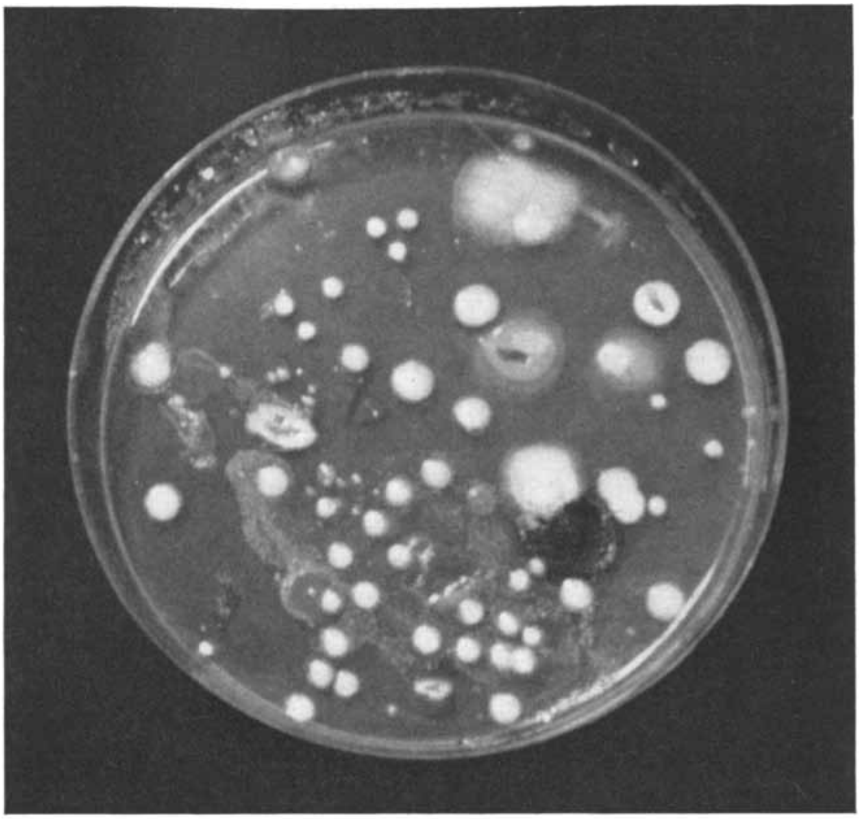
"Organisms were collected by digging about five inches below the surface of the ground and placing about 10 grams of soil in a sterile container with a close-fitting cover. Subsequently two grams of each specimen was transferred to a sterile test tube containing 10 milliliters of distilled water. The solution was shaken vigorously for 30 seconds and placed in the test-tube rack, where it was allowed to settle for five minutes. Subsequently a loopful of the clear fluid from the test tube was streaked over plates of agar.

"Early in the project tests disclosed that the maximum variety of organisms could be grown using only three of the five nutrients: nutrient agar, Sabouraud agar and Littman agar. Use of the actinomycetes agar and potato agar was discontinued. The organisms of every soil specimen were thereafter cultured on agar plates of these three types.

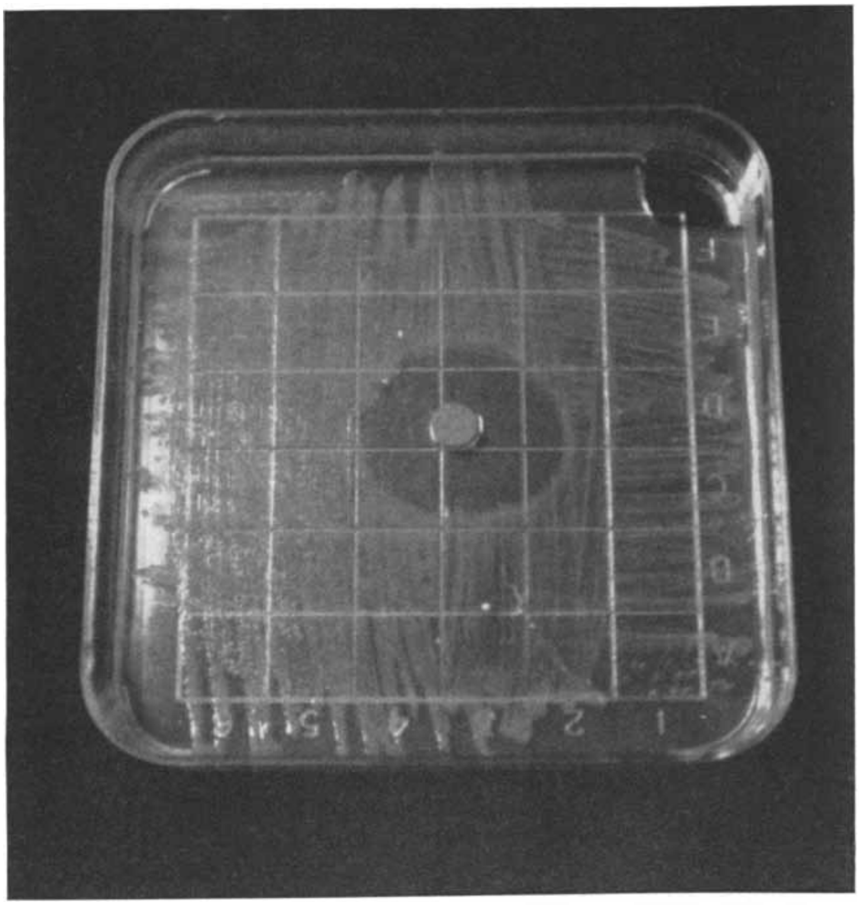
"The inoculated plates were incubated at 84 to 88 degrees F. for intervals ranging from four to seven days, depending on apparent growth. All cultures were inspected daily. The colonies grow in varied forms. Some appear as irregular white patches, others as fuzzy greenish mounds. Still others seem to consist of white hair and to grow in concentric circles. Some are green with fuzzy white edges.

"As large, readily identifiable colonies appeared, specimens were transferred from the colony (by means of an inoculation needle) to nutrient broth for subculturing. The subcultures were incubated for intervals ranging from seven to 10 days at the same temperature as the primary cultures. Unfiltered broth was then tested for antibiotic activity. Incidentally, all culture vessels were labeled and detailed records were kept of every step in all experiments.

"For evaluating the activity of the subcultures, plates of nutrient agar were first inoculated with *Sarcina lutea* bac-



Cultures of soil organisms growing on agar



Zone of inhibition surrounding antibiotic disk teria. A small disk of blotting paper was then cut with a paper punch from a sheet of paper that had been sterilized in the kitchen oven by being baked at 300 degrees F. for 30 minutes. The disk was moistened with the subculture broth to be tested, placed in the center of the inoculated agar plate and incubated at the same temperature as the cultures for seven days. Inhibition zones, if any, were then measured and recorded. In cases where antibiotic activity was indicated I immediately inoculated additional test tubes of nutrient broth with the responsible organism to ensure a continuing supply. The test was then repeated. In cases where plates became contaminated or a zone of inhibition was in doubt, the test was promptly repeated.

"In the course of the project I also checked a number of commercial antibiotics with the same procedures. Sensi-Disks bought from Difco Laboratories, for example, were used for observing the antibiotic activity of tetracycline, chloramphenicol, penicillin, triple sulfa, streptomycin and oxytetracycline. I also prepared penicillin by culturing *Penicillium notatum* strain No. 10002, obtained from the American Type Culture Collection. The organism was kept alive by weekly reculturing on potato agar and was tested by the same technique used for evaluating soil specimens. The resulting zones of inhibition were not as large as those produced by Sensi-Disks of penicillin but ranged from two to eight millimeters in diameter, averaging three millimeters.

"In all I analyzed 23 specimens of soil in four and a half months of experimenting. From these I identified 129 grossly different colonies of soil organisms and subcultured them in nutrient broth. Two of the specimens that exhibited antibiotic activity produced zones larger than three millimeters wide, two produced zones that ranged from one to three millimeters, and the zones of five measured less than one millimeter. Three cultures from the most interesting soil specimens were submitted to a commercial laboratory for evaluation. Two turned out to be penicillium molds. The third, which I had labeled specimen No. 113, proved to be a mixture of gram-positive and gram-negative bacteria. Only the gram-positive bacteria had antibiotic activity. This substance was identified as Fluvomycin, one of the lesser-known antibiotics, which is effective against pathogenic bacteria and fungi. As they say, you can't win 'em all—or even very many—but it is fun to try!"

BOOKS

A modern assessment of the philosophy of Hegel

by Ernest Nagel

HEGEL: REINTERPRETATION, TEXTS, AND COMMENTARY, by Walter Kaufmann. Doubleday & Company, Inc. ($6.95).

Goethe once remarked, in commenting on the artificial and pompous manner of thought and expression he found in one of Hegel's disciples: "What are the English and the French to think of the language of our philosophers when we Germans do not understand it ourselves?" The appalling obscurity so frequently encountered in Hegel's own writings has nevertheless been no obstacle (and may even have been a help) to their having a profound influence on subsequent philosophical and religious thought, on the study of human history and culture, and on political, legal and social theory. The fruits of this influence are a mixed harvest, some of which Hegel would surely have disowned. Partly because his language is often ambiguous and cryptic, and partly because many of his central ideas are basically unclear, his followers have been able—not always on cogent grounds—to construe even his views on major issues in quite different ways and to develop them in divergent directions. For example, his philosophy has been esteemed as valuable by some professed disciples because of its allegedly systematic account of reality as the progressive manifestation of an immanent World Spirit, and by others because of its use of a supposedly distinctive dialectical method. His social philosophy has been interpreted as a rationale for political conservatism, as a foundation for a truly liberal society, and as a justification of totalitarianism. He influenced thinkers in various disciplines who rejected his philosophy as a whole or who were even unfamiliar with it at first hand. Some of them, such as Karl Marx and John Dewey, used the conceptions they borrowed from him only after transforming them almost beyond recognition. Hegel is the source of a broad stream of historically significant ideas, but the stream has always had numerous branches.

The academic study of Hegel since his death in 1831 has had fluctuating fortunes. It has been flourishing in Germany for the better part of a century after recovering from a period of sharp decline, and it has been receiving increasing attention in countries where Marxism is official doctrine. On the other hand, although it was firmly entrenched in major universities in Britain and the U.S. during the latter part of the 19th century and the first decade of the 20th, it has steadily lost ground in these countries since World War I. One factor contributing to this decline was the impact of new developments in logical analysis on Anglo-American philosophers, who used the standards of intellectual workmanship they had acquired from modern logic to deflate many pretensions of Hegelian metaphysics. Philosophical systems do not, however, succumb easily, even to apparently devastating criticism; they can often be reinterpreted in such a way as to reveal neglected merits or minimize the significance of admitted failings by dissociating them from acknowledged virtues. In any case, interest in Hegel among Anglo-American scholars has been growing in recent years, and the latest fruit of the revival is this book by Walter Kaufmann of Princeton University.

Kaufmann's aim is to present a comprehensive reinterpretation of Hegel's thought. His book also contains translations or relevant documents hitherto unavailable in English, and a fresh translation, with detailed commentary, of the important preface to *The Phenomenology of the Spirit,* Hegel's first and possibly most original major work. The book is the only one in English that makes extensive use of recently discovered Hegel correspondence and other manuscript material, and it clothes its meticulous scholarship and wide learning in an eminently readable style. Kaufmann sketches the climate of opinion in which Hegel lived and gives a good account of his personal fortunes. He presents the development of Hegel's ideas as attempts to resolve intellectual problems that agitated reflective men of his time; he states what he believes is the gist of all but one of Hegel's books published during his life (the exception being *The Philosophy of Right*), and he corrects a number of gross but common misconceptions about Hegel, for example the belief that Hegel's dialectic proceeds according to the familiar triadic sequence of thesis-antithesis-synthesis, and that he subordinated every human aspiration to the interests of the state.

It is central to Kaufmann's approach to distinguish between what Hegel maintained his philosophy established and what it actually accomplished; indeed, Kaufmann takes issue with various expositions of Hegelian doctrines for failing to understand them in the light of this distinction. Kaufmann believes many of Hegel's claims are in fact spurious. For instance, he denies that Hegel established the existence of a distinctive dialectical process in human history, or of a uniquely determined sequence of all possible world views proceeding from the crudest to the most profound, and he asserts that in spite of Hegel's pretension to have constructed a tightly knit system of thought "what is systematic [in it] is merely the arrangement." He nevertheless shows that if Hegel's philosophy is read in the context of the problems to which it was addressed, rather than from the perspective of Hegel's claims for it, much in it is richly illuminating and merits serious study. Kaufmann's book is on many counts a substantial contribution to the understanding of Hegel.

Although the import and validity of many things in Hegel are debatable, the locus of his problems and the broad objectives of his philosophy are reasonably clear. Born in 1770, he came to maturity during a turbulent period when hallowed beliefs about the nature of man and society were being seriously challenged—sometimes from opposite directions—by a wide assortment of ideas. In one way or another Hegel responded vigorously to the rationalism of the French Enlightenment, the conceptions of human excellence advocated in the literature of German classicism and romanticism, the Kantian notion of the moral life as the pursuit of duty divorced from inclination, and the skeptical conclusions concerning the scope of human reason that are implicit in Kant's account of man's cognitive powers. Although Hegel was no simple-minded idolator of traditional institutions, he was sensitive to their values. At the same time, in spite of his lack of sympathy for some views that were highly critical of the established order, he did not find them without merit, nor was he unaware of incongruities between other ideas, also critical of tradition, to which he was attracted. Accordingly he felt a great need for reconciling all these ideas, in order "to restore the human being again in his totality."

Hegel welcomed the downfall of the *ancien régime,* and he believed social institutions must be subjected to rational scrutiny. On the other hand, he condemned the egalitarian doctrines of the French Revolution, and he was a severe critic of the rationalism of the Enlightenment. As he construed the individualistic theory of absolute natural rights on which their social criticism and programs were based, the theory cannot do justice to the civilizing role of social institutions or the hierarchical organization of society; indeed, he blamed the influence of the theory for Germany's national disunity. Moreover, he rejected the ideal of human freedom advocated by the Enlightenment, on the ground that it gives absolute priority to the satisfaction of individual desires, and mistakenly supposes that man is free by nature but becomes enchained by the state. In Hegel's view, which was greatly influenced by the enthusiasm of Goethe and Schiller for Greek antiquity, the state provides the necessary conditions for the fulfillment of man's nature, so that "genuine" human freedom can be achieved only through a philosophically informed (or "self-conscious") participation in the organized cultural activities of society. There are therefore good reasons for assuming that one of Hegel's cardinal objectives was to mediate between critics and defenders of the social order, by showing that in spite of the limitations inherent in every form of organized society every institution has an indispensable function in the social economy of its time and plays an important role in the development of human freedom. "The insight to which philosophy should help us," Hegel declared in a revealing passage of his posthumous *Philosophy of History,* "is that the actual world is as it ought to be.... Thus philosophy is not a comfort; it is more, it reconciles, it transfigures the actual, which seems unjust, into the rational."

Hegel's philosophical system is in part a generalization of this approach to reconciling differing social ideals and conflicting evaluations of social institutions. Whatever else the system contains, it does present a boldly imaginative account of the virtues and corresponding failings that characterize not only various forms of institutionalized life but also different human attitudes and passions, scientific and commonsense notions, religious doctrines and philosophical perspectives. This aspect of Hegel's thought is particularly prominent in his *Phenomenology,* and it is the one on which Kaufmann sets greatest store. Hegel surveyed an impressively wide-ranging series of recurrent outlooks on things, with the intent of showing that none is tenable if it is embraced without reservation, and that each extreme view somehow generates another contrasting extreme. According to him, for example, naïve confidence in the certainty of sensory experience overlooks the general assumptions implicit in the interpretation of what is directly experienced, and it leads to an equally naïve confidence in the certainty of intuitively evident intellectual principles; similarly, a morality based on unreflective custom opens the gates to an individualistic morality of worldly success that is disruptive of custom.

But Hegel's philosophy is more than a gallery of such contrasting types of social institutions and intellectual commitments. Even in the *Phenomenology* the portraits of psychological attitudes and world views are not arranged in arbitrary sequence. The sequence has a definite hierarchical order that is alleged to be uniquely determined by a "dialectical" process to which Hegel believed he held the clue. The order is in effect an attempt at a theodicy—a justification of the essential rationality at the heart of things; it represents the manifestations of the World Spirit in an endless series of embodiments, each a fuller realization of the Spirit's nature than its predecessors. Hegel believed that this order is implicit in the categorial features of human thought as well as of its objects, and that it is generated by the intrinsic incompleteness of everything finite. He maintained that the concepts of both common sense and science are radically incomplete—in his language they are "abstract" and the products of the "Understanding"—because the various traits that finite things possess are not theirs "absolutely," but only by virtue of the roles the things play in the endless series of increasingly more inclusive systems of which things are parts. Accordingly "the truth is the whole," a Hegelian dictum that condemns all discursive thought as being at best "one-sided" and "relative." Hegel does not explain, however, how his own contention that reality is spiritual escapes this condemnation, nor does he make clear why what is admittedly only a part of the "whole truth" (the fact that 5 is a prime number, say) cannot be absolutely true about some part of the whole.

Hegel persuaded himself that since every abstract concept stands in relations of logical opposition to its various contraries as well as to other concepts (for example, being a man is logically opposed to being a woman, and also to being a king), it is intelligible only by virtue of its relations to them. In consequence he maintained that the contraries of a term are somehow involved in both the meaning of the term and in the things to which it is applicable. There is thus an alleged latent "contradiction" in the concepts of the Understanding and in the things subsumed under them—an internal strain that is fatal to the apparent self-sufficiency of anything which falls short of the infinite totality of things, and which ultimately results in changes that absorb the finite in "sublimated" form into a more complete reality. Accordingly, except for purely physical things, whose changes Hegel believed are "perpetually self-repeating" and produce nothing new, everything else—particularly ideas and social institutions—is subject to inevitable dialectical transformations.

Although Hegel contended that these dialectical transitions are "necessary" because of the inherent "contradictions" in everything finite, he used words in such a scandalously loose manner that it is difficult to know what he meant by this assertion. The transitions are certainly not established by deductive argument; they are based on more or less plausible but usually tacit assumptions, or on suggestive ambiguities and even puns. As Kaufmann points out, the sequence of transitions is not always the same in Hegel's own presentation of them. According to Kaufmann, Hegel

employed the German equivalent of *necessary* as an inclusive antonym of *arbitrary* rather than as a synonym of *logically necessary;* he therefore thinks that Hegel's intent is misrepresented by commentators who construe the word in the latter sense. Kaufmann may be right, but he is not entirely convincing. Hegel did not clearly distinguish causal relations from logically necessary relations, and even when he was dealing with dialectical transformations in society, he discussed them without mentioning specifically causal determinants of such changes as distinct from logical determinants. Nor is it clear whether Hegel understood dialectical transitions to be temporal or logical or both. He often described them in ostensibly temporal terms, and he maintained that he was able to explain them in terms of their role in the genesis of more developed systems. On the other hand, he presented such changes no less frequently as a logical progression of forms of reality when the forms are analyzed so as to exhibit their increasing structural complexities, irrespective of the temporal order in which they may be realized.

However this may be, Hegel believed that a "rational" order is embodied in everything actual, and that in particular there is an immanent purpose or "reason" in human history. In fact, he tried to show with some attention to detail that the rise and fall of nations has not been just a series of meaningless happenings, but that on the contrary history exhibits the cunning operation of the World Spirit in the progressive development of "genuine" human freedom. Hegel's assertion that he had thus established the identity of the rational with the actual, and had demonstrated the "insight" that "the actual world is as it ought to be," is effectively punctured by Kaufmann. Nevertheless, Kaufmann thinks it is seriously misleading to characterize Hegel's reading of the past as inhumanly optimistic; in partial support of his own interpretation that Hegel had a tragic vision of history, he cites Hegel's famous description of history as a "slaughter bench on which the happiness of peoples, the wisdom of states and the virtue of individuals have been sacrificed." In his admirable effort to be fair to Hegel, however, Kaufmann is sometimes overly generous. It is difficult to defend Hegel from the accusation that he was insensitive to human suffering, when one finds him saying that the contemplation of the agonies men have so commonly endured must not make us "fall into the Litany of Lamentations"—since the "so-called well or ill faring of these or those isolated individuals cannot be regarded as an essential element in the rational order of the Universe." There is real substance in Santayana's judgment that Hegel sanctified "a brutal law of success and succession" and "despised every ideal not destined to be realized on earth."

Contrary to the familiar adage, Peter's ideas of Paul are not always better clues to Peter's nature than they are to Paul's. Still, Kaufmann's predominantly humanistic interests are certainly reflected in the negligible attention he pays to Hegel's philosophy of nature and sociopolitical doctrines. He dismisses Hegel's views on physics, chemistry and biology in less than a page as "comparatively unimportant"—undoubtedly a sound summary judgment when those views are assessed for their current influence. His book seeks, however, "to establish a comprehensive reinterpretation of Hegel —not just of one facet of his thought but of the whole phenomenon of Hegel." Surely "the whole phenomenon" cannot be understood without a reasonably full examination of Hegel's essentially anthropomorphic and teleological view of nature, and without a careful analysis of his intellectual method in order to make clear why, for example, it enabled him to denigrate Newton's analytical procedures in astronomy as inferior to Kepler's "holistic" approach. Perhaps a more serious shortcoming of Kaufmann's book is the absence of any discussion of Hegel's views on various sociopolitical topics—the family, the rationale of private property, representative government, crime and punishment. This omission cannot be defended on the ground that Hegel's treatment of these themes is unimportant. To be sure, Kaufmann does flatly deny that *The Philosophy of Right,* Hegel's chief political treatise, is the work of an apologist for the Prussian monarchic state, but he gives little evidence to support this denial, and he does not mention Hegel's personal role in opposing the extension of political suffrage. Moreover, although Kaufmann is informative concerning Hegel's influence on a number of later philosophers, particularly on Heidegger and Sartre, he is disappointingly silent on the important role Hegelian ideas have played in the development of legal thought, functionalism in anthropology, and relativism in social science and history.

Kaufmann's interpretation of Hegel deals with him primarily as a great seer —as a "physician of culture," to use a phrase of Nietzsche's—rather than as a philosopher whose dimensions are to be measured by the adequacy of his vision and the cogency of his arguments. In any event, Kaufmann does not attempt to go through Hegel's thought "bit by bit" in order to untangle the countless gnarls in it. But since he has no illusions about the validity of Hegel's claims either for the system or for the dialectic, he does not make clear why Hegel merits attention as a major philosopher. In a review four years ago of a book on Hegel, Kaufmann wrote: "What is still wanted is a good book on Hegel that shows how he dealt with many of the problems with which Marx and Kierkegaard, sociologists and theologians, pragmatists and existentialists, analytic philosophers and literary critics have been dealing since." Kaufmann's book is undoubtedly a useful one, but the good book he described four years ago as unavailable is still unpublished.

Short Reviews

THE SCIENCE OF SMELL, by R. H. Wright. Basic Books, Inc., Publishers ($4.95). R. H. Wright is a physical chemist who has spent some years as a member of the British Columbia Research Council studying olfaction and olfactory responses. One of the practical aims of his research is to find chemical substances that, without being toxic, would lure insects to traps or saturate their sensory mechanisms so that they could not locate mating partners. This is only one of the many topics treated in this exceptionally interesting book. A series of experiments on fish migration demonstrated that after fish have been spawned in freshwater streams and have journeyed out to sea they find their way back home by recognizing the smell of the water; fish that had their olfactory pits plugged were quite unable to smell their way home. Insects have an acute smelling apparatus and will travel great distances in the direction of an alluring scent. As the smell draws them on they must, as another series of experiments showed, be able to navigate their course by taking their bearings from the environment; for example, they need to see the bottom below them, and if their view of the bottom is obscured, they are quite unable to make their way to the source of the odor. The olfactory powers of dogs, it turns out, are not much keener than man's, although they may be sensitive to certain odors to which man does not respond. It is remarkable how many branches of science are brought into the study of smell: nerve physiology, which

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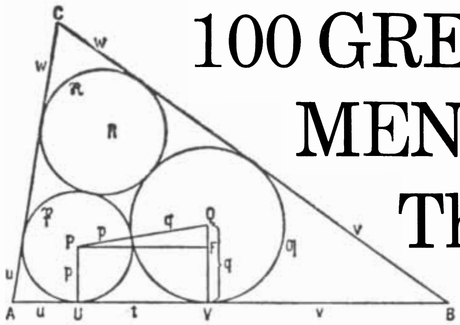

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discloses that the olfactory bulb in the brain is only one synapse away from the primary smell-sending surface, so that there is direct contact between the brain and the outside world; organic chemistry, which establishes the features of the molecules we are able to smell; experimental psychology, which establishes a scale of keenness in smelling; communication and information theory, which enables the experimenter to break down the complex structure of odor stimuli. Wright makes the point that the sense of smell is so fundamental in evolution and in enabling organisms to regulate their activities on the basis of "information received" that Descartes's *Cogito ergo sum* should probably yield priority to *Olfacio ergo cogito* (I can smell and therefore I can think). Intelligence, he supposes, may well have had its beginnings "as apparatus for handling olfactory signals from the chemicals that bathed our first progenitors in the primeval ooze."

ATLAS OF EVOLUTION, by Sir Gavin de Beer. Thomas Nelson & Sons, Ltd. ($15). Based on De Beer's *Handbook on Evolution*, published by the British Museum, this large-format volume crammed with charts, maps and some 500 other illustrations offers a comprehensive and authoritative survey of the theory of evolution and the overwhelming evidence in support of it. It traces the history of the theory, including of course the observations that led Darwin to his famous hypothesis of natural selection, presents data confirming the theory that are drawn from various sciences from morphology to paleontology, skillfully explains the concept of variation and the genetic mechanism and describes the number, nature and origin of species and the major steps of evolution in plants and animals. It concludes with a chapter on the evolution of man, discussing his place in nature, the transition from ape to man, the spread and the races of man. If the book has a fault—and it is a minor one—it is in attempting to cover too much ground. The result is that many pages are so crowded with text and illustrations (accompanied by detailed captions that repeat parts of the text) that the reader's eyes scarcely know where to alight. This is nonetheless a fine popularization that affords abundant instruction in a difficult subject.

AFTER TWENTY YEARS: ALTERNATIVES TO THE COLD WAR IN EUROPE, by Richard J. Barnet and Marcus G. Raskin. Random House, Inc. ($5.95). It is a pity that this book was published just as the Vietnam crisis was shifting into high gear, thus, for the time being at least, deflecting attention from a chronic, much more important and much less artificial source of conflict between the U.S. and the U.S.S.R. What to do about the division of Germany, for example, is a real, not a contrived, issue, having nothing to do with such rhetorical matters as national honor; everyone at least knows where Berlin is. Barnet and Raskin trace the evolution of the Atlantic alliance, explain how and why we got into the cold war and argue strongly not only that we have committed ourselves to an enormously costly burden but also that the burden is in large part self-imposed and a threat to the realization of social and economic betterment. They offer suggestions for reform of our present foreign policies, which, in their opinion, would lead to a stable European settlement—including the gradual reunification of Germany and the removal of the great wall between East and West. Their proposals are not as impressive or as well thought out as their analyses of present difficulties, in part because they tend to consider the conflict in Europe without sufficient attention to circumstances elsewhere in the world, particularly in Asia; this does not, however, materially detract from the value of their book, which is well tempered and full of cogent observations.

PSYCHOPATHIA SEXUALIS, by Richard von Krafft-Ebing. Stein and Day Publishers ($10). First published in the early 1890's, this study of abnormal behavior is a work of historic consequence but little contemporary scientific value. Krafft-Ebing was a highly respected German psychiatrist and neurologist, attracted (as Sigmund Freud was) to the study of sexual problems and prepared (also like Freud) to risk social and professional disapproval for describing in print the pathologies he had observed and offering his own ideas on the subject. His collection of case histories brought dark matters into the open and forced physicians and others to recognize the scope and importance of sexual psychopathology. The book shocked earlier readers as much as it fascinated them. When it appeared in English, *The British Medical Journal* expressed considerable doubt as to the propriety of reviewing it and questioned whether it should have been translated at all—a German version was bad enough. "Better," said the *Journal*, "if it had been written entirely in Latin, and thus veiled in the decent obscurity of a dead language." Today Latin is dead but sex survives, which may be partial justification for this first complete, unexpurgated translation into English (by Franklin S. Klaf) of Krafft-Ebing's major work. In an age of paperbacked Freud, Henry Miller and Fanny Hill, it is no longer likely to be regarded as a spicy item by adolescents, the vulgar or the prurient, but it still holds some interest for students of the history of psychology and it is a respectful tribute to a courageous and pioneering physician.

LECTURES ON GENERAL RELATIVITY: VOLUME I, by A. Trautman, F. A. E. Pirani and H. Bondi. Prentice-Hall, Inc. ($5). The notes contained in this volume are based on lectures given at Brandeis University in the summer of 1964. Trautman discussed the foundations and current problems of general relativity, Pirani gave an introduction to gravitational radiation theory and Bondi took up some special solutions to the Einstein equations. This is scientific material of importance and one is gratified to be able to get it in a comparatively inexpensive paperback edition, but a shadow crosses the mind as one notes in the foreword that these lectures were in part supported by funds from NATO. Is it no longer possible for scientists to come together to discuss even relativity without being endowed by a politico-military organization?

HIGH STEEL, HARD ROCK, AND DEEP WATER: THE EXCITING WORLD OF CONSTRUCTION, by Richard W. O'Neill. The Macmillan Company ($12.95). A popular account of some of the more dramatic aspects of large-scale construction work: digging and drilling, erecting skyscrapers and bridges, pouring concrete, boring tunnels, raising dams, sinking missile silos, laying roads and rail lines. Many of the photographs are excellent, but the writing is heavy with the jargon of the game (a nuisance only partially eased by the glossary), and the author describes an undertaking such as the building of the early-warning line in Canada in an almost uninterrupted state of fervor. If the men who did the work had been as excited as he, they would all have collapsed the first day on the job.

SOVIET RESEARCH AND DEVELOPMENT: ITS ORGANIZATION, PERSONNEL AND FUNDS, by Alexander G. Korol. The M.I.T. Press ($11). A careful reference study, supported by abundant statistical data, of research and development activities in the U.S.S.R. Korol describes the recent history of Soviet research, the various research organizations, the distribution of scientific workers by function, training, age, specialization, sex and nationality, and tabulates the amounts expended in different departments. Much of this information is hard to obtain, there are many gaps in the raw data, and it is often difficult to apply our own research and development concepts and categories to Soviet activities in this sphere; for example, there is no single Russian term equivalent to "research and development," nor are some of "the ostensibly identical terms ... conceptually equivalent." In the face of these and other obstacles, Korol has assembled a valuable compendium.

THE LETTERS OF FREDERIC WILLIAM MAITLAND, edited by C. H. S. Fifoot. Harvard University Press ($12.50). Some 500 letters written between the middle 1880's and 1906 by the distinguished legal scholar and medieval historian whose publications included a history of English law (with Sir Frederick Pollock) and the famous *Domesday Book and Beyond*. The letters range widely in subject matter, from purely personal and social concerns to professional interests. They are written in a style always easy and relaxed, they show how enormously productive Maitland was and how thoroughly he enjoyed, in spite of recurrent ill health, pursuing his exacting researches. They give us a clear picture of what must have been an honest and attractive man.

SOME LESSONS IN MATHEMATICS, edited by T. J. Fletcher. Cambridge University Press ($2.95). This handbook on the teaching of mathematics, prepared by members of the British Association of Teachers of Mathematics, offers a good deal of useful information on the newer methods of teaching both the classical and the more modern topics, including binary systems, group theory, the use of machines, sets and relations, linear programming, numerical methods, topology, vectors and matrices. There are helpful suggestions on classroom methods and on the psychology of teaching, sensible diagrams and examples. Paperback.

THEORETICAL AND MATHEMATICAL BIOLOGY, edited by Talbot H. Waterman and Harold J. Morowitz. Blaisdell Publishing Company ($12.50). The chapters of this book are based on discussions and lectures on theoretical and mathematical biology given at Yale University in 1962. Among the contributors are N. Rashevsky ("Models and Mathematical Principles in Biology"), J. D. Bernal ("Molecular Structure, Biochemical Function, and Evolution"), H. Quastler ("General Principles of Systems Analysis") and Richard Levins ("Genetic Consequences of Natural Selection").

THE CONQUEST OF TUBERCULOSIS, by Selman A. Waksman. University of California Press ($5). A microbiologist who was awarded a Nobel prize for his work on streptomycin, a key drug in combating tuberculosis, recounts the history of tuberculosis, of earlier attempts to treat it and of the major breakthrough by the use of antibiotics that has brought the disease under control. Waksman also gives personal reminiscences of his encounters with victims of the disease who were saved by the new drug. Illustrations.

UKRAINE, A CONCISE ENCYCLOPEDIA: VOLUME I, edited by Volodymyr Kubijovyc. University of Toronto Press ($37.50). The first volume of the English translation of a three-volume work published in Ukrainian in 1949 by the Shevchenko Scientific Society. It contains an enormous amount of material on this ancient land and its people: long, scrupulously detailed, illustrated articles on such subjects as history, geography, soils, climate, the Black Sea, flora and fauna, physical anthropology, population structure and distribution, ethnic composition, folk culture, oral literature, art and handicraft, language. Many photographs, maps and other illustrations.

THE CONCISE OXFORD DICTIONARY OF MUSIC, by Percy A. Scholes, second edition edited by John Owen Ward. Oxford University Press, Inc. ($7). A thoroughly revised edition, with numerous new entries, of a standard reference book filled with information about all aspects of music and designed for the use of the ordinary listener. Like all other Oxford "concise" publications, an attractively made volume.

Notes

INFINITY: AN ESSAY IN METAPHYSICS, by José A. Benardete. Oxford University Press, Inc. ($7.20). A philosophical essay on various aspects of the concept of infinity, which is described as a "return to rationalistic metaphysics" in the sense of attacking the views of the finitists and attempting to solve paradoxes of the foundations of mathematics by restoring the "actual infinite" to its untarnished glory.

Controls from Within, by Fritz Redl and David Wineman. The Free Press ($1.95). A soft-cover reprint of a civilized book on techniques for the treatment of the aggressive child.

Psychosomatic Research: A Collection of Papers, by J. J. Groen in collaboration with others. Pergamon Press ($12). This gathering of papers on psychosomatic medicine reports on work done by the author and his collaborators in Amsterdam and Jerusalem.

Foundations of the Theory of Algebraic Numbers, by Harris Hancock. Dover Publications, Inc. ($5.50). A two-volume soft-cover reprint of a standard work on the advanced theory of numbers.

History of Economic Doctrines, by Eduard Heimann. Oxford University Press, Inc. ($1.50). A reissue of a well-received introduction to economic theory first published in 1945. Paperback.

The Oxford Book of Birds, by Bruce Campbell. Oxford University Press, Inc. ($10). A congenial and unpretentious text-and-picture volume covering all the birds that have ever been recorded in Britain. The notes for each species are informative and present interesting odd facts.

A Shakespeare Companion, by F. E. Halliday. Schocken Books Inc. ($10). A revised and enlarged edition of a comprehensive handbook on Shakespeare's life and work, his friends and acquaintances, the Elizabethan and Jacobean theater and on many other circumstances connected with the production and editing of his writings over the past three and a half centuries.

Logic, by W. E. Johnson. Dover Publications, Inc. ($4.50). An unabridged republication in three soft-cover volumes of a respected survey of logic first published between 1921 and 1924.

The International Council of the Aeronautical Sciences, edited by Theodor von Kármán. Spartan Books, Inc. ($48). Proceedings of the third congress of the council, which was held in Stockholm in 1962, covering a broad range of advances in the aeronautical sciences.

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