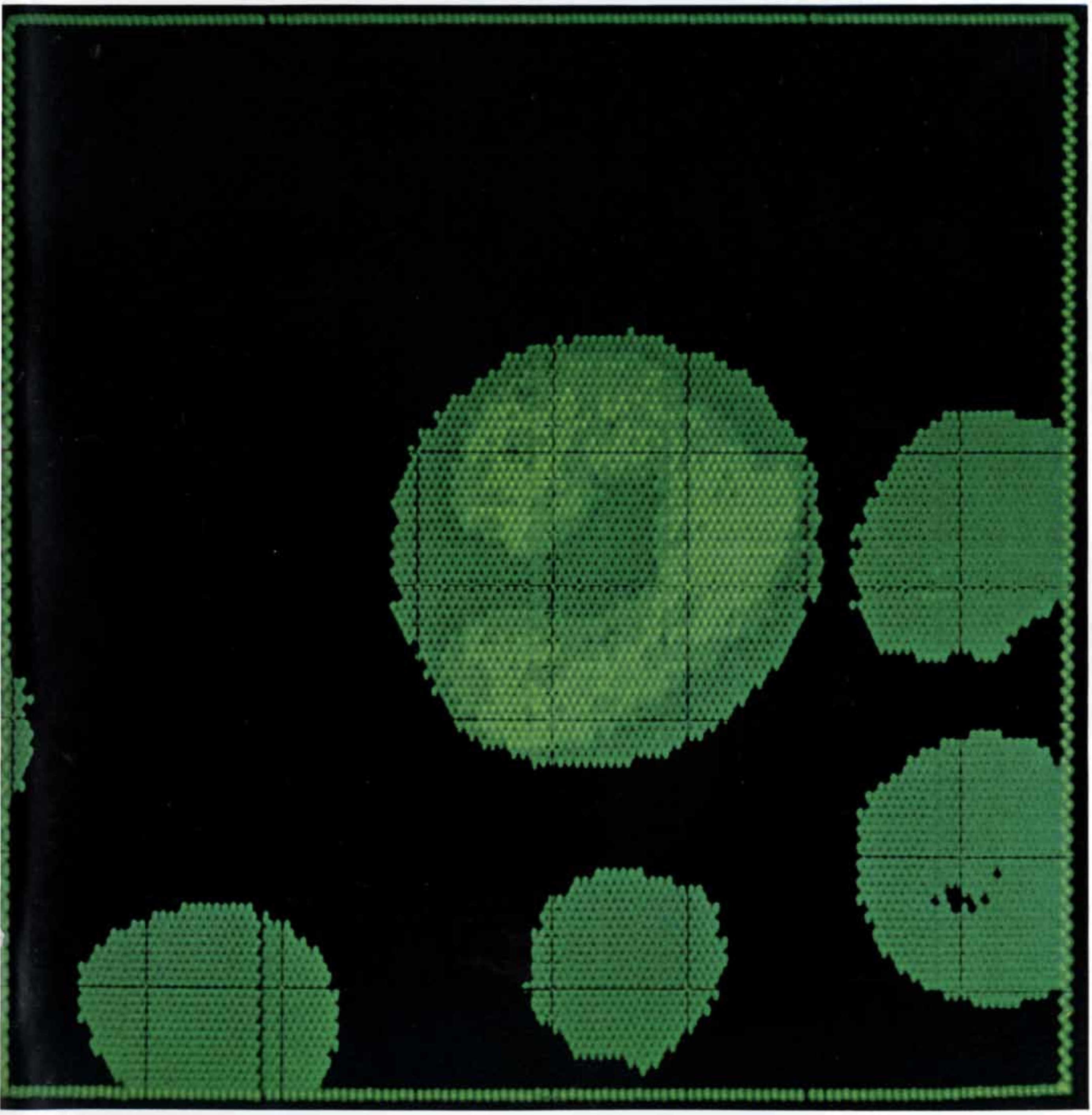
SCIENTIFIC AMERICAN



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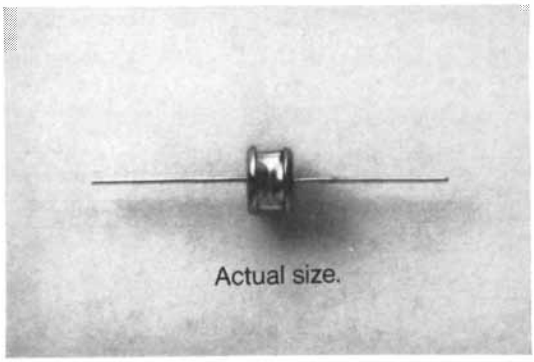
Lightning is just one of the many voltage transients that can affect expensive electronic equipment. Some of the other sources are static discharges, internal switching of inductive components, short circuits, and inductive influences through grounded shorts.



Actual size.

Before the use of semiconductors or other delicate components, voltage transients did not present a serious problem to the design engineer. Today, however, solid-state circuitry and a greater degree of electronic sophistication demands greater attention to voltage protection.

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Established 1845 **SCIENTIFIC AMERICAN** November 1970 Volume 223 Number 5

ARTICLES

DEPARTMENTS

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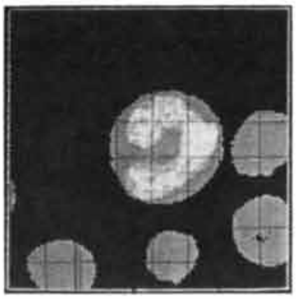

THE COVER

The picture on the cover is an image of blood cells that was formed by an automatic microscope, processed by a computer and displayed on an oscilloscope in a research laboratory of the Perkin-Elmer Corporation. The large object at the center is a white blood cell—a "stab," or unsegmented neutrophil—its bright irregular nucleus surrounded by cytoplasm. The smaller objects around it are red blood cells. Microscopic examination of blood cells is an important procedure for the diagnosis of disease. An automatic process has been developed that locates white cells in a blood smear, classifies them as to type and counts them, and also yields quantitative data on the characteristics of each cell (see "Automatic Analysis of Blood Cells," page 72).

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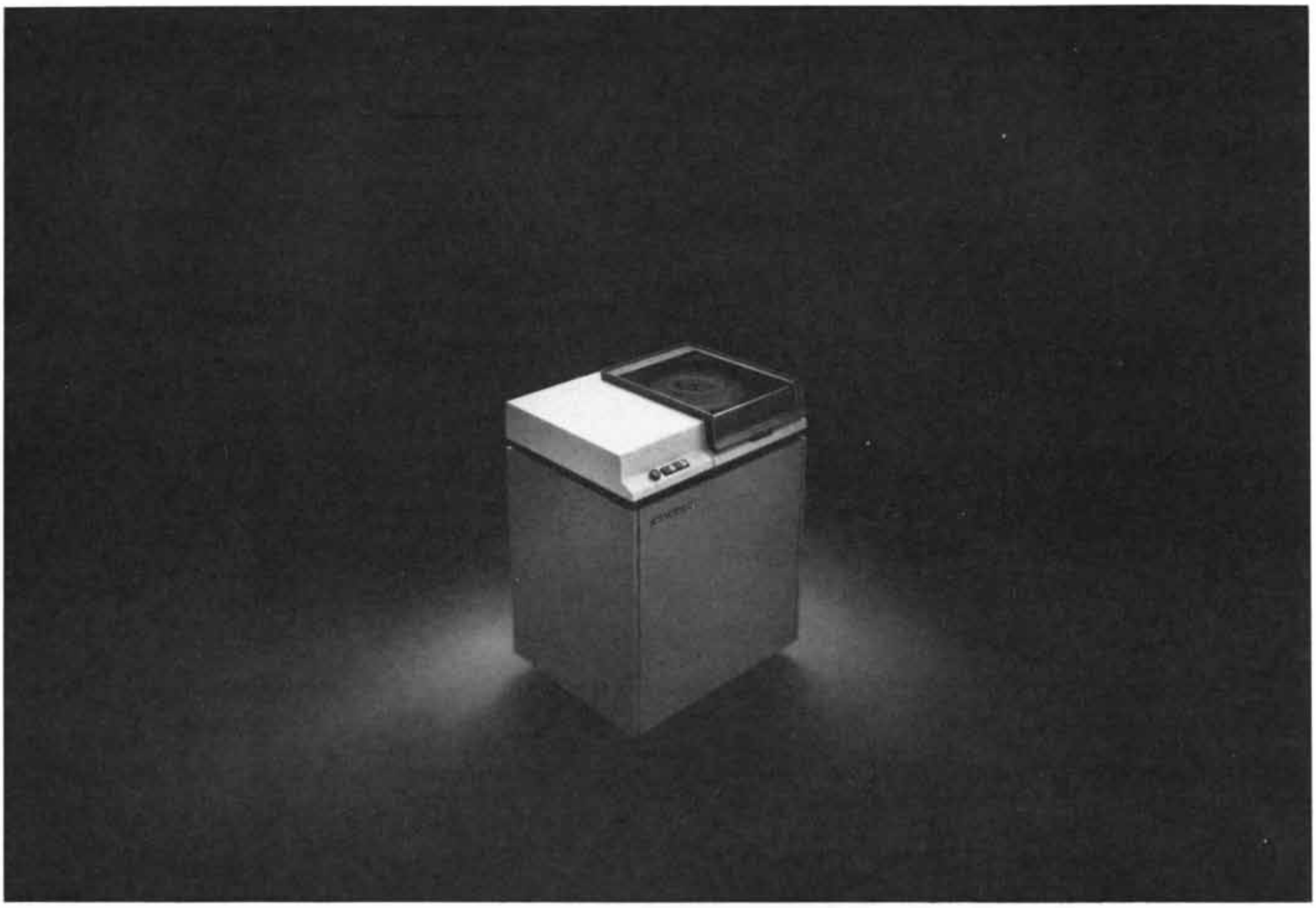

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LETTERS

Sirs:

The article "Conversion to the Metric System," by Lord Ritchie-Calder [SCIENTIFIC AMERICAN, July], prompts me to make a suggestion as long as we are contemplating change. The awkward system of naming decimal multiples of a unit such as pico $= 10^{-12}$ is really only necessitated by the cumbersome way we name numbers. "Ten to the minus twelve" is simply too long an expression, so we invent "pico" to replace it. If we are going to do something like that, we should do it in the simplest manner possible. The names of the units should agree with the way we name numbers, and the fundamental trouble lies there. The expression "times ten to the" is too long and should be simplified. I propose that we write and *name* numbers by the floating-decimal-point method.

To make this idea explicit, suppose we write 1,690,000,000 as 1.69_{+9} (or in the case that a subscript is unavailable for printing, as 1.69; + 9, or as computers already do, 1.69E + 9). The subscript is a decimal indicator telling how many digits to the right (to the left for negative subscripts) the decimal must be moved (adding zeros if necessary) to get the conventional form of the number. We can express this by appending the indicator to a single prefix, say "plo," so that our number is called "one point six nine plonine." Likewise, $0.000000136 = 13.6_{-8}$, using the prefix "mi" (pronounced like the word "my") for negative indices; this would be called "thirteen point six mieight." A number without an indicator implies that the number has indicator zero and is understood in the conventional way.

The algorithms for arithmetic with such numbers are very simple. To add, numbers must first be changed so that they all have the same indicator. To multiply, multiply the numerical parts and add the indicators.

Conversion from the scientific system of writing numbers is, of course, immediate: $6.04 \cdot 10^{23}$ becomes 6.04_{23}. Thus the single syllable "plo" replaces "ten to the plus" and "mi" replaces "ten to the minus."

In such a system, the so-called multiple units have a natural name, no harder to say than the artificial prefixes such as nano, etc. Thus a million-meter unit is a plosixmeter, written $_{+6}$m. An angstrom is a mitenmeter, written $_{-10}$m. A kilometer would have another name, plothreemeter, and would be abbreviated as $_{+3}$m. Thus 45 angstroms would become 45_{-10} m. In the ambiguity about whether the -10 indicator belongs to the number or to the unit lies the real invention and improvement. Naturally it makes no difference and the notation arranges that. Similarly, the distance to the sun is 160 million kilometers or 160 plosix plothreemeters $= 160_{+6+3}$ m and the indicators are, of course, to be combined as written to 160_{+9} m.

In this system "plosix" and "million" are synonymous and, as for any other synonyms in language, gradually usage will determine the most convenient expressions. The same goes for such words as centimeter and mitwometer; either can be used interchangeably, but for the larger multiples and submultiples that are usually used in more technical situations it would be hoped that the new and more universally understandable and useful system could become standard usage.

RICHARD P. FEYNMAN

California Institute of Technology
Pasadena, Calif.

Sirs:

In "Mercury and Mud" ["Science and the Citizen," SCIENTIFIC AMERICAN, September] it is stated, "As any chemist knows, the safest place to keep mercury is under water," etc. I am a chemist, and it is true that chemists know that about mercury. Unfortunately we appear to know something that isn't so. In the May 1969 issue of *Fusion*, the publication of the American Scientific Glassblowers Society, William Stein describes some experiments with mercury in water (page 27). He found that a Beckman mercury detector would detect mercury vapor in air, even if the mercury was covered with water.

WALTER R. AVERETT

Vicksburg, Miss.

Sirs:

Apropos of your discussion of palindromes in "Mathematical Games" [SCIENTIFIC AMERICAN, August], I would like to offer an example of what I believe to be the most complex and exquisite type of palindrome ever invented. It was devised by the Sanskrit aestheticians, who termed it *sarvatobhadra*, that is, "perfect in every direction." The most famous example of it is found in the epic poem entitled *Śiśupālavadha.*

sa - kā - ra - nā - nā - ra - kā - sa -
kā - ya - sā - da - da - sā - ya - kā
ra - sā - ha - vā vā - ha - sā - ra -
nā - da - vā - da - da - vā - da - nā.
(nā da vā da da vā da nā
ra sā ha vā vā ha sā ra
kā ya sā da da sā ya kā
sa kā ra nā nā ra kā sa)

Here hyphens indicate that the next syllable belongs to the same word. The last four lines, which are an inversion of the first four, are not part of the verse but are supplied so that its properties can be seen more easily. The verse is a description of an army and may be translated as follows: "[That army], which relished battle [rasāhavā], contained allies who brought low the bodes and gaits of their various striving enemies [sakāranānārakāsakāyasādadasāyakā], and in it the cries of the best of mounts contended with musical instruments [vāhasāranādavādadavādanā]."

GEORGE L. HART III

University of Wisconsin
Madison, Wis.

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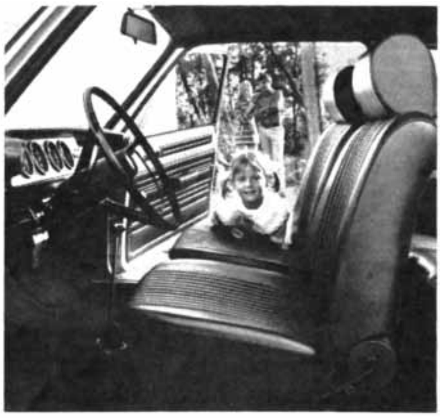

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

NOVEMBER, 1920: "Much interest has recently been aroused by the announcement of the German physicists L. Grebe and A. Bachem that they have found the shift of the lines in the solar spectrum that was the third test of the Einstein theory, the others being the motion of the perihelion of the orbit of Mercury and the apparent displacement of stars due to the gravitational field of the sun. The predicted shift is toward the red and is in the spectrum of the sun's edge, or limb. By making a careful microphotometric study of three spectrograms of solar absorption lines, the source of which is now ascribed to nitrogen, Grebe and Bachem were able to select nine lines in the ultra-violet that are free from the contaminating influence of superposed lines of metallic origin. Expressed in terms of the equivalent Doppler effect, the final result was a displacement of .56 kilometer per second, which agrees very closely with that predicted by Einstein (.6 kilometer per second)."

"The production of helium on an extensive scale, which began during the war when it was proposed to use the gas for filling balloons and dirigibles, has led to considerable discussion as to other ways in which helium can be used. It can be used as a filling for thermionic amplifying valves of the ionization type, for filling tungsten incandescent lamps, especially for signal purposes where rapid dimming is essential, and for producing gas arc lamps with tungsten terminals. Nutting has shown that Geissler tubes filled with helium are suitable under certain conditions as light standards in spectrography. Elihu Thomson has suggested that if divers were supplied with a mixture of oxygen and helium, the rate of expulsion of carbon dioxide from the lungs might be increased, and thus the period of submergence might be considerably lengthened. The widest application of helium, however, appears to be in the field of low-temperature research, as liquid helium—and perhaps eventually solid helium—enables one to reach the lowest temperatures attainable by any means."

"The last figures that have come to hand with regard to the London-Paris air service indicate the steadily increasing popularity of that route. During July 933 persons so traveled, making a daily average of 30 passengers."

"More than once since the armistice Scientific American has drawn public attention to the fact that, although in agreement with our history and traditions we are protagonists of disarmament and have proclaimed ourselves to be the champions of right and liberty as against might and enslavement, yet these same United States are today the only country in the world, with the exception of Japan, that is engaged in warship construction. Moreover, our plans for development are upon such a stupendous scale that we have no fewer than 18 capital ships under construction, all of which are of far greater fighting power than those of any other nation. Scientific American can never be accused of favoring a weak-kneed naval policy, or one that carries any color of pacifism. For a quarter of a century we have urged that the United States should possess a navy sufficient for her security and commensurate with her dignity; but we possess some sense of proportion, we hope, and the present situation, that this country of all free countries should be engaged in huge military constructions at a time when others have abandoned them, seems to be both illogical and inconsistent with our own national principles."

SCIENTIFIC AMERICAN

NOVEMBER, 1870: "Dr. Lyon Playfair, M.P., the new president of the Midland Institute in Birmingham, in succession to the late Mr. Charles Dickens, has given an eloquent and thoughtful address on the union of science and labor. Ridiculing the idea that advances in science have been the result of accident, he points out that man's wants led to the industrial arts, and that the practice of these arts and long-continued experience gave birth to science. Such advances were not promoted by a leisured aristocracy but as a rule by men rising from the industrial classes. Stephenson was a collier, Davy and Dalton were druggists, Faraday was a bookbinder, Harrison a carpenter, Watt an instrument maker and Arkwright a barber."

"The surrender of Metz together with the army of Bazaine, amounting to 173,000 men, has left the French without an organized army. Paris is so closely besieged that no supplies can reach its inhabitants, and the cry of distress is already heard. The case of France is utterly hopeless, yet notwithstanding all this Gambetta and his associates, who are unable to stay anywhere very long for fear of being caught by the Prussians, are urging the people to rise *en masse* to expel the invaders; but when asked for arms these crazy leaders are obliged to confess that they have none."

"In front of Krupp's establishment shells of the largest caliber are to be seen lying. They are in the form of a pointed cylinder and are three feet long and 14 inches in diameter. When filled with their charge (76 pounds of powder), they weigh 739 pounds. A hundred of these explosive projectiles have been ordered to be forwarded to the siege of Paris as speedily as possible."

"Iron for ships is rapidly superseding wood in English ship yards. In 1865 there were 806 wooden ships built in England, in 1869 but 324. In 1868 the tunnage of iron ships built was 235,937, against 66,977 wooden and 24,121 of composite. Iron ships are more durable, require fewer repairs and stand heavier storms than those of wood, and it will not be long till the latter must be entirely superseded."

"Professor Young of Dartmouth College has succeeded in obtaining photographs of protuberances on the sun's limb, of which copies were exhibited at the Lyceum of Natural History. They were made by attaching a small camera to the eye-piece of the telescope and opening the slit somewhat widely and working through the hydrogen line *G*. If this apparatus can be made to work, we can obtain such pictures without an eclipse."

"To enable the earth to resist the tide-generating force of the sun and moon, so as to leave the phenomena as they are actually found, Professor Thompson considers that its crust must have a thickness not less than 2,000 or 2,500 miles. Such a conclusion is of course quite inconsistent with the hypothesis that the earth is a mass of molten matter inclosed by a thin, solid shell."

THE AUTHORS

GLENN T. SEABORG and JUSTIN L. BLOOM ("Fast Breeder Reactors") are respectively chairman of the U.S. Atomic Energy Commission and staff assistant to the chairman. Seaborg is best known for his work on synthesizing elements heavier than uranium; he is co-discoverer of nine of the 13 generally recognized transuranium elements. For his work on the chemistry of the transuranium elements he shared with his colleague E. M. McMillan of the University of California at Berkeley the Nobel prize for chemistry in 1951. Seaborg, who was graduated from the University of California at Los Angeles in 1934, took his Ph.D. at Berkeley in 1937 and remained there for a number of years; he is still on leave as professor of chemistry at Berkeley. During World War II he was chiefly responsible for the development of the chemical-separation procedures used in the manufacture of plutonium. Returning to Berkeley in 1946, he was chancellor of the university from 1958 until his appointment as chairman of the AEC in 1961. Bloom, who was graduated from the California Institute of Technology in 1948, has served in several technical and managerial capacities on the AEC staff since 1956.

URSULA W. GOODENOUGH and R. P. LEVINE ("The Genetic Activity of Mitochondria and Chloroplasts") are at Harvard University: Miss Goodenough, who is also Mrs. R. P. Levine, is a postdoctoral research fellow in biology and Levine is professor of biology. Miss Goodenough was graduated from Barnard College in 1963 and obtained her Ph.D. at Harvard in 1969. Her work has focused on the ultrastructure of the unicellular green alga *Chlamydomonas reinhardi.* Levine was graduated from the University of California at Los Angeles in 1949 and received his Ph.D. there in 1951. At that time his research was concerned with the genetics and physiology of *Drosophila* from natural populations. Later he turned to the study of gene recombination in *Drosophila.* When he went to Harvard in 1953, he continued this work on *C. reinhardi.* Recent research in his laboratory is centered on the genetic functions of the DNA and ribosomes of *C. reinhardi* chloroplasts.

GEOFFREY WAINWRIGHT ("Woodhenges") is Inspector of Ancient Monuments for the Ministry of Public Building and Works in Great Britain. He writes that his work involves "excavation of prehistoric sites in Britain in advance of their destruction by industrial or agricultural agencies." Born in Wales, he was graduated from the University of Wales in 1958 with a degree in archaeology. In 1961, after obtaining his doctorate from the University of London, he became visiting professor of environmental archaeology at the University of Baroda in India, where he specialized in problems of Pleistocene archaeology in the Indian subcontinent. He took up his present work in 1963.

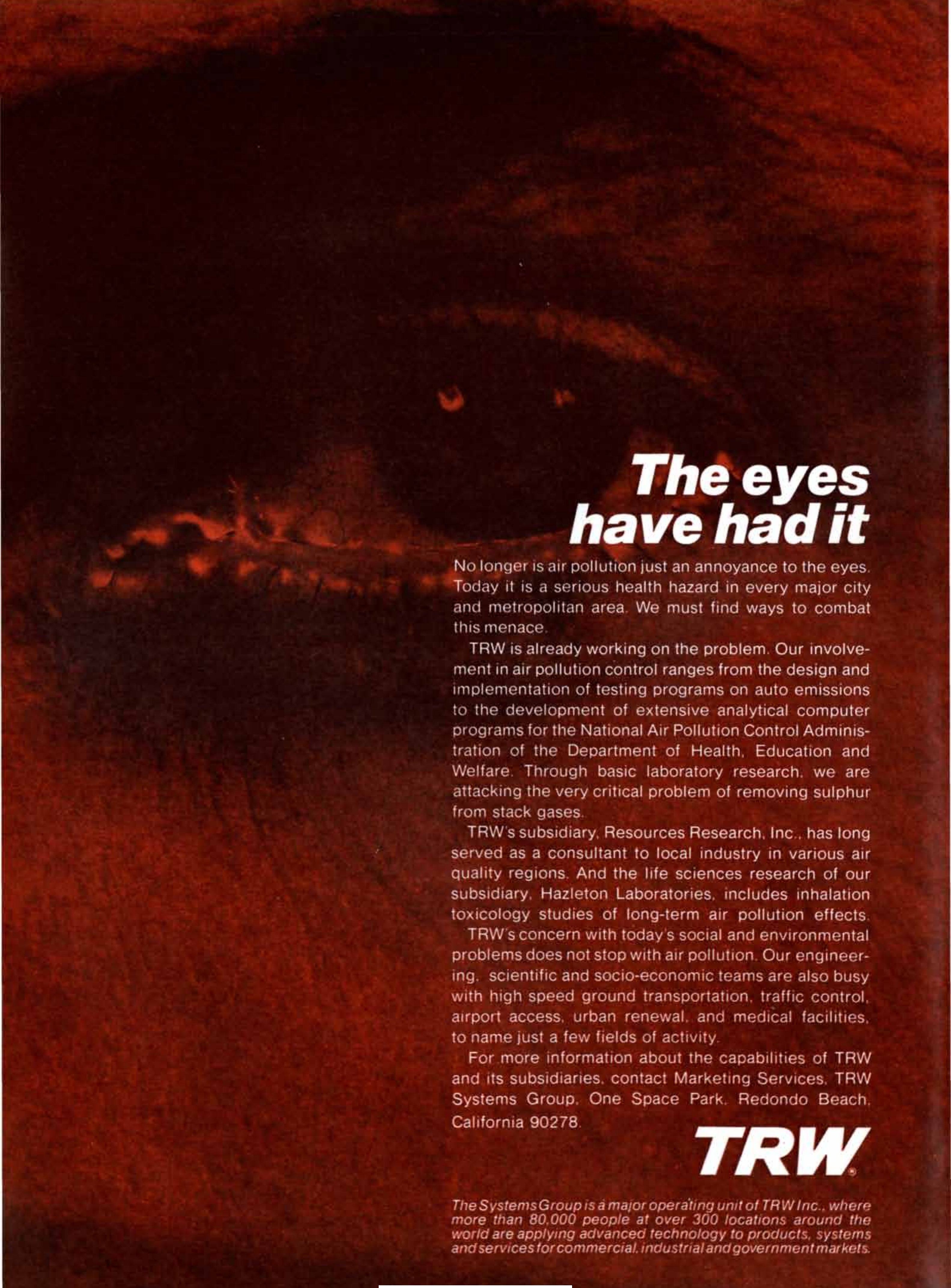
BORIS V. DERJAGUIN ("Superdense Water") is founder and director of the Department of Surface Phenomena in the Institute of Physical Chemistry of the U.S.S.R. Academy of Sciences. He has held the title of Academician since 1946. From 1935, when he founded the laboratory, until 1941 he worked with Academician M. M. Kusanov investigating the forces involved in the coagulation of material suspended in solution. His studies have also included the molecular theory of friction and the theory of adhesion of particles.

MARYLOU INGRAM and KENDALL PRESTON, JR. ("Automatic Analysis of Blood Cells"), are respectively associate professor at the University of Rochester and senior staff scientist with the Perkin-Elmer Corporation. Miss Ingram's professorship is in radiation biology and biophysics at the university's School of Medicine and Dentistry, of which she is a graduate and where she also is senior instructor in medicine. This year she is on leave at the Jet Propulsion Laboratory of the California Institute of Technology to participate in a program designed to apply technology developed for the analysis of photographs from space vehicles to the analysis of medically interesting microscopic images. Preston, who received both his bachelor's and master's degrees from Harvard University, was involved in computer research and development at the Bell Telephone Laboratories for seven years until he joined Perkin-Elmer in 1960. His work entails research in automatic image processing, acoustic holography, solid-state light modulators and detectors, and coherent optics.

W. L. N. TICKELL ("The Great Albatrosses") is lecturer in zoology at Makerere University College in Uganda. After his graduation from the University College of North Wales in 1954 he worked for several years in the Antarctic as a meteorologist and biologist. Obtaining his master's degree from Wales in 1959, he then spent six years at Johns Hopkins University, again undertaking periods of fieldwork in the Antarctic. He received his doctorate from Johns Hopkins in 1967. From 1966 to 1968 he was with the Nature Conservancy in Great Britain, serving as a warden-naturalist and studying seals and seabirds. His other interests include mountaineering and film-making.

HENRI TAJFEL ("Experiments in Intergroup Discrimination") is professor of social psychology at the University of Bristol. "My biography," he writes, "is by no means a simple one, as you might perhaps expect of a Jew born in Poland in 1919. When the war broke out, I was in Paris as a student at the Sorbonne. Together with two million others I was taken prisoner of war in June, 1940, and spent the next five years in prisoner-of-war camps in Germany, France and Austria. After the war I worked for international organizations of relief for victims of war, successively in France, Belgium and West Germany. Then and later I studied psychology at the universities of Paris, Brussels and finally London, where I took my doctorate. As you might expect, all of this left me with an intense interest in all aspects of intergroup relations." Tajfel taught at the University of Durham and the University of Oxford before going to Bristol in 1967.

FERREN MACINTYRE ("Why the Sea Is Salt") is research associate in the Marine Science Institute of the University of California at Santa Barbara. He writes: "I worked for eight years in the real world—as lumberman, machinist, machine designer, loftsman—before retiring to college. Turned chemist because Ambrose Nichols, then at San Diego State, was the best teacher I've ever met. B.A. in chemistry from the University of California at Riverside, 1960; Ph.D. in physical chemistry from the Massachusetts Institute of Technology in 1965. Spent three years at the Scripps Institution of Oceanography, where my specialty was the 'top half' of the ocean (on a logarithmic scale), examining the physicochemical hydrodynamics of the top few millimeters of the sea and the interchange of chemicals between sea and air. But anyone can be a specialist; the problem is to generalize sufficiently to find our way back to a human habitat that reflects our claim to intelligence. My other interests include folk music, building musical instruments and rock-climbing."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Fast Breeder Reactors

Nuclear reactors that use fast neutrons to produce more fuel than they consume are a promising approach to producing electric power with a minimum of strain on energy resources and the environment

by Glenn T. Seaborg and Justin L. Bloom

The need to generate enormous additional amounts of electric power while at the same time protecting the environment is taking form as one of the major social and technological problems that our society must resolve over the next few decades. The Federal Power Commission has estimated that during the next 30 years the American power industry will have to add some 1,600 million kilowatts of electric generating capacity to the present capacity of 300 million kilowatts. As for the environment, the extent of public concern over improving the quality of air, water and the landscape hardly needs elaboration, except for one point that is often overlooked: it will take large amounts of electrical energy to run the many kinds of purification plants that will be needed to clean up the air and water and to recycle wastes.

A related problem of equal magnitude is the rational utilization of the nation's finite reserves of coal, oil and gas. In the long term they will be far more precious as sources of organic molecules than as sources of heat. Moreover, any reduction in the consumption of organic fuels brings about a proportional reduction in air pollution from their combustion products.

Nuclear reactors of the breeder type hold great promise as the solution to these problems. Producing more nuclear fuel than they consume, they would make it feasible to utilize enormous quantities of low-grade uranium and thorium ores dispersed in the rocks of the earth as a source of low-cost energy for thousands of years. In addition, these reactors would operate without adding noxious combustion products to the air. It is in the light of these considerations that the U.S. Atomic Energy Commission, the nuclear industry and the electric utilities have mounted a large-scale effort to develop the technology whereby it will be possible to have a breeder reactor generating electric power on a commercial scale by 1984.

Nuclear breeding is achieved with the neutrons released by nuclear fission. The fissioning of each atom of a nuclear fuel, such as uranium 235, liberates an average of more than two fast (high-energy) neutrons. One of the neutrons must trigger another fission to maintain the nuclear chain reaction; some neutrons are nonproductively lost, and the remainder are available to breed new fissionable atoms, that is, to transform "fertile" isotopes of the heavy elements into fissionable isotopes. The fertile raw materials for breeder reactions are thorium 232, which is transmuted into uranium 233, and uranium 238, which is transmuted into plutonium 239 [*see illustrations on next page*].

We have mentioned that breeding occurs when more fissionable material is produced than is consumed. A quantitative measure of this condition is the doubling time: the time required to produce as much net additional fissionable material as was originally present in the reactor. At the end of the doubling time the reactor has produced enough fissionable material to refuel itself and to fuel another identical reactor. An efficient breeder reactor will have a doubling time in the range of from seven to 10 years.

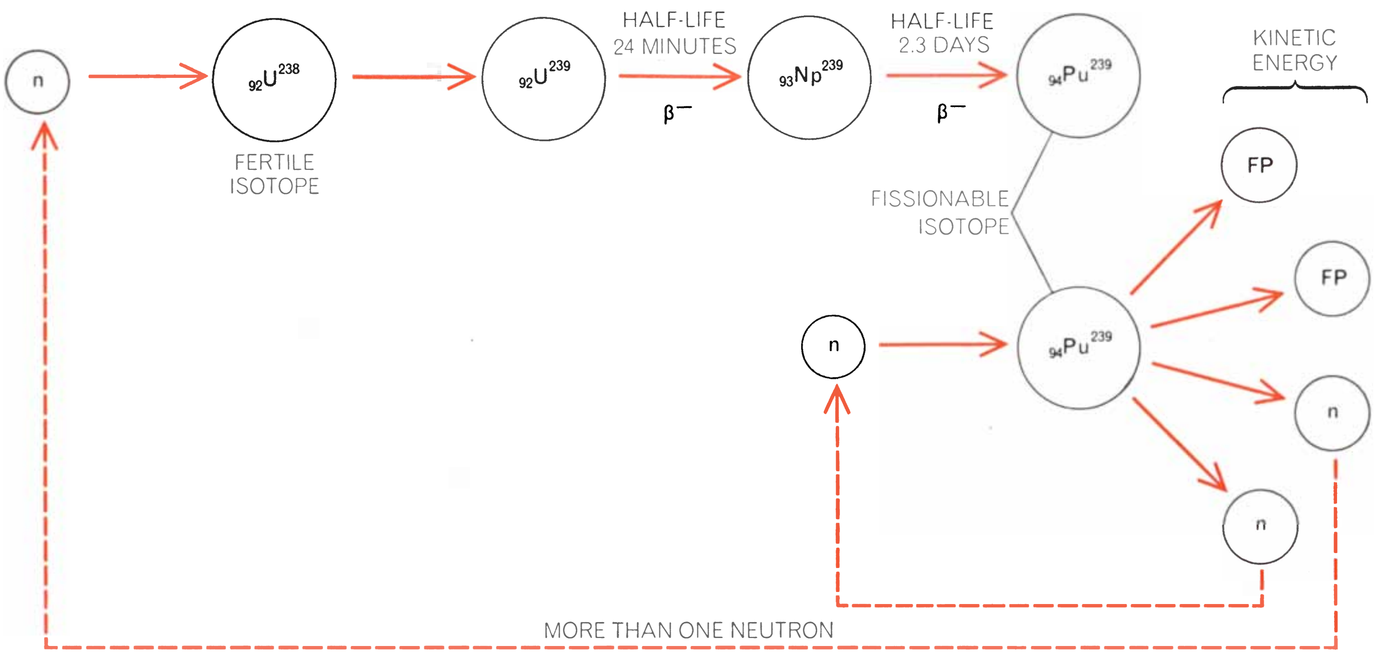
Two different breeder systems are involved, depending on which raw material is being transmuted. The thermal breeder, employing slow neutrons, operates best on the thorium 232–uranium 233 cycle (usually called the thorium cycle). The fast breeder, employing more energetic neutrons, operates best on the uranium 238–plutonium 239 cycle (the uranium cycle). Nonproductive absorption of neutrons is less in fast reactors than it is in thermal reactors, resulting in a decrease in the doubling time.

The concept of the breeder reactor is almost as old as the idea of the nuclear chain reaction. In the early stages, soon after World War II, many types of breeder reactor were visualized. Some were thermal and some were fast. Another important differentiation involved the type of coolant employed to carry off the heat of fission and deliver it to a power-generating system. Among the coolants proposed were water and molten salts for thermal breeding and inert gas (such as helium), liquid metal (such as sodium) and steam for fast breeding.

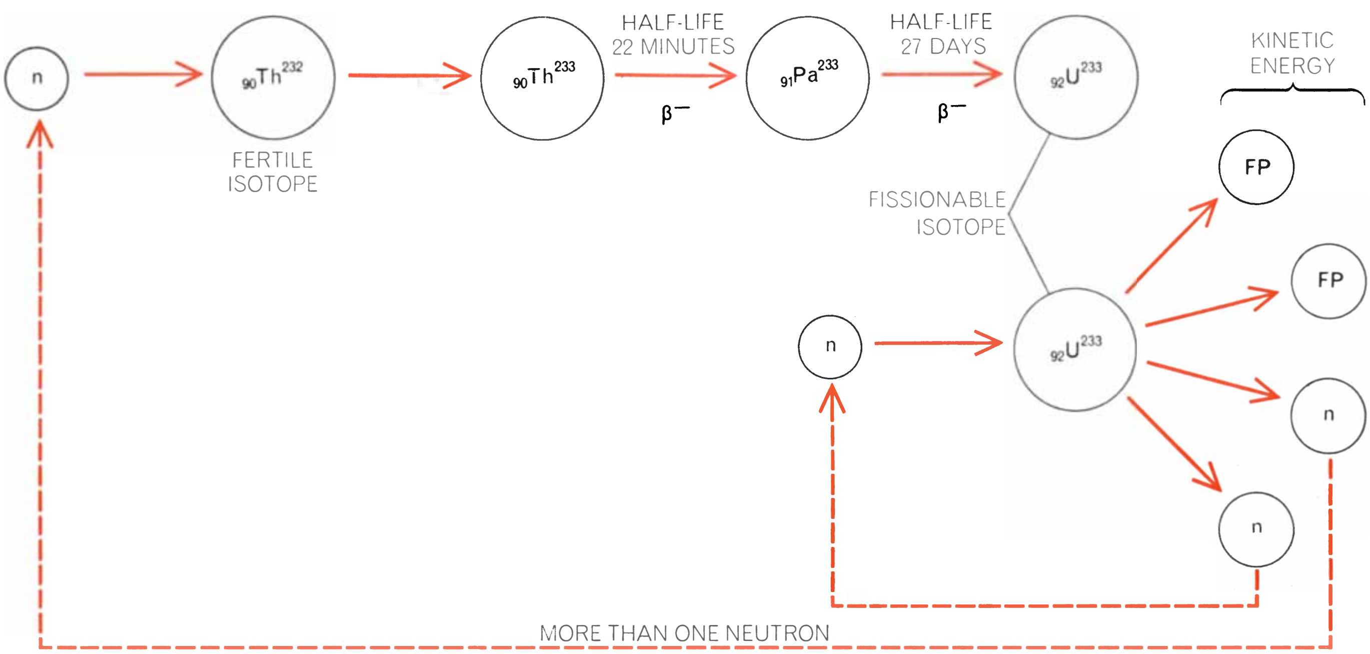
In the U.S. and several other countries decisions were made rather early that a fast breeder reactor cooled with liquid metal was the most attractive concept to pursue. This concept is known to atomic energy workers as the LMFBR (liquid-metal-cooled fast breeder reactor). Since the greater part of breeder-reactor development is now proceeding on the basis of this concept, this article is mainly devoted to the liquid-metal fast breeder. A serious alternative effort is being pursued, chiefly by utility companies, to develop the technology of a gas-cooled fast breeder reactor using pressurized helium as the coolant. In the U.S. two thermal-breeder-reactor concepts operating on the thorium cycle are being developed: the light-water breeder reactor at the Bettis Atomic Power Laboratory and the molten-salt reactor at the Oak Ridge National Laboratory.

In the design of a liquid-metal-cooled fast breeder reactor several features are noteworthy. The core of a fast reactor can be quite small. For economic reasons the reactor must be operated at a much higher power density than ordinary fission reactors are. The active core volume is therefore only a few cubic meters and is roughly proportional to the power output. The power density is about .4 megawatt per liter.

To carry off the heat while maintaining the fuel at a reasonable temperature sodium must flow through the core at a rate of tens of thousands of cubic meters per hour. In order to provide channels



URANIUM CYCLE for breeding in a fast breeder reactor relies on fast, or highly energetic, neutrons. In the cycle an atom of fertile uranium 238 absorbs a neutron and emits a beta particle to become neptunium, which then undergoes beta decay to become fissionable plutonium 239. When an atom of plutonium 239 absorbs a neutron, it can fission, releasing energy, fission products (*FP*) and at least two neutrons. One of the neutrons is needed to continue the chain reaction, but the others are available to transform a fertile isotope into a fissionable one, thereby "breeding" fuel. Within a few years a breeder doubles its original fuel inventory.



THORIUM CYCLE of breeding is similar to the uranium cycle except that it works best in a thermal breeder reactor, where it relies on thermal, or relatively slow, neutrons. Thorium 232 is the fertile isotope that becomes protactinium and then uranium 233.

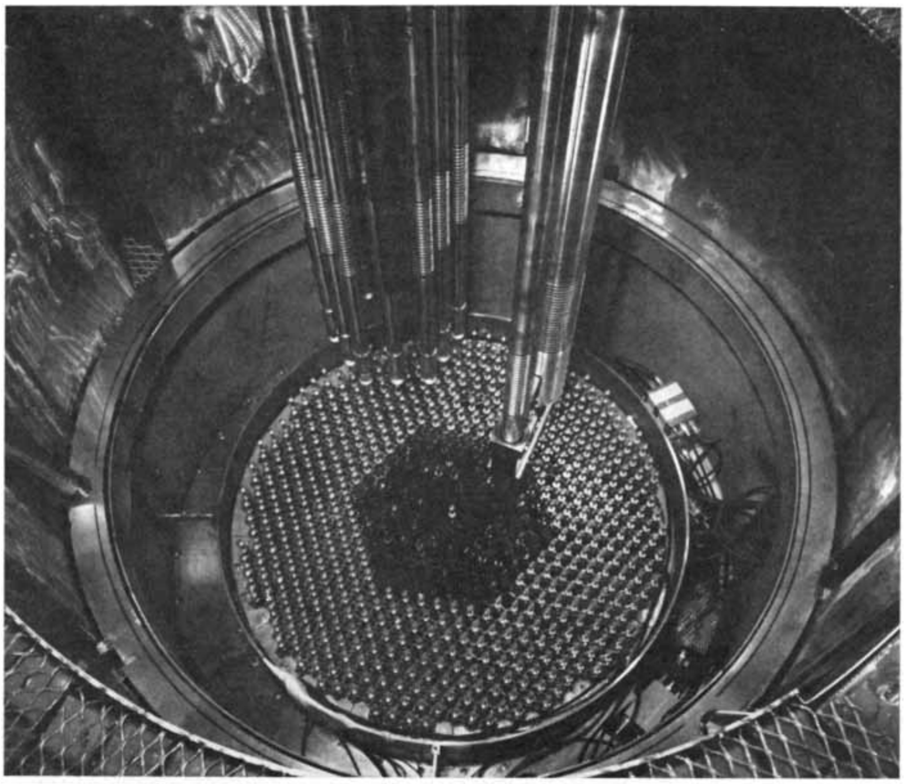
for the flow of sodium the fuel is divided into thousands of slender vertical rods, which are usually referred to as pins. Each pin is sealed in stainless steel or another high-temperature alloy.

The fuel is preferably in a ceramic form such as oxide or carbide, since these ceramics are stable during long exposures to heat and radiation, have very high melting points and are relatively inert in liquid metal. The fissionable component of the fuel can be enriched uranium 235, plutonium 239 or a mixture of the two. Typically the fuel is diluted with uranium 238, so that part of the breeding takes place within the core. The uranium 238 also serves a safety function in the core, which we shall explain in more detail below. For maximum economy and performance the fuel must be able to accept neutron irradiation at many times the rate common in present nuclear reactors of commercial scale. Furthermore, the consumption of fuel between reprocessing steps is to be at least twice that of thermal reactors. The development of a fuel meeting these stringent criteria requires the testing of numerous fuel combinations in reactors and accounts for a major element of the breeder development program.

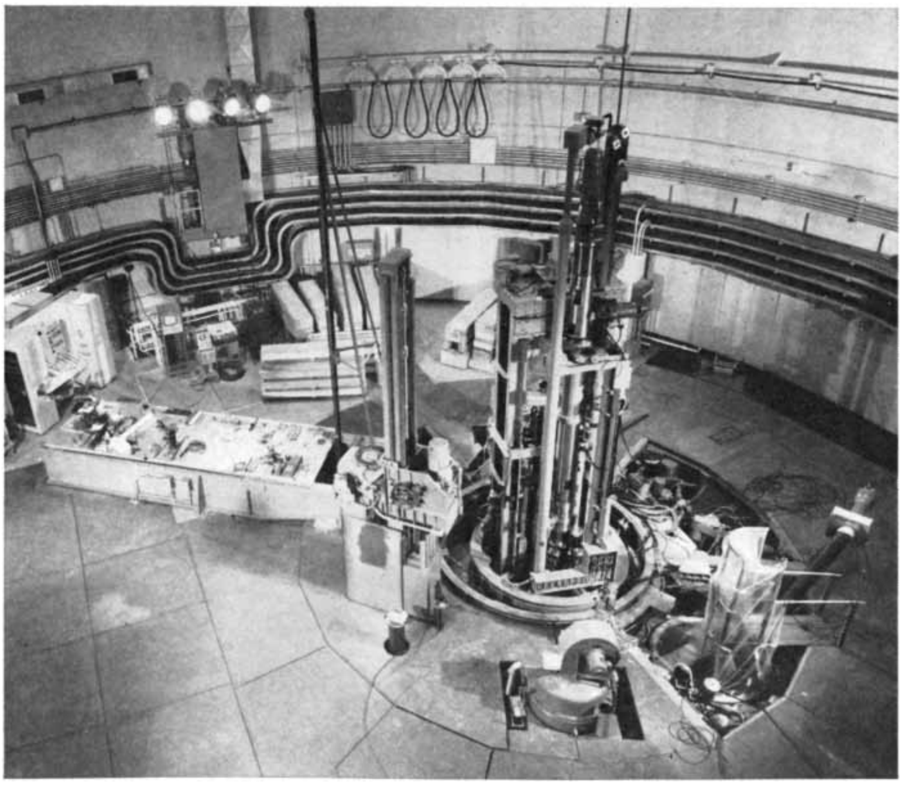
A second major feature of a fast breeder reactor is the "blanket" that surrounds the core. Much of the breeding takes place here, and so the blanket consists of uranium 238 in stainless-steel tubes. (It can be uranium that is depleted in the isotope uranium 235 as a result of enrichment procedures designed to make uranium 235 as a fuel for nuclear reactors; large stocks of such depleted uranium are now available.) Since there is a certain amount of fission in the blanket, it too must be cooled by the flow of sodium. The blanket also has an important nuclear function. Not all the neutrons entering the blanket are captured; a fairly large proportion are reflected back into the reactor core, enhancing the neutron economy there.

The sodium coolant has excellent heat-transfer characteristics. Moreover, it can be used at a fairly low pressure even though it emerges from the reactor at a temperature (above 500 degrees Celsius) that with water would give rise to high pressures. Indeed, the sodium pressure arises solely from the force required to maintain the high rate of flow through the maze of tubes in the core and the blanket. Compared with coolants such as water and gas, sodium requires low pumping power. It is not particularly corrosive to the reactor.

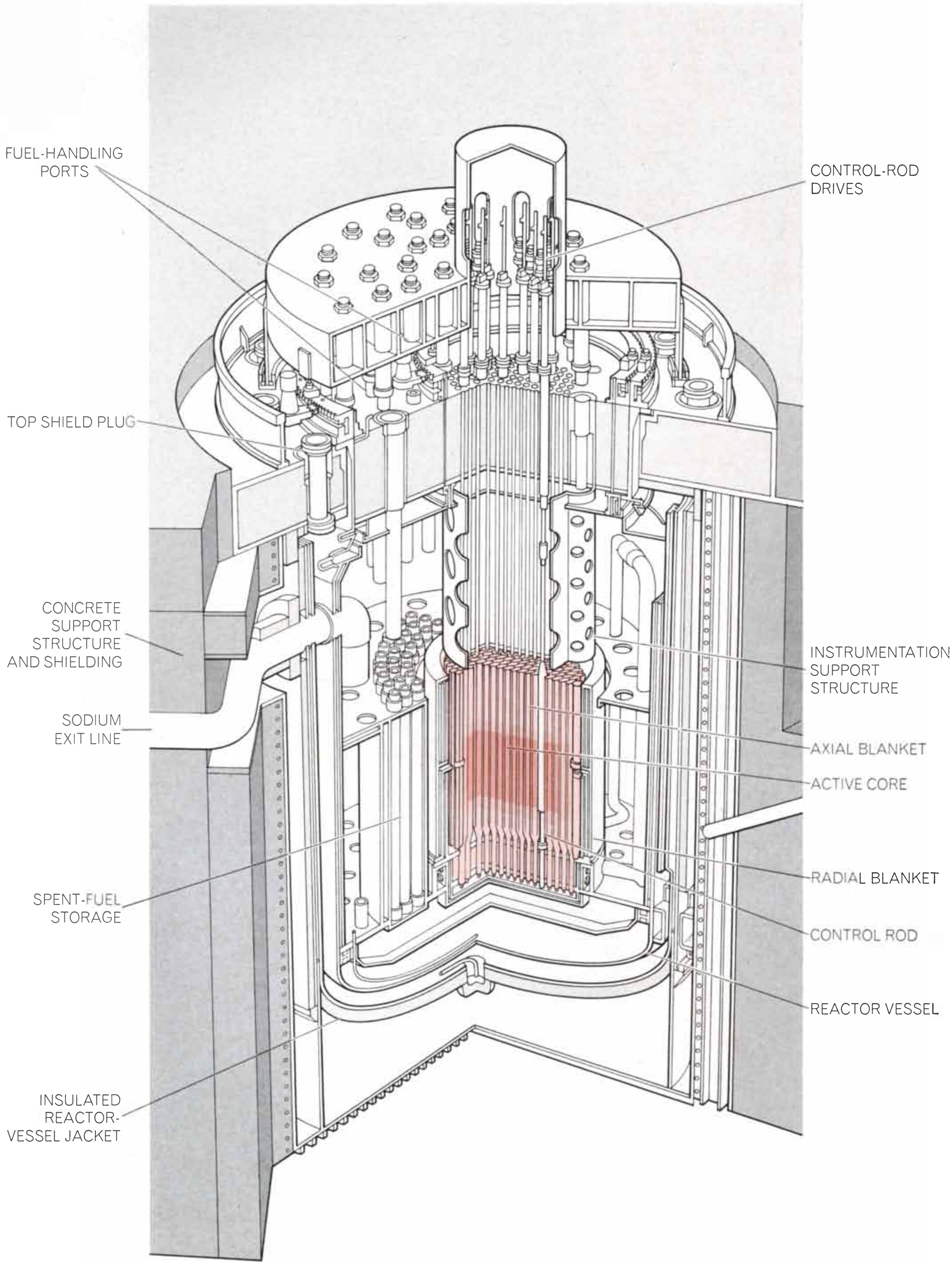
Sodium does, however, have certain



CORE AND BLANKET of a fast breeder reactor, Experimental Breeder Reactor II, are the heart of the breeding operation. The dark hexagonal area is the core, where fuel elements can be installed and removed by the gripper mechanism at right center. Rods clustered at left center are connected to control rods in the core. Around the core is the blanket, consisting of rods containing uranium 238, which is converted to plutonium during the breeding.



EXPERIMENTAL BREEDER REACTOR II is operated by the U.S. Atomic Energy Commission at the National Reactor Testing Station in Idaho. The primary components of the nuclear reactor are under the floor in a tank that is 26 feet high and 26 feet in diameter and contains liquid sodium, which is the coolant. Vertical assembly at right center contains mechanisms for operating the control rods and for handling fuel elements within the reactor. The reactor is used to test fuels and materials for breeder reactors of commercial scale.



LIQUID-METAL REACTOR of the fast-breeder type is depicted on the basis of a design for a demonstration plant that would produce some 500 megawatts of electricity. A full-scale commercial plant, scheduled for operation by 1984, would be of 1,000-megawatt capacity. This design is of the loop type, meaning that the reactor proper, which is contained in a large tank of liquid sodium, is separated from the primary heat exchangers and the associated pumps by loops of piping through which sodium coolant flows.

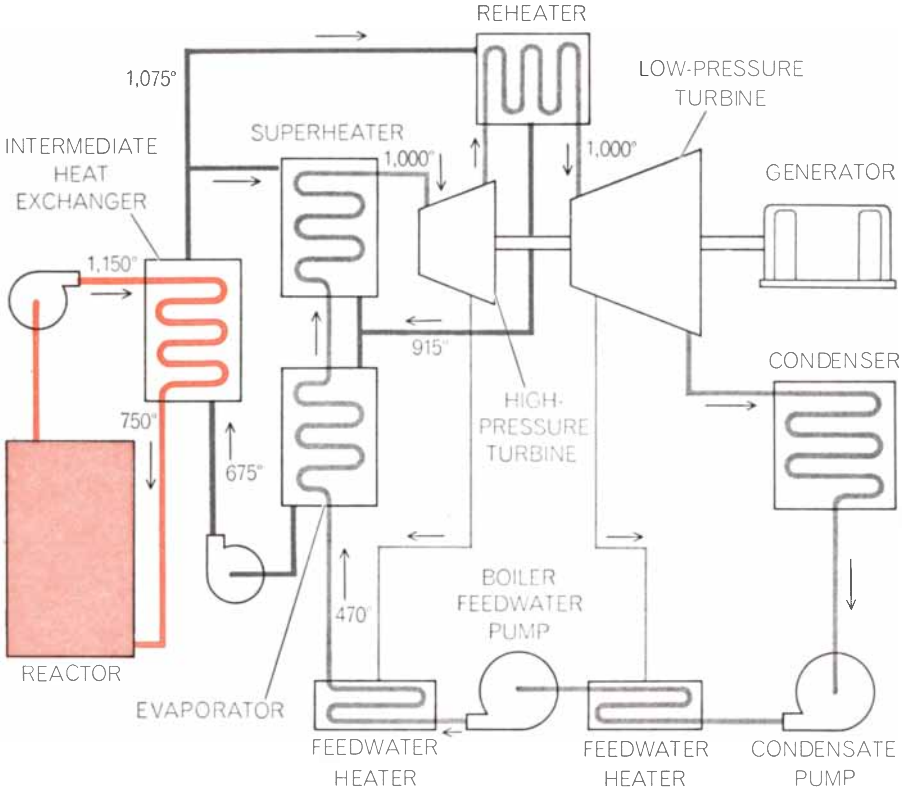
disadvantages that markedly influence the design of a reactor. Since sodium is opaque, provision must be made for the maintenance and refueling of the reactor without benefit of visual observation. Sodium is of course highly reactive chemically, and it becomes intensely radioactive when it is exposed to neutrons, even though its "cross section," or neutron-absorption capacity, is relatively low. Hence the sodium must be kept out of contact with air or water, and radiation shielding must be used to protect workers who are near sodium that has been through the core and blanket of an operating reactor.

Interspersed through the core region are numerous rods with safety and control functions. They maintain the power output at the desired level and provide the means for starting and stopping the reactor. The rods are filled with neutron-absorbing material such as boron carbide or tantalum metal.

All materials have markedly lower neutron-absorption probabilities for fast neutrons than for thermal ones. The lower cross sections reduce the effectiveness of fast-reactor control rods of sizes comparable to those in thermal reactors. On the other hand, a large amount of excess fuel is present in the core of a thermal reactor to compensate for the fuel that will be consumed by fission and to counteract the poisoning effect of the fission products. (The fission products capture neutrons without yielding significant amounts of energy.) With extra fuel there must be extra controls. Fast breeder reactors require fewer control rods because their greater effectiveness in converting uranium 238 to fissionable plutonium 239 compensates for depletion of the initial fuel charge and because fast neutrons are not absorbed by fission products as much as thermal neutrons are.

During a fission reaction not all the neutrons are released at the precise instant that each nucleus disintegrates. A small proportion of the neutron population is created by the decay of fission products. One thus distinguishes delayed neutrons from the "prompt" neutrons emitted directly by the fissioning nuclei. It is the delayed neutrons that keep the chain reaction from escalating into an essentially instantaneous propagation of one generation of neutrons to the next.

The fraction of delayed neutrons depends appreciably on which nucleus is fissioning. Most thermal reactors are fueled with uranium 235, whereas the fast breeder will be fueled with plutonium 239. The fraction of delayed neutrons produced by the fission of uranium 235 is about .0065 and by plutonium 239 fission about .003. The smaller fraction of delayed neutrons present in a fast reactor is not of major concern under normal operation. It does increase the sensitivity of the reactor to adjustments of the control rods and to other inputs that affect reactivity, such as temperature variations in the core.



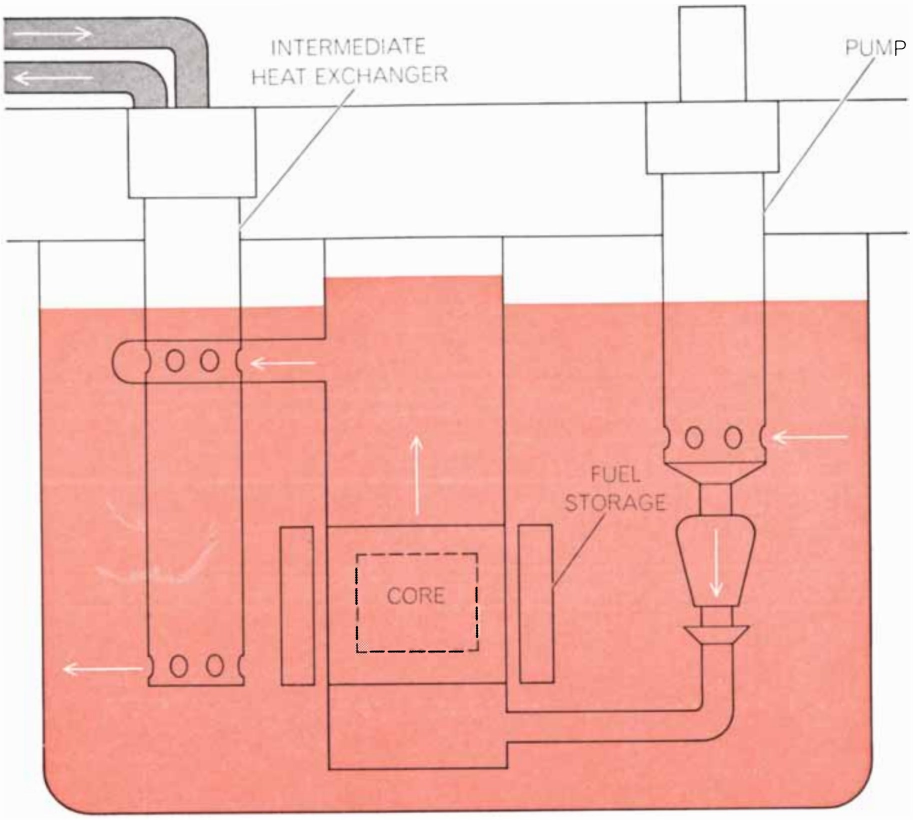
FLOW PLAN for a liquid-metal fast breeder reactor entails pumping the sodium coolant (*color*) through the reactor, where it becomes radioactive, and then to an intermediate heat exchanger, where heat is transferred to a separate stream of sodium (*dark gray*) that is not radioactive. The heat of that stream is put into a water and steam cycle (*light gray*) that is employed to generate electricity. The numerals give temperatures in degrees Fahrenheit.

Two different designs of containers for the core-and-blanket assembly and the primary heat-transfer system are under consideration: the pot type and the loop type [*see illustrations on next page*]. In the pot type a large tank filled with sodium encloses (1) the reactor vessel, (2) sodium pumps that take sodium from the pool and move it through the core and blanket and (3) intermediate heat exchangers that transfer heat from the radioactive sodium to another sodium stream. In the loop type only the reactor vessel is filled with sodium; the liquid metal is circulated by pumps through heat-exchange loops mounted outside the reactor container. The pot type has the advantage of a much greater heat capacity in the event of pump failure, but it also requires a much larger inventory of sodium.

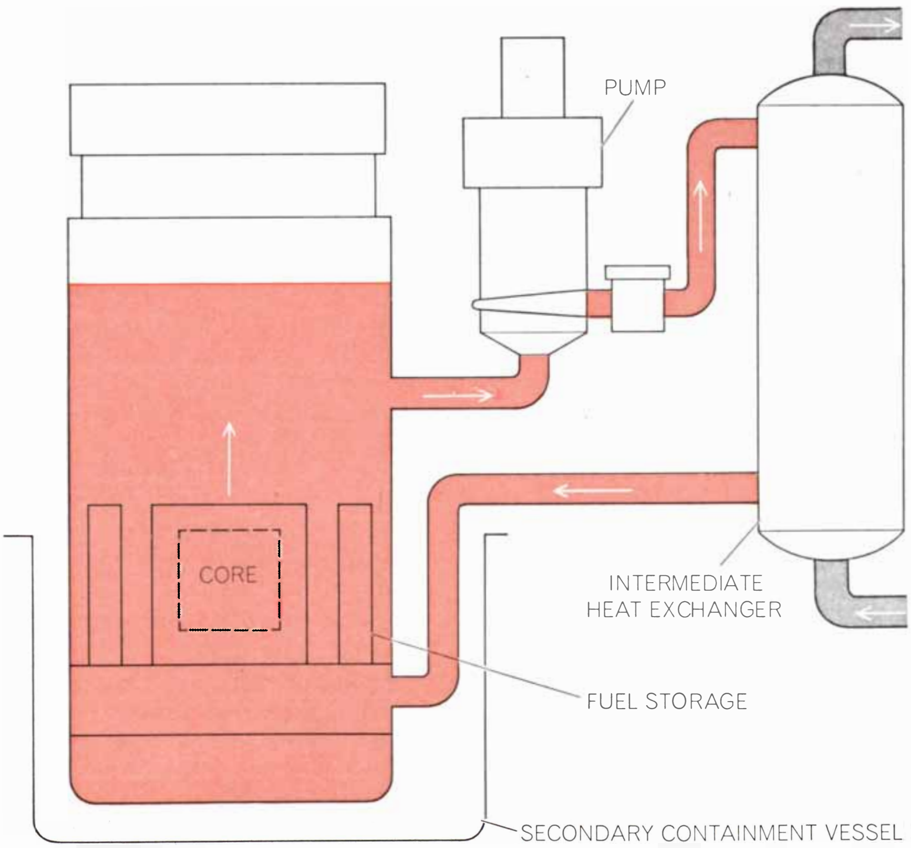
In both the pot and the loop design the liquid-metal fast breeder reactor employs a complex heat-transfer arrangement to isolate the sodium that flows through the core from the steam-generating equipment. This is the role of the intermediate heat exchangers. They transfer heat from the radioactive sodium to nonradioactive sodium, which then flows through the steam generator. Subsidiary streams of sodium are required to superheat the steam and to reheat it from time to time as it works against the blades of the turbine.

Both the pot and the loop design require sealing of the part of the structure that is in direct contact with the radioactive core and blanket. In routine operation there would be no release of radioactive fission products to the environment. Because of the inherently low pressure of the sodium coolant, the reactor vessel and its associated piping need be designed to withstand only moderate operating stresses, in marked distinction to the pressure vessels and other primary-system components of a pressurized-water reactor, a boiling-water reactor or a gas-cooled reactor.

At present the pot design seems to be attracting the most interest. It is inherently a less complicated arrangement than the loop design. Nonetheless, it



POT SYSTEM is one of two designs for containing the core-and-blanket assembly of the reactor and the primary heat-transfer system. The pot is a tank that is filled with sodium and also contains the reactor, pumps that take sodium from the pool and move it through the reactor, and intermediate heat exchanger where heat is transferred to nonradioactive sodium.



LOOP SYSTEM has most of its heat-exchange apparatus outside the reactor. Only the reactor vessel is filled with sodium, which is circulated by pumps through heat-exchange loops mounted outside the reactor vessel. In the present state of breeder-reactor technology both of the designs in the schematic illustrations on this page are being pursued.

does present certain problems, notably in gaining access to the reactor for maintenance.

The gas-cooled fast breeder reactor is receiving attention (comparatively modest so far) as a parallel and complementary concept to the liquid-metal fast breeder. Gas-cooled thermal reactors are already in operation, and a gas-cooled fast breeder would not represent a large step in terms of coolant technology. The design and testing of the fuel for a gas-cooled fast breeder have much in common with the work on fuel for the liquid-metal fast breeder.

The essential difference between the two fast breeders is that the gas-cooled one uses helium gas at a pressure of from 70 to 100 atmospheres rather than molten sodium to transport the heat from the reactor core to the steam generators. Since the gas does not become radioactive and cannot react chemically with the water in the steam generator, there is no need for an intermediate heat exchanger. The resulting simplification of the system is a helpful offset against the need to design for a higher coolant pressure with gas.

The use of helium as a coolant has other special advantages for a fast breeder reactor. Helium does not interact with the fast neutrons in the reactor core, resulting in both simplified control of the reactor and enhanced breeding of new fissionable fuel from fertile material. In addition helium is transparent and chemically inert, providing visibility during refueling and maintenance operations, a simpler engineering design and freedom from corrosion problems.

In a gas-cooled fast breeder the reactor core, helium circulators and steam generators are all contained in a prestressed-concrete reactor pressure vessel. These major components and their arrangement are almost the same as in a thermal gas-cooled reactor.

The development of a gas-cooled fast breeder reactor could result in substantial additional savings beyond those that would be achieved by liquid-metal fast breeders. Neutrons are moderated, or slowed, less in helium than they are in sodium. Hence the doubling time is short. It is also possible to foresee the development of a gas-cooled fast breeder with a direct power cycle wherein the gas coolant flows from the reactor directly to a gas turbine that drives the electrical generator. Such a cycle should help to reduce the capital cost of fast breeder reactors.

Three major reactors will carry the burden of the Atomic Energy Commission's program to develop a liquid-metal fast breeder reactor. Two of them are already in operation: the Experimental Breeder Reactor II (EBR-II) and the Zero Power Plutonium Reactor (ZPPR).

EBR-II is a fast-neutron test reactor operated by the Argonne National Laboratory at the commission's National Reactor Testing Station in Idaho. This reactor, which as of July 1 had a cumulative record of more than 35,000 megawatt-days of operation, is the focal point of the program of testing fuels and irradiating materials for the liquid-metal fast breeder reactor. At present almost 800 experimental fuel pins and more than 100 capsules containing hundreds of structural, control-rod and shield-material specimens are being irradiated in the reactor. EBR-II achieved its design power of 62.5 megawatts (thermal) last year.

The Argonne National Laboratory is also operating the ZPPR, which went into operation last year. (Zero power in this context means that the reactor does not generate a significant amount of heat.) It is the nation's largest zero-power fast reactor and the only one in the world that is big enough and has a large enough inventory of plutonium (at least 3,000 kilograms) to allow full-scale mock-ups of the plutonium fuel arrangements that will be used in the large commercial breeders envisioned for the 1980's and beyond. The reactor will provide important information on the behavior of neutrons in breeder-reactor cores.

The third reactor is now being designed on the basis of data obtained from EBR-II, the ZPPR and smaller facilities. Called the Fast Flux Test Facility, it will operate at a very high neutron flux (defined as the number of neutrons passing through a square centimeter of area per second) to produce the radiation effects on fuel and structural materials that will take place in a commercial breeder reactor. The reactor, which will cost about $100 million, will operate at a power level of 400 megawatts (thermal) with no conversion to electric power. It will be built at the Atomic Energy Commission's site in Richland, Wash.; construction should start next year and full power should be achieved by the middle of the decade.

Following the lessons learned in the development of thermal reactors, the commission has taken the first steps toward construction of one or more liquid-metal fast-breeder demonstration plants. The cost will be shared by the Government and industry. The first such plant, with a capacity of from 300 to 500 megawatts (electric), will accumulate valuable operating experience with both the reactor and the power-conversion equipment. Such a plant will not compete economically with existing nuclear or conventional plants because of its relatively small size and early stage of development. The full-scale liquid-metal fast breeder reactor of the 1980's will be rated at 1,000 megawatts (electric) or more.

Much consideration is being given to safety in the fast breeder development program. The waste products of fission are the elements in the middle of the periodic table that represent the split nuclei of the fuel atoms. Many isotopes

	NAME	COUNTRY	POWER		INITIAL OPERATION	TYPE (POT OR LOOP)
			MEGAWATTS (THERMAL)	MEGAWATTS (ELECTRICAL)		
OPERATING	BR-5	U.S.S.R.	5	—	1959	LOOP
	DFR	U.K.	60	15	1959	LOOP
	EBR-II	U.S.	62.5	20	1964	POT
	FERMI	U.S.	200	66	1963	LOOP
	RAPSODIE	FRANCE	40	—	1967	LOOP
	SEFOR	U.S.	20	—	1969	LOOP
	BOR-60	U.S.S.R.	60	12	1970	LOOP
UNDER CONSTRUCTION	BN-350	U.S.S.R.	1,000	150	1971	LOOP
	PFR	U.K.	600	250	1972	POT
	PHENIX	FRANCE	600	250	1973	POT
	BN-600	U.S.S.R.	1,500	600	1973/75	POT
	FFTF	U.S.	400	—	1974	LOOP
PLANNED	KNK-II	WEST GERMANY	58	20	1972	LOOP
	JEFR	JAPAN	100	—	1973	LOOP
	PEC	ITALY	140	—	1975	MODIFIED POT
	SNR	WEST GERMANY	730	300	1975	LOOP
	DEMO #1	U.S.	750-1,250	300-500	1976	NOT DECIDED
	JPFR	JAPAN	750	300	1976	LOOP
DECOMMISSIONED	CLEMENTINE	U.S.	.025	—	1946	LOOP
	EBR-I	U.S.	1	.2	1951	LOOP
	BR-2	U.S.S.R.	.1	—	1956	LOOP
	LAMPRE-I	U.S.	1	—	1961	LOOP

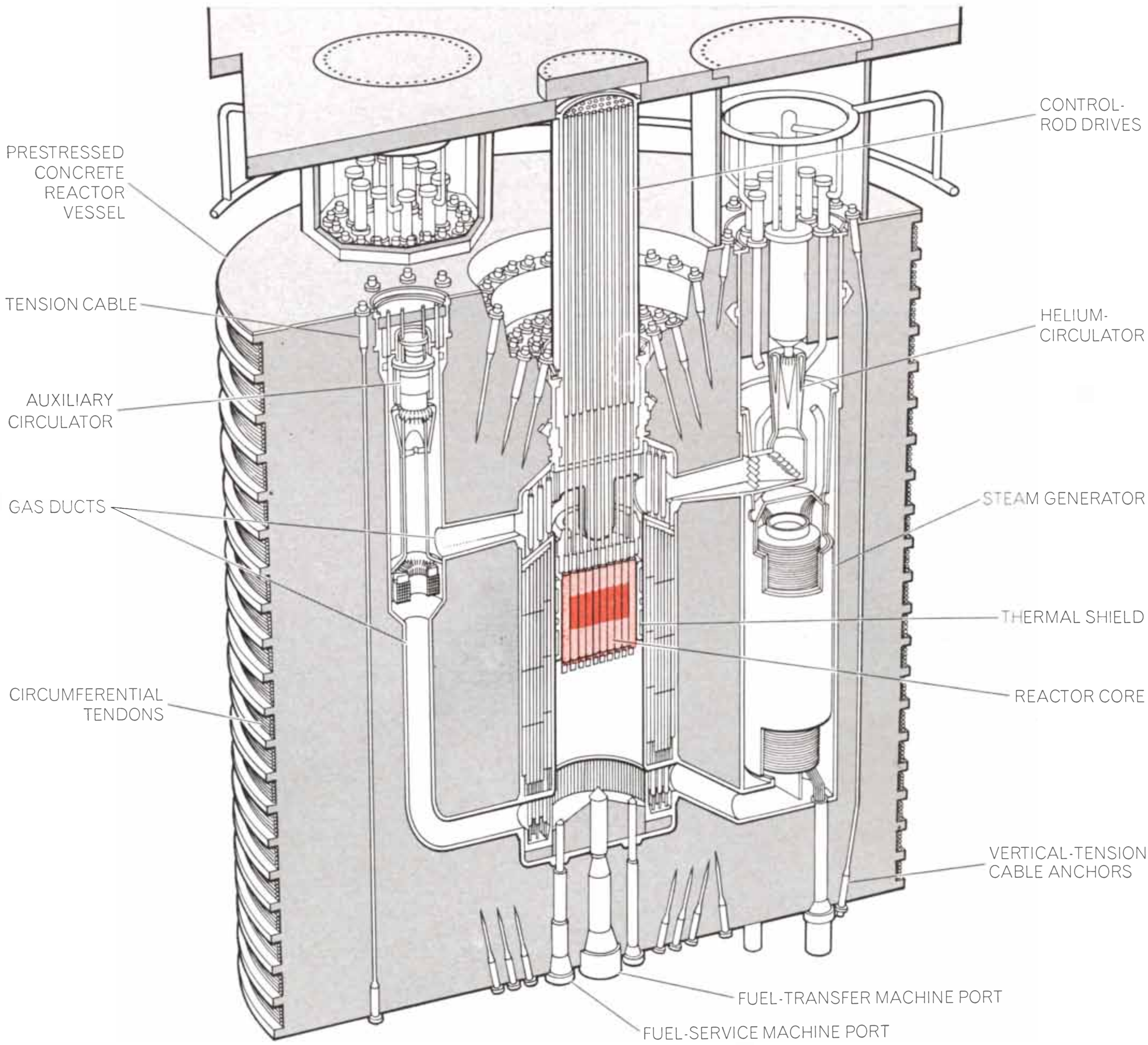
LIQUID-METAL FAST REACTORS built or planned are summarized. Those that produce electricity have far less capacity than the 1,000-megawatt commercial fast-breeder plant that the development program of the U.S. seeks to have in operation by 1984.

of these elements are radioactive. The permanent control of the fission products has been recognized as essential from the early stages of reactor development and is routinely achieved in the fuel cycle. In addition to making fission products, fast breeders will also contain large amounts of plutonium, which in certain forms is radiologically toxic. The standard procedure in both thermal and fast reactors is to ensure the confinement of all potentially hazardous substances under all foreseeable conditions, including earthquakes.

Perhaps the most significant safety feature of commercial nuclear reactors is that they are self-regulating, that is, they are designed to compensate inherently for any incident that could lead to an unintentional increase of power output. In water reactors the compensation is usually achieved through the decrease in reactivity caused by the decrease in the density of water as its temperature increases. In a fast reactor the change in density of the coolant with temperature may lead in the opposite direction.

Compensation is provided in a fast breeder by the Doppler effect, which results from the increase in the rate at which neutrons are absorbed by uranium 238 as the temperature of the fuel in the core rises. Since a sudden power increase will necessarily be accompanied by increased fuel temperature, there will be increased neutron absorption and a consequent tendency toward reduction of power. A small sodium-cooled fast reactor has been built in Arkansas with private funds to measure this effect under conditions analogous to those in a large power reactor. It is called the Southwest Experimental Fast Oxide Reactor.

The fact that a decrease in coolant density or coolant content can result in an increase in reactivity leads to other safety considerations for sodium-cooled fast reactors. For example, if one postulates a bubble of gas or another void whereby an area of the core might overheat without detection, some of the fuel pins in the area would be expected to fail. Further disturbances of flow might ensue. A continued sequence of such events would not necessarily result in an automatic shutdown of the reactor. Thus



GAS-COOLED REACTOR is depicted in the form it might take for a demonstration breeder plant with a capacity of 300 megawatts of electric power. The chief difference between such a reactor and a liquid-metal one is that the coolant here is helium at high pressure instead of liquid sodium at low pressure. Because of the pressure the reactor is contained within a prestressed-concrete vessel.

it is necessary to preclude by design the propagation of fuel-pin failures.

This control can be achieved by a number of techniques. The addition of a moderator such as beryllium oxide increases the magnitude of the neutron Doppler effect. A change in the ratio of coolant to fuel can reduce the void effect. Other methods include distributing the fuel in such a way that the potential reactivity of coolant voids is decreased by increasing the number of neutrons leaking from the core.

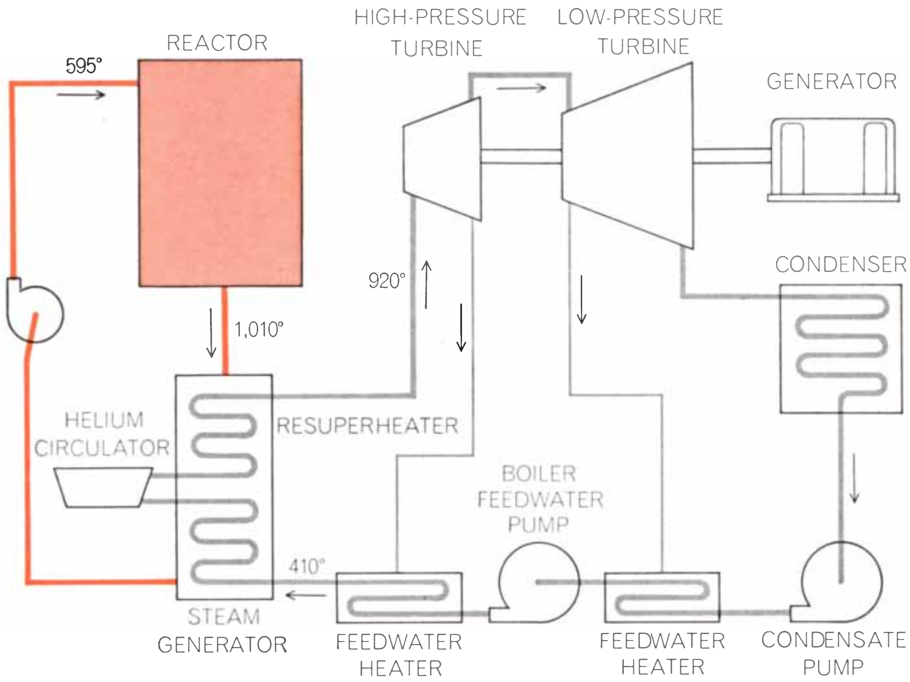
In a gas-cooled fast reactor there is no problem with voids because a bubble cannot form in gas. There is, however, another condition to be guarded against: a sudden loss of coolant pressure resulting from an event such as rupture of the pressure vessel. This possibility is minimized by the use of the prestressed-concrete type of reactor vessel.

Having made sure that perturbations in normal operating conditions do not escalate, one looks to the possibility of other problems. One is a loss of cooling by mechanical blockage. Such accidents have occurred, but they will become less likely as engineering experience is gained. In this type of accident any significant release of fission products is precluded by providing several layers of structural containment for the entire reactor system.

Another possibility is an increase in power to the point where heat is being generated faster than it can be carried away by the coolant. Such an accident took place in EBR-I some years ago. Here again the answer has been found in improved design. Even beyond this, structural containment sufficient for any foreseeable accident will be provided.

Much consideration is also being given to environmental factors in the design of fast breeder reactors. Because fast breeder reactors will operate at far higher temperatures than are encountered in contemporary water reactors, they will have greater thermodynamic efficiency. Today's water reactors operate at an overall efficiency of about 32 percent, meaning that 32 percent of the thermal energy produced is converted to electrical energy. Modern fossil-fueled plants operate at about 39 percent efficiency. Hence water reactors add more waste heat to the environment per unit of electrical energy produced than fossil-fueled plants do. Fast breeder reactors will probably attain efficiencies equal to that of the most modern fossil-fueled plant, thereby reducing the nuclear waste-heat problem.

The release of radioactivity to the air from fast breeders will be near zero.



PATTERN OF FLOW in a gas-cooled fast breeder reactor entails the transfer of the heat from the helium coolant (*color*) to a water-steam cycle (*gray*). The system operates without an intermediate heat-exchange cycle. Numerals give temperatures in degrees Fahrenheit.

Even the small amounts of radioactive fission-product gases (primarily krypton 85 and tritium) now released under controlled conditions from water-moderated reactors will be eliminated because the necessity of hermetically sealing the core area will give an inherently effective method for collecting and disposing of the gases, which can then be rendered harmless. Moreover, since the coolant in a fast breeder is kept in a closed system, and since the water used to generate steam is never exposed to neutrons, there should be no formation of radioactivity in aqueous effluents from the plant.

The economic potential of fast breeder reactors lies mainly, but not entirely, in the fact that they would conserve resources of nuclear fuel. Over the next 50 years the use of breeders as planned can be expected to reduce by 1.2 million tons the amount of uranium that would be consumed without breeders. That is the energy equivalent of about three billion tons of coal.

The development of a breeder economy also appears to offer a direct dollar gain of large proportions. Studies have indicated that the cost of research and development of the liquid-metal fast breeder will be more than $2 billion through the year 2020 for the Atomic Energy Commission alone, with large industrial expenditures added. If the first commercial breeder is introduced by 1984 as planned, however, reductions in the cost of electrical energy thereafter (to 2020) are estimated at $200 billion in 1970 dollars.

The present cost of producing electricity in the U.S. ranges from five to 10 mills per kilowatt-hour delivered to the transmission system, depending on the type, age and location of the plant. This range covers most plants, although there are a few outside of either extreme. The liquid-metal fast breeder reactor is predicted to produce power at a saving of from .5 to one mill per kilowatt-hour. Large breeder-reactor systems that eventually bring the cost of electricity down by as much as two mills per kilowatt-hour will make it possible to extract, use and reuse resources in ways that cannot be afforded today. It will be possible to tap substantial resources in the oceans and on land and to use land not now habitable or productive.

Indeed, we believe breeders will result in a transition to the massive use of nuclear energy in a new economic and technological framework. The transition may be slow, and it will require the introduction of a series of innovations in the technologies of industry, agriculture and transportation. The innovations will include large-scale, dual-purpose desalting plants; electromechanization of farms and of means of transportation; electrification of the metal and chemical industries, and more effective means for utilizing wastes. The key to these possibilities is abundant low-cost electrical energy, and the route to that is by way of the breeder reactor.

The Genetic Activity of Mitochondria and Chloroplasts

These organelles of cells contain DNA, RNA and their own apparatus for synthesizing proteins. Their resemblance to bacteria suggests that they may be descended from free-living bacteria-like organisms

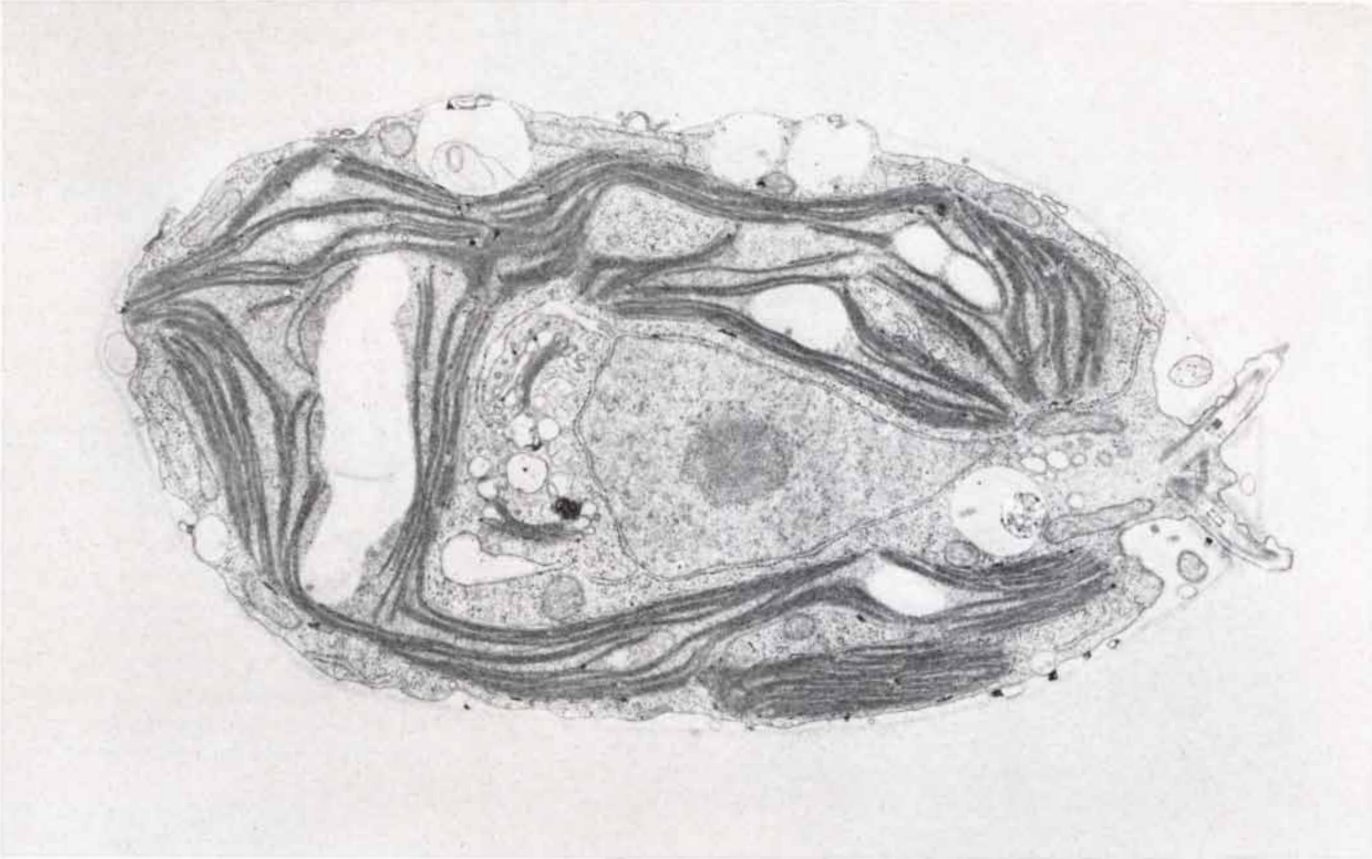
by Ursula W. Goodenough and R. P. Levine

The genetics of the living cell is more remarkable than capsule statements allow. Thus it is commonly said that the DNA—the molecular double helix—found in the nucleus of each cell of a plant or animal contains the complete genetic blueprint for reconstruction of the total organism. Geneticists have recognized for some time, however, that this statement cannot be rigorously true, since the cytoplasm (the nonnuclear region) of all plant and animal cells contains certain organelles, or subcellular structures, that have DNA of their own. One such organelle, the mitochondrion, is found in the cells of all plants and animals; mitochondria are responsible for packaging energy in the form of adenosine triphosphate (ATP) and for producing a variety of other essential small molecules. Another DNA-containing organelle, the chloroplast, is found only in algae and higher plants. Chloroplasts contain chlorophyll and related pigments for capturing the energy of sunlight and for producing carbohydrates by photosynthesis. In the process chloroplasts also produce ATP. There are occasional reports of DNA in other organelles as well, but even if such reports are substantiated, mitochondria and chloroplasts will probably remain unique in that they contain not only nucleic acids (DNA and RNA) but also a complete apparatus for the synthesis of proteins. One attractive hypothesis is that the mitochondria and chloroplasts present today in plant and animal cells once were free-living organisms, distantly related to present-day bacteria, that were incorporated into larger cells and became endosymbionts during the subsequent course of evolution.

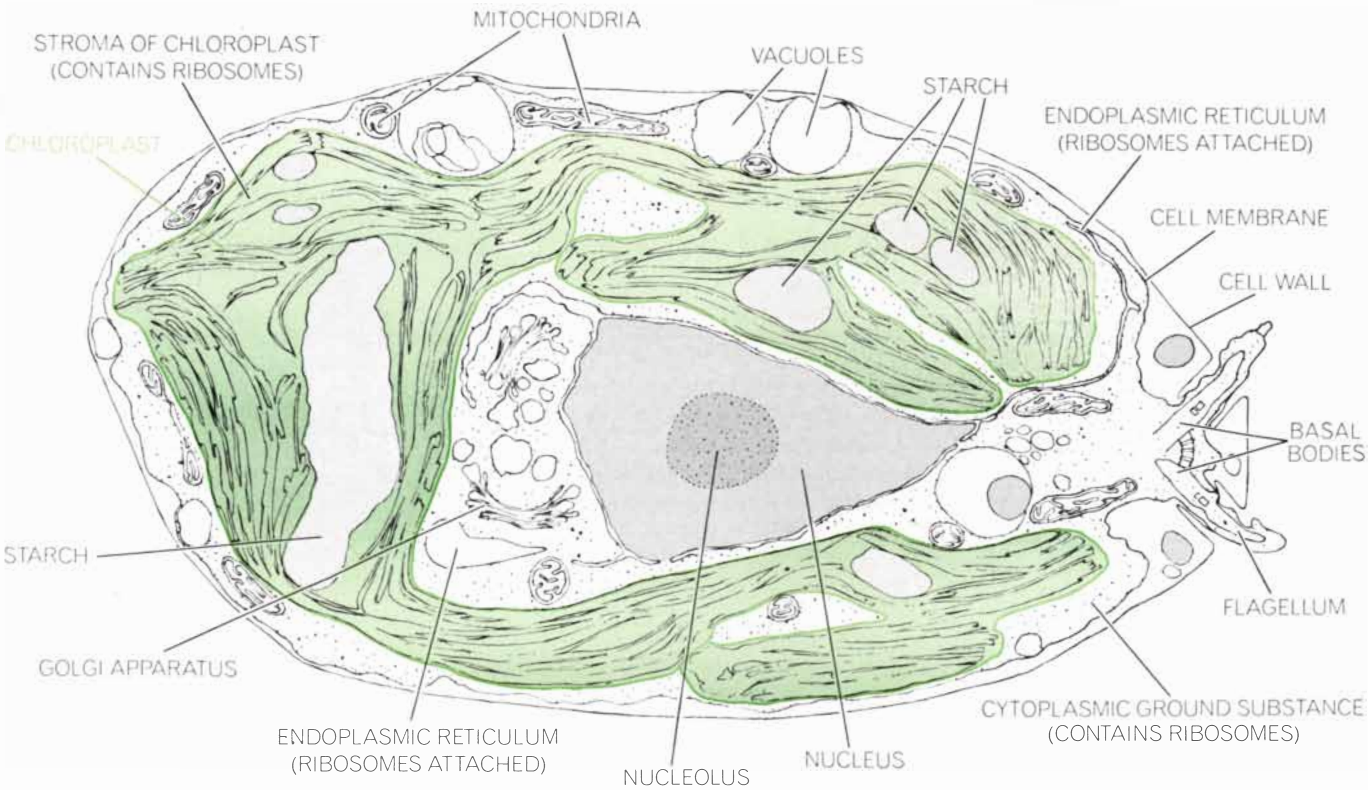
When cell biologists of the 19th century first studied mitochondria and chloroplasts with the light microscope, they were struck by their apparently independent behavior within the cell. The organelles often reproduce themselves by fission at times when the cell itself is not dividing, and they commonly develop in size and in functional complexity. For example, the precursors of chloroplasts in plant seedlings are tiny colorless bodies known as proplastids. Certain proplastids remain in the plant roots and become differentiated into colorless amyloplasts, starch-filled particles that predominate in such vegetables as potatoes. Other proplastids, when exposed to light, mature into chloroplasts by acquiring a complex system of membranes and the chlorophyll and carotenoid pigments essential for photosynthesis [*see illustration on page 24*]. Chloroplasts in tomatoes and similar fruits ultimately differentiate into chromoplasts by accumulating large amounts of red carotenoids [*see illustration on page 25*]. The structural development of mitochondria is usually less dramatic than that of chloroplasts, but with the electron microscope one can trace the transformation of the small mitochondria of embryonic cells into such large, membrane-filled organelles as those found in heart muscle [*see top illustration on page 26*]. Many factors influence the growth and development of chloroplasts and mitochondria. Our principal concern in this article, however, is how the DNA of these organelles influences their structure and function and to what extent the organelles may be under the control of the DNA in the cell nucleus.

Deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) are the only two types of molecule known to be capable of encoding and transmitting genetic information. In addition to DNA mitochondria and chloroplasts contain DNA-dependent RNA polymerases, enzymes that carry out the synthesis of several kinds of RNA. One kind, known as messenger RNA, transcribes genetic information from DNA. Other kinds are called transfer RNA's (*t*RNA's) because they "recognize" individual amino acids and deliver them in their proper sequence, as dictated by messenger RNA, for the synthesis of a specific protein. To effect this synthesis mitochondria and chloroplasts also possess ribosomes, small but complex particles made up of at least two kinds of RNA and some 30 to 50 kinds of protein. Ribosomes act as "jigs" for holding messenger RNA while *t*RNA's deliver amino acids to their assigned places. Indeed, if mitochondria and chloroplasts are isolated from the rest of the cell and are provided with the proper substrates, they can replicate their own DNA, synthesize new RNA and incorporate amino acids into proteins. No comparable genetic capacities have been reported for other cell organelles, such as the endoplasmic reticulum, the Golgi apparatus, centrioles, basal bodies and glyoxysomes [*see illustrations on opposite page*].

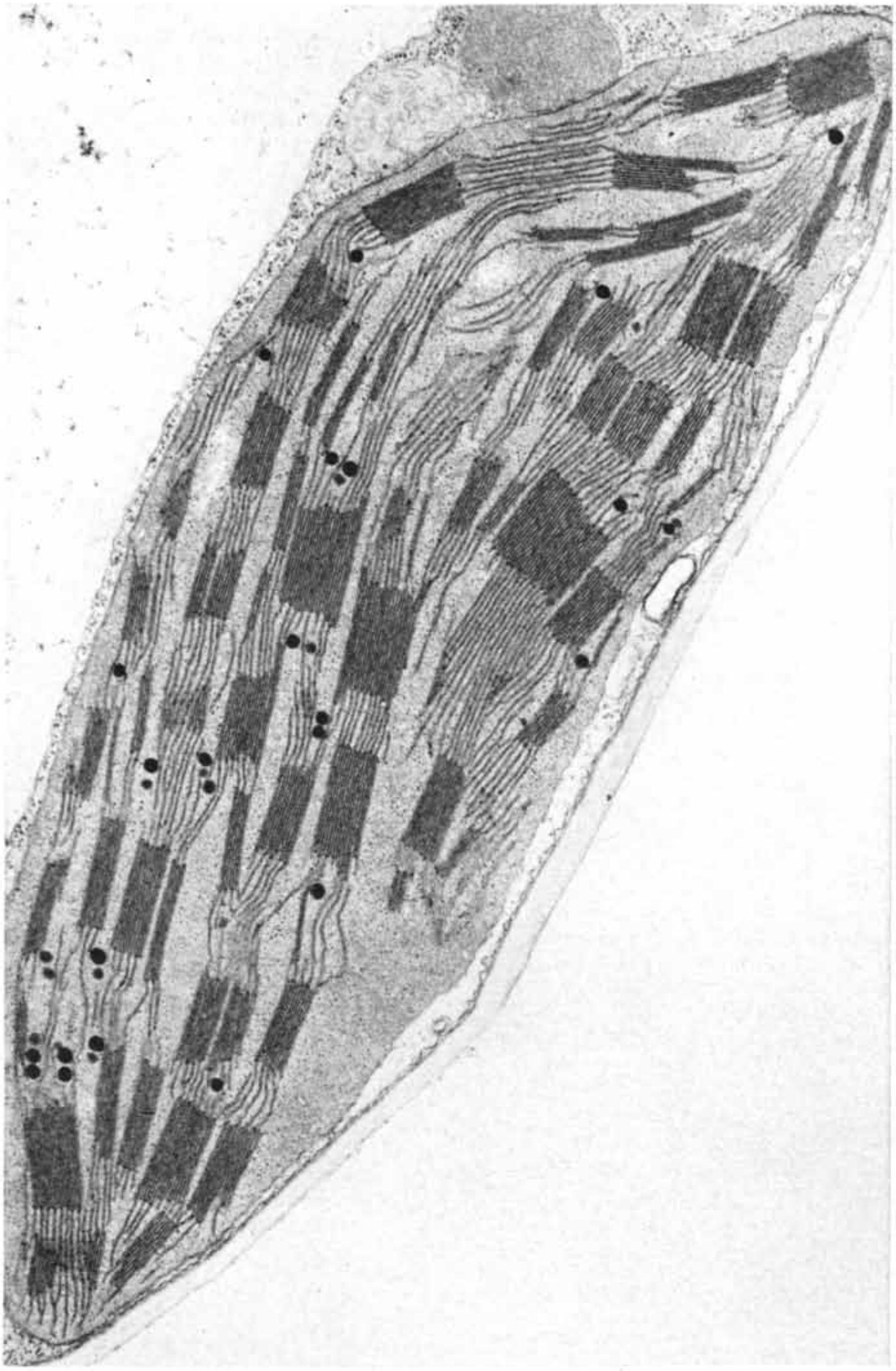
The ability of mitochondria and chloroplasts to carry out genetic functions would not be considered very interesting if they simply compartmentalized pieces of DNA from the cell nucleus along with ribosomes and enzymes from the cytoplasm. This is not the case, however. The genetic apparatus of these organelles is distinctly different from that

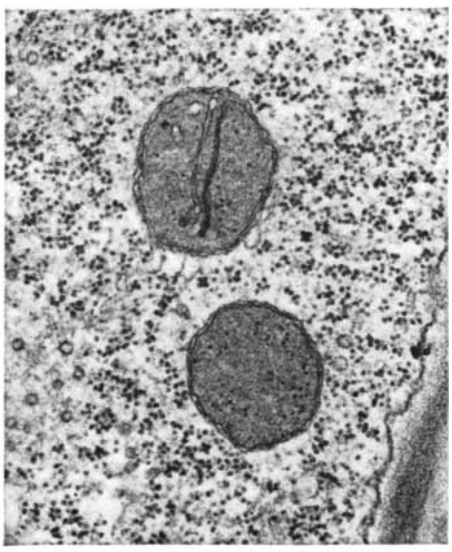


UNICELLULAR GREEN ALGA *Chlamydomonas reinhardi* is endowed with both chloroplasts and mitochondria, two organelles known to contain deoxyribonucleic acid (DNA), as well as apparatus for the synthesis of proteins. The cell is enlarged 15,500 diameters in this electron micrograph made by one of the authors of this article (Goodenough). Cell features are identified below.



CHLOROPLAST IN *C. REINHARDI* (*area in color*) consists of many folded membranes surrounded by an envelope. Chloroplast ribosomes, the particles on which proteins are synthesized, are found in the stroma, the chloroplast's soluble phase. Cytoplasmic ribosomes, synthesized in the nucleolus, are found in the cytoplasmic ground substance and attached to the endoplasmic reticulum. Only two of several mitochondria are labeled. "Vacuole" describes a cytoplasmic vesicle surrounded by a membrane.





MATURE CHLOROPLAST, at an enlargement of 22,000 diameters above, is from a leaf of timothy grass. Such chloroplasts develop from proplastids, two of which are shown magnified 38,000 diameters at left. Although the proplastids are from a root tip of the common bean, their simple structure is characteristic. They contain a few scattered ribosomes and, in one case, the start of a folded membrane. In the mature chloroplast the membranes are organized into numerous stacks called grana. The grana are connected by other membranes called stroma lamellae. Within the stroma one can see many chloroplast ribosomes (*small black dots*). The function of the large black droplets, "osmiophilic granules," is unknown. The micrographs were taken by William P. Wergin in the laboratory of Eldon H. Newcomb of the University of Wisconsin.

present in the nucleus or the cytoplasm. One indication of this difference is found by comparing the chemical composition of nuclear DNA with that of mitochondrial DNA. The DNA molecule consists of two intertwined strands whose subunits, called nucleotides, are always complementary. Thus a nucleotide containing the base adenine (*A*) always pairs with one containing thymine (*T*); the nucleotides of guanine (*G*) and cytosine (*C*) are similarly always paired. Although it is extremely difficult to establish the actual sequence of nucleotides in a specimen of DNA, it is fairly easy to determine the ratio of the nucleotide pairs. It has been found that the percentage of *G* plus *C* in mitochondrial DNA is usually quite different from that in nuclear DNA from the same cell. In a plant cell the *G* plus *C* content is often different for the three DNA species—nuclear, mitochondrial and chloroplast—so that the three can be separated from one another by high-speed centrifugation in a gradient of cesium chloride [*see top illustration on page 28*].

Unlike nuclear DNA, organelle DNA does not associate with proteins known as histones, and thus it exists within the organelle as a naked fiber. In mitochondria the naked DNA fibers usually close on themselves, forming circular molecules of DNA. Such loops have not yet been identified in chloroplasts; instead the DNA appears as masses of long strands [*see bottom illustration on page 26*].

Naked DNA fibers, devoid of histones and often existing as ring-shaped molecules, are apparently unique to chloroplasts and mitochondria in cells having nuclei, but they are not unique in the biological kingdom. All known bacteria and blue-green algae contain chromosomes that exactly fit this description. Is this a coincidence? Many biologists think not. It has been proposed that mitochondria and chloroplasts are modern descendants of primitive forms of bacteria and/or blue-green algae that took up residence within primitive cells and there enjoyed an independent evolution. It is supposed that the primitive cells that possessed such "resident" bacteria and blue-green algae were provided with additional means for the generation of energy and were thus "fitter" than those without them.

Bacteria and blue-green algae are known as prokaryotes, meaning they lack the membrane-limited nucleus possessed by nucleate organisms, or eukaryotes. (*Karyon* is Greek for nucleus.) The DNA of bacteria and algae is confined to "nucleoids," a term that describes certain regions not enclosed by membranes. Such nucleoids are also found in mitochondria and chloroplasts [*see illustration on page 29*], which lends additional support to the hypothesis that they were once free-living prokaryotes.

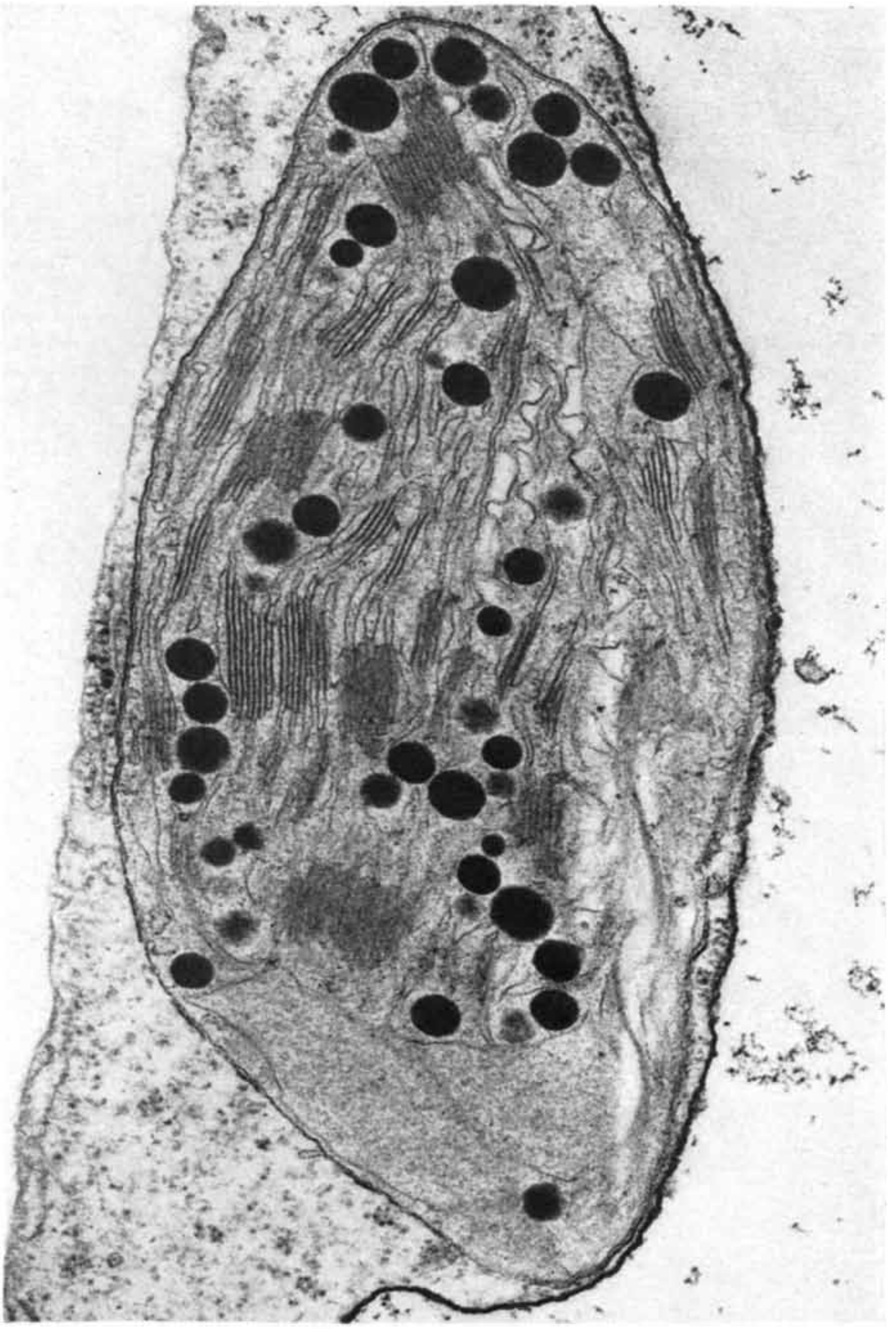
Perhaps the most striking resemblance between mitochondria and chloroplasts and present-day prokaryotes is in their apparatus for synthesizing proteins. For example, the ribosomes in all three are very similar: when they are centrifuged, they have a sedimentation coefficient of 70 Svedberg units (70 S). The sedimentation coefficient is a relative measure of the size of a ribosome: the larger the coefficient, the larger the particle. The ribosomes found in the cytoplasm of eukaryote cells have a sedimentation coefficient of 80 S. Thus if one prepares a total homogenate of plant or animal cells and centrifuges it in a gradient of sucrose solutions of differing densities, the ribosome population separates into two fractions, one large peak corresponding to 80 S and a smaller one to approximately 70 S [*see bottom illustration on page 28*]. As one exception to this general rule, certain fungi such as yeast and the red bread mold *Neurospora* have mitochondrial ribosomes with a coefficient of 77 S.

If ribosomes are dissociated into their two major RNA constituents, the resemblance between prokaryote ribosomes and the ribosomes of mitochondria and chloroplasts persists. All three contain a heavier RNA species with a sedimentation coefficient of 23 S and a lighter species of 16 S. In contrast, in cytoplasmic ribosomes the heavier RNA species has a coefficient of 25 to 28 S and the lighter species a coefficient of 18 S.

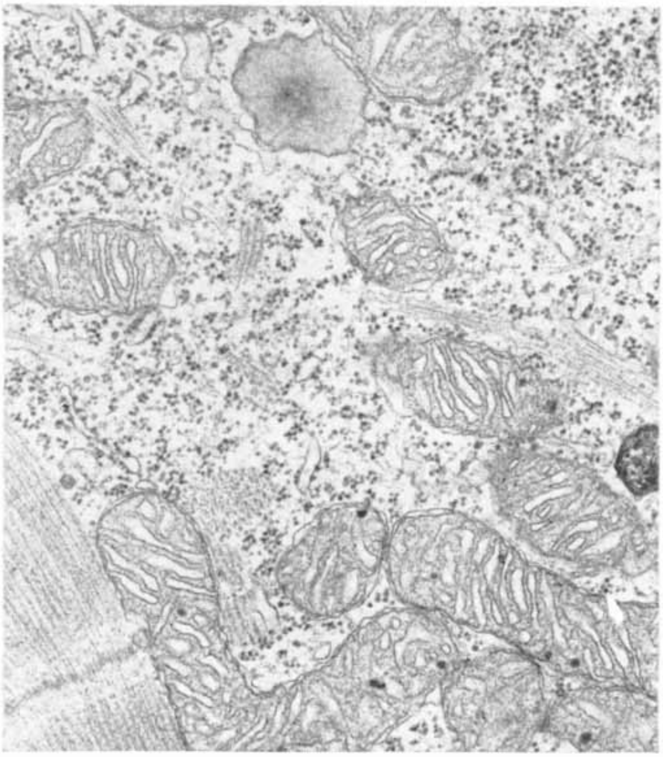
The types of protein contained in 70 S and 80 S ribosomes also appear to fall into two distinct families, as one can demonstrate by their response to certain drugs. A variety of antibiotics (including streptomycin, chloramphenicol and tetracycline) are thought to kill bacteria by reacting with specific proteins in bacterial ribosomes, thus preventing the synthesis of other bacterial proteins. These same antibiotics effectively inhibit the 70 S ribosomes of mitochondria and chloroplasts from synthesizing proteins but have no effect on the 80 S ribosomes of plant and animal cells. Conversely, the fungicide cycloheximide inhibits protein synthesis by 80 S ribosomes but has no effect on the 70 S ribosomes of prokaryotes or organelles.

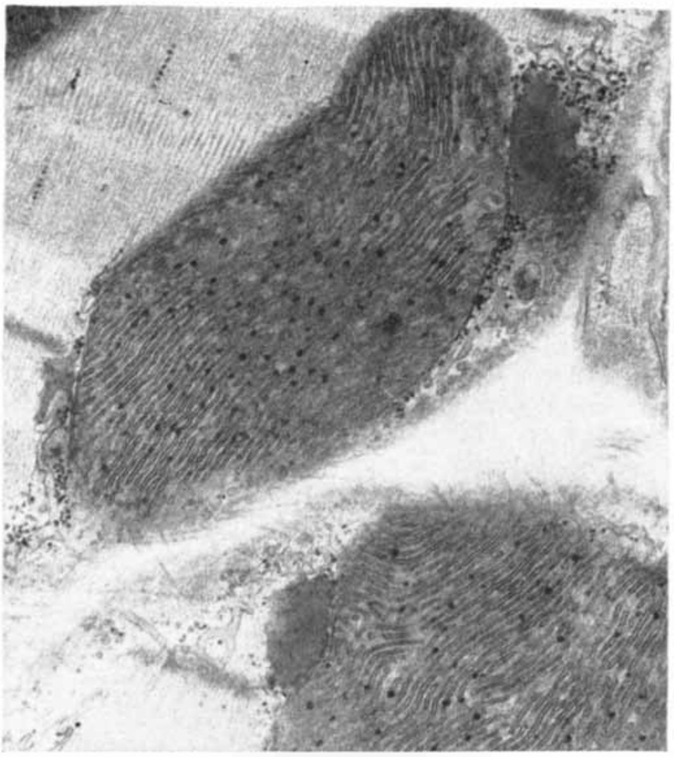
Antibiotics offer other clues to the similarities between the genetic apparatus of prokaryotes and organelles. Rifampicin, a recently discovered antibiotic, will bind to (and thus inactivate) the DNA-dependent RNA polymerase found in bacteria but will not bind to the polymerase in the nucleus of eukaryote cells. The antibiotic also inhibits RNA synthesis in chloroplasts and mitochondria, indicating that the RNA polymerase in these organelles resembles that in bacteria.

The observation that mitochondria and chloroplasts have genetic systems similar to those in bacteria, and the supposition that they share common ancestors, is not to say they are alike in all respects. Modern prokaryotes, and presumably primitive prokaryotes as well, contain all the genetic information needed for their self-reproduction. Given a suitable environment and a supply of carbon, nitrogen and minerals, they will synthesize everything they need for growing and dividing. Mitochondria and chloroplasts, on the other hand, are unable to synthesize most of their component proteins and would soon die if

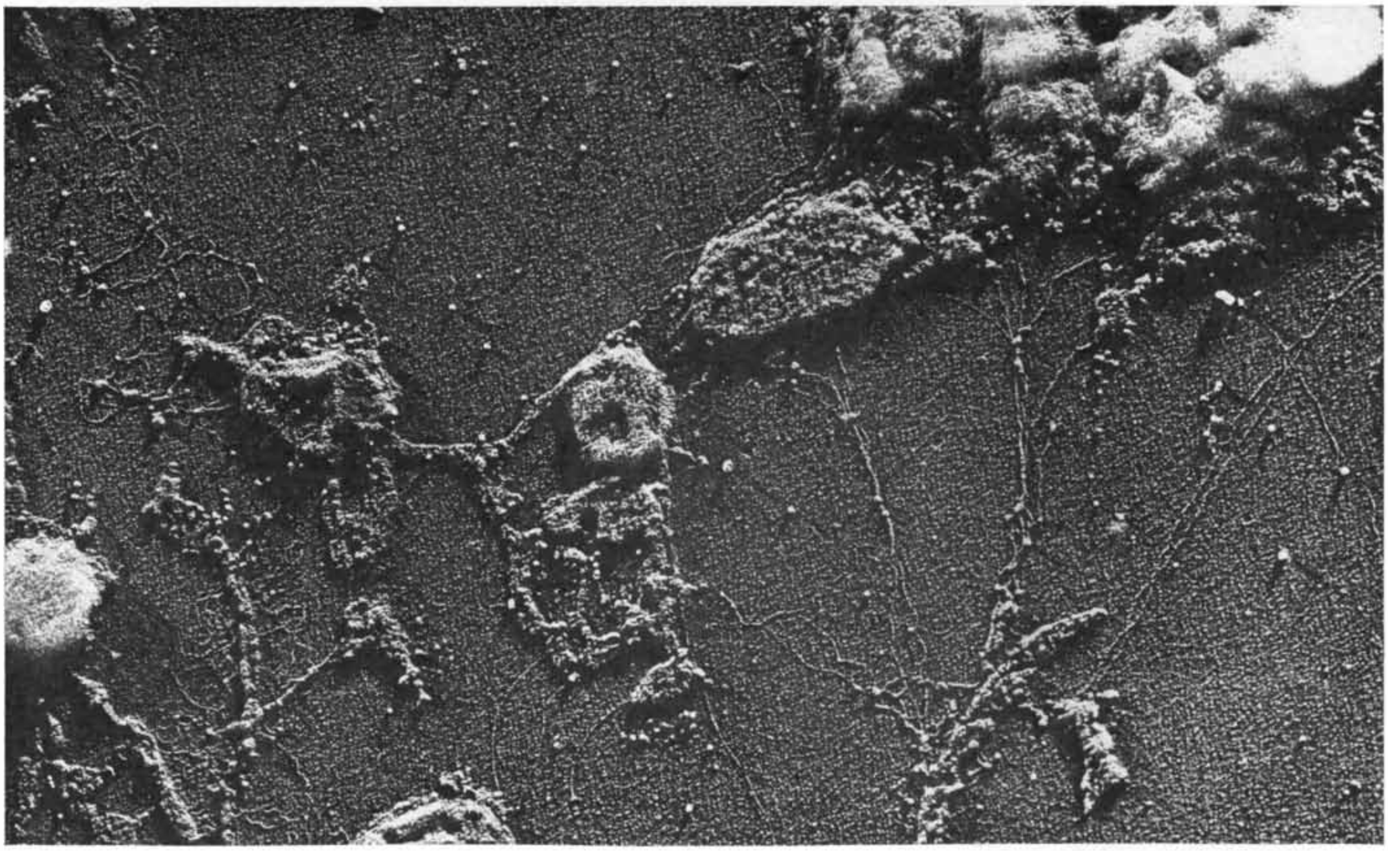


TOMATO CHROMOPLAST represents a chloroplast that is becoming differentiated by the accumulation of large amounts of red carotenoid pigment. The grana-like architecture of the chloroplast membrane is lost in the differentiation process. This electron micrograph, enlarged 45,000 diameters, was made by William M. Harris of the University of Arkansas.





DEVELOPMENT OF MITOCHONDRIA is illustrated in these two electron micrographs, both at an enlargement of 35,000 diameters. The picture at left shows immature mitochondria in a muscle cell taken from the regenerating tail of a tadpole. The mitochondria in this young cell exhibit few cristae, the shelflike infoldings of the inner membrane. The mature mitochondria at the right, densely packed with cristae, are in a muscle cell obtained from the heart of a bat. In this mature cell muscle filaments are neatly arrayed whereas in the tadpole cell they appear as disorganized bundles. The electron micrograph of the tadpole cell was made by Robert Warren of the University of Texas. The micrograph of the heart muscle cell was made by Keith R. Porter of the University of Colorado.



CHLOROPLAST DNA obtained from spinach leaves appears as a meshwork of fibers in this electron micrograph made by Christopher L. F. Woodcock of Harvard University. The enlargement is 32,000 diameters. Bulk of chloroplast appears at upper right. The purified chloroplasts were burst osmotically on a water surface, releasing DNA fibers along with granal and intergranal membranes.

they were isolated from the rest of the cell. The organelles lack many of the enzymes necessary for the biosynthesis of nucleotides, amino acids and other essential molecules. The required enzymes are located exclusively in the cytoplasm of the host cell. Thus the organelles are true endosymbionts, dependent on their host for key metabolic services.

That mitochondria and chloroplasts are, or have become, so dependent on their hosts is hardly surprising. In the interest of economy and efficiency it seems reasonable that molecular building blocks needed in various parts of the cell should be synthesized in the cytoplasm where they are freely accessible to all the organelles. What is surprising to discover is that the great majority of the enzymes and components found *exclusively* within mitochondria and chloroplasts are synthesized under the direction of genes located in the DNA of the cell nucleus.

Many examples are available. The most clear-cut is provided by cytochrome *c*, an essential component in the respiration process by which mitochondria oxidize carbohydrates and store energy in ATP. In the eukaryote cells of plants and animals cytochrome *c* is found only in mitochondria. In yeast, a much studied eukaryote, many gene mutations have been found that prevent the formation of cytochrome *c* and thus block respiration. Such mutant strains can grow only by fermentation. It has been shown (largely through the work of Fred Sherman and his colleagues at the University of Rochester School of Medicine and Dentistry) that most of the mutations alter a nuclear gene that contains the code for the primary amino acid sequence in the protein portion of the cytochrome *c* molecule. Another nuclear gene codes for a minor species of the molecule, cytochrome c_1. If a strain of yeast carries mutations in both of these genes, no *c*-type cytochrome can be detected anywhere in the cell, including the mitochondria. One can conclude, therefore, that the DNA in the mitochondria does not store the information for the synthesis of this mitochondrial protein. Bernhard Kadenbach of the University of Munich has demonstrated further that the cytochrome *c* protein is synthesized on 80 S ribosomes in the cytoplasm and then imported into the mitochondrion. Cytochrome *c* is not an isolated case. For example, nuclear genes control the soluble enzymes of mitochondria that are involved in respiration. Other nuclear genes are responsible for the chlorophyll, carotenoids, cytochromes and many photosynthetic enzymes of the chloroplast.

Nuclear genes are distinguished from organelle genes in most organisms by the way they are inherited during the sexual process. Male and female germ cells contain equal amounts of nuclear DNA, and thus the offspring will inherit an equal number of nuclear genes from each parent. Such a pattern of inheritance is called Mendelian after its discoverer, Gregor Mendel. The female germ cell, or egg, however, has a substantial amount of cytoplasm, including mitochondria and proplastids, whereas male germ cells and pollen contribute almost no cytoplasm to the zygote at fertilization. As a consequence offspring inherit their organelle DNA almost entirely from the female parent. This pattern of inheritance is termed non-Mendelian or maternal.

What kinds of non-Mendelian gene mutation have been identified that affect organelle functions? The most extensively studied class of such mutations is found in yeast. These mutations, collectively termed ρ^-, turn out to be quite complex. First described in the early 1950's by Boris Ephrussi of the Centre de Génétique Moléculaire in Gif-sur-Yvette, they are currently being studied in many laboratories, notably that of Piotr P. Slonimski, also in Gif.

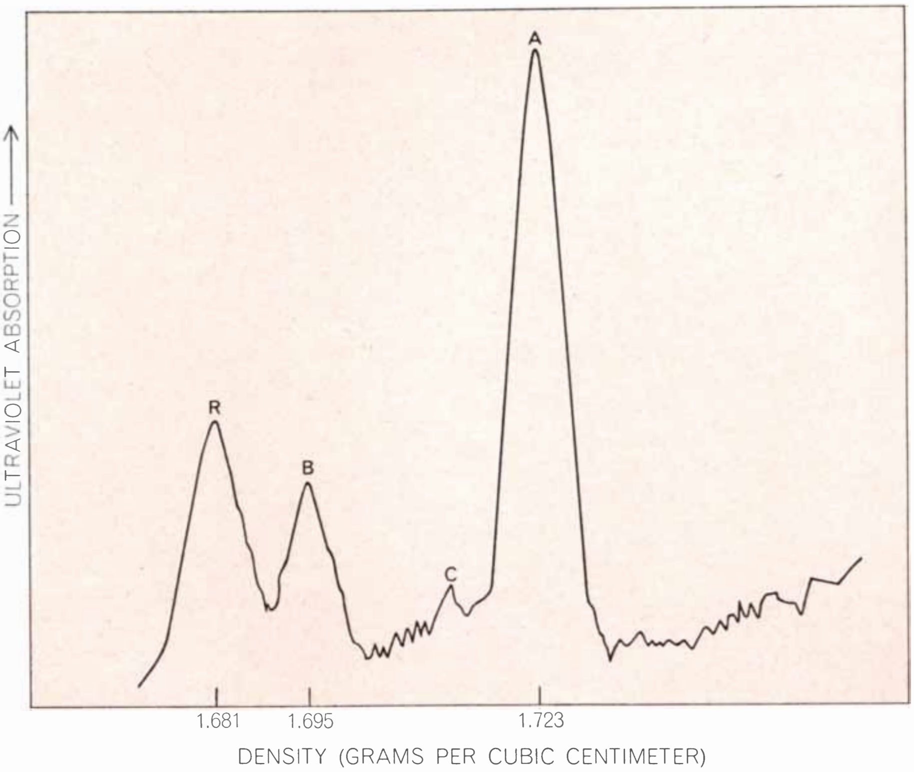
Yeast cells that are ρ^- cannot respire and can only grow slowly by the process known as glycolysis. Because they form small colonies they were termed "petites" by their French-speaking discoverers. The mitochondria in ρ^- cells are characteristically rudimentary, but different strains of ρ^- cells differ widely in the severity of such defects. Moreover, in some mutants the nucleotide composition of the mitochondrial DNA is similar to that found in normal strains; in other mutants the *G*-plus-*C* content is dramatically altered. Such disruptions in the genetic information of yeast mitochondria occur spontaneously but can also be induced by a variety of mutagens.

Unlike the "point" mutations that often occur in DNA, the more general disruptions caused in ρ^- mitochondrial DNA are perplexing to analyze. A point mutation, since it affects only one gene in the genome, or complete set of genes, will typically lead to the absence of a single enzyme. When the entire mitochondrial genome is rendered nonfunctional and the resultant mitochondrion is deficient in many enzymes and many activities, it is difficult to know what has happened. Possibly the ρ^- state simply prevents the synthesis of one or two critical proteins, perhaps important to the integrity of certain structures, which then leads to a variety of secondary defects. Or perhaps the ρ^- state involves such an extensive disruption of mitochondrial DNA that many proteins fail to be synthesized.

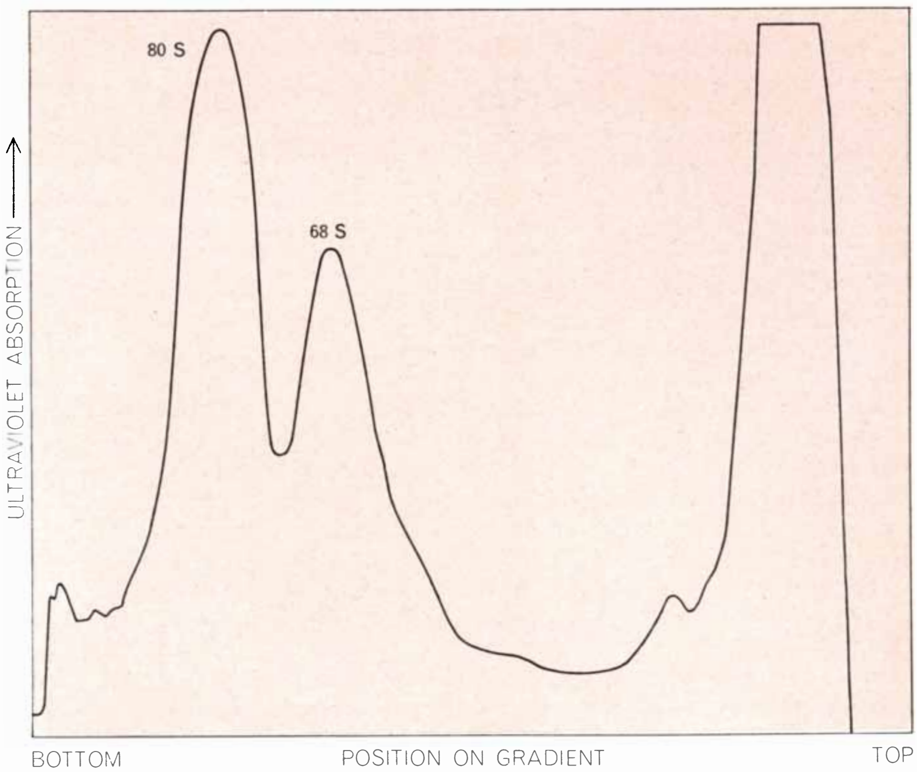
Similar problems beset the study of non-Mendelian mutations that affect chloroplasts. In most cases these mutations do not lead to a tidy, readily analyzed loss of a single protein or enzyme. Instead one observes a generally unhealthy organelle, commonly deficient in chlorophyll or carotenoids, highly disorganized in structure and devoid of photosynthetic activity. In such cases, what is the primary effect of the mutation and what is due to a secondary breakdown of the organelle's integrity? It may be extremely difficult to discover. One fact, at least, is clear: the presence of normal organelle DNA is essential for the formation of a normal organelle; the DNA is by no means a superfluous holdover from a former prokaryotic existence.

Recently a few maternally inherited mutations have been induced that are more amenable to biochemical analysis. These enable yeast to resist the effects of antibiotics, such as those listed above that specifically inhibit protein synthesis on 70 S ribosomes. The existence of these mutations suggests that mitochondrial DNA contains genes that control the synthesis of certain proteins that make up the 70 S ribosomes of mitochondria; the normal proteins are evidently inactivated by the antibiotics whereas the mutant proteins are not. Ruth Sager of Hunter College and others have studied similar mutations that confer drug resistance on the unicellular green alga *Chlamydomonas reinhardi*, but they have not yet established whether the mutations reside in the DNA of the alga's mitochondria or in chloroplasts.

The existence of mutations to antibiotic resistance would suggest that one of the functions of organelle DNA is to contain information for the construction of the organelle's protein-synthesizing apparatus. That organelle DNA is indeed responsible for the synthesis of the organelle's ribosomal RNA has been demonstrated in a number of organisms. A widely used technique is to isolate ribosomal RNA from organelles grown in a radioactive culture and incubate them with nonradioactive organelle DNA to see if a stable complex, or hy-



THREE KINDS OF DNA form separate peaks according to their buoyant density when extracted from the single-celled alga *C. reinhardi* and centrifuged in a cesium chloride gradient. Peak *R* is a reference peak of synthetic DNA of known density. The most abundant DNA in the cell (*A*) presumably comes from the cell nucleus. The next most abundant fraction (*B*) is probably derived from chloroplasts. The small peak (*C*) is thought to represent DNA from mitochondria, but this has not been proved. The experimental results presented here were obtained by Kwen-sheng Chiang of the University of Chicago.

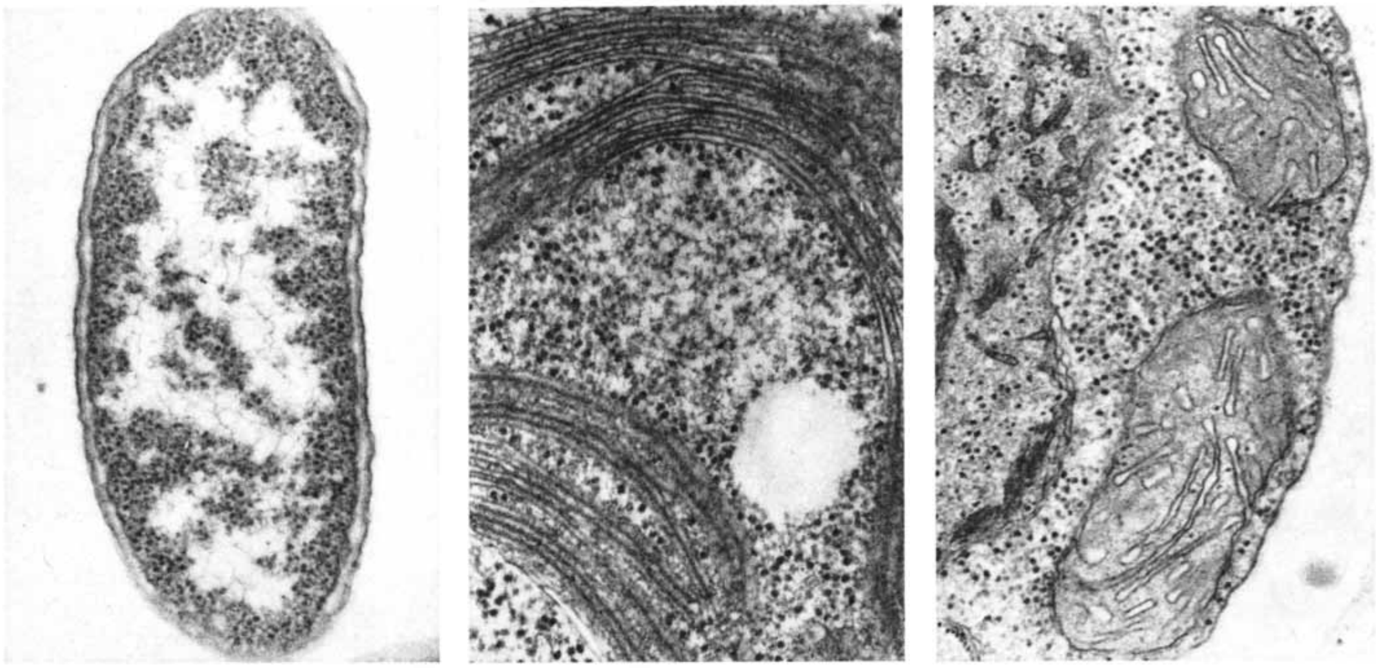


RIBOSOMES OF *C. REINHARDI* form two peaks when centrifuged in a sucrose gradient. The larger consists of cytoplasmic ribosomes with a sedimentation coefficient in Svedberg units of 80 S. The smaller peak consists of lighter ribosomes (68 S), presumably from the chloroplasts of *C. reinhardi*. The wide absorption band at the far right is produced by chlorophyll. The curve was obtained by Stefan J. Surzychi of the University of Iowa.

brid, forms between them. Successful hybridization indicates that the DNA contains sequences of nucleotides that are complementary to the sequences in the RNA, and thus the RNA is presumably synthesized from the DNA template. Such experiments have demonstrated a complementarity between both mitochondrial and chloroplast DNA's and their corresponding ribosomal RNA's. Another approach to the same question, taken by Stefan J. Surzychi of the University of Iowa, makes use of rifampicin, the antibiotic that inactivates the variety of DNA-dependent RNA polymerase found in bacteria and blue-green algae. In the presence of rifampicin, *C. reinhardi* is unable to synthesize the 16 S and 23 S species of ribosomal RNA found in chloroplasts, indicating that these RNA's are synthesized from a chloroplast DNA template.

What about the rest of the protein-synthesizing apparatus of organelles? Both mitochondria and chloroplasts contain at least certain species of *t*RNA that exhibit properties different from those of their cytoplasmic counterparts. Are these also transcribed from organelle-located genes? Perhaps, but not necessarily. Until it is proved otherwise by hybridization experiments or other means, the existence of a unique type of RNA in an organelle does not mean it must have been transcribed from organelle DNA. Cytoplasmic *t*RNA, for example, may migrate into the chloroplast or mitochondrion and there be modified in some critical way so that its biochemical properties are adapted to the protein-synthesizing system of the organelle.

We have already seen that certain nuclear genes code for proteins that are eventually localized exclusively within organelles and that, for the well-documented case of cytochrome *c* in yeast, the cytochrome's protein component is entirely synthesized on the 80 S ribosomes present in the cytoplasm and transported into the mitochondrion. There is no reason to assume, however, that this route must be followed by the messenger RNA derived from all nuclear genes that specify organelle proteins. Since ribosomes are apparently able to translate any messenger RNA that is supplied to them, it is possible, although it has not yet been demonstrated, that messenger RNA from the nucleus is imported into an organelle and translated on the organelle's 70 S ribosomes. Conversely, organelle-derived messenger RNA might be translated either in the chloroplast or in the cytoplasm.



BACTERIA, CHLOROPLASTS AND MITOCHONDRIA have certain features in common, suggesting that these modern organelles and bacteria may have common ancestors. The cylindrical bacterium (*left*) is surrounded by a cell wall and a cell membrane but contains no membrane-bound organelles. It does, however, contain densely packed ribosomes and nucleoids, in which one can see strands of DNA. The chloroplast of *C. reinhardi* (*middle*) also contains densely packed ribosomes and nucleoids with threads of DNA. Two mitochondria from *C. reinhardi* (*right*) are shown embedded in cytoplasm. They contain very few ribosomes, and mitochondrial DNA is not visible. The three electron micrographs, all at an enlargement of 50,000 diameters, were made by Miss Goodenough.

These considerations are important in giving the proper interpretation to certain types of experiment. For example, isolated organelles have been shown to incorporate amino acids into relatively insoluble proteins that are thought to be components of organelle membranes. Such experiments indicate that the isolated organelles contain messenger RNA that carries information for membrane proteins, but they cannot in themselves tell us the location of the genes for these proteins. Similarly, it has been shown that the synthesis of certain organelle-specific proteins is inhibited by antibiotics specific for 70 S ribosomes, whereas the synthesis of other proteins is not inhibited.

Bearing these considerations in mind, we can summarize what is currently, and tentatively, believed to be the genetic capacity of organelles. Mitochondrial DNA probably contains information for mitochondrial ribosomal RNA, for at least a few mitochondrial ribosomal proteins and for at least a few proteins necessary for the structural and functional integrity of mitochondrial membranes. Mitochondrial ribosomes are involved in the synthesis of a few proteins, probably but not demonstrably those coded for by mitochondrial DNA. Most of the enzymatic apparatus of mitochondria is apparently encoded in nuclear DNA and synthesized in the cytoplasm. Hence the mitochondrial genome does not appear to contain many genes, which is not surprising when one considers its size. A typical DNA molecule ("chromosome") found in the mitochondria of animal cells has a molecular weight of about 11 million, or somewhat less than that of the smaller viruses. That is enough DNA to represent perhaps 10 to 25 average-sized genes.

The average molecular weight of chloroplast DNA is more difficult to determine, but it appears to be some 300 times greater than that of mitochondrial DNA and should therefore be able to carry a great deal more information. This information probably includes several genes for chloroplast ribosomal RNA, at least a few for chloroplast ribosomal proteins, several genes for the proper organization of chloroplast membranes and one or more genes for the synthesis of a functional photosynthetic apparatus. Chloroplast ribosomes are probably involved in the synthesis of most of these proteins. In *C. reinhardi* the chloroplast ribosomes participate in the synthesis of ribulose-1,5-diphosphate carboxylase, an enzyme involved in the photosynthetic fixation of carbon dioxide. Apparently, however, the DNA of the chloroplast does not encode information for the synthesis of this enzyme.

We have studied a mutant strain of *C. reinhardi* called *ac-20* that can make very few chloroplast ribosomes under certain growth conditions. The photosynthetic and structural lesions suffered by such cells are quite similar to cells whose protein synthesis is blocked by chloramphenicol, as one might expect. Significantly, the *ac-20* gene is inherited in a Mendelian fashion, suggesting that the nucleus may exert control over the synthesis of organelle ribosomes. Nuclear control over the synthesis of organelle DNA has also been reported. If it proves to be a general case that the nucleus has acquired substantial control over the production of organelle genetic systems, then it becomes difficult to understand why these genetic systems continue to be produced at all—why mitochondria and chloroplasts have not, regardless of their origins, evolved into ordinary enzyme-containing organelles whose perpetuation is entirely controlled by the nucleus. It can only be assumed that this has not happened because the organelle DNA contains essential genes whose functions, for whatever reason, cannot be taken over by nuclear genes and that at least certain of these genes must be transcribed and translated by a primitive, bacteria-like protein-synthesizing apparatus.

WOODHENGES

The celebrated Stonehenge is only one of 80 henge monuments known in Britain. Recent excavations at two of the largest henges show that they enclosed structures that were made not of stone but of wood

by Geoffrey Wainwright

The circular array of massive stones on Salisbury Plain known as Stonehenge is so well known that it has given most people a distorted view of the other monuments of the same kind that were raised in Neolithic Britain. All henge monuments consist primarily of a circular embankment surrounding a ditch. In a few instances, as at Stonehenge, the earthwork encloses a group of stone uprights. Recent archaeological work at two of Britain's largest henge monuments has revealed, however, that their huge earthworks enclosed structures built not of stone but of timber. This finding increases the number of henge monuments known to have contained timber structures from two to four, and the number of timber structures known to have existed within henge enclosures to eight. What is more important, the wood structures suggest something of the function served by these vast constructions of the second millennium B.C.

The Neolithic inhabitants of the British Isles built at least 80 henges during a period from the end of the third millennium B.C. to about the middle of the second millennium. In terms of human labor the effort was genuinely monumental. For example, the construction of one of the four largest henges, the enclosure at Avebury in Wiltshire, required that a ditch 30 feet deep and 70 feet wide be dug to form a circle more than three-quarters of a mile in circumference. The excavated earth was used to raise a bank outside the ditch that was 18 feet high and 75 feet wide. The entire task is estimated to have taken more than 1.5 million man-hours.

There has been much speculation about the function of the henges. Their cumulative cost in human energy implies a society sufficiently stable to allow the diversion of manpower from the primary task of food production to major construction projects. Our knowledge of Neolithic domestic settlements in Britain, although it is sketchy, would scarcely lead us to believe that a society prosperous enough to permit such corporate efforts then existed. The excavation of the two new "woodhenges" has sharpened our appreciation of this apparent paradox. It will be useful, before giving an account of our findings there, to place these henges in their proper perspective.

The four largest of Neolithic Britain's henges are all in an area of southern England notable for the number of henges of all sizes found in it. One of the four, Mount Pleasant, lies near the Dorset coast some 60 miles southwest of Stonehenge. The other three, from north to south, are Avebury, Marden and Durrington Walls in Wiltshire. All are adjacent to the River Avon and none is more than 30 miles from any other. Work on roads in the area led the Department of Ancient Monuments, a division of the Ministry of Public Building and Works, to undertake salvage archaeology at Durrington Walls in 1966–1967. The findings made there led to further work at Marden in 1969.

Over more than two centuries of amateur and professional investigation only a quarter of the many henges excavated in Britain have yielded remains that could be dated. The tradition of building circular earthworks, however, appears to have been firmly established in the British Isles sometime during the third millennium B.C. At first the ditches around the central enclosures were not continuous; these interrupted circles came to be known as "causewayed camps." Archaeological evidence indicates that the early earthworks were not, as was first suggested, either dwelling sites or cattle pens. The abundance at many of the sites of the remains of slaughtered animals, of grain-grinding tools and of different types of pottery implies that causewayed camps were more probably centers where people from miles around gathered from time to time in large numbers. Even today one cannot visit a well-preserved henge monument without feeling that it was designed for public gatherings of some kind. The bank, raised high above the area it encloses and seeming even higher because of the deep ditch inside it, makes an ideal grandstand for viewing the activities in the interior precinct.

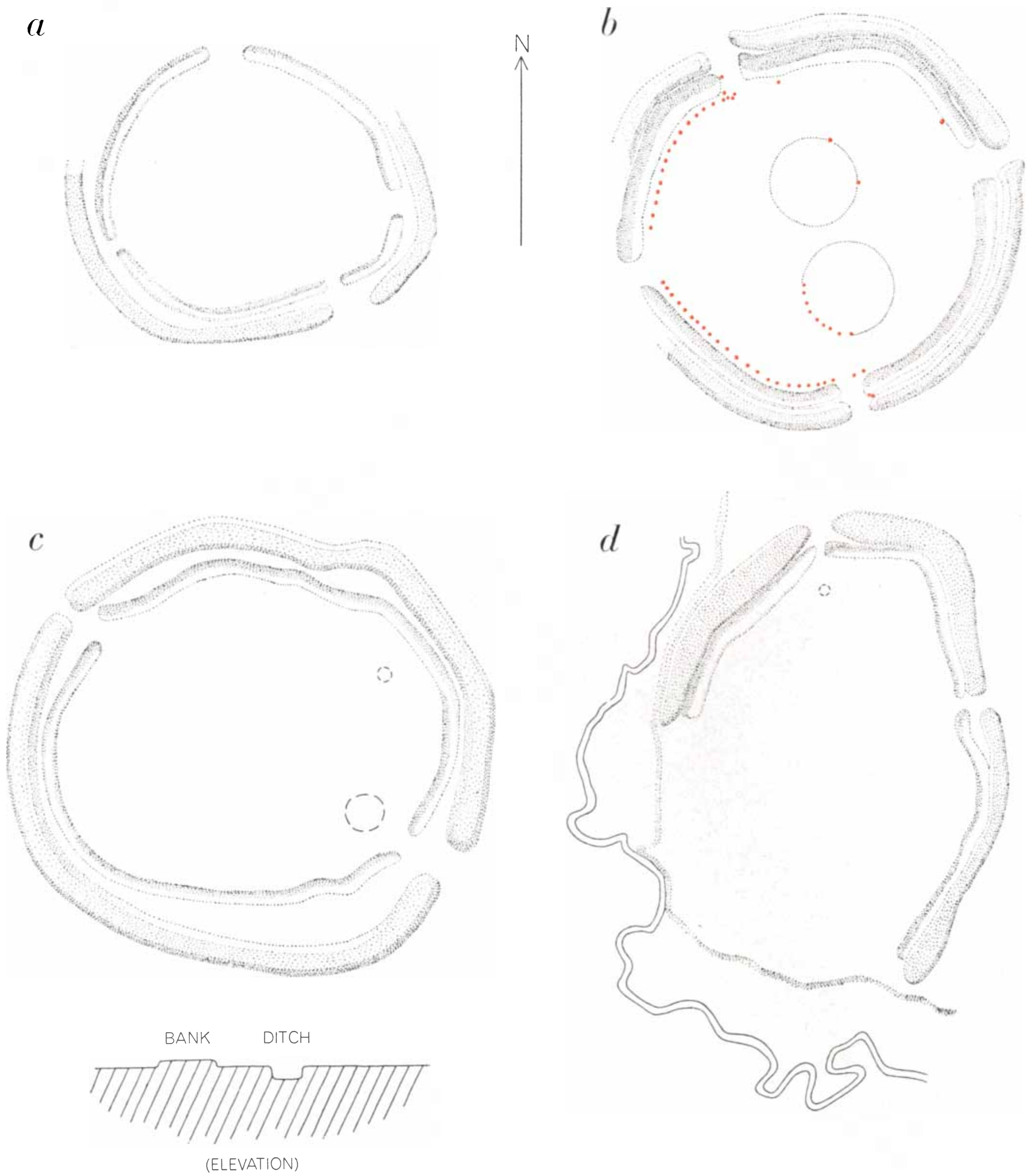
No such prospect greets the visitor to Durrington Walls, although the dimensions of the monument are impressive enough. Its outer bank, originally 90 feet wide, averages more than 1,550 feet in diameter; the top of the bank once stood some nine feet above ground level. Inside the bank a level zone from 20 to 140 feet wide extends to the edge of the ditch, which was originally 50 feet wide and nearly 19 feet deep. I have estimated that construction of the ditch and bank at Durrington Walls required about 900,000 man-hours. Some 30 acres of a dry valley descending to the River Avon are enclosed by the earthwork. Little of the monument's former grandeur is now perceptible; generations of plowing have all but obliterated the bank, the ditch and evidence of the two causeways that formerly provided access to the enclosure from the northwest and the southeast. One can nonetheless imagine the view of the valley that was once to be had from the top of the bank and even speculate that the site was selected with this objective in mind.

In 1966 permission to build a road across the eastern half of the Durrington Walls enclosure was granted subject to a prior archaeological investigation

STRIP EXCAVATION seen in this aerial photograph crosses the ditch that once surrounded the great henge monument at Durrington Walls in Wiltshire. Some 90 feet inside the enclosure (*right center*), the diggers unearthed traces of a former timber structure.

along the proposed route. Fieldwork, begun in 1966 and completed in 1967, entailed excavating a strip that followed the line of the proposed road and included a part of the ditch and the southwest causeway. Where the ditch and the causeway met we unearthed large quantities of broken pottery, animal bones, flint tools and picks made from the antlers of deer. The objects had evidently been thrown into the ditch by people crossing the causeway to enter or leave the enclosure.

Some 90 feet inside the enclosure our excavation uncovered the postholes of a complex circular structure. They lay under a protective mantle of plow soil nearly five feet thick on a comparatively flat piece of ground at the bottom of the valley. As digging progressed, it became apparent that there had been not one but two structures at the site, which we named the Southern Circle. The evidence of the earlier structure was a se-



FOUR LARGEST HENGES in the British Isles are seen in plan view above. They are Mount Pleasant (*a*), Avebury (*b*), Durrington Walls (*c*) and Marden (*d*). Plans show the present or reconstructed dimensions of each enclosure's bank and ditch. The outlines of timber structures unearthed at Durrington Walls and at Marden are shown in black, the array of stones at Avebury in color.

ries of four almost concentric circles of holes that had supported slender timber uprights; the outermost circle was 99 feet in diameter and the innermost one seven feet in diameter. The earlier structure had been replaced by a larger one consisting of six nearly concentric rings of upright posts. Many of the postholes of the larger structure intersected or altogether obliterated the postholes of the earlier one.

The outer circle of posts associated with the later structure was 127 feet in diameter. The postholes increased in size from the outer circle, which we labeled Ring *A*, to the next to innermost, labeled Ring *E*. The holes of Ring *E* averaged a little less than six feet in diameter and were some seven feet deep; they had evidently held posts about two feet in diameter. The structure had a single entrance that opened to the southwest, facing the adjacent causeway. The entrance was marked by two postholes larger than any of the others in Ring *A*. One hole was six feet in diameter and the other five feet; they had supported posts respectively 3.5 feet and three feet in diameter.

Outside the entrance to the structure stood a platform built of blocks of chalk and a rubble of flint gravel. A succession of fires had burned on the platform, and the earth around it contained quantities of broken pottery, flints, bits of antler and animal bones. To the north of the structure a hollow had been scooped in the chalk bedrock and then partially surrounded by a fence of small stakes. The hollow was filled with a black ashy soil that contained more broken pottery, flints and animal bones.

As excavation continued we found the remains of a second circular structure some 400 feet to the north of the first. We named it the Northern Circle; it proved to be much simpler and smaller than its neighbor. Four large postholes outlined an inner circle 25 feet in diameter. Concentric with the inner circle was a circle of smaller postholes, some 48 feet in diameter. The single entrance to the structure faced almost due south; it evidently had been approached along an avenue irregularly marked by freestanding timber uprights and had been screened from view at a distance of 20 feet by closely spaced uprights set on both sides of the avenue roughly perpendicular to the line of approach.

Visitors apparently came to Durrington Walls for more than 500 years. Carbon-14 analysis of charcoal samples found at the bottom of the ditch indicates that it was dug into the chalk bedrock somewhat before 2000 B.C. One of

SHALLOW DITCH at Marden is seen in process of excavation; the view is outward from the enclosure. The level area at left, a few feet below the present surface, is the northern causeway that gave access to the interior. The collection of cobbles at upper right is the only remnant of the bank that once formed a partial perimeter around the 35-acre precinct.

the postholes in the Southern Circle contained charcoal and fragments of animal bone and antler; carbon-14 analyses of these remains indicate that the later of the two structures was erected between 2000 and 1900 B.C. Charcoal from two hearths in the ditch showed on analysis that fires were being kindled at Durrington Walls as late as 1600 B.C.

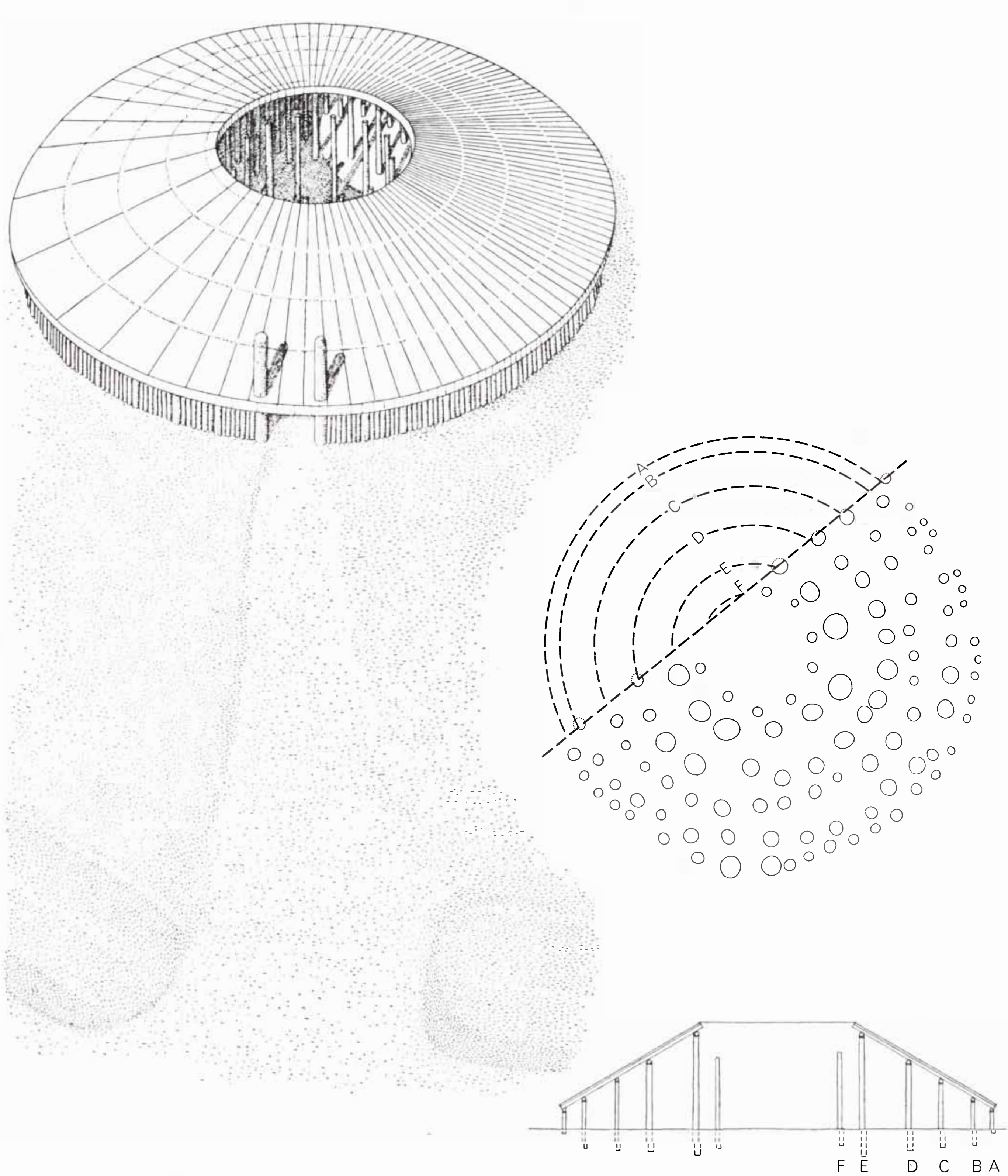
The most fundamental question about the structures at Durrington Walls is whether the timber uprights comprised some kind of open-air display or whether they supported roofs. My colleague C. R. Musson has considered this question. The only form of building he finds appropriate to the pattern of later postholes at the Southern Circle is a ring-shaped, roofed enclosure, covered with a thatch that sloped downward and outward from a high ridge at Ring *E*. The building would have surrounded an open central court, and the sloping roof would have ended at an outside wall represented by Ring *A* [*see illustration on next page*]. Assuming a roof pitch of 25 degrees and an outside height of about nine feet, the roof would have been a little more than 30 feet high at Ring *E*. The uprights that formed Ring *F* can be interpreted as a circle of freestanding poles in the central court that provided the focus of the building. Musson takes the postholes of the Northern Circle to be the remains of the frame for a less ambitious roofed building, with a conical outer ring-roof of thatch and a separate "lantern roof" at the center, supported by the four large uprights there.

The material remains from all parts of the Durrington Walls excavation come to an impressive total, particularly in view of the fact that most henge monuments have yielded very little. The abundant pottery belongs in general to a late Neolithic ceramic tradition known as Grooved Ware. A careful piecing together of individual sherds shows that fragments from the same pot were sometimes deposited with care in different places. For example, pieces of a single vessel were put next to various posts in the Southern Circle; in one instance a fragment of a pot was rested against a post within the structure there and another fragment was placed in the midden outside. We shall return to the possible significance of these actions.

The ditch, the postholes, the platform and the midden yielded a total of some 12,000 struck flints, including 360 finished implements; among them were 200 scrapers and 60 arrowheads, mostly of the transverse type [*see illustration on page 35*]. The 30 bone implements found at the site included both awls and pins. The majority of the animal remains that have been identified are pig bones. The complete or fragmentary remains of 440 picks made of deer antler—the principal digging implement of the period—

give some indication of the effort involved in constructing the henge and erecting its interior buildings.

Of the 29 henge monuments in England, Wales and Ireland that have been excavated since 1951, only nine have produced evidence of human activity in the interior precinct. It was therefore with some pessimism that last year we approached Marden, the biggest of the four large henges. Situated in the Vale of Pewsey on flat, low-lying ground close to the headwaters of the Avon, the Marden earthworks are some 10 miles from Durrington Walls and eight miles from Avebury. They enclose an area of 35 acres. Centuries of plowing have almost obliterated the mound and the ditch, which in any case do not form a circle; all of the southern boundary of the enclosure and half of its western quadrant are formed instead by the meanderings of the Avon [*see illustration*



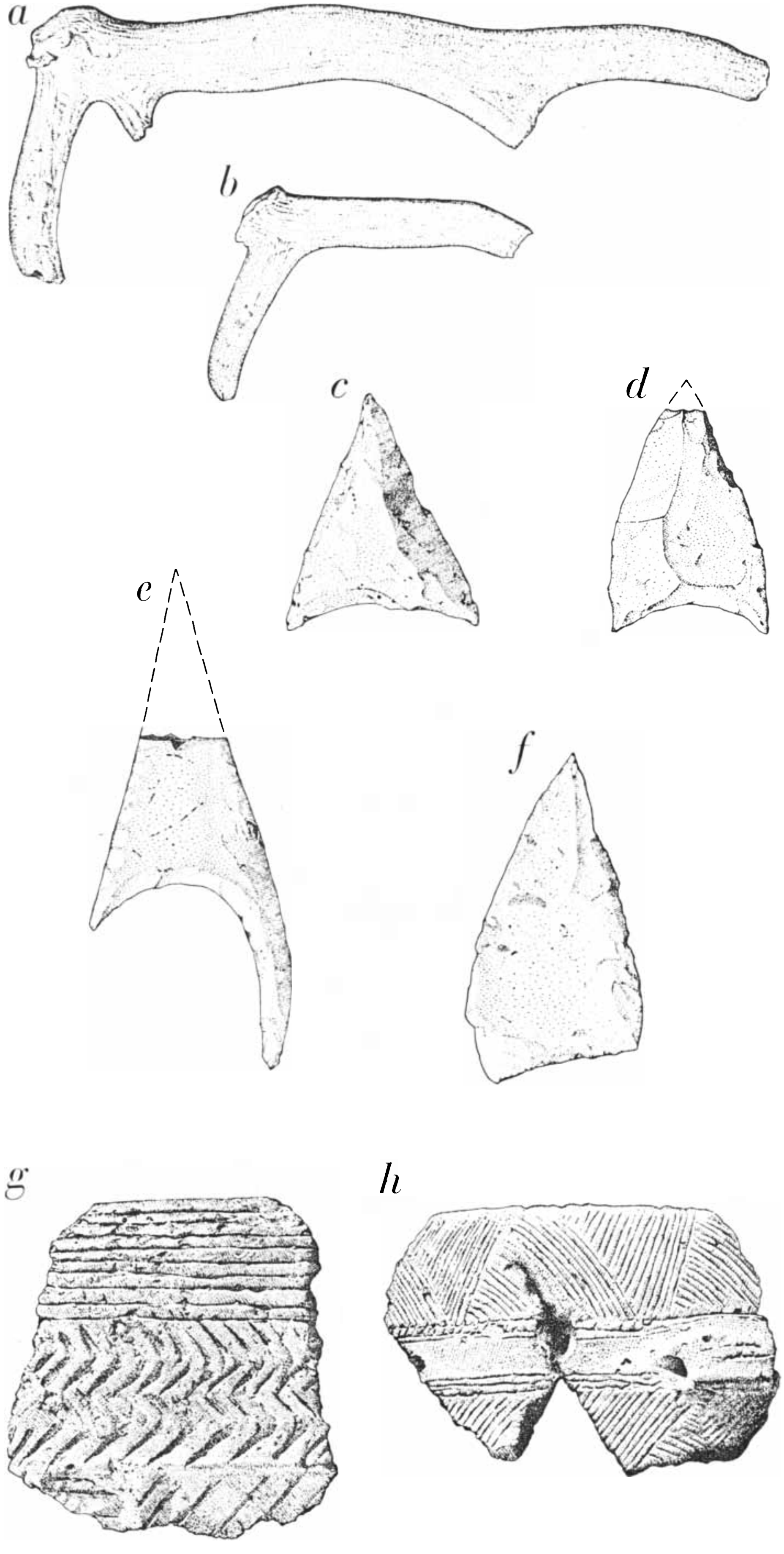
MAJOR STRUCTURE at Durrington Walls is reconstructed at top left. The plan view of the rings of postholes at right center indicates that the excavation did not expose the entire structure. The elevation view at bottom right shows how the length of the uprights probably increased from ring to ring in an inward direction. This is the later of two buildings at the henge's Southern Circle.

on page 32]. Marden is unique among British henge monuments not only in this respect but also because its two entrances, rather than being diametrically opposed, lie at right angles, one on the north and the other on the east.

With 35 acres to choose from and only a limited time to work, the question we faced was where to begin. Owing to the nature of the subsoil and millenniums of mole burrowing, remote sensing devices were of no use to us in searching for evidence of timber structures. Eventually it was decided to excavate the northern entrance to Marden and in addition to clear two 30-foot squares within the enclosure, located roughly 100 feet inside the entrance. We chose this course on analogy with our success at Durrington Walls. The Southern Circle there had been discovered some 100 feet inside the southeast entrance. We hoped there might be a similarity between the sites.

The ditch at Marden turned out to have been more than 50 feet wide but only six feet deep. The original dimensions of the mound surrounding it are uncertain. As at Durrington Walls, the part of the ditch we uncovered adjacent to the entrance causeway contained quantities of potsherds, flint tools, antler picks and animal bones left there by people entering or leaving the enclosure [*see illustration on next page*]. When work began on the two selected areas inside the enclosure, we found that the analogy between Marden and Durrington Walls applied here as well. Our excavation uncovered a circle of postholes roughly 32 feet in diameter; three more postholes were set in a row at about the center of the circle. Centuries of plowing had removed so much of the soil above the remains that only the very bottom of each hole was preserved. A few more years of deep plowing at the site would have obliterated all traces of the structure.

The Marden postholes contained some flint tools and sherds of pottery. Like the pottery found in the ditch, the posthole sherds belong to the Grooved Ware ceramic tradition we had already found at Durrington Walls. This suggests that the two sites, only 10 miles apart, had once served their public function contemporaneously, perhaps over a period of centuries. The Durrington Walls henge, however, may have had a greater longevity. Some of the pottery fragments unearthed there show the stylistic influence typical of a group of emigrants from Europe known as the Beaker people. These newcomers to Britain made implements of copper and bronze, and their arrival marks the beginning of the end of



ARTIFACTS unearthed at Durrington Walls included 440 intact or fragmentary picks made of antler; two are shown, one-fourth actual size (*a*, *b*). Among the flint artifacts at the site were 60 arrowheads, most with unstemmed bases; four are shown, two-thirds actual size (*c*, *d*, *e*, *f*). Most of the pottery fragments were of Grooved Ware, common in the British Isles during late Neolithic times; two examples are shown, one-fourth actual size (*g*, *h*).

the British Neolithic period. No sherds of the Beaker type are found at Marden, which suggests that people were visiting Durrington Walls at a later date. The point may well be clarified when the carbon-14 analyses of the organic remains from the Marden site become available.

Up to now no archaeological work has been done at Mount Pleasant, the large henge monument in Dorset. There both the bank and the ditch have been heavily eroded by plowing; about all that remains evident is that the enclosure, an oval measuring 900 by 1,200 feet, had a single causeway entrance, located in the southeast quadrant. The fourth of the large henges, Avebury, has been studied intensively. I have already mentioned its bank and ditch. Between the two lies a strip of level ground that varies in width; access to the enclosure is afforded by four separate entrances, spaced roughly at 90-degree intervals. Avebury is the only henge monument in Britain with so many entrances.

As at Stonehenge, the earthwork at Avebury encloses an array of stones, but there the similarity ends. Stonehenge essentially consists of four ranks of stones: two outer concentric circles within which lie two concentric semicircles, or "horseshoes." The outermost circle, which originally included 30 stone uprights, is 100 feet in diameter and the surrounding earthwork has a diameter of 300 feet. In contrast, the great stone circle at Avebury, just inside the ditch, is some 1,100 feet in diameter and may originally have included a total of 98 large monoliths. Within this array of stones stood two stone circles, each of them larger than Stonehenge. The northern circle is 160 feet in diameter; the southern, 170 feet. The monoliths at Avebury are blocks of native sandstone that are naturally shaped and were not quarried. For centuries the local people have taken one after another and broken them up for building purposes, so that now less than half of the original array remains.

Portions of the Avebury enclosure were excavated in the 1930's by a wealthy amateur archaeologist, Alexander Keiller. The silt in the Avebury ditch yielded so few objects that it has been suggested that Avebury was deliberately kept clean by its Neolithic visitors. On the original surface, buried under the bank, Keiller found sherds that included some pieces of Grooved Ware and two flint arrowheads of the transverse type, which suggest that the site may be contemporaneous with Durrington Walls and Marden. No further excavation of the Avebury enclosure has been undertaken since Keiller's time.

What can one conclude from the results of investigating, however tentatively, three of Britain's four largest henge monuments? Let us first consider some additional facts about the Avebury henge and its surroundings. An "avenue" of stones leads from the henge to a point nearly 1.5 miles away. There stands a small stone henge known as "the Sanctuary," consisting of concentric circles of upright stones. Excavation in 1930 revealed, however, that the Sanctuary had not always been a stone structure. It was originally made of timber, and it was rebuilt in wood at least twice before it

ARTIFACTS AT MARDEN were most abundant where the northern causeway crossed the ditch. Several antler picks and fragments of animal bone, including the partial mandible of a pig, are seen in the photograph, still lying where they were abandoned by visitors.

was finally replaced by stone. The first structure at the Sanctuary, possibly a hut, is represented by a posthole circle some 14 feet in diameter. This was replaced by a second timber structure 35 feet in diameter, and that in turn was superseded by a third timber structure more than 60 feet in diameter.

Stone monuments, then, can have timber ancestors. This being true for the Sanctuary, only investigation will show whether or not it is true of the Avebury henge itself. In this connection, it is interesting that, although the greater part of the central enclosure at Stonehenge remains unexcavated, work there in the 1920's by William Hawley of the Society of Antiquaries revealed a large number of timber postholes, some of which may be ancient. Stonehenge has also yielded sherds of Grooved Ware.

At Durrington Walls there is a small henge monument only 60 yards outside the main enclosure. Known as Woodhenge, it was excavated between 1926 and 1928. As its name indicates, it had been a timber structure. Its remains are six concentric rings of postholes. The rings are oval in outline and have a maximum diameter of nearly 135 feet. Stuart Piggott of the University of Edinburgh suggested in 1940 that the postholes represent a single large structure, probably with an open central court and a roof that sloped both inward and outward from a high central ridge. My colleague Musson suggests as an alternative that the Woodhenge postholes are the remains of two successive timber structures, each with a central court but an outward-sloping roof, as at Durrington Walls. No evidence exists to suggest which of the two reconstructions may be the right one.

It is thus clear that the three structures at Durrington Walls and the one unearthed at Marden, although they are the most recently discovered, are far from being the only timber structures that are known from Neolithic British henges. Three were erected consecutively at the Sanctuary, one or two (depending on the preferred reconstruction) at Woodhenge, probably one at Stonehenge and possibly others at Avebury and still others at Mount Pleasant, Durrington Walls and Marden. Before considering the purpose these timber structures may have served, let us see what the remarkable preservation of the remains at Durrington Walls has revealed about the main building there.

PARTIAL SKELETON of an adult human was found among the refuse in the ditch next to the northern causeway at Marden. Weight of the overlying soil has crushed the skull.

Identification of charcoal from the postholes at the Southern Circle shows that the structural material of the later building was oak. The diameter of the uprights can be estimated from the size of the holes they occupied; in what follows their length has been calculated on the basis of Musson's reconstruction. In addition to the uprights a quantity of smaller timbers would have been required for cross bracing and for the framework that supported the thatch. Calculations indicate that more than 3,000 running feet of timber of various substantial sizes would have been needed for the uprights of the structure and more than 4,500 running feet of smaller timbers for the beams, rafters and other elements. The two entrance posts, the largest in the structure, weighed five tons and 3.5 tons; the total weight of timber must have been more than 260 tons. It would take the felling of nearly nine acres of oak forest to supply so much wood, yet this was only one of several timber structures in the neighborhood. It is not too much to say that the rate of destruction of natural forest cover in southern England must have gathered considerable impetus at the start of the second millennium B.C.

Although many variables need to be considered, it is possible to estimate the length of time the building lasted. Research at the Forest Products Research Laboratory shows that the service life of a timber set upright in the soil is directly proportional to the timber's diameter. Oak posts like those used at Durrington Walls have a service-life expectancy of about 15 years for each inch of heartwood radius. On this basis the later building at the Southern Circle would have lasted a minimum of 100 years and probably for the best part of 200. The massive entrance posts would have stood for 270 and 315 years respectively, but since they are not key structural elements their endurance is irrelevant to the longevity of the building as a whole. Amortized over a span of considerably more than a century, the probable investment in man-hours necessary to fell the timber and erect the structure does not seem excessive.

What purpose did the woodhenges serve? The first question is whether their buildings were domestic dwellings or structures designed for communal functions. The open court at the center of the building at Woodhenge and the central court decorated with freestanding uprights at Durrington Walls both seem more suited to ceremonial purposes than to domestic use. The timbered avenue of approach and the protective façade screening the northern structure at Durrington Walls are other features one would not expect to encounter in a domestic context. One must also consider that the last timber structure at the Sanctuary was replaced with circles of stone uprights, linked to the great enclosure at Avebury by an avenue. The final arrangement in stone seems undeniably ritualistic. May not the same have been true of the earlier timber structures?

A further fact suggestive of communal rather than domestic activities at the woodhenges is the nature and condition of the artifacts found in them, the pottery fragments in particular. Although the refuse at Durrington Walls, in the ditch and elsewhere, included hundreds of potsherds, and although a few of these —found in separate locations—could be pieced together, not one complete pot can be assembled out of the entire collection. It is not possible to distinguish the refuse of a domestic occupation from the debris of ceremonial practices; the evidence of the pottery at Durrington Walls, however, strongly argues against a domestic role for these sites.

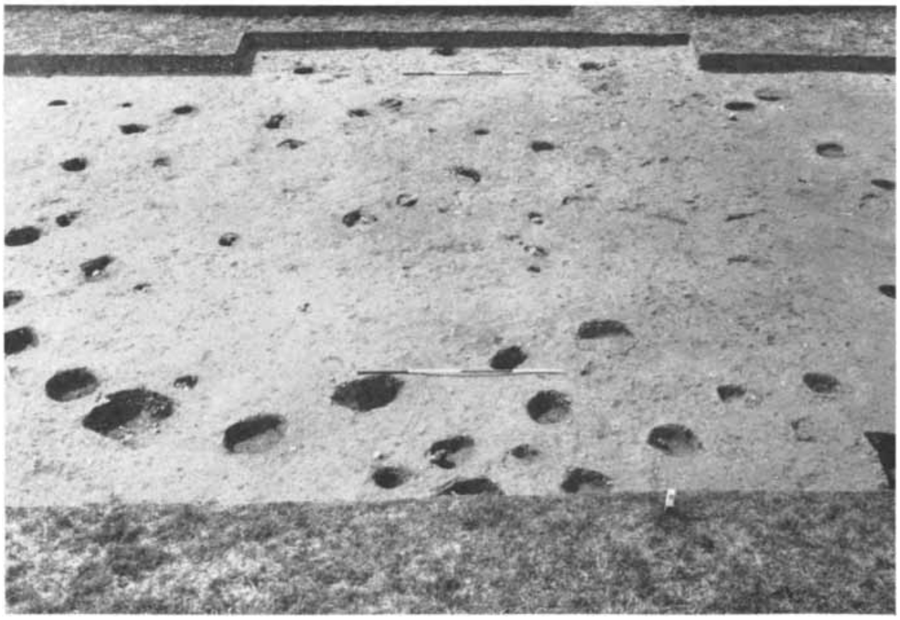
An ethnographic parallel to the woodhenges of Neolithic Britain exists in the 17th- and 18th-century council houses of the Creek and Cherokee Indians, which were described by a number of early travelers in the American Southeast. The parallel is particularly rewarding because, in addition to eyewitness descriptions, there exists a detailed archaeological record of one these structures. It had been built between A.D. 1550 and 1600 on a bluff of the Savannah River, and it was excavated by workers from the University of Georgia between 1937 and 1940. One is able to turn from ethnographic to archaeological evidence and back again, taking information from both to fill the gaps that exist in each record considered singly.

The naturalist William Bartram, describing a Creek council house of the 1700's, wrote: "The great... house or rotunda... is a vast conical building or circular dome, capable of accommodating many hundred people. There is but one large door, which serves at the same time to admit light from without and [to allow] the smoke to escape when the fire is kindled." Discussing the construction of such a building, Bartram states: "They first fix in the ground a circular range of posts or trunks of trees about six feet high, at equal distances, which are notched at top to receive into them, from one to another, a range of beams or wall plates; within this is another circular order of very large and strong pillars, about twelve feet high, notched in a like manner at top to receive another range of wall plates." One of the activities that took place within the council house, according to Bartram, was the imbibing of a "sacred" drink known as "cassine." Because the drink was sacred, the vessels used on the occasion may also have taken on a special character.

The council house excavated in Georgia was part of the Irene Mound site. In addition to the remains of the circular building, which had a single entrance, a central hearth and an outside diameter of more than 110 feet, the excavators uncovered a number of square and rectangular domestic dwellings. The shape of the main structure was evident from a pattern of six concentric circles of palisade trench. The outermost circle was the wall of the council house; the five inner circles were partitions that incorporated the supports for the roof. Just outside the wall was found a rubbish pit containing only the fragments of several pottery vessels contemporaneous with the structure itself. The excavators speculate that the vessels may have been used for drinking cassine and then been placed together in the pit, broken either intentionally or by accident. The parallel between this ceremonious disposal of pottery by New World Indians and the painstaking distribution of some of the Neolithic potsherds at Durrington Walls, while scarcely exact, is nonetheless suggestive of ritual in both contexts.

In spite of a difference in time of more than 3,000 years, Bartram's description of a Creek council house of the 18th century could be applied to the woodhenges of Britain without putting too much strain on credibility. It would be tempting to offer the known uses of the one in answer to our questions about the unknown uses of the other. This, of course, is impossible. Not only the difference in time but also geographical distance and immeasurable disparities in culture prevent it. Nevertheless, where the evidence is at all comparable, it tends to confirm the hypothesis that the woodhenge structures served a communal function and not a domestic one.

Assuming that the hypothesis is correct, further questions immediately arise. Were these structures "temples"? Did they serve some more secular purpose? Or was their function a combination of the religious and the secular? Surveys with magnetometers, which indicate discontinuities in the soil, suggest that many more timber structures once stood within the enclosure at Durrington Walls; this may also be true at Marden and elsewhere. If that is the case, are all the structures communal ones, visited on occasion by people from domestic settlements as yet undiscovered? Or do the woodhenges, like the Irene Mound site, include both communal and domestic buildings? The character of British domestic settlements in the Neolithic period is virtually unknown, yet such settlements must have existed to provide the labor needed to raise the great earthworks of the period and to erect the structures they enclosed. In the absence of evidence that domestic settlements are to be found elsewhere, the first search for them must surely begin within the enclosures of Durrington Walls, Marden, Mount Pleasant and Avebury. The four largest henge monuments—two of them surrounding timber structures—are properly regarded as some of the finest examples of Britain's late Neolithic tradition of the ceremonial circle. They may also turn out to be the first places where we can study the British domestic settlements of the second millennium B.C.



CIRCLE OF POSTHOLES, roughly 32 feet in diameter, was found 100 feet inside the north entrance at Marden. Centuries of plowing had destroyed all but bottom of the holes.

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Some mud sticks more than other mud. Sticky pitch bleeds from some trees. Such facts were noticed 100,000 years ago. As men grew cleverer they learned to use stickiness. You were younger than 3 when you first understood clearly that one thing can be made to stick to another. Can you explain how it happens?

* * *

In 1943 sharp-seeing aerial reconnaissance lenses were coming apart. Canada balsam, the only optical cement anybody had ever heard of, had generally been used on smaller, more pampered optics. Bob Dann, a Kodak chemist anxious to do his bit, worked hard and found something better. Now there are six KODAK Optical Cements, none of them Canada balsam, all known to those who need to know about them, probably.[1] We find it hard to make money selling optical cement, but our lenses hold together well.

* * *

EASTMAN 910 Adhesive has become very well known but not as an optical cement, though it was discovered when an attempt to measure the refractive index of methyl cyanoacrylate permanently stuck together the prisms of one of our refractometers. Now we feel strong excitement at the prospect of how much of the world's goods—even its clothing—might be put together with EASTMAN Adhesives, which don't all have to be cyanoacrylates and indeed are not. Meanwhile we have announced improved versions of cyanoacrylate EASTMAN 910 Adhesive.[2]

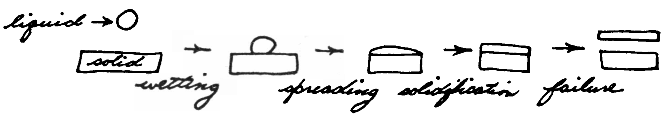
* * *

Adhesion matters to us for more than industrial adhesives. Why do our photographic emulsions stick so nicely to our film base? "Why?" like "how?" can be a deep question. J. R. Dann's work and thought on adhesion have developed to the point of asserting on p 321 of the February, 1970 issue of *Journal of Colloid and Interface Science:*[3]

> A modification of the Good-Girafalco-Fowkes-Young equation is used to calculate nondispersion interactions I_{SL}^P at the interface for nine polymeric solids and four polar series of liquids. The relationship of I_{SL}^P to work of adhesion W_A and the spreading coefficient S_c is shown. A linear relationship is found to exist between I_{SL}^P and $\gamma_L{}^P$, the nondispersion energy component of the liquids, for the series of polar liquids and the solids studied. The slopes of the I_{SL}^P vs. $\gamma_L{}^P$ curves vary depending upon the polymer surface. Intercepts of the curves may be a measure of π_S, the reduction in the surface energy of the solid resulting from adsorption of vapor from the liquid.

* * *

Dann is asked why this appears under the title "Forces Involved in the Adhesive Process." He steps to the blackboard and draws:



That's the history of a bond, he explains. Surface energetics of wetting and spreading are what the paper is about. It examines the significance of the cosine of the angle of contact as a measure of work required to form interface. Misconceptions, if any, will be cleansed in the flames of controversy. Then it will be necessary to tackle the rheology of the system: kinetics of spreading, viscoelastic behavior of both the adhesive and the substrate. Solidification follows—by polymerization, freezing, or solvent evaporation. Some of the best of chemists will continue to study degree and orientation of crystallinity, glass transition temperatures, melting points, moduli, and their relation to molecular architecture. Fracture mechanisms constitute, of course, still another discipline.

It has been a long haul since 1943. There is still a long way to go.

* * *

Dann is asked to explain "nondispersion" in his subtitle "Nondispersion Forces at Solid-Liquid Interfaces." Does it refer to dispersing the liquid from the solid? Does it relate to a paint-maker's conception of the term, or a smokestack inspector's? No, no, "dispersion" comes in from a 1936 treatment by F. London of intermolecular forces arising from correlated electron motion in closely spaced molecules rather than from polarity. One of his equations resembled one for wavelength dispersion of refractive index. The term has stuck. Stuck like pitch.

Is work good for people?

Rather few of us 113,000 souls here spend our working hours thinking beautiful patterns of thought. The rest of us live by a more literal concept of work. Of our many thousands of products and services, not many flow in such majestic torrents that the only human help possible must come from the brain's topmost centers. Some of us—archaic though it may seem—are actually paid to use our hands, eyes, and feet. This in turn provides employment for 15 of us drawn from the disciplines of engineering, medicine, psychology, and physiology to grapple with such questions as:

- Despite appearances, are some jobs too taxing to the body or the human spirit to do day-in and day-out?
- Despite appearances, which jobs are insufficiently taxing to keep the jobholder vigilant?
- How would workers benefit by variations in work methods, changes in rest periods, or job rotation?
- What kind of tests would best match people to difficult jobs?
- Where can redesign of equipment and work environment help productivity and quality through worker comfort?
- How much should production workers and inspectors know about the use of the product?
- How can these human-factors studies guide design of the products to help the humans who use them?

Is it true that irregularity in foot-tapping indicates psychomotor stress?

What kind of window glass in the work-break rooms of our new film manufacturing plant on the Front Range of the Rockies will least affect time for return of dark adaptation?

[1] If we have missed you, complain to Special Products Sales, Kodak Apparatus Division, Rochester, N.Y. 14650.

[2] Details from Industrial Chemicals Division, Eastman Chemical Products, Inc., Kingsport, Tenn. 37662.

[3] Reprint on request from Kodak, Department 55W, Rochester, N.Y. 14650.

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MARC-III

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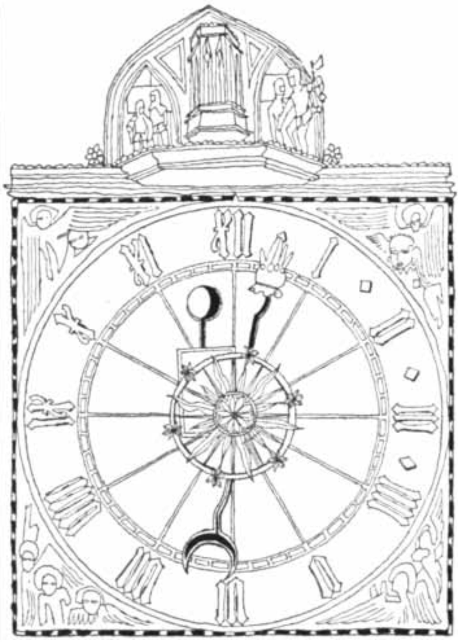
MARC-II

SCIENCE AND



Advice and Dissent

Does pornography cause criminal or deviant behavior or adversely affect public or individual morality? The answer is no, according to the Federal Commission on Obscenity and Pornography. After two years of research employing a variety of social science techniques the commission last month recommended the repeal of all legislation prohibiting the sale, exhibition or distribution of sexual materials to consenting adults. Fourteen of the commission's 18 members concurred in its basic findings and 12 subscribed to the major recommendation. Others dissented sharply. So did spokesmen for the Administration, members of Congress and much of the nation's press.

The commission was established by Congress and its members were appointed by President Johnson in 1968. Its investigation was conducted by staff members and through 50 contracted research projects. On the basis of its own study and surveys of the literature the commission reported: "Extensive empirical investigation... provides no evidence that exposure to or use of explicit sexual materials plays a significant role in the causation of social or individual harms such as crime, delinquency, sexual or nonsexual deviancy or severe emotional disturbances." Such exposure may indeed affect behavior, the majority said: "Many persons become temporarily sexually aroused... and the frequency of their sexual activity may increase for short periods"—but only "the type of sexual activity already established as usual activity for the particular individual."

In support of its major recommendation the commission cited its finding that "a majority of the American people presently are of the view that adults should be legally able to read or see explicit sexual materials if they wish to do so." It found, on the other hand, that "a large majority of Americans believe that children should not be exposed to certain sexual materials." For this reason, as well as for lack of conclusive research data concerning children and because of a feeling that parents should be able to control their children's exposure to sexual materials, a majority recommended legislation prohibiting the distribution or sale "of certain sexual materials to young persons." And to prevent "unwanted intrusions upon individual sensibilities" a majority asked for laws against "public displays of sexually explicit pictorial materials" and approved of postal regulations restricting unsolicited sexually explicit advertisements. Three members disagreed with this proposal, one because he opposed any repeal of restrictive legislation and two because they opposed any "specific statutory restrictions on obscenity or pornography" as being ambiguous, unenforceable and inferior to "informal social controls."

In addition to making its legislative recommendations the commission majority called for "a massive sex education effort... aimed at achieving an acceptance of sex as a normal and natural part of life." It also urged continued research to develop factual information about the effects of obscenity and pornography, noting that "some of the facts developed by the commission are contrary to widely held assumptions."

The dissenters made it clear that this was indeed the case. One member said: "To deny the need for control is literally to deny one's senses.... Credit the American public with enough common sense to know that one who wallows in filth is going to get dirty. This is intuitive knowledge.... The report of the majority of the commission does not reflect the will of Congress, the opinion of law enforcement officials... and, worst of all, flaunts the underlying opinions and desires of the great mass of the American people."

The prospects for the legislation recommended by the commission are considered poor. The body of research compiled by the commission may nevertheless eventually have a significant effect on future judicial decisions concerning alleged obscenity and pornography.

Giant Step for Robotkind

Although the U.S.S.R. has not attempted to put men on the moon, it now seems there was a race to the moon after all. The race was to see which nation would bring back the first sample of moon dust. On July 13, 1969, three days before the launching of *Apollo 11,* the U.S.S.R. dispatched an unmanned craft, *Luna 15,* toward the moon. A day after *Apollo 11*'s safe descent on the Sea of Tranquillity, *Luna 15* crashed into the surface not far away, its mission never specified. There was speculation at the time that its goal was to scoop up some lunar material and bring it back to the earth before *Apollo 11* could return with its own treasure.

The speculation seems to be confirmed by the successful flight of *Luna 16,* the "automatic station" that landed on the Sea of Fertility, obtained a core of soil (reportedly about 35 centimeters long) and relaunched itself toward the earth, arriving safely in Kazakhstan late in September. The lunar landing site was closer to the eastern limb of the moon than any of the sites planned for Apollo. The actual weight of sample obtained has not been disclosed, but it can hardly be less than a few kilograms. This should be enough for extensive studies, considering that many U.S. laboratories had to work with Apollo samples weighing less than a gram. Unless the sample includes a sizable fragment of rock, however, it may be difficult to run a good age determination. All dating of Apollo samples was done with rocks.

"The message of the whole Luna series," says one U.S. space physicist, "is that the Russians have undertaken a very big lunar program as well as a big planetary program. The *Luna 16* rocket was larger than anything we have ever used for an unmanned spacecraft. Their effort curve is still going up while we're liquidating Apollo as fast as possible. After four more Apollo flights we have absolutely nothing. By 1976 we hope to have a robot on Mars, but we have no plans for bringing back a sample. It now seems possible that the Russians will have one before 1980."

Discrimination by I.Q. Test

Citing the guarantee of equal treatment contained in the Civil Rights Act of 1871, a group in Boston has entered suit against city and state school officials in Federal District Court, charging that misclassification of pupils on the basis of I.Q. scores does irreparable harm to those of normal intelligence who are placed in "special" classes for the retarded. The action follows an incident in 1969 when 21 children from Boston's predominantly black and Puerto Rican South End, classified as retarded on the basis of I.Q. scores, were tested a second time. More than half of the children had been misclassified. The present suit is filed on behalf of seven Boston schoolchildren and their parents by interested organizations in the area and is being handled by attorneys of the Boston Legal Assistance Project and the Harvard Center for Law and Education.

Encouraged by a recent court decision in California that has halted the use of I.Q. tests in English for Spanish-speaking pupils, the Boston plaintiffs claim that the Stanford-Binet and Wechsler tests, used in the Boston schools, are not sufficiently sensitive to distinguish between retardation or emotional disturbance on the one hand and lack of facility in English or similar cultural differences on the other. These comparatively insensitive tests are used, the suit charges, because the "minimally trained" psychologists in the Boston school system are incompetent to administer more refined ones. A nearly inescapable result of assignment to a special class noted by a spokesman for one party to the action, the Research Institute for Educational Problems, is that "when you tag a kid as a dummy, everyone understands he's a dummy, and he never again has a chance to show what he can do."

How to Exhaust Exhaust

Seven automobiles that were declared winners in a "clean-air car race" put on by college students this summer will be tested further by the National Air Pollution Control Administration. The seven were among 43 automobiles that started the race on August 24 at the Massachusetts Institute of Technology; 37 of them made it across the finish line at the California Institute of Technology within the time limit set by the organizers. On the basis of points derived by means of a formula taking into account performance, race time, fuel consumption per mile and pollution emission, a car designed and built by students at Wayne State University in Detroit was named the overall winner. Winners were also chosen in five of the six categories established for the race. The categories were internal combustion (gaseous fuel), internal combustion (liquid fuel), hybrid electric, electric, turbine and steam. Two cars were designated as co-winners in the hybrid-electric class; none of the steam cars finished.

The object of the competition was to design and build a car that would meet or exceed exhaust-level standards set by the Federal Government and due to be in effect by 1975: .5 gram of hydrocarbons, 11 grams of carbon monoxide and .9 gram of nitrogen oxides per mile driven. The winning car was a 1971 Ford Capri powered by a gasoline-burning internal-combustion engine. The car used unleaded gasoline and had a fuel-injection afterburner, an exhaust-gas recirculator and four catalytic mufflers to clean the exhaust. This car and the winners in the five classes will be incorporated into the National Air Pollution Control Administration's Clean Car Incentive Program. Each winning team will receive a $5,000 lease from the agency, which will then make additional tests of the car's potential for reducing the emission of pollutants.

Undogmatic Dogma

In living cells the normal direction for the transmission of genetic information is from deoxyribonucleic acid (DNA) to ribonucleic acid (RNA) to protein. Thus a linear and sequential molecular code in DNA is transcribed into a closely similar code in RNA and then translated into the specific sequence of amino acids constituting a protein. It was discovered several months ago that a number of tumor-producing viruses make an enzyme that constructs DNA on an RNA template, thereby reversing the normal direction of flow of genetic information. This was regarded in some quarters as a damaging blow to the facetiously named "central dogma" of molecular biology, attributed to Francis H. C. Crick of the University of Cambridge, codiscoverer of the double-helix structure of DNA. In a recent issue of *Nature* Crick explains the "true meaning" of the central dogma and why he believes "it is still an idea of fundamental importance."

"The two central concepts," he writes, "were those of sequential information and defined alphabets." On this hypothesis one tried to formulate "the general rules of information transfer from one polymer with a defined alphabet to another." Two of the polymers, DNA and RNA, use four-letter alphabets; the third, protein, uses a 20-letter alphabet. Crick reproduces an information-flow triangle ("actually drawn at that time [1958]") with DNA at the apex and RNA and protein at the other two corners. Arrows show that information might flow from the molecule in any corner to any other, and also that each molecule might reproduce itself, thus exhausting all possible transfers.

Crick explains that the transfers can be divided into three classes. Class I, the most likely, consisted of four transfers: DNA to DNA, DNA to RNA, RNA to protein and RNA to RNA. Class II consisted of two transfers "for which there was neither any experimental evidence nor any strong theoretical requirement": RNA to DNA and DNA to protein. Class III, the least likely transfers, consisted of protein to protein, protein to RNA and protein to DNA. "There were good general reasons against all three possible transfers in Class III.... I decided, therefore, to play safe, and to state as the basic assumption of the new molecular biology the nonexistence of transfers of Class III.... The central dogma could be stated in the form 'once (sequential) information has passed into protein it cannot get out again.' About Class II, I decided to remain discreetly silent."

The recently discovered transfer from RNA to DNA falls in Class II. Its existence may explain how RNA viruses can infect a cell and seemingly disappear, yet leave a covert "blueprint" of itself to destroy the cell later. The blueprint may be a fragment of DNA (transcribed from viral RNA) that becomes attached to the cell's normal DNA and is thus passed on to the cell's descendants.

"In looking back," Crick writes, "I am struck not only by the brashness which allowed us to venture powerful statements of a very general nature, but also by the rather delicate discrimination used in selecting the statements to make. Time has shown that not everybody appreciated our restraint."

The Chips Are Down

The International Business Machines Corporation, which lagged behind the rest of the computer industry by not adopting monolithic integrated circuits in early models of its third-generation computers, is now the first major company to introduce a computer with a main memory composed entirely of such circuits. For more than 15 years the standard high-speed computer memory has been tiny magnetic "cores" strung on a mesh of fine wires. The new memory system appears in IBM's System 370 Model 145, a medium-sized machine designed to take the place of Model 40 in the 360 series.

The circuit "chips" in Model 145 can provide 512,000 characters of high-speed storage in the same space required by the core memory in the 360/Model 40, which had only half the capacity. The operating speed of the 370/145 is up to five times that of the 360/40. The 145 can store a character in its main memory in 608 nanoseconds (including the time needed to generate error-correcting codes) and retrieve it in 540 nanoseconds.

The main memory is assembled from silicon chips, each less than an eighth of an inch square, comprising 788 transistors and 646 other circuit elements. The 1,434 elements are linked to form 128 memory circuits and 46 support circuits, or 174 circuits in all. A complete memory system for 512,000 characters requires a total of some 47,000 individual chips, which occupy a total of 5.3 cubic feet.

Circumcision v. Circumspection

Over the past few decades the circumcision of newborn male infants, once a traditional ritual performed largely among Jews and Moslems, has become almost routine in the U.S. Lately the procedure has been coming into question. A number of physicians have cast doubt on its presumed medical benefits, have called attention to its risks and disadvantages and have even suggested that it is in a class with routine tonsillectomy. In an article in *The Journal of the American Medical Association* E. Noel Preston, formerly of the Vandenberg Air Force Base Hospital in California, reviews the literature and concludes that routine circumcision is "an unnecessary procedure."

Preston cites the advantages that are attributed to circumcision. They range from the medical (prevention of venereal diseases, cancer and other conditions) to the aesthetic (one authority asserted that "circumcision is a beautification comparable to rhinoplasty," or nose-straightening) and psychological (to ensure against locker-room embarrassment). He depreciates these arguments. He finds only equivocal statistical evidence in favor of circumcision as a protection against venereal disease and cancers of the penis, prostate and cervix; any such effect, he says, is from an increase in cleanliness—something he insists can be brought about in most populations by proper personal hygiene. As for the aesthetic argument, "beauty is in the eye of the beholder, and... most Renaissance works of art show the male organ draped, if not with a fig leaf, at least with a foreskin." As for psychological benefit, this is a time "supposedly to celebrate individuality and freedom of choice... independence and originality of expression."

There are complications of circumcision: hemorrhage, infection and surgical accidents. Preston concludes that the "questionable benefits" are outweighed by the "small but definite incidence of complications and hazards. These risks are preventable if the operation is not performed unless truly medically indicated. Circumcision of the newborn is a procedure that should no longer be considered routine."

Exotic Atoms

One of the most useful techniques employed in recent years by high-energy physicists to probe the subtleties of nuclear structure involves the creation of "exotic" forms of an atom by substituting one or another of a variety of negatively charged subnuclear particles for one of the electrons in the atom's usual structure. After "orbiting" the nucleus of the atom for some time, the comparatively heavy substitute particle loses some of its energy and falls through a succession of lower energy levels toward the nucleus; in most cases it ends up being absorbed by the nucleus. As the particle falls it emits its excess energy in the form of X rays, whose characteristic spectrum of wavelengths corresponds to the set of quantized energy-level differences for that particular atom. It is by studying the emerging X rays that one learns about the nuclear phenomena under investigation.

The existence of such exotic atoms was predicted on theoretical grounds as early as 1947. Five years later the first ones were observed; because negative pi mesons, or pions, were used to take the place of the electrons in this case, the resulting exotic atoms were called pionic atoms. Subsequently both muonic atoms and kaonic atoms were discovered.

Now two more exotic atoms have been added to the list. In an experiment performed recently at the Meyrin Laboratory of the European Organization for Nuclear Research (CERN) a team of German physicists from the University of Karlsruhe and the Max Planck Institute in Heidelberg have succeeded in producing antiprotonic atoms (using the antimatter equivalent of the proton) and sigmic atoms (using a particularly massive subnuclear particle called the sigma hyperon). Both discoveries were made with the help of the 28-GeV proton synchrotron at the CERN accelerator center.

Since the masses of both the antiproton and the sigma hyperon are much greater than that of the electron, the lower energy levels of these substitute particles actually correspond to "orbits" below the "surface" of the nucleus; hence such systems can in effect be used as subsurface probes of nuclear structure. In addition to demonstrating the existence of antiprotonic and sigmic atoms, the current experiments at CERN are expected to produce more accurate information about the mass of the antiproton, the structure of the surface of the nucleus and the distribution of particles within the nucleus.

Blowholes

The hypothesis that at least some of the surface features of the moon have resulted from processes that are endogenic (internally caused) rather than exogenic (externally caused) has been strengthened by the outcome of a series of "table top" experiments carried out by investigators at Colorado State University. The experiments, which were designed to determine the types of landforms that develop when varying thicknesses of granular material are fluidized by the emission of gas through an assortment of underlying vents, are described in a recent issue of the *Geological Society of America Bulletin* by S. A. Schumm, a geologist at Colorado State.

The experimental apparatus used for the tests consisted of a flume 2.4 meters long, 30 centimeters wide and 27 centimeters deep; built into the floor of the flume was a roofed trough, five centimeters wide and 2.5 centimeters deep, which was connected to a compressed-air line at one end. By boring holes or cutting slots in the roof of the sealed gas chamber, various sizes and patterns of gas vents could be formed at the bottom of the flume. The test material placed in the flume to simulate the lunar regolith, or soil layer, was a mixture of sand and fine marble dust.

In general it was found that two types of crater formed above single vents: "explosion craters" with steep sides and little or no floor and "fluidization craters" with low rims and flat floors. Crater chains were observed to form above multiple vents. Under certain conditions a "fluidization trough" was produced by the coalescence of a chain of craters above a series of vents or by the emission of gas along a linear or sinuous vent. Within such a trough the fluidized granular material tended to migrate not only downslope but also from areas of thick material to areas of thin material. The result was a channel with a well-defined head that decreased in depth away from the head.

When these experimental observations are compared with selected Ranger, Lunar Orbiter and Surveyor photographs of the lunar surface, a number of striking similarities appear. Of particular interest is the close correspondence between the sinuous fluidization troughs produced in the laboratory and the long, narrow channels known as rilles that meander across the lunar surface. The origin of these puzzling features has been a subject of much speculation, especially since the publication of the first high-resolution Lunar Orbiter photographs.

The results of the Colorado State experiments, concludes Schumm, "leave little doubt that some crater chains, crater clusters, and sinuous rilles are the result of endogenic processes and probably are the result of fluidization of lunar regolith by gases venting from fractures in the lunar crust."

Closed Cycle

Eutrophication literally means "nourishing well," but in current usage it refers to the inadvertent nourishing of algae in lakes to the detriment of other living things. Now it seems that eutrophication can be applied in its original beneficent sense—to chicken farming. A considerable problem in modern chicken factories, where chickens are automatically maintained in wire cubicles, is the disposal of chicken manure. A group of workers at the University of California at Berkeley has devised a scheme whereby the manure is used to grow algae that are then recycled to feed the chickens.

The scheme has worked well for two years with a flock of 100 chickens, and the developers are planning to test it next in a 4,000-chicken installation. They point out that a rather small chicken farm of 10,000 birds produces more than two tons of waste per day, making the disposal of manure a substantial part of the cost of operation. A traditional method of disposal involves spreading the manure on fields, but that method is becoming less feasible as land values rise and the demand for organic fertilizers decreases. The Berkeley scheme works as follows. Wastes are flushed hourly from below the chickens to a holding tank, where liquids are separated from solids. The liquid portion is sent to an algae pond; the solids are processed in a digester that turns most of them into fluid or gas. The fluid is sent to the pond and the gas is available as a fuel. Algae grow rapidly in the pond. They also provide oxygen for the microorganisms that feed on the waste matter that has been delivered to the pond. Harvested algae in dry form yield a protein-rich animal feed, which can be given to the chickens in amounts of up to about 10 percent of their diet.

Cool Pants

When a dog cools itself by panting, it appears to be rapidly breathing in and out through its mouth. This, it turns out, is not the case. Knut Schmidt-Nielsen, William L. Bretz and C. Richard Taylor of Duke University reasoned that if it were, the cooling effect would be insufficient. The mouth is not well shaped for evaporative cooling, so that the metabolic effort required to circulate an adequate volume of air through it would outweigh the cooling effect. On the other hand, Schmidt-Nielsen and his colleagues write in *Science*, the moist surfaces of the nasal cavity provide a highly efficient evaporative surface. In-and-out breathing through the nose, however, would mean that much of the water vapor taken up by the air on inhalation would be recondensed on exhalation, so that here too the reduction of the heat load would be inadequate. The ideal system, the investigators concluded, would be inhalation primarily through the nose and exhalation primarily through the mouth.

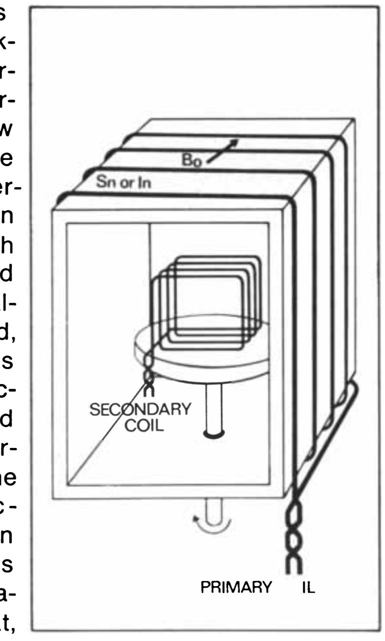
To test their conclusion Schmidt-Nielsen and his colleagues trained dogs to wear fiber-glass masks that divided the nasal air flow from the oral and then wrapped the dogs in an electric blanket to induce panting. Measuring the separate air flows, they found that the nasal inhalation was much greater than the nasal exhalation, and that the oral exhalation far outweighed the oral inhalation. Reflecting on how a dog's nasal mucosae are supplied with the quantities of moisture needed for long periods of evaporative cooling, Schmidt-Nielsen and his colleagues point out that dogs possess a special nasal gland with no known specific function; they suggest that it may provide water for cooling.

The inside story of electron behaviour

In 1831, Faraday "discovered" electromagnetic induction. Closing an electrical circuit containing a coil, he detected a current transient in a second coil coupled with it.

Last year, Dr. W. F. Druyvesteyn of Philips Research Laboratories, Eindhoven, the Netherlands, carried out a related experiment. His purpose was to study the properties of conduction electrons in extremely pure metals at very low temperatures. The experiment also verified a theoretical statement which has appeared in Solid State Physics text books for more than thirty years.

Harking back to Faraday and Maxwell, he knew that if he "screened" one coil from the other by enclosing the second in a metal box, he would normally be unable to detect any signals if the walls of the box were much thicker than the skin depth at the measuring frequency. However, under certain conditions he could still show mutual inductance: – one wall of the box had to be pure metal at low temperature (e.g. tin or indium at 4° K), in order to have a long mean free path for electrons and it had to be placed in a constant magnetic field B_0 parallel to this wall. Because of the field, the thermal motion of electrons is along cyclotron orbits. Those electrons that skim both the outer and inner surfaces of the wall may carry a signal from the outside to the inside. Appreciable mutual inductance only occurs when the direction and magnitude of B_0, the thickness of the wall and its crystal orientation combine in such a way that, for a "sizeable" number of conduction electrons, the orbits just fit within the box wall. According to the laws of quantum mechanics, this number can only be provided by those electrons which occupy states near the Fermi surface – i.e. the surface of constant energy in momentum space which separates the occupied (lower energy) states from the empty states.



By his experiment Dr. Druyvesteyn could determine the shape and dimensions of the Fermi surface. Others had done this previously, using single plates, but the box technique allows improved accuracy of measurement. The additional opportunity to orientate the secondary coil for maximum coupling also enabled him to determine the direction in which the "coupling" electrons skimmed the inner surface of the wall, and hence their thermal velocity in three dimensions.

The results provided the first direct experimental proof that the thermal velocity of conduction electrons in solids is perpendicular to the Fermi-surface – at least, within the experimental error of 2 degrees!

In the Research Laboratories of the Philips group of companies, scientists work together in many fields of science. Among these are: Acoustics, Cryogenics, Information Processing, Mechanics, Nuclear Physics, Perception, Solid State, Telecommunications and Television.
This work was carried out at the Philips Research Laboratories, Eindhoven, the Netherlands.

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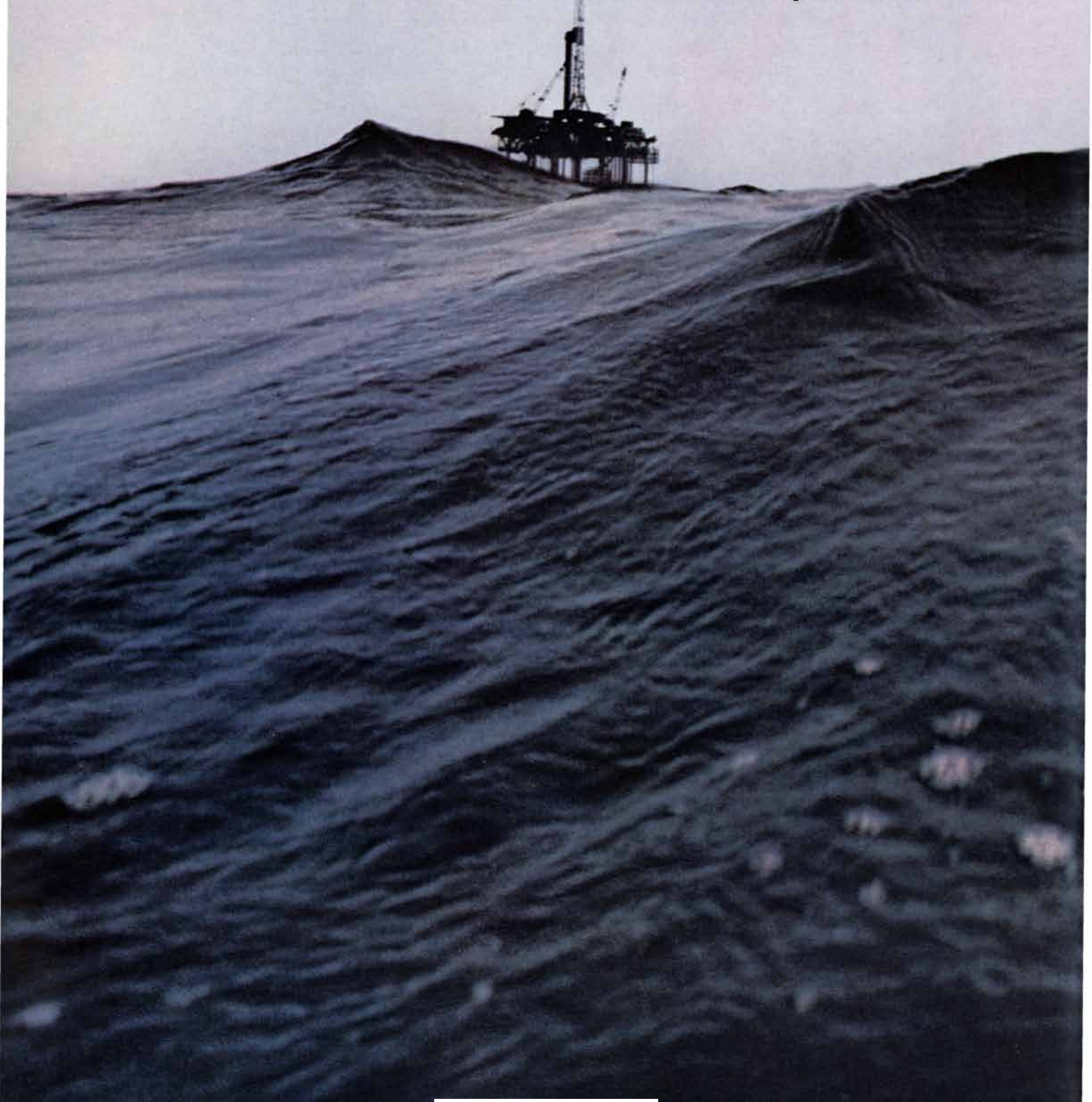
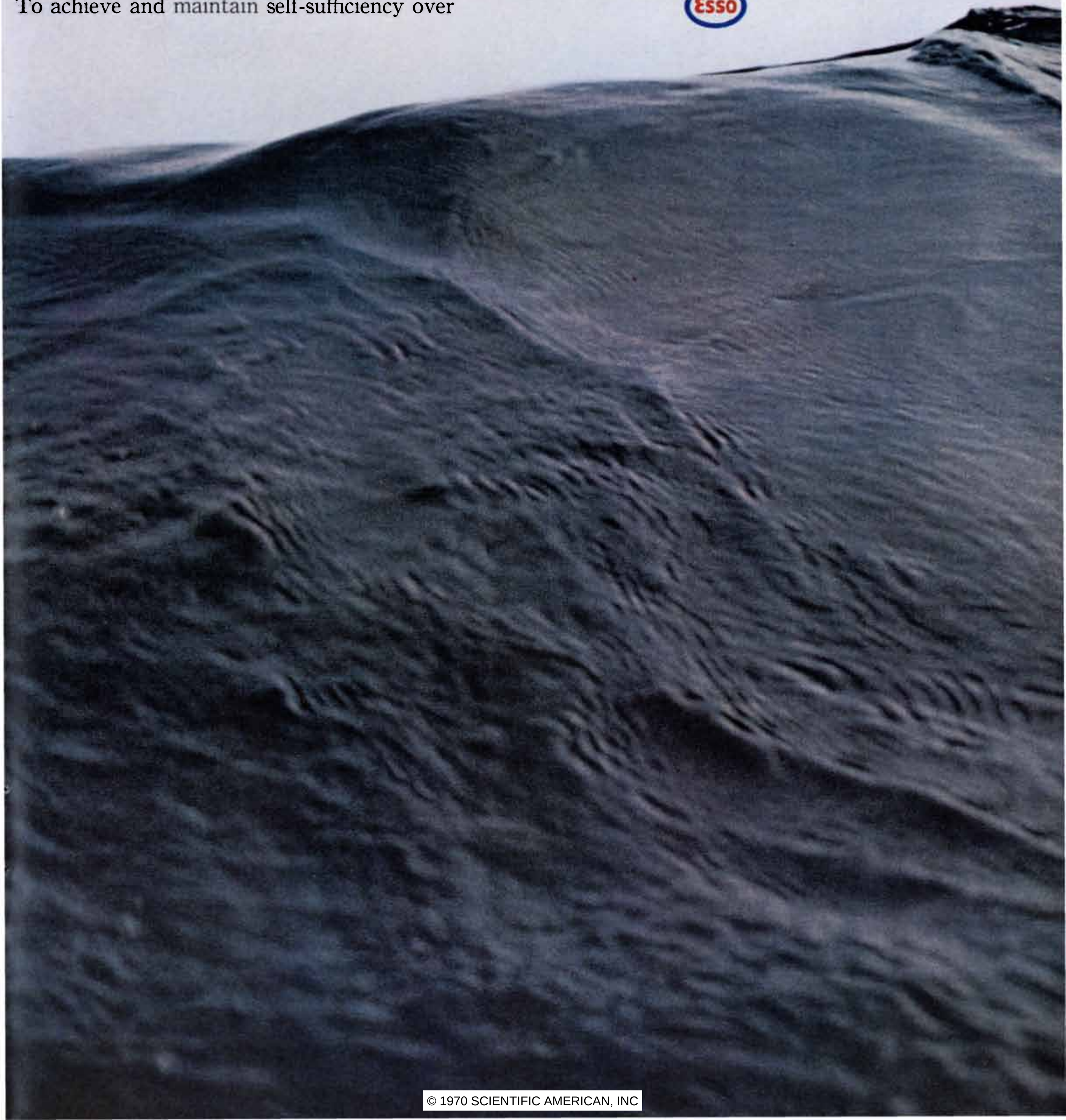
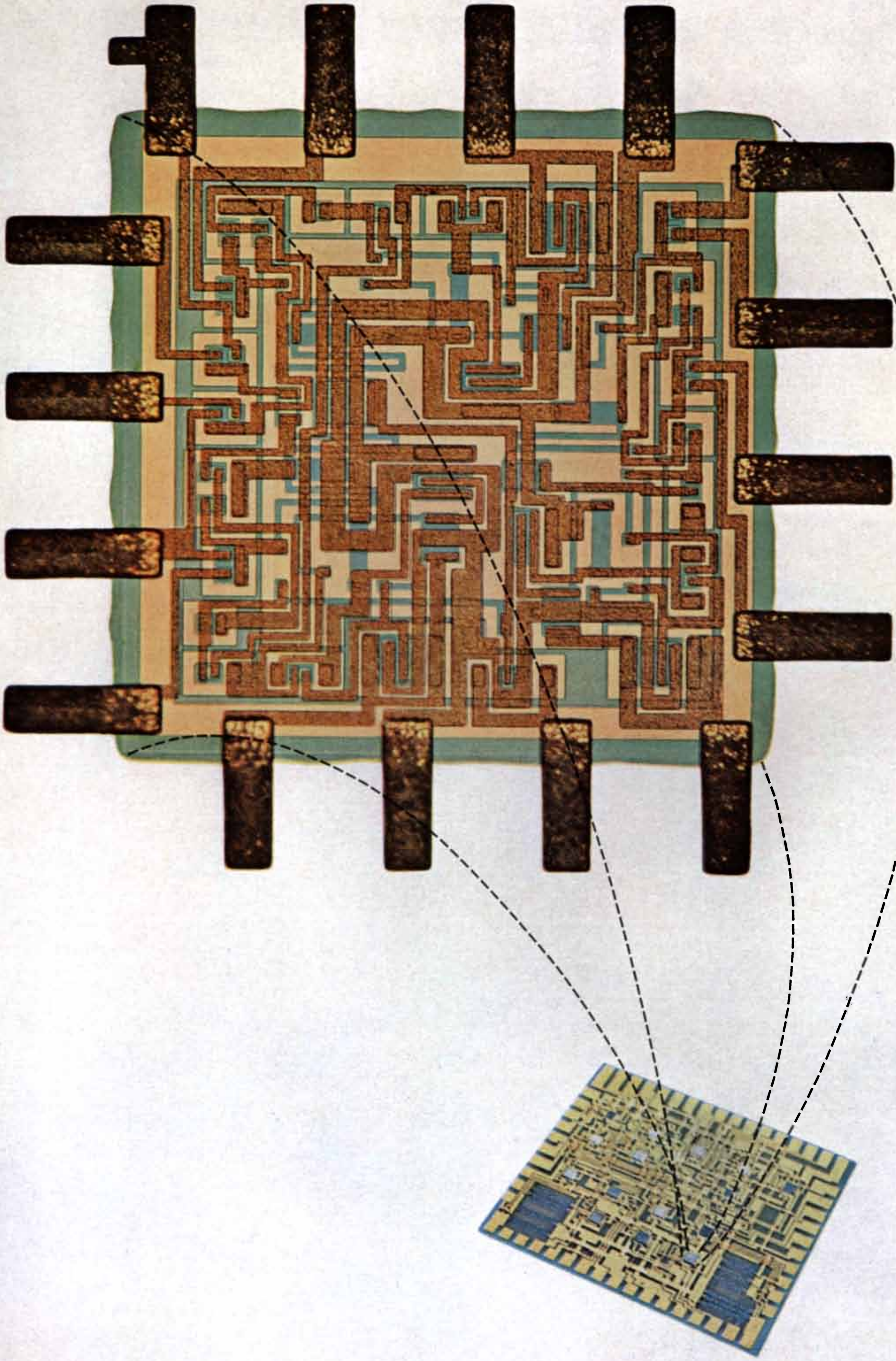






SUPERDENSE WATER

One of the codiscoverers of this remarkable substance takes up the question of whether it represents a new, polymeric form of water or is merely ordinary water with impurities

by Boris V. Derjaguin

There is an unwritten tradition among physical chemists to regard the properties of liquids as essentially invariant. In contrast to gases, liquids are only slightly compressible. In contrast to crystalline solids, liquids do not exhibit variability due to changes in crystalline structure. In contrast to glassy solids (which are sometimes considered to be highly viscous liquids), liquids of normal viscosity appear to be incapable of existing for long in a state of nonequilibrium.

These characteristic properties of liquids were the reason the commonest of them, water, was adopted as the basis for the definition of several international standards of measurement. The choice of a cubic centimeter of water as the international unit of mass, for example, was motivated by the fact that any given sample of water has a maximum density at a specific temperature (4 degrees Celsius), near which small changes in the temperature cause vanishingly small changes in the density and hence negligible changes in the mass of the standard volume.

The time has come, however, to reconsider the universal recognition that has been accorded to the notion of the constancy of the properties of liquids, in the light of an accumulation of experimental facts indicating the opposite. For a number of years my colleagues and I at the Institute of Physical Chemistry of the U.S.S.R. Academy of Sciences have been conducting an extensive series of experiments on the variability of the properties of liquids in a special set of laboratory conditions: under the influence of forces generated by contact with the surfaces of other bodies, either solid or liquid. In general we have found evidence for two kinds of change brought about by such surface forces: reversible, or short-term, changes and irreversible, or persistent, changes. In particular our investigations led to the truly astonishing discovery in 1962 of a new, stable form of water with a density almost one and a half times that of ordinary water and a molecular structure that can only be described as polymeric. We named this new form of water water II to distinguish it from ordinary water, or water I; some workers in the U.S. call it polywater.

In view of the fact that our findings have generated considerable controversy and a certain amount of misunderstanding outside the U.S.S.R., it seems worthwhile to set down in as straightforward a way as possible an account of the investigations leading to the discovery of water II, along with a summary of the studies we have undertaken since 1962 on the nature of this remarkable substance.

Liquids in General

A question central to much of our work from the very beginning has been this: How deep does the influence of a surface penetrate into a liquid, substantially changing its properties? We know that every substance creates near its surface an electromagnetic field whose intensity at each point fluctuates randomly in both magnitude and direction. On the average a force of attraction, directed at right angles to the interface, acts on the molecules of any liquid located within such a field. Since the law according to which this force decreases with distance is known, it would seem to be a comparatively simple matter to answer the question about the depth of penetration of the surface's influence into a liquid.

The situation, however, is more complex than it first appears. First of all it is necessary to agree on what is to be understood by the phrase "substantial changes of the properties of a liquid." For instance, under the influence of the surface field the liquid may become denser. Calculations relating the effect of such forces to a certain pressure, however, show that an appreciable increase in density (of the order of a few percent) can occur only in layers whose thickness is of the order of a few molecules. On the other hand, we have observed in our laboratory changes in a number of properties at depths of up to hundreds of molecules. Clearly it is necessary to seek an explanation for the effect of the interface on the adjoining layers that is not reducible to a simple increase in density under the influence of molecular forces.

That other mechanism, as we shall see below, must involve changes in the structure of the liquid. Again let us agree on definitions; the phrase "structure of a liquid" is used here to denote the mutual arrangement of the nearest molecules with respect to one another. This arrangement may resemble the regular distribution of molecules in a crystal over the sites of the crystal lattice, but the resemblance and the regularity vanish if the arrangement of the neighbors farther away is considered. Thus the phrase "structure of a liquid" should be understood in its strictly limited sense of short-range ordering, not in the sense of the long-range ordering characteristic of crystals.

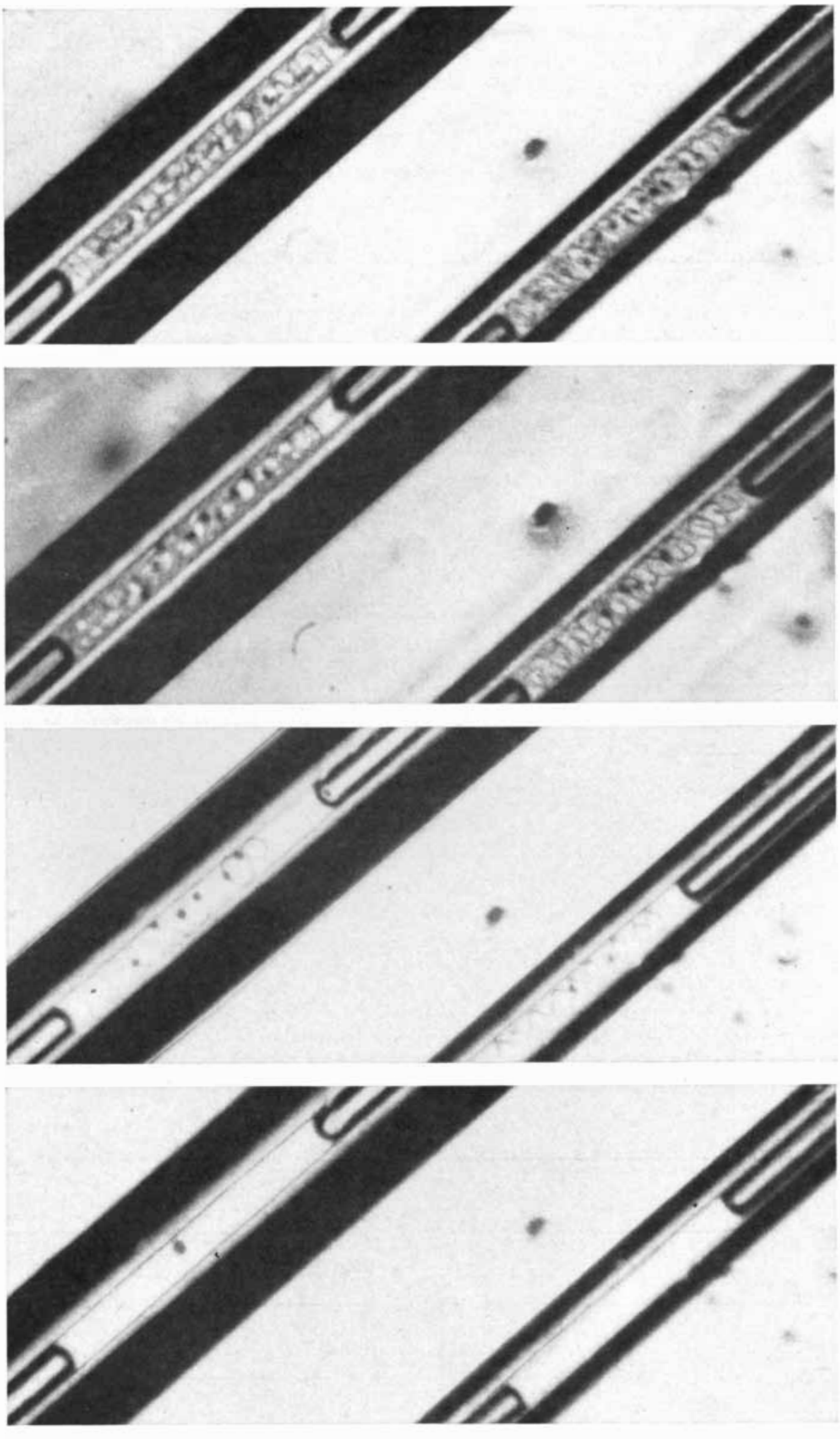
All of this leads naturally to the following question: If the presence of a molecule affects the arrangement of only its nearest neighbors (that is, those separated by a distance of two or three molecular diameters), then does it not follow that an interface will also be able to impose some kind of special structure only on layers that are two or three molecules thick? Conversely, one might just as reasonably ask if the structural influence of a flat surface might penetrate much deeper than a few molecules, in analogy to the way the electric field of a charged surface is not subject to the inverse-square law obeyed by the field of a unit charge. Obviously the final answer to these questions can be obtained only by experiment.

Among the properties of liquids there are those that in general do not depend on the arrangement of the molecules but only on their species. Molecular refraction belongs to such a class; it is, for example, the same for ice, water and water vapor. Such properties are called structurally insensitive. Properties that are structurally sensitive depend to a greater or lesser extent on the structure of the liquid; a typical property belonging to this class is viscosity.

For a long time no suitable method existed for observing how a structurally sensitive property such as the viscosity of a liquid changes as one approaches a solid wall or moves away from it. Then about 30 years ago a method was developed; it is called the method of "blowing away" [*see top illustration on next page*]. A liquid film with a thickness of several microns is applied to the lower surface of a slotlike channel. An air current streaming through the slot creates a uniform tangential force, causing a flow of the layers of the film parallel to the substratum, or lower surface, of the channel. The picture of this flow resembles a pack of playing cards pushed into a sloping pile. As a result of such sloping, in which neighboring layers are shifted by sliding over one another, the edge of the liquid film is changed into a mildly sloping wedge with a definite profile.

It is obvious that the larger the friction between any two neighboring layers, the shorter will be their relative slippage, and consequently the steeper will be the profile of the wedge at their level. Since this friction is proportional to the viscosity of the liquid at the place of contact of both layers (in other words, at a given distance from the solid substratum), it follows that from the shape of the film's profile after "blowing away" one can judge the distribution of the values of the viscosity near the wall. The accuracy of the information obtained by this method depends primarily on the accuracy with which the thicknesses of the finest nonuniform liquid films can be measured. This aspect of the problem was solved in 1948, largely through the efforts of V. V. Karasev and N. N. Zakhavaeva of our laboratory, who considerably improved an existing optical method based on the observation of the polarization of reflected light.

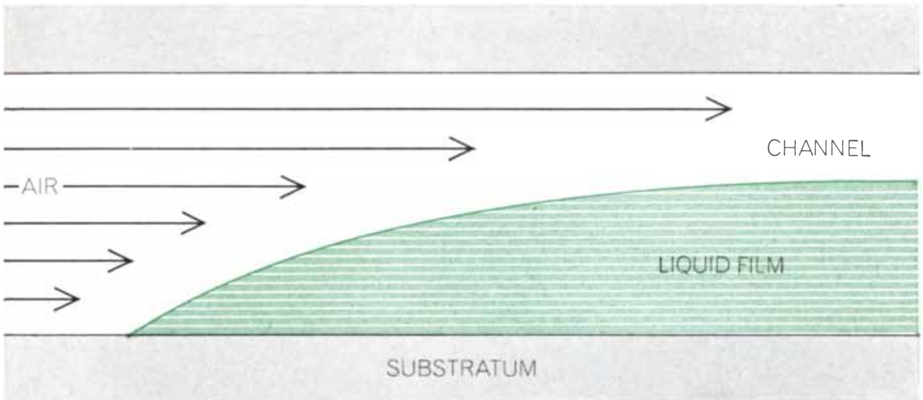
For a vaseline oil that has been thor-



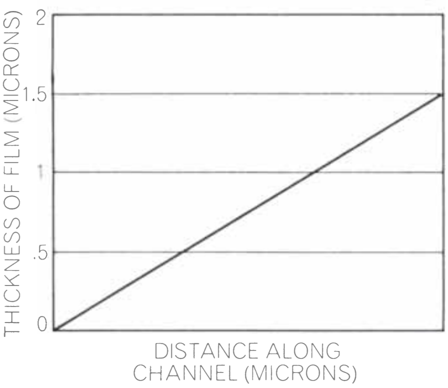
SAMPLES OF SUPERDENSE WATER appear inside a pair of ultrathin quartz capillaries in these photographs made by S. B. Brummer of Tyco Laboratories, Inc. Brummer and his associates are engaged in an attempt to produce large enough quantities of this substance to help resolve the question of whether it indeed represents a new polymeric form of water, called by some workers "polywater." In this investigation of the two-phase freezing and melting behavior of an anomalous water solution two capillaries containing different concentrations of the anomalous component in a solution of ordinary water are shown at various temperatures. The upper capillary in each case contains one part of polywater to 20 parts of ordinary water; the lower one has a concentration of one part in six. In the photograph at top both samples are shown frozen at −43 degrees Celsius. The evident turbidity of the samples can be shown to result not from the incorporation of air bubbles but rather from a genuine phase separation. The next two photographs, made at −10 degrees C. and −8 degrees C. respectively, show that melting proceeds more rapidly in the more dilute sample. In the bottom photograph, made at −6 degrees C., both samples have become completely one-phase. This behavior is similar to that reported in 1966 by the author and his colleagues.

oughly purified of "polar" molecules (that is, molecules with chemically active groups on their ends), the profile of the wedge turned out to be exactly a straight line [*see illustration at bottom left below*]. This proved that the viscosity of such an oil, carefully rid of impurities, is the same both in bulk and at distances from the substratum of the order of a few millionths of a millimeter. In fact, values of the viscosity calculated from the steepness of the film's profile exactly coincide with values for the bulk viscosity of the oil, measured in a conventional viscosimeter. This proves the reliability of the quantitative information obtained about viscosity by the method of blowing away and its independence of possible microscopic irregularities on the polished surface.

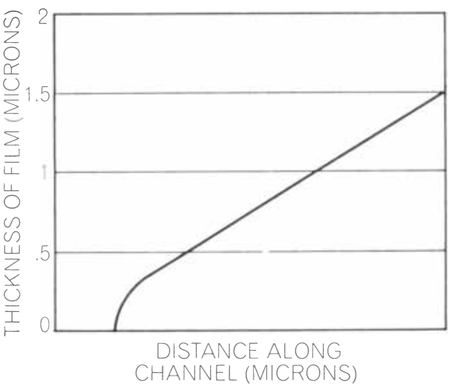
In the case of the blowing away of liquids whose molecules may specifically interact with the substratum, the profile of the film after blowing away never turns out to be a straight line. For example, the profile of a film consisting of long-chain polar molecules of an ether compound exhibits a region of greatest steepness, and consequently of greatest viscosity, in immediate proximity to the wall [*see illustration at bottom right below*]. With increasing distance from the wall the viscosity passes through a minimum, after which it rises until it reaches the "normal" value characteristic of the bulk of the sample.



METHOD OF "BLOWING AWAY" was utilized by the author's group to study how the viscosity of a liquid varies in the vicinity of a solid wall. A liquid film several microns thick is applied to the lower surface of a slotlike channel. An air current, flowing through the slot, causes the layers of the film to flow over one another parallel to the substratum. As a result the edge of the film is changed into a sloping wedge with a definite profile. The steeper the profile at a given distance from the wall, the greater the viscosity of the liquid at that point.



FOR A VASELINE OIL that has been purified of "polar" molecules (that is, molecules with chemically active groups on their ends), the profile of the film after blowing away turned out to be exactly a straight line. Thus the viscosity of such a liquid, when thoroughly purified, is the same both in bulk and at distances from the substratum of the order of a few microns. Such measurements proved the reliability of the quantitative information obtained about viscosity by the method of blowing away.



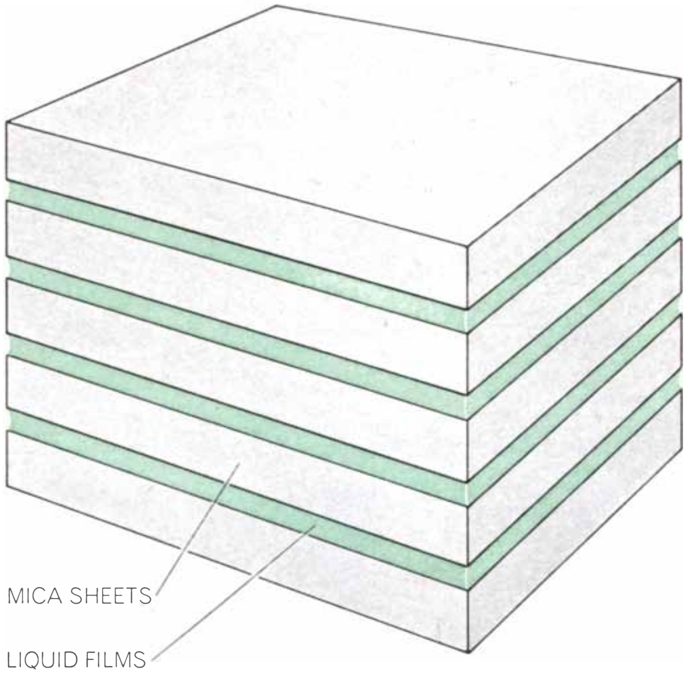
FOR AN ETHER COMPOUND, whose long-chain polar molecules may specifically interact with the substratum, the profile of the film after blowing away exhibits a region of greatest steepness, and hence of greatest viscosity, in immediate proximity to the wall. With increasing distance from the wall the viscosity passes through a minimum, after which it rises until it reaches the value characteristic of a bulk sample. Such measurements can be explained only by changes in the structure of the liquid near the wall.

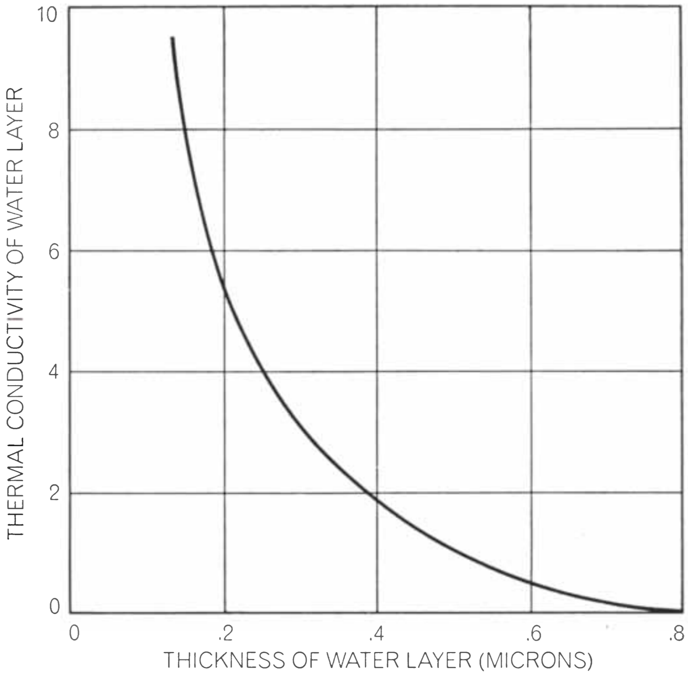
It is impossible to explain such measurements of viscosity by anything except changes in the structure of the liquid near the solid wall. There is reason to believe the increase of the viscosity near the wall is attributable to the fact that the molecules are aligned with their longitudinal axes perpendicular to the wall. Conversely, a horizontal distribution of the axes of the molecules explains the minimum of the viscosity at a certain distance from the wall. The most important and unexpected result of such tests is the fact that the bulk value of the viscosity and consequently the normal close ordering in a liquid are established only at distances from the wall of the order of half a micron, which corresponds to hundreds of molecular layers. Similar data have been obtained for many other polar liquids, and also for solutions of polar molecules in nonpolar liquids, even solutions of low concentration.

In a number of cases the change in the viscosity with increasing distance from the solid wall takes place with a jump at a certain distance. The possibility of an abrupt change of structure has already been demonstrated by the behavior of "liquid crystals," in which regions with a particular parallel distribution of the axes of the molecules may border on regions with a random distribution. This makes it possible to conjecture that many other liquids, when in the vicinity of foreign substrata, are in a state corresponding to a special boundary phase in which the molecules are distributed in a more highly ordered state than they are in the bulk sample. In contrast to the state of affairs in liquid crystals, however, such boundary phases would have a strict boundary of small thickness (on the order of a fraction of a micron), which uniformly decreases with increasing temperature.

Unfortunately the method of blowing away cannot easily be applied to volatile liquids such as water. In such liquids information about changes of the structure in boundary layers must be obtained by other methods, a large number of which exist at the present time. One property that is extremely sensitive to the structure of a substance is thermal conductivity, which increases abruptly on crystallization.

The thermal conductivity of a multilayered sandwich formed by small sheets of mica, separated by interlayers of water or other liquids, was measured by M. S. Metsik of Irkutsk University in 1967 [*see illustration on opposite page*]. In these measurements the heat flow was parallel to the mica sheets. By sub-





THERMAL CONDUCTIVITY of water and other liquids was determined by M. S. Metsik of Irkutsk University by measuring the heat flow across a multilayered sandwich formed by small sheets of mica separated by interlayers of the sample liquid (*diagram at left*). By subtracting the thermal conductivity of the mica sheets alone from the total thermal conductivity of the sandwich, Metsik was able to obtain the thermal conductivity of the liquid layers. When the resulting value for a sample of water, say, is plotted as a function of the thickness of the layers (*graph at right*), it becomes evident that sufficiently thin layers have a thermal conductivity up to several tens of times larger than the normal bulk value. Since thermal conductivity is an extremely structure-sensitive property, such measurements provide information about changes in the structure of such liquids near solid boundaries.

tracting the contribution of the sheets from the total thermal conductivity, Metsik was able to determine the thermal conductivity of the liquid layers. When the thermal conductivity of layers of water or alcohol is plotted as a function of the thickness of the layer, it becomes evident that sufficiently thin layers have a thermal conductivity up to several tens of times larger than the normal bulk value. The increase of the thermal conductivity also vanishes when the temperature is raised to between 60 and 70 degrees C. This means that the particular ordered structure of the liquid layers is destroyed by thermal motion.

Just as in liquid crystals, the ordering of the molecular distribution assumed above (which consists of a definite orientation of the molecular axes) leads to the conclusion that the index of refraction of such thin films must depend on the direction of the light oscillations. As is well known, a similar anisotropy of optical properties in certain crystals leads to the phenomenon of double refraction.

Small crystals of a particular type of clay, montmorillonite, possess the special property of swelling dramatically in water or in an aqueous solution of sodium chloride, in some cases growing up to several dozen times their original thickness. The result is a multilayered sandwich similar to those constructed by Metsik out of mica and water. The basic difference consists in the thinness of the layers; in the process of swelling montmorillonite splits into layers each of which is only 12 angstroms thick, whereas the interlayers of the aqueous solution have a thickness that increases with a decrease in the salt concentration, reaching at extreme dilution as much as 200 to 300 angstroms or more.

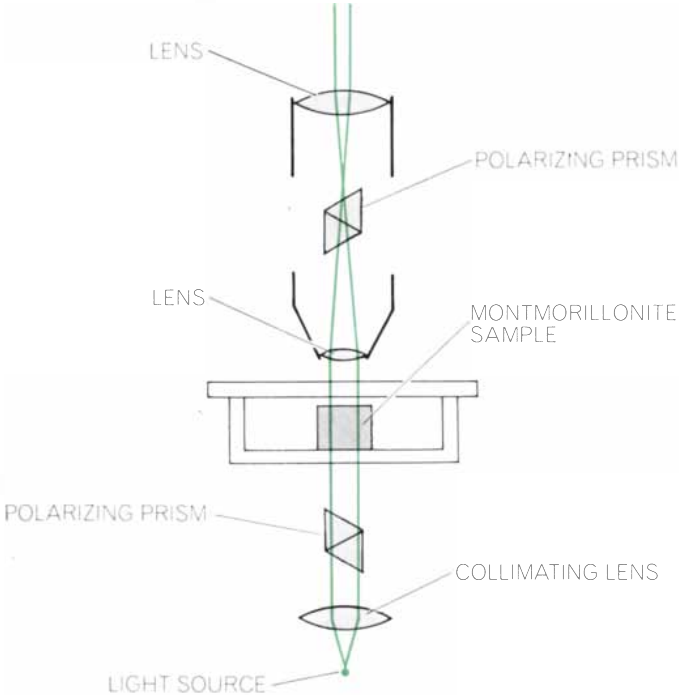
In a study carried out by the British worker R. Green-Kelly and myself during the time of his stay in Moscow it was observed that the aqueous films between the layers of montmorillonite are birefringent, the difference between the two indexes of refraction of the aqueous films being about .002 [*see illustration at top left on next page*]. We were also able to calculate that it is impossible to attribute such a value for the double refraction to the influence of the electric field that exists in thin films as a result of the accumulation on their surface of an excess of ions of one sign at the expense of a shortage of such ions in their interior. The electric field generated in this way, which tends to orient the axes of the molecules in one direction, is not enough in itself to account for more than a tenth of the observed difference in the indexes of refraction. The major portion of this difference can depend only on the orientation of the water molecules in the films under the specific influence of the surfaces of the montmorillonite layers.

The subsequent observation of a particular structure in films of so nonpolar a liquid as benzene was completely unexpected. This finding was first reported in 1963 by Z. M. Zorin of our laboratory on the basis of his measurements of the thickness of a benzene film on a flat surface of mercury in equilibrium with benzene vapor that was close to saturation [*see illustration at top right on next page*]. By carrying out the observations in oblique polarized light Zorin was able to judge the thickness of the benzene layers from their reflectance. For a certain adjustment of the polarizing optics of the apparatus it was possible to extinguish the light reflected from the benzene films, thereby making the field of view black. This did not always happen, however. Under certain conditions one could observe in the black background luminous "islands" of various irregular shapes, all of which had the same brightness and hence the same thickness [*see bottom illustration on next page*]. By changing the position of the optical elements standing in the path of the light rays to the eye it was possible to simultaneously cancel the rays reflected from these islands, after which they appeared to be black in the reflected light.

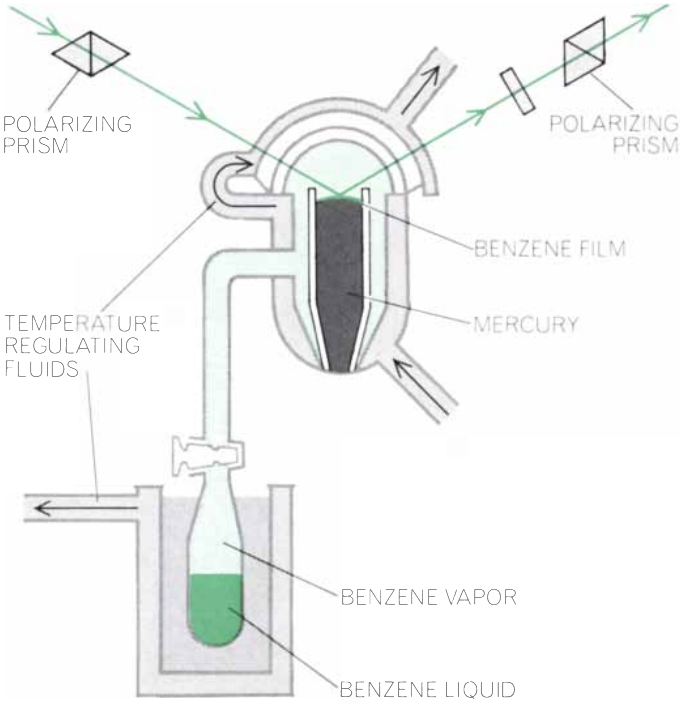
The thicknesses of the benzene film and of the islands were calculated by a rather simple procedure. When saturated benzene vapor was above the films, the thickness of the "background" turned out to be 70 angstroms, while that of the islands was 220 angstroms.

Here a double contradiction of orthodox opinion was exposed. It had been assumed that in the process of saturation of a space by the vapor of some kind of liquid, the film that is formed from it on any substratum must thicken monotonically and, on reaching saturation itself, acquire an indefinitely large thickness, in which case the properties of the film are no different from the properties of the bulk liquid. In fact the thickness of layers in equilibrium with completely saturated vapor is definitely limited.

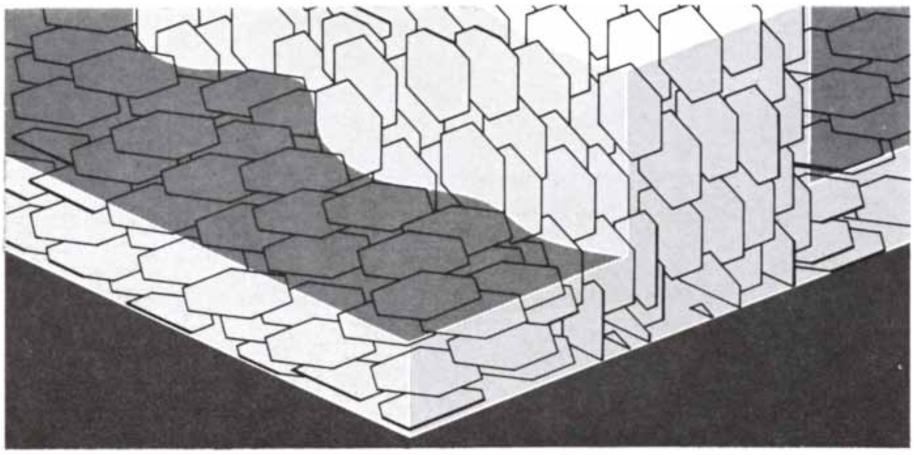
How does one account for this phenomenon, which appears to be rather common, having been observed by Zorin and the author during an earlier investigation of various liquid films (including water and several alcohols) on both glass and mica? In the case of benzene on mercury the matter is compli-



DOUBLE REFRACTION of light rays by thin films of an aqueous solution trapped between layers of montmorillonite clay was observed by the British investigator R. Green-Kelly and the author at the author's laboratory in Moscow, using the experimental arrangement shown in this schematic diagram. The observed difference between the two indexes of refraction of the aqueous films (approximately .002) could be explained only in terms of the orientation of the water molecules within the thin aqueous films under the specific influence of the surfaces of the montmorillonite layers.



BENZENE FILMS were unexpectedly found to have a well-defined structure by Z. M. Zorin of the author's group, using the experimental arrangement shown here. With the aid of oblique polarized light Zorin was able to measure the reflectance and hence the thickness of the benzene layers formed on a flat surface of mercury in equilibrium with benzene vapor that was close to saturation. For a certain adjustment of the apparatus it was possible to extinguish the light reflected from the benzene film, thereby making the field of view black. This did not always happen, however.

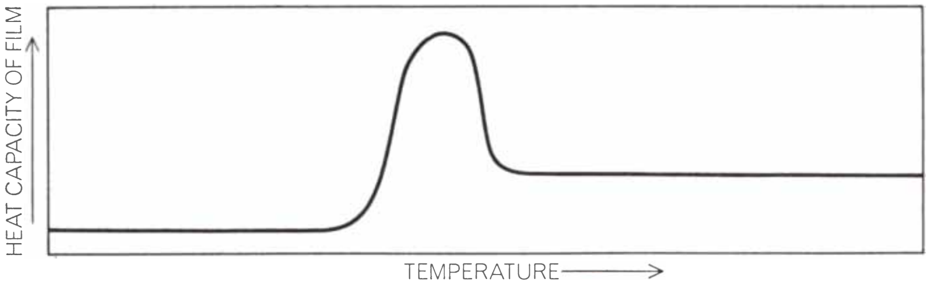


LUMINOUS IRREGULAR "ISLANDS," all with the same brightness and therefore with the same thickness, were sometimes observed by Zorin against the black background normally seen through the microscope attached to his apparatus (*left*). When saturated benzene vapor was above the benzene films inside the apparatus, the thickness of the background measured 70 angstroms, but that of the islands turned out to be 220 angstroms. This puzzling observation can be accounted for by assuming that the films that are 70 angstroms thick are formed of benzene rings whose planes are parallel to the substratum, whereas the islands of approximately three times that thickness are formed of benzene rings that are standing on edge on the surface of the mercury (*right*).

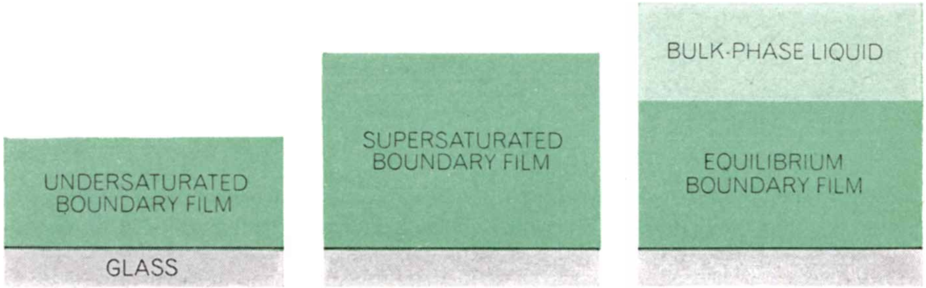
cated by the fact that in different regions of the film the two different thicknesses (of either 70 or 220 angstroms) can occur in equilibrium with the saturated vapor. The very definiteness of this thickness is evidence that, in spite of the fact that the films have a thickness of the order of several tens of molecular monolayers, they retain clear differences between their properties and the properties of the bulk liquid, the only exception being the vapor pressure, which is of course the same for both. Obviously this difference must be associated with a different ordering of the molecules. One can postulate, for example, that the films that are 70 angstroms thick are formed by benzene rings whose planes are parallel to the substratum, whereas the islands of approximately three times that thickness are formed by benzene rings that are standing on edge on the surface of the mercury. Unfortunately at present there is no more direct information concerning the structure and properties of these films.

The properties of films of nitrobenzene and its solutions in benzene on a glass surface have been studied much more thoroughly. Information about them is derived from measurements of the heat capacity of glass powders, whose particles are covered by uniformly thick layers of nitrobenzene. By measuring the heat capacity of the moistened powder with the aid of a sensitive calorimeter and subtracting from it the heat capacity of the powder when dry, one can determine the specific heat capacity of the nitrobenzene film. These experiments showed that if the surface of the powder is treated in a glow discharge for the purpose of purification, then the heat capacity of the nitrobenzene films is sharply reduced compared with the normal value. When the thickness of the films is smaller than a certain value (.1 micron at 20 degrees C.), the reduction is equal to approximately 20 percent and does not change with a further decrease of the thickness. This undoubtedly shows that such films have a structure and structure-dependent properties that are different from the structure and properties of a bulk sample. At the same time, to the extent that one can judge from the specific heat, these films are homogeneous across their thickness.

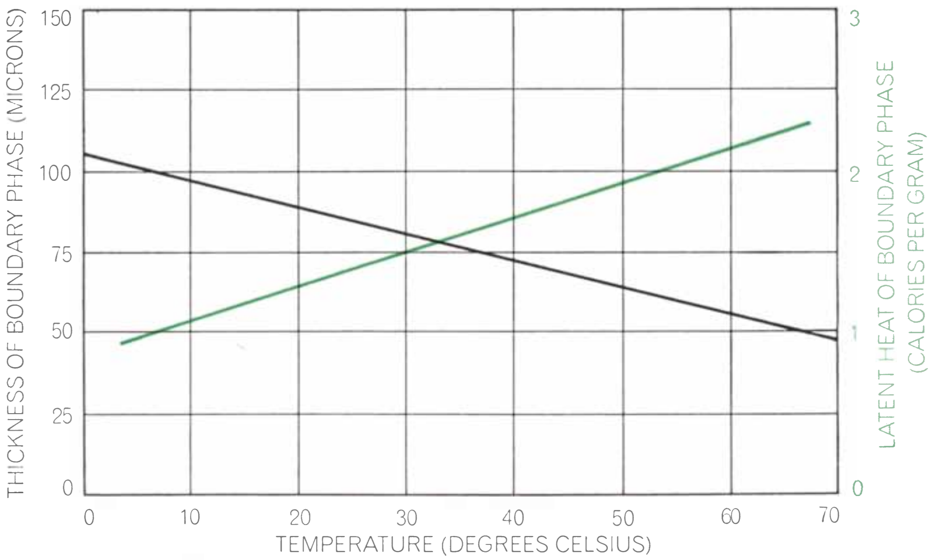
If the temperature-dependence of the specific heat of benzene films is measured by raising the temperature, it turns out that at a certain temperature the expenditure of heat abruptly increases. After a transition through a comparatively narrow temperature interval the



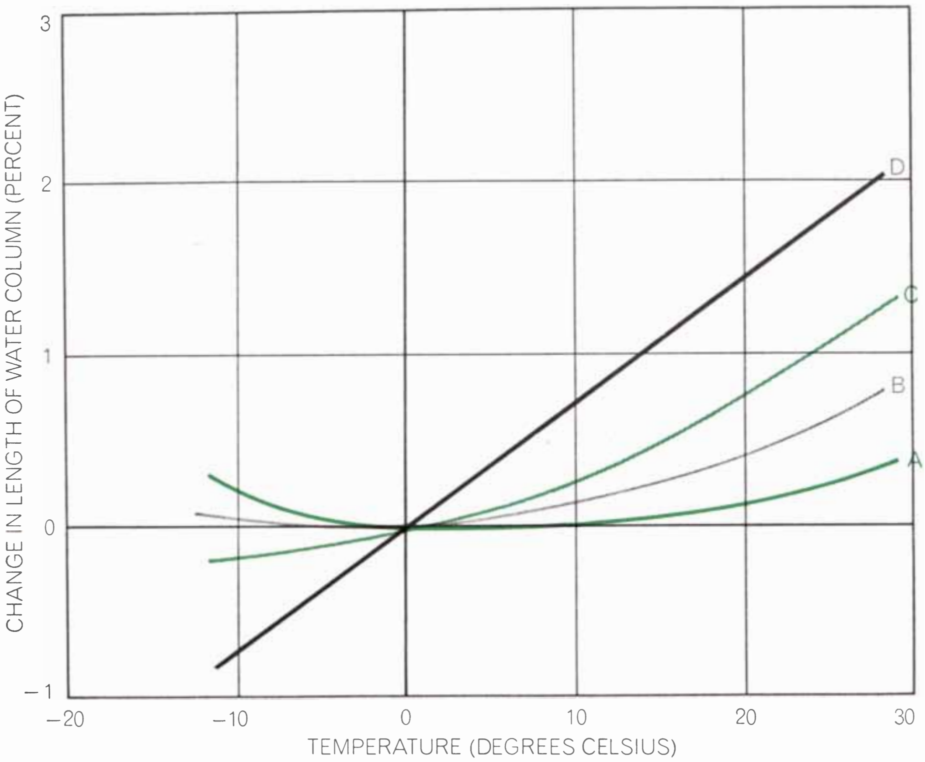
HEAT CAPACITY of nitrobenzene films deposited on particles of glass powder was determined by measuring the heat capacity of the moistened powder with a calorimeter and then subtracting from it the heat capacity of the powder when dry. It was found that when the thickness of the films is below a certain value (.1 micron at 20 degrees C.), the heat capacity of the nitrobenzene films is much less than the normal bulk value. When the temperature of the films is raised, the expenditure of heat abruptly increases at a certain temperature. After a transition through a comparatively narrow temperature interval the amount of heat consumed in heating by one degree decreases somewhat but remains above the value that corresponds to the initial reduced heat capacity of thin nitrobenzene films.



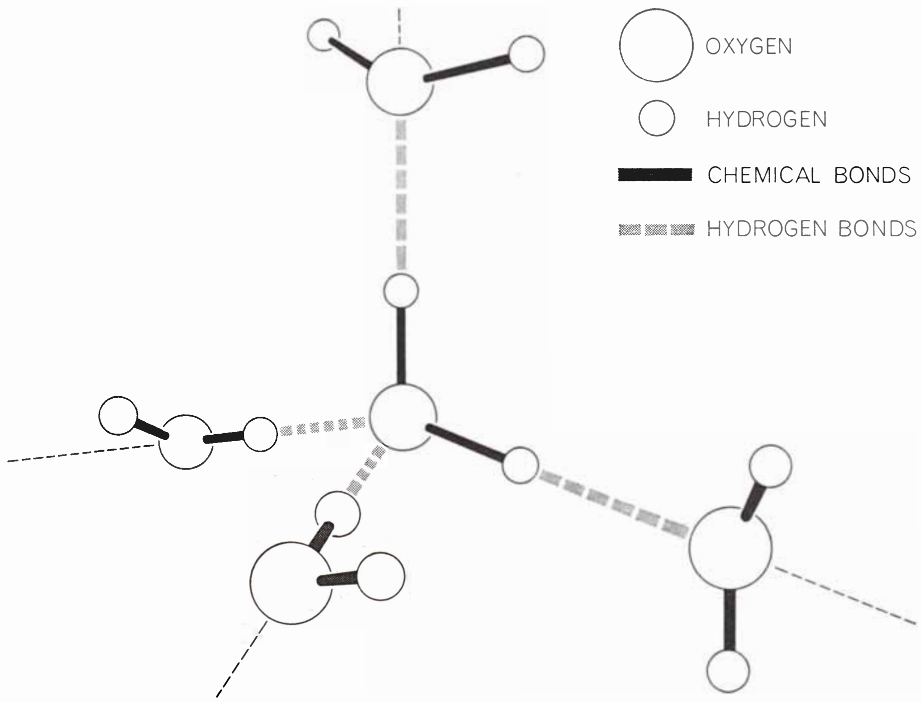
BOUNDARY-PHASE HYPOTHESIS was put forward by the author to account for the observed temperature-dependence of the specific heat capacity of nitrobenzene films on glass powder. The rise in the expenditure of heat associated with the attainment of a certain temperature is explained by an incipient transition of the boundary phase into the bulk phase (*left, middle*). The abrupt burst of heat associated with the onset of "melting" of the peripheral layers of the film is explained by the fact that the transition of the boundary phase into the bulk phase is delayed somewhat. Once it has started, the phase transition accelerates rapidly and makes up for the delay, thus leading to a rapid decrease in thickness to its equilibrium value (*right*). After this stage is passed the film becomes two-phased: the boundary film is located on the surface of the glass, and above it is found the bulk phase.



THERMODYNAMIC CHARACTERISTICS of the transition of a nitrobenzene film from the boundary phase into the bulk phase are summarized. The colored curve shows the latent heat of the transition as a function of the temperature. The black curve shows the thickness of the boundary phase as a function of the temperature. The latent heat of the transition has an order of magnitude corresponding to about 100 molecular layers of nitrobenzene.



THERMAL EXPANSION OF WATER was first proved to be dependent on proximity to a solid substratum in 1961 by the experiments of N. N. Fedyakin, then working at the Kostroma Polytechnical Institute. When the expansion of columns of water in glass capillaries of various radii was plotted as a function of temperature, it became apparent that in capillaries with a radius greater than one micron (*A*) the water expands as it does in a bulk sample, displaying a maximum density at 4 degrees C. As the capillaries are made narrower (*B*, *C*) the expansion begins to proceed differently; in ultranarrow capillaries (*D*) the minimum of the volume vanishes and the coefficient of thermal expansion becomes constant.



HYDROGEN "BRIDGES" (*broken gray lines*) link each atom of oxygen appearing in the structure of any given water molecule with four other water molecules; two of these bridges involve the participation of the hydrogen atoms of the given water molecule, and the other two involve the participation of hydrogen atoms belonging to other water molecules. The energy of such hydrogen bonds is intermediate between the energy of the usual chemical bond that exists between the atoms in a given molecule (*solid black lines*) and the energy of molecular attraction between neighboring molecules. In the form of the structure shown here the geometric arrangement of the atoms is that encountered in ordinary ice, or ice I.

amount of heat consumed in heating by 1 degree C. decreases somewhat but remains above the value that corresponds to the initial reduced heat capacity of thin nitrobenzene films [*see top illustration on preceding page*].

These observations can be explained satisfactorily only by assuming that the thickness of films associated with reduced specific heats depends in a definite manner on the temperature: the higher the temperature, the smaller the thickness. Thus films of nitrobenzene covering a surface of glass possess the basic characteristic of a distinct phase of matter: they are separated by an abrupt boundary from another phase, the bulk liquid. Accordingly the term "boundary phase" is used to describe them.

In contrast to ordinary phases of matter, whose volumes can be arbitrary, the thickness of such a boundary phase cannot exceed a certain value, which depends on the temperature. In our experiments the rise in the expenditure of heat associated with the attainment of a certain temperature could be explained by an incipient transition of the boundary phase into the bulk phase, a transition that leads to a gradual thinning of the boundary phase because of a "melting" of the peripheral layers. Consequently in contrast to ordinary melting, which occurs at a quite definite temperature (for example at zero degrees C. for ice), boundary phases melt gradually over a wide temperature interval, within which the temperature of the onset of melting depends on the thickness of the film.

At the same time the abrupt burst of heat associated with the onset of melting could be explained by the fact that the transition of the boundary phase into the bulk phase is delayed somewhat, beginning at a temperature when the equilibrium, or normal, thickness of the boundary phase has already become substantially smaller than the actual thickness. (Such a retardation is analogous to a retardation of boiling caused by the removal of the centers facilitating the formation of bubbles of vapor.)

Once having started, the phase transition accelerates vigorously and makes up for the delay, thus leading to a rapid decrease in thickness to its equilibrium value. This rapid phase transformation also absorbs an increased amount of heat, which is consumed by the latent heat of the transition. After this quick stage is passed the film becomes two-phase: the boundary phase is located on the surface, and in equilibrium with it is found the bulk phase with normal properties [*see middle illustration on preceding page*].

The foregoing account, which deals only with the essence of the phenomena involved, demonstrates that calorimetric measurements performed with sufficient accuracy are able in principle to give not only the specific heat of boundary layers of nitrobenzene at different temperatures but also both the latent heat of its transition into the bulk liquid and the thickness of the boundary phase in equilibrium with the bulk phase. In actuality these measurements cannot be achieved as directly as this account suggests. Since it is not feasible to go into the details of the measurements here, however, I shall present only the obtained dependences of the latent heat and the thickness of the boundary phase in the form of a graph [*see bottom illustration on page 57*]. From the graph it is evident that the latent heat has an order of magnitude corresponding to 100 molecular layers of nitrobenzene, a finding that undoubtedly must lead to a reconsideration of several orthodox views.

As it happens, the latent heat is of the same order of magnitude as the heat of transition for a number of liquid crystals into the normal liquid state. Thus one is justified in pursuing the analogy between the state of the boundary layers of nitrobenzene and the liquid-crystalline state. The basic difference between these two states of matter consists in the fact that the volumes in which molecules of the liquid-crystalline phases may exist in a definite state of orientation are indefinite and frequently extend to thicknesses of several millimeters, whereas the boundary layers of nitrobenzene films are definitely limited. In both cases, however, the special structure may be induced by a glass substratum and propagated from layer to layer over thicknesses of up to many monolayers.

The Anomalies of Water

Water is distinguished from all other liquids by the fact that its structure (that is, the mutual arrangement of the nearest molecular neighbors) is very strongly and specifically reflected in its properties. Certain of these structure-dependent properties differ so much from the properties of other liquids that it is justifiable to talk about the anomalies of water. Among them the best-known is the anomaly concerning the expansion of water, which (as was mentioned above) is characterized by a maximum density at 4 degrees C. It is natural to expect as a result of this fact that if a solid substratum is capable of changing the structure of contiguous layers of water, then their thermal expansion must also be changed simultaneously.

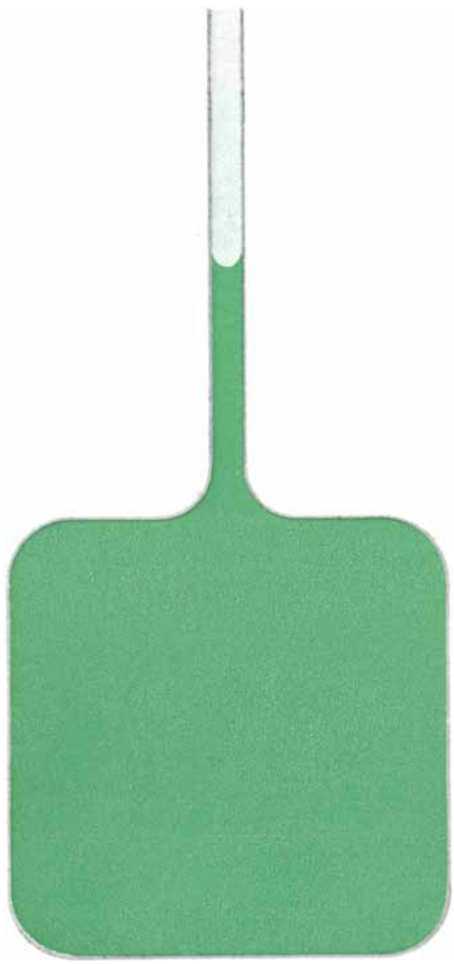
This expected dependence was first detected experimentally in 1961 by N. N. Fedyakin, then working at the Kostroma Polytechnical Institute, in the course of his observations of the expansion of columns of water in ultrafine capillaries [*see top illustration on opposite page*]. When the increase in the length of a column of water was plotted as a function of the temperature in glass capillaries of various radii, it became apparent that in capillaries with a radius greater than one micron the water expands in the expected way, displaying a maximum density at 4 degrees C. (In subsequent experiments by the American physicist Joseph A. Schufle, in which the accuracy of the measurements of the lengths of the columns was much higher, deviations from the normal expansion of water were noticed even for radii of up to several microns.)

For very narrow capillaries the expansion proceeds differently, and in ultranarrow capillaries it is changed to the point of unrecognizability. In the ultranarrow capillaries not only does the minimum of the volume disappear but also the coefficient of expansion is made constant over the entire temperature range studied; in short, the anomalous expansion of water completely vanishes!

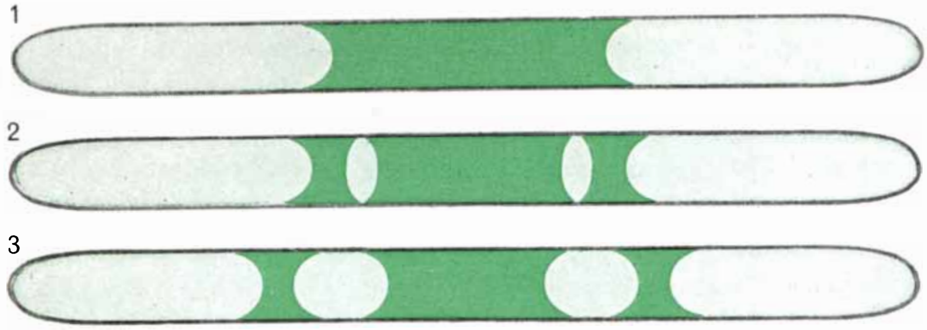
It is well known that the anomalous expansion of water under normal conditions results from its loose structure. This porousness in turn is determined by the influence of the hydrogen bond, in which the hydrogen atom serves as a bridge connecting two oxygen atoms belonging to two different water molecules, with an energy that is intermediate between the energy of the usual chemical bond (such as the bond, say, between the oxygen and hydrogen atoms in an individual molecule of water) and the energy of molecular attraction between neighboring molecules. Each atom of oxygen appearing in the structure of any given water molecule is able to be joined by hydrogen bridges with four other molecules; two of these bridges involve the participation of the hydrogen atoms of the given water molecule, and the other two involve the participation of hydrogen atoms belonging to other water molecules [*see bottom illustration on opposite page*]. Thus oxygen exhibits, in addition to its normal double valency, which is expended on the formation of the molecule itself, an extra "quasi-valence" of two enabling it to be joined with two more water molecules by hydrogen bonds.

The most "pure" and complete form of such a system of hydrogen bridges is formed in a crystal of ordinary ice, or ice I. In ice I each molecule is joined by a hydrogen bond to its four nearest neighbors. The crystal as a whole is a skeleton-like structure formed by a network of hydrogen bonds. It is precisely such a structure, in which each molecule has only four nearest neighbors, that determines the porousness of ice, thereby accounting for a number of its properties, in particular its ability to float in water. One can say, taking the quasi-chemical nature of the hydrogen bond into account, that a crystal of ice essentially represents a single polymer molecule in which the oxygen acts as if its valence were four. In this respect an ice crystal resembles a crystal of diamond, which is composed of a network of chemical bonds between carbon atoms with a valence of four.

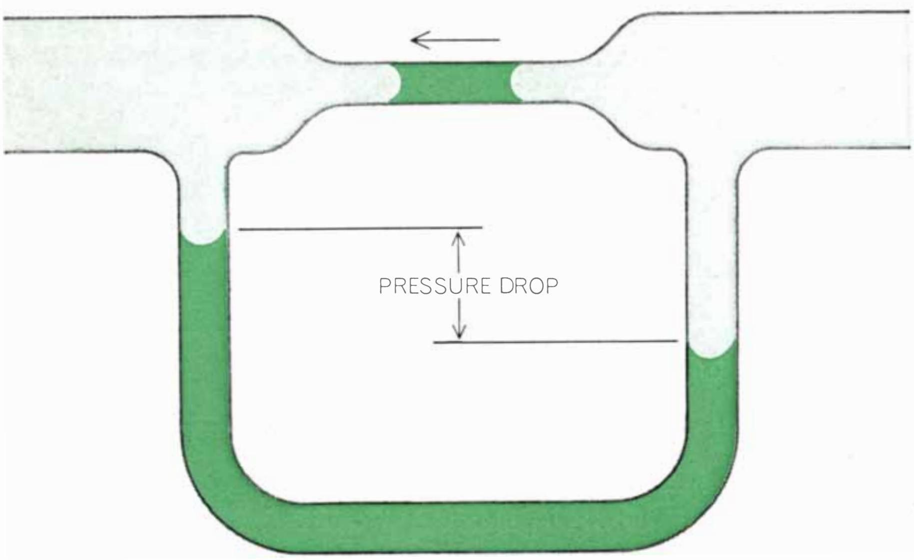
When ice melts, the perfect regularity



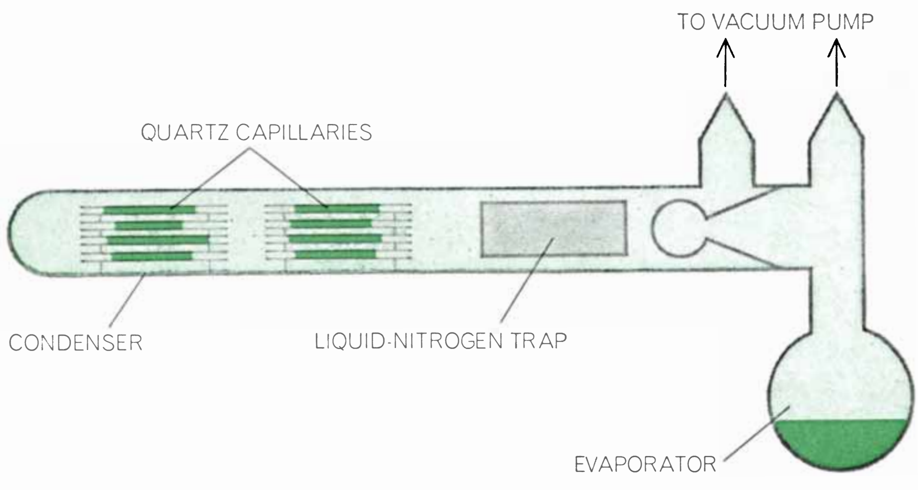
LATER EXPERIMENT by the author's group showed that the expansion of water in the pores between particles of quartz (SiO_2) powder changes in the same way that it does in ultranarrow capillaries. After removing the water from the powder its normal expansion was reestablished. This tended to discount the possibility that the special properties of water observed in ultranarrow capillaries were influenced by impurities leached out from the walls of the capillaries.



"DAUGHTER" COLUMNS were observed by Fedyakin to form in comparatively wide, sealed capillaries at a certain distance from the meniscuses of the initial water column and to grow at the expense of the latter. He was later able to show that the pressure of the saturated vapors of the daughter columns was below the normal pressure existing for the "mother" column, an observation that led to the assumption that this effect results from some kind of structural difference between the primary and the secondary columns.



EFFECT WAS FURTHER INVESTIGATED by Fedyakin and the author using the setup shown here, in which the viscosity of the water columns was measured by setting them in motion with a given drop of the pressure. Since the velocity of a column's movement is inversely proportional to its length and viscosity, one can calculate the viscosity by knowing these two quantities. It was found that the secondary columns observed earlier by Fedyakin had a viscosity that was several times larger than that of the primary columns.



IMPROVED METHOD for obtaining columns of anomalous water in wider quartz capillaries in the absence of air or any other contaminating gas was later developed in the author's laboratory. It was designed primarily to reduce the possible influence of the leaching-out process. The apparatus consists entirely of blown glass without any joints or stopcocks. The liquid-nitrogen trap serves to prevent the entrance of oil vapors from the pump.

of the distribution of the water molecules and of the network of hydrogen bonds is destroyed, but not completely. With a subsequent increase of the temperature from zero degrees C., the thermal motion of the molecules destroys an ever increasing number of the hydrogen bridges, a process favoring the occupation of the empty spaces in the structure of the liquid. Therefore water contracts in spite of the fact that the thermal motion simultaneously tends to increase the average distance between the molecules. Only above 4 degrees C. does the latter tendency take the upper hand, whereupon water begins to expand.

Returning to the experiments of Fedyakin, it is clear that we can now explain them by the fact that in very narrow capillaries, owing to the influence of the walls, the formation of the skeleton of hydrogen bridges between the water molecules is impeded, removing the restriction on the number of nearest neighbors and making it possible for the molecules to be arranged more densely. As a consequence, further contraction does not take place with an increase of the temperature, as is the case for the ordinary state of water near zero degrees C., and water in narrow capillaries expands as a normal liquid.

The foregoing account raises an important question: To what extent are the properties of water columns with special properties free from the influence of the products of dissolution, or leaching out, of the walls of the capillaries? This possibility was discounted by the experiments of Karasev, E. N. Khromova and the author, which showed that the expansion of water existing in pores between particles of quartz (SiO_2) powder changes in the same way [*see illustration on preceding page*]. Moreover, after removing the water from the powders its normal expansion was reestablished, which would be impossible if everything were determined by a solution of SiO_2 in water. Simultaneously this result demonstrated that in pores near a surface of SiO_2 water experiences an unstable, reversible change of its properties that vanishes after it is removed from the surface.

More Odd Behavior

The curves shown in the top illustration on page 58 could be obtained by Fedyakin only thanks to a remarkable technique developed by him for pulling out and calibrating the very finest capillaries, some with radii as small as 160 angstroms. Curiously, an important observation was made by him in comparatively wide capillaries, with radii around one micron. By sealing columns of water and certain other liquids such as methyl alcohol, acetic acid and acetone in such capillaries Fedyakin kept the columns under prolonged observation. In this situation as a rule the creation of new "daughter" columns was observed [*see top illustration on opposite page*]. They appeared at a certain distance from the meniscuses of the initial column and grew at the expense of a contraction of the latter.

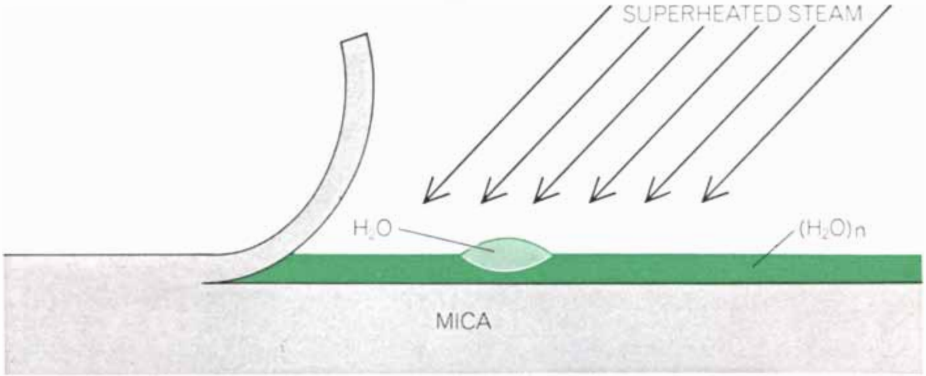
The systematic nature of this phenomenon required a rational explanation. First of all Fedyakin concluded that the systematic growth of the daughter columns at the expense of the "mother" column indicated that the pressure of the saturated vapors of the daughter columns was below the normal pressure existing for the mother column. In order to confirm this conclusion experiments were set up in which empty capillaries were placed in an atmosphere of somewhat incompletely saturated vapor. The resulting columns grew gradually over a period of many days.

The difference in the pressure of the saturated vapors associated with an identical chemical composition led to what appeared to be the only possible conclusion, that a difference of the structure in the secondary and primary normal columns must serve as the origin of this effect. The assumption, which later turned out to be only half true, was first confirmed by Fedyakin by showing that on being heated by about 20 to 50 degrees the secondary columns of water expanded one and a half times faster than the primary columns, in spite of the fact that the experiments were carried out in capillaries with a radius of approximately one micron.

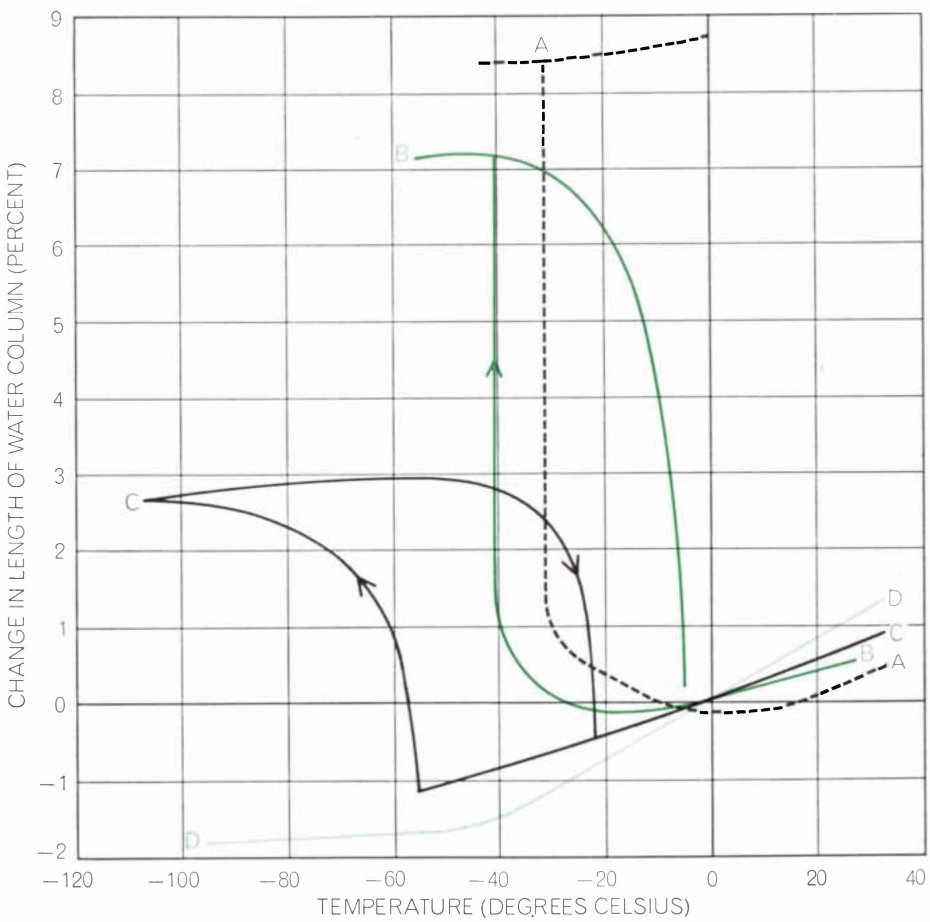
It was at about this time that Fedyakin and I joined forces to undertake further systematic investigation of this phenomenon at the Department of Surface Phenomena of the Institute of Physical Chemistry in Moscow. We were soon able to report an important finding: The secondary columns observed earlier by Fedyakin had a viscosity that was several times larger than that of the primary columns. In order to measure the viscosity the columns were set in motion by a given decrease in pressure [*see middle illustration on opposite page*]. The velocity of a column's movement is inversely proportional to its length and viscosity. Therefore by knowing the length of the liquid column and its velocity of motion one can readily calculate the viscosity.

At the same time it was noted that the increase of the viscosity might partially vanish after the columns were disturbed. Unfortunately too much weight was assigned to this last result, and it gave rise to an unjustified conclusion that simple motion can eliminate from a secondary column any differences between it and the normal liquid. In actual fact the reduction of the viscosity only indicates a destruction of the secondary structure in these columns, whereas this structure is reestablished at rest.

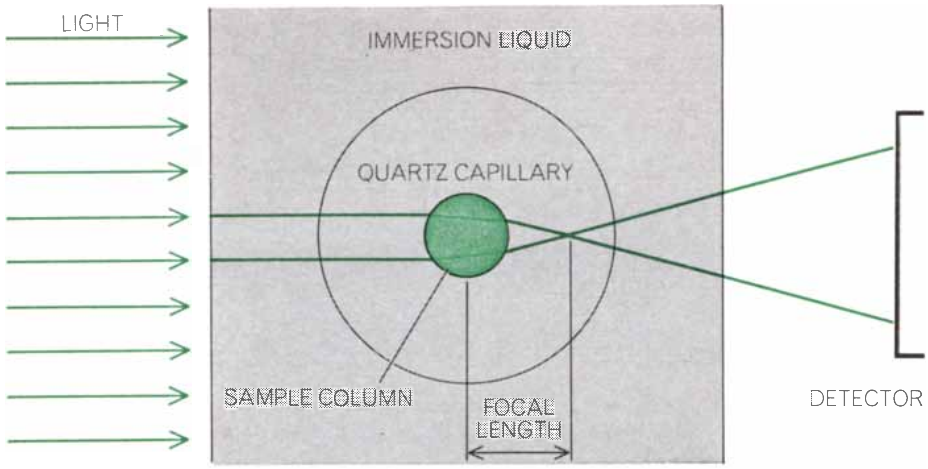
Our first observations, which were published in 1962, gave rise to an attempt to reduce them to a rather trivial cause: the leaching out of impurities



EARLY EVIDENCE of the anomalous behavior of the condensed vapors of water on a solid substratum was obtained by D. H. Bangham and his collaborators in 1937. He observed that when a freshly cleaved piece of mica was exposed to a jet of supersaturated steam, thin liquid layers with abnormal properties formed on the surface of the mica. Drops of ordinary water, for example, did not spread over a film of the condensate.



AT NEGATIVE TEMPERATURES the change in the lengths of water columns was found to vary widely from sample to sample, depending on the concentration of the anomalous component. Curve *A* shows the behavior of ordinary water, which has a minimum volume at 4 degrees C. Curves *B* and *C* correspond to columns in which the anomalous component has been raised to a different extent by maintaining an increasingly drier atmosphere. Curve *D* was obtained after exposure of the initial column to a vacuum, which led to the evaporation of the normal water. The study was done by B. V. Zheleznyi of the author's laboratory.



INDEX OF REFRACTION of water II (as it is called to distinguish it from ordinary water, or water I) was determined by immersing a fused-quartz capillary containing a sample of the substance in a liquid whose index of refraction is identical with that of quartz. From the position of the focus at which parallel light rays are collected after refraction at the boundary of the column with the walls of the capillary it was possible to determine that the index of refraction of water II is equal to about 1.48 to 1.49; the value for pure water is 1.33.

from the wall by the film that forms from the condensation of the vapors of water and of other liquids. In order to disprove this conjecture, Fedyakin and I, in collaboration with our colleague M. V. Talaev, set up experiments to obtain anomalous columns in wider quartz capillaries in the absence of air or any contaminating gas [*see bottom illustration on page 60*]. This reduced the influence of the leaching-out process to almost zero for several reasons. In the first place, fused quartz glass is the most stable of walls, dissolving in water very slowly in amounts not larger than .02 percent. In the second place, although the saturation of columns by leaching products cannot be achieved in wider capillaries (those with a diameter of up to 100 microns) during a time of the order of an hour, an experiment in vacuum made it possible to shorten the time for the appearance of columns of appreciable length to such a period. Having verified that the phenomena cannot be attributed to a trivial cause, we now found that the observations in wide quartz capillaries, however, presented a number of new questions.

The original similarity of the thermal expansion of anomalous columns and columns in ultrathin capillaries gave us reason to conjecture that in the anomalous columns the liquid, under the influence of the surface of the wall, exists in a boundary-phase state that exceeds its equilibrium thickness—in short, the same phenomenon that was observed by us in the case of superheated films of nitrobenzene. Here it is appropriate to recall some remarkable observations published as long ago as 1937 by D. H. Bangham and his collaborators concerning the formation of thin liquid layers with abnormal properties on a surface of freshly cleaved mica exposed to a jet of supersaturated vapors. The abnormality was evident because drops of the same liquid did not spread over a film of the condensate [*see top illustration on preceding page*]. In Bangham's experiments, however, there were no indications of a decreased pressure of the vapors of the layers; rather the contrary was true. Against the analogy with boundary layers nitrobenzene films are able to superheat and consequently to maintain their increase in comparison with the equilibrium thickness only for a short time, and then not by much. Meanwhile the anomalous columns might preserve their different properties for an indefinitely long period even in capillaries with radii of the order of several tens of microns.

Thus the puzzle obviously required a different answer. This answer finally became clear after the behavior of the change in the length of the anomalous columns of water was studied at negative temperatures and in connection with a change in the vapor pressure of the water around them. In these and subsequent investigations of the anomalous columns of water, carried out under the joint direction of N. V. Churaev and myself, it was learned that under constant pressure of the vapors around capillaries containing the anomalous columns their length, after changing for a while, finally settled at a certain equilibrium value. If the vapor pressure was changed after this, then a new length of the column was established during a time interval that was longer the longer the length of the column; the new length was smaller or larger depending on whether the pressure of the water vapor was decreased or increased. Such behavior clearly indicated that the anomalous columns contain some slightly volatile substance that is soluble in water. When the anomalous column contracts, the concentration of this substance increases, and accordingly the vapor pressure of the solution falls, eventually establishing equilibrium with the surrounding atmosphere.

This explanation was soon confirmed by the measurements of B. V. Zheleznyi of our laboratory, who plotted the change in the length of the water columns at negative temperatures [*see bottom illustration on preceding page*]. The curve showing the behavior of normal water has a minimum volume at 4 degrees C. Below zero degrees C. normal water does not freeze immediately, remaining in a supercooled state and continuing to expand as the temperature is lowered. At a certain temperature it changes to ice; on heating the column melts and abruptly contracts precisely at zero degrees C.

Columns of water obtained by the condensation of water vapor behave quite differently. For them the minimum of the length shifts to the left. The abrupt change of length on freezing is smaller and a gradual decrease of the length is observed on heating in a certain temperature range. The loop of changes is closed at a certain negative temperature. The pronounced difference in the behavior of the anomalous columns appears in the fact that the jump in the expansion is accompanied by the appearance of turbidity in the column. After further heating it becomes clear that the contents consist of droplike inclusions with a smaller index of refraction than that of the remaining liquid. With an increase of the temperature the number and dimensions of the inclusions decrease—as if they were melting away. Indeed, they were found to be particles of pure ice. Because it is in an environment of anomalous water, however, the last icicle melts at a certain temperature below zero.

Various other curves in the bottom illustration on the preceding page correspond to columns in which the concentration of the anomalous component is raised to a different extent by maintaining the capillaries in an increasingly drier atmosphere. The higher the concentration of the "carriers of anomalousness" is, the more the loop on the expansion diagram differs from the loop for pure water.

Finally, one curve was obtained after

prolonged exposure of the initial column to a vacuum. This led to evaporation of the normal water. As a result neither turbidity nor a jumplike change of the expansion sets in at any temperature; in other words, ice cannot be frozen out because of the absence of normal.

The Water-II Hypothesis

The curve of monotonic contraction associated with cooling shows a sharp bend at a temperature around −45 to −50 degrees C., becoming almost horizontal. Such behavior is characteristic of all liquids that do not crystallize on cooling and, as a consequence of an enormous increase in the viscosity, change into a glasslike state (examples are borax, glycerin and tar). The totality of factors that have been discussed cannot be explained just by singularities in the structure of the anomalous columns. The initial reason for their remarkable behavior must be sought in the formation of molecular complexes with the structure $(H_2O)_n$, resulting from the condensation of water vapor on glass or fused-quartz surfaces. After evaporation of the ordinary molecules of H_2O only these complexes remain, forming what we shall for the sake of brevity call water II. Thus the columns that result from the condensation of vapors in capillaries consist of solutions of water II in water I.

It is a natural desire to determine the basic properties of water II. The index of refraction, the easiest of all to determine, is measured by the following approach. A capillary is placed in an immersion liquid whose index of refraction is identical with that of fused quartz [*see illustration on opposite page*]. From the position of the focus at which parallel beams are collected after refraction at the boundary of the column with the walls of the capillary, one can determine that the index of refraction for water II is equal to about 1.48 to 1.49. When water II is diluted with water I, this value drops to the value for pure water, 1.33.

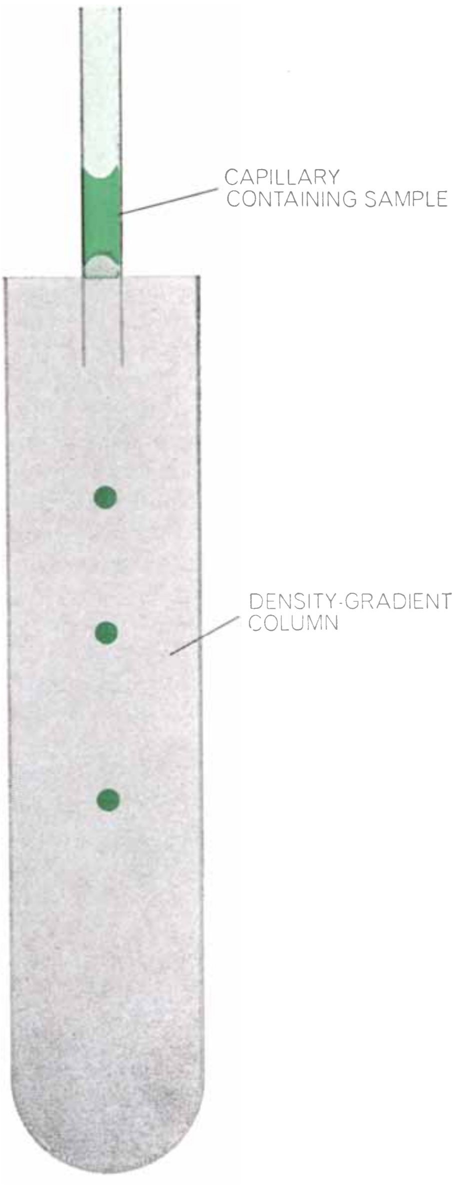
It turned out to be somewhat more complicated to measure the density of water II. In view of the fact that in the best case the column of water II had a mass of only one microgram, it was impossible to determine the density by dividing the weight by the volume. Therefore D. S. Lychnikov, K. M. Merzhanov and Ya. I Rabinovich of our laboratory applied a method based on one of the oldest laws of physics: Archimedes' principle. For this purpose the water columns were pushed out of the capillary and placed in a vertical density-gradient tube containing an inhomogeneous mixture of carbon tetrachloride and vaseline oil [*see illustration at right*]. Measuring from the bottom up, the concentration of vaseline oil increased from 0 to 100 percent, as a consequence of which the density of the mixture varied over a wide range. A falling drop of a solution of water II in water I comes to rest in a short time at the level where the density of the mixture is equal to the density of the drop. Knowing the density of the mixture in the tube at various heights, it was possible to determine the density of the drop. The density measured in this way turned out to be different depending on the concentration of water II, varying from 1 to 1.2. (Drops with higher concentrations of water II and correspondingly with higher densities possess such high viscosities that it was not possible to force them out of the capillary.)

After the apparent halt of the drop its fall did not stop completely but only slowed down abruptly. This second stage of the sinking is explained by the fact that molecules of water I are slowly extracted from the drop, passing into the surrounding mixture in which water is slightly soluble. The resulting increase in the concentration of water II in the drop increases its density, which therefore causes a further sinking. All the drops sank to a level where the density was equal to 1.4, which is equal to the density of pure water II.

The close relation between the measurements of the density and the index of refraction of water II proves that the increase in the refractivity of water II in comparison with that of water I can be completely attributed to an increase in the number of water molecules per unit volume, without making any assumptions about a substantial change in the refractivity of the molecules themselves. This implies that the forces that govern the formation of the polymer complexes $(H_2O)_n$ of the molecules and that act between the molecules and the atoms of these complexes are not so strong as to deform their electron shells enough to substantially change their refractivity. Similarly, when water vapor passes into the liquid or crystalline state, the molecular refraction changes very little, in spite of the forces of hydrogen bonding.

The important question arises: Just how stable are the polymer molecules of water II, and what are the forces responsible for their stability? The experiments by Rabinovich and Talaev gave an answer to the first question; these experiments involved the distillation of columns of anomalous water from one end of a capillary to the other [*see top illustration on next page*]. If the initial column is heated to a temperature that does not exceed 50 to 80 degrees C., then as a consequence of the nonvolatile nature of water II at this temperature its concentration in the column will increase and the condensate will be pure water. By this method one can separate water II from water I, having determined its gravimetric concentration.

With an increase of the temperature above 150 degrees C., water II also begins to be distilled. At a temperature of 300 degrees C. the distillation is com-



DENSITY of water II was determined by pushing drops of the sample out of the capillary into a density-gradient column containing an inhomogeneous mixture of carbon tetrachloride and vaseline oil. The falling drop comes to rest in a short time at the level where the density of the mixture is equal to the density of the drop. The density measured in this way varies depending on the concentration of water II in the drop. All the drops eventually sink to a level where the density is 1.4, which is taken to be the density of pure water II.

pleted rather quickly. The condensate possesses approximately the same properties as it does in the initial column. Thus one can conclude that the molecules of water II are not destroyed by evaporation and distillation; otherwise the properties of the condensate would be closer to the properties of normal water than to the properties of the initial column.

Distillation through a thermal barrier (a zone in which the capillary is heated from the outside by a spiral of wire) is even more convincing in this respect. When the temperature of the barrier exceeded 700 to 800 degrees C., the condensate lost all differences from normal water. From this finding it follows that at this temperature the polymer complexes are broken up. Moreover, under the conditions of the experiment described, even if the condensation of water vapors not containing any molecules of water II leads to a new formation of water II, it does so in amounts that are much smaller than they are in the initial column. Thus the preservation of the properties of the initial column during its distillation through a barrier with a lower temperature is unambiguous; without any doubt it proves the existence of the passage into vapor and the presence in the vapor of all the molecules of water II of the initial column. The possibility of their creeping along the capillary walls is also disproved both by experiments with a moderate thermal barrier, through which the surface films of course cannot creep, and by experiments involving distillation from one capillary to another [*see bottom illustration below*].

We therefore carefully considered the question of the distillation of columns for two reasons. First, this process makes it possible to combine columns originally obtained in many smaller capillaries in one larger capillary. In the second place, in spite of the clearness and overall validity of the conclusion about the presence of polymer molecules in the vapor of water II, it has been stated that the molecular weight of this vapor is 18, the molecular weight of ordinary water. This statement is based on the fact that the mass spectrometric method has not yet been able to observe particles with higher molecular weights. Since such particles in actual fact do exist, the reason for the apparent contradiction should be sought in the special properties of the mass spectrometric method; in particular one can assume that under the impact of the electrons on the molecules of water II, which is necessary in order to charge the latter in the mass spectrometer, these molecules are immediately broken down into ordinary molecules of H_2O.

Skepticism Concerning Water II

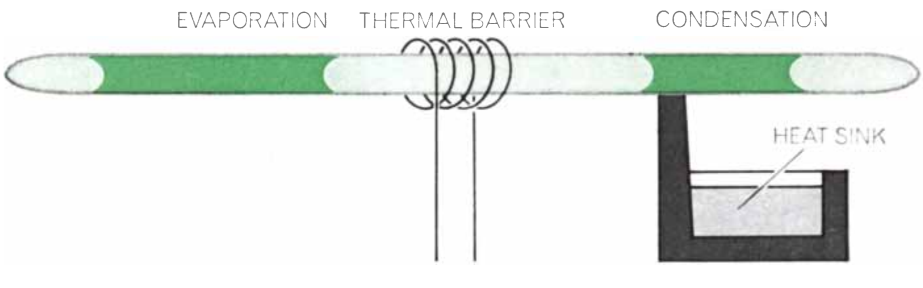
The first publications of the work on the production and analysis of the properties of water II and its solutions in water I were met by many with numerous reservations and even with a large amount of skepticism: the results of the investigations were too unusual and the conclusions based on the results were too contradictory to current views. It would have been easier to become reconciled to the conclusions if the situation had not involved water. Surely, it must have seemed to some, water has been so well investigated that one should not expect such surprises from it.

At the same time all the objections raised could be reduced to attempts to explain the properties of water II as being a result of the presence of foreign impurities in it. The shortcoming of all these attempts is that by explaining only part of the facts they ignore those facts that contradict the hypothesis of contaminants. The only acceptable explanation is one that does not contradict a single one of the total set of facts. Many critics, without even attempting to explain the properties of anomalous water, were satisfied by only the single statement that in this or the other sample of it impurities were observed.

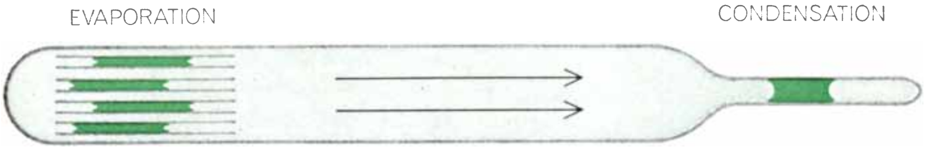
Let us consider the reasons, based on a thorough analysis of the facts, that make it impossible to explain the properties of water II and of other modified liquids by the existence of impurities. First of all, this assumption contradicts the observed fact that the change in the properties of the liquid takes place only under the specific conditions of condensation of its vapors on a fused-quartz surface at low temperatures and can never be achieved by the introduction into the same capillaries of water in liquid form even under conditions of prolonged contact at temperatures of up to 400 degrees C. Even after long contact with the highly extended surface of powders of silica gel at an elevated temperature, water did not change substantially and its properties were stable. In other words, in these cases one can observe only those temporary, reversible changes of the properties in layers near the surface of the particles of silica gel that were discussed at the beginning of this article.

The second proof consists in the fact that heating the vapors of water II up to temperatures of the order of 800 to 900 degrees C. leads to the result that after their condensation a liquid is obtained that has all the properties of ordinary water.

In addition there exist a number of proofs of an analytic nature. Thus we have been able to show in our laboratory that when water II is prepared in completely sealed, blown-glass apparatus without any joints or stopcocks and with protection (by means of two traps containing liquid nitrogen) against the entrance of oil vapors from the pump, all



DISTILLATION of a column of water II through a thermal barrier from one end of a capillary to the other was used to test the stability of the polymer molecules of water II. Below 700 to 800 degrees C. the condensate has approximately the same properties as the initial column. At higher temperatures the condensate loses all differences from normal water. Hence it was concluded that the polymer complexes break up in this temperature range.



FURTHER PROOF that the molecules of water II are conveyed unchanged by the distillation process from the evaporated column to the condensed column was provided by this experiment, carried out in the author's laboratory. By distilling the columns from one capillary to another the possibility that the films creep along the capillary walls was disproved.

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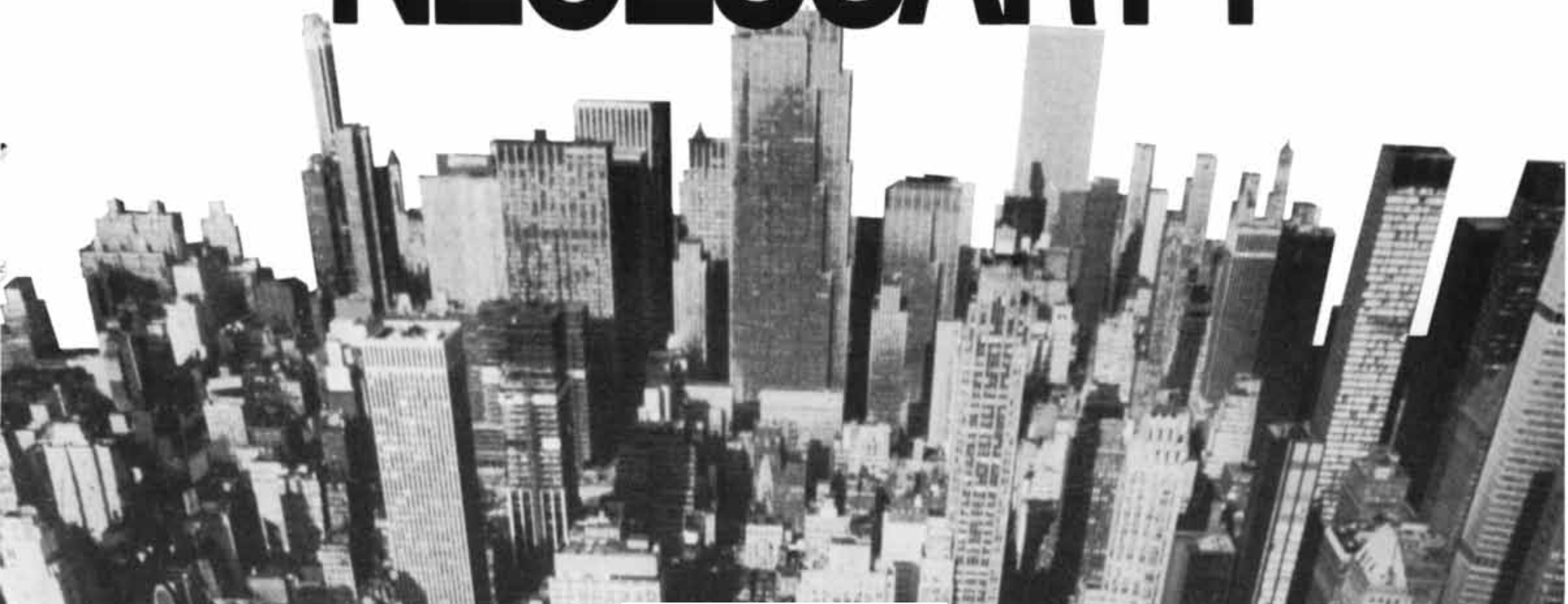

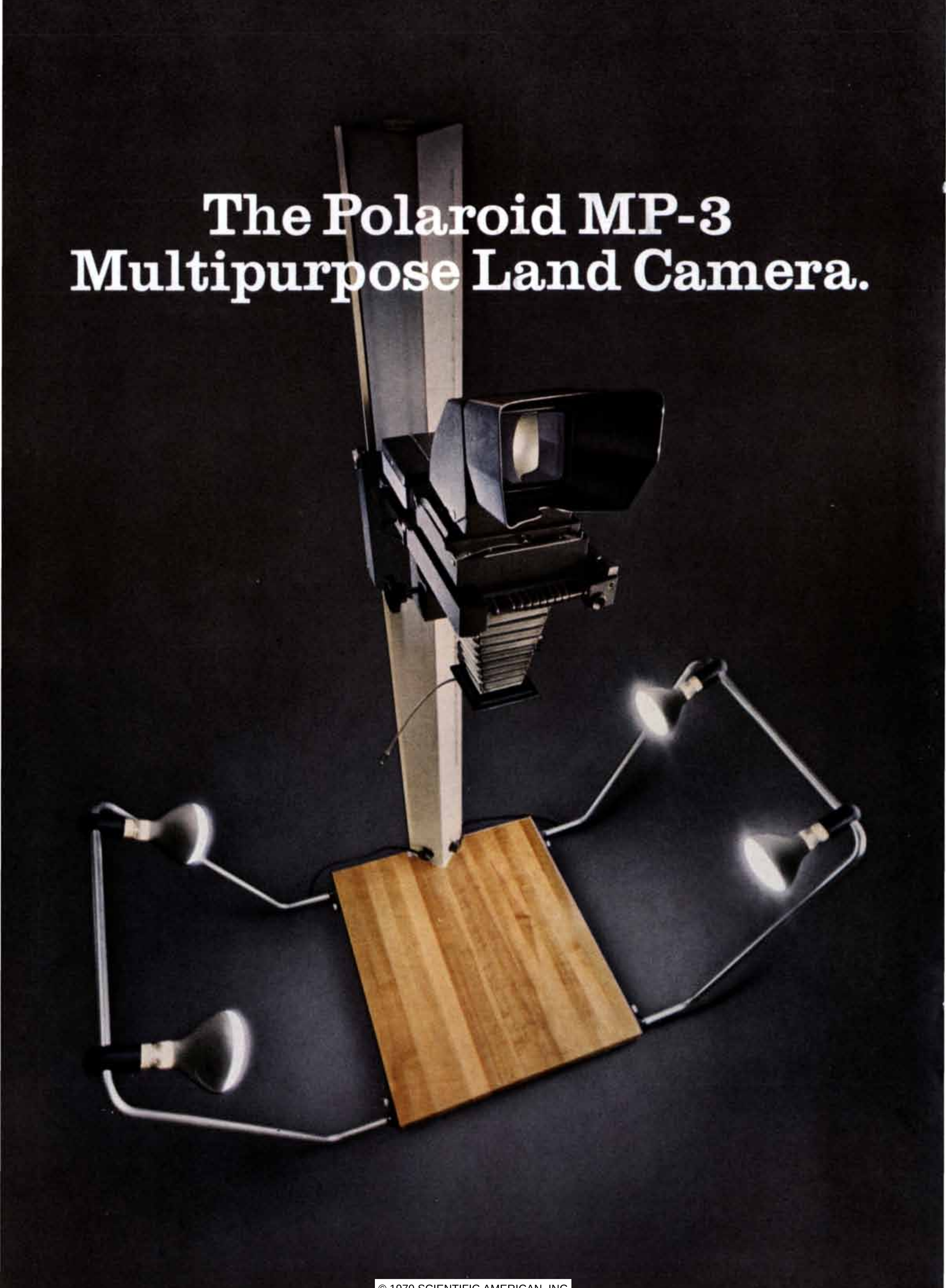
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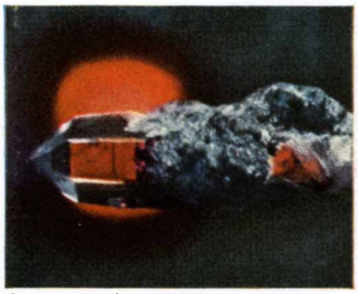
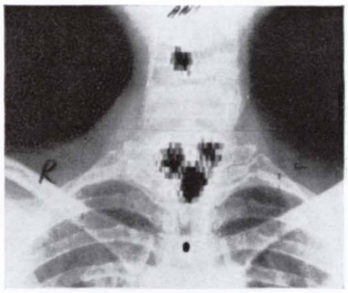
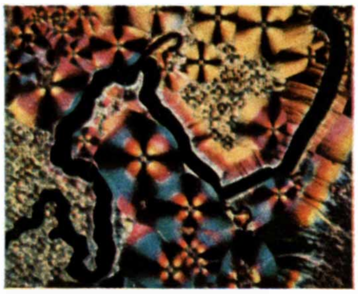
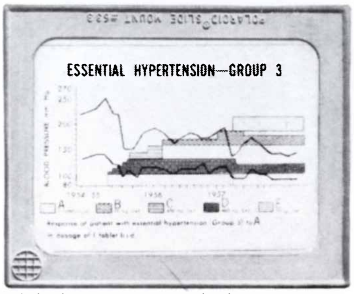

Quartz crystal on pyrite. Polacolor Type 58 film.


Copy of X-ray with isotope scan overlay. Type 107, 3000-speed film.

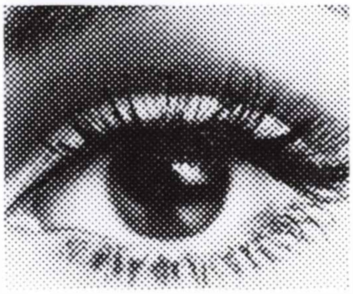

Macrophotograph, bacteria culture. Polacolor Type 108 film.


Macrophotographic section of wire nut. Polacolor Type 58 film.

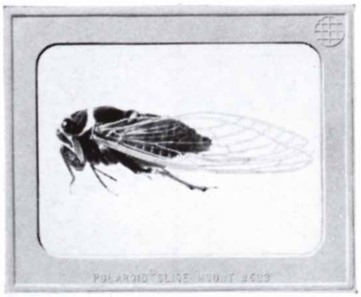

Photomicrograph, crystals under polarized light. Polacolor Type 58 film.

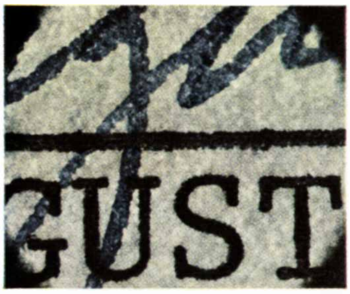


Slide for presentation, high contrast. Type 146L projection film.

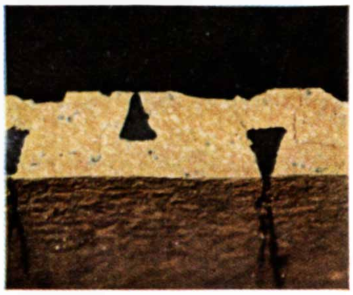

Instant screened print for printing reproduction. Type 51 high contrast film.


Coins, *circa* 100 A.D., catalog illustration. Polacolor Type 108 film.

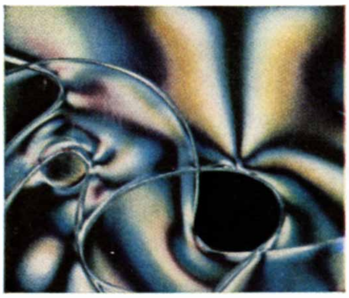

Biology study slide, continuous tone. Type 46L projection film.

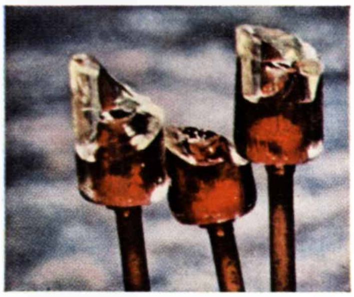

Handwriting study for legal investigation. Polacolor Type 58 film.


Perforated ulcer of the stomach. Polacolor Type 58 film.


Macrophotographic section of battery grid. Polacolor Type 58 film.

Copy of fingerprint record (negative). Type 55 Positive/Negative film.


Stress analysis under polarized light. Polacolor Type 58 film.


Diode fractures, for QC report. Polacolor Type 108 film.


Macrophotograph, insect mouth structure. Polacolor Type 58 film.

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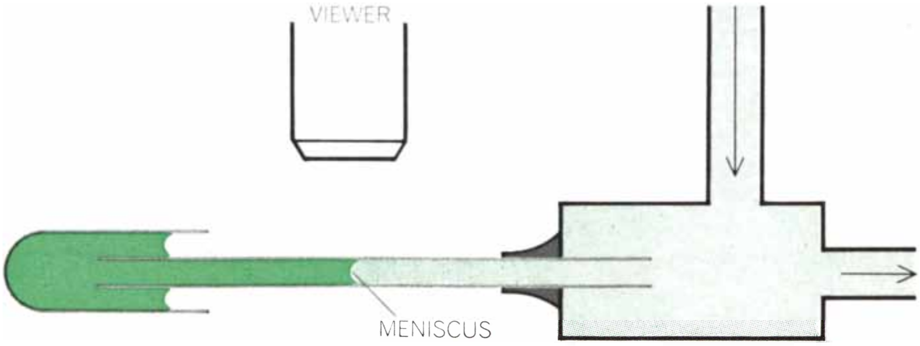
indications of the presence inside the quartz capillaries of carbon atoms in the columns of modified water vanish. In this experiment, conducted by members of our group in collaboration with V. L. Talrose of the Institute of Chemical Physics of the U.S.S.R. Academy, an oxidizing method of analysis was used on the carbon; it involved estimating the mass of the carbon dioxide that was produced. Taking the sensitivity of the method into consideration, one can state that the amount of organic compounds one can consider probable in the columns of water is much smaller than the amount necessary to explain the marked differences from normal water.

The conclusion that follows from our determinations of the surface tension of these columns based on measurements of the capillary pressure of the meniscus (which is proportional to the surface tension) is even more categorical [*see top illustration at right*]. It was shown that in columns containing a concentration of water II on the order of 20 percent (per weight) the surface tension increased by 3 percent. Under the maximum possible concentrations that follow from an analysis of the carbon content, it is impossible to ascribe such an increase to any of the known organic substances. Thus large amounts of these compounds are not observed, and small amounts are not adequate to explain the increased value of the surface tension in columns of modified water.

The increase of the surface tension of water I with increasing concentration of water II in it, which we have observed, makes it possible to explain one effect that at first appeared to be very puzzling. According to observations made by Zakhavaeva in our laboratory, if a column of a solution of water II in water I exists close to one of the two open ends of a capillary placed in an atmosphere of unsaturated water vapor, then the column begins to move even closer to that end [*see bottom illustration at right*]. Gradually gaining velocity as a result of its inertia, the column sometimes springs out of the capillary. Apparently this strange phenomenon is explained by the fact that the evaporation of water I from the meniscus nearer the end of the capillary is more intense the closer it is to the end of the capillary; this increases the surface concentration of water II and consequently also increases the surface tension. As a result the surface tension of the nearer meniscus exceeds the surface tension of the farther meniscus, thereby setting the column in motion. In a similar manner one can explain the ability of films of anomalous water to creep along a wall in the direction of decreasing moisture content of the air.



SURFACE TENSION of columns of water I containing varying amounts of water II in solution was determined by measuring the capillary pressure of the meniscus. It was found that the surface tension of the columns increased with increasing concentration of water II.

SPONTANEOUS MOTION of a column consisting of a solution of water II in water I was observed to take place when the column is close to one of the two open ends of a capillary placed in an atmosphere of saturated water vapor. The column moves with increasing velocity toward the closer end, sometimes springing out of the capillary. The evaporation of water I from the meniscus nearer the end of the capillary apparently is more intensive the closer it is to the end of the capillary. This increases the surface concentration of water II, and consequently also increases the surface tension, thereby setting the column in motion.

As for inorganic compounds, some important data have been obtained by workers in the U.S. by the method of spectral-emission analysis and by an "electron probe" method in which water II is placed in an electron beam and the spectrum of X rays resulting from the electron bombardment is recorded. Using the latter method, Ellis R. Lippincott and his collaborators at the University of Maryland and the National Bureau of Standards did not observe the presence of foreign atoms in the amounts that are necessary to explain the pronounced differences of the properties of water II from those of normal water. In particular, the necessary amounts of silicon atoms that might be extracted from the walls of the capillaries were not observed.

Besides such negative evidence, positive indications of the presence of water II were found. The most important piece of evidence in this category is the constancy of the properties of water II produced in different laboratories in a number of countries. Everywhere a liquid is obtained with a density of 1.4, an index of refraction between 1.48 and 1.49 and a unique absorption spectrum in the infrared part of the spectrum.

Finally, we have been able to show that water II in solution in water I has a definite molecular weight that is approximately 10 times larger than the molecular weight of ordinary water. Two methods were applied in order to measure the molecular weight. One is based on measuring the reduction of the vapor pressure of water I on a solution containing a known amount of water II in water I; in this case the molecular weight is inversely proportional to the reduction of the vapor pressure. The second method is based on a reduction, in comparison with the normal melting temperature of ice, of the temperature at which the last crystals of ice I vanish on heating a column containing a solution of a given concentration of water II in water I that was frozen in advance and hence separated into two phases.

Both methods gave similar values for the molecular weight of water II: approximately 180. Repeated determinations of the molecular weight for columns of anomalous water, obtained under various conditions and in different apparatuses, gave materially concordant results.

All of this suggests that the proper target for skepticism must be the belief that the substance we call water II, which possesses such definite properties, is some kind of foreign substance, which for some reason nobody up to now has been able to name, and which is produced even under highly controlled conditions. This ubiquitous but imperceptible and unknowable contamination collects precisely and only on the condensation of water vapors. When it proceeds by the condensation of vapors of, say, methyl alcohol, then another contaminant supposedly collects with entirely different properties and with a completely different spectrum.

Obviously, when the total collection of accumulated facts is considered, it becomes clear that water II cannot consist of anything except water.

Gaining Wider Acceptance

The skeptical attitude taken at first toward the existence of water II by many workers, particularly in the U.S., began to change after the results of investigations of the infrared absorption spectrum of modified water appeared. These analyses were first performed by L. J. Bellamy and Lippincott and were continued by Lippincott and various colleagues, working with pure water II prepared by Robert R. Stromberg and his associates at the National Bureau of Standards. It was this group that coined the term "polywater" for the substance under investigation. According to Lippincott, the British crystallographer J. D. Bernal had a considerable influence on the setting up of these investigations.

At present many laboratories in the U.S., Britain and Belgium are busy with investigations of persistent changes in the properties of water and of other liquids accompanying a condensation of their vapors. The first work that partially confirmed our original findings was done by B. A. Pethica and his collaborators at the Unilever Research Laboratory in Britain. Having obtained what appeared to be columns of water containing a very low concentration of water II in water I, Pethica was unable to observe either the characteristic infrared absorption lines of water II or changes in the infrared spectrum of the "solvent."

In later work by Lippincott's group the basic results of our work were completely confirmed. In addition to the liquids investigated by Fedyakin, it was shown that persistent changes of various properties are also observed for formic acid. No less important was the confirmation of the existence of a symmetric, short hydrogen bond between two oxygen atoms, which was obtained by a number of theoreticians in the U.S. using the calculational methods of quantum chemistry. Their calculations confirmed Lippincott's suggestion that a structure with oxygen atoms at the corners of a planar hexagon has particular stability [*see illustration below*].

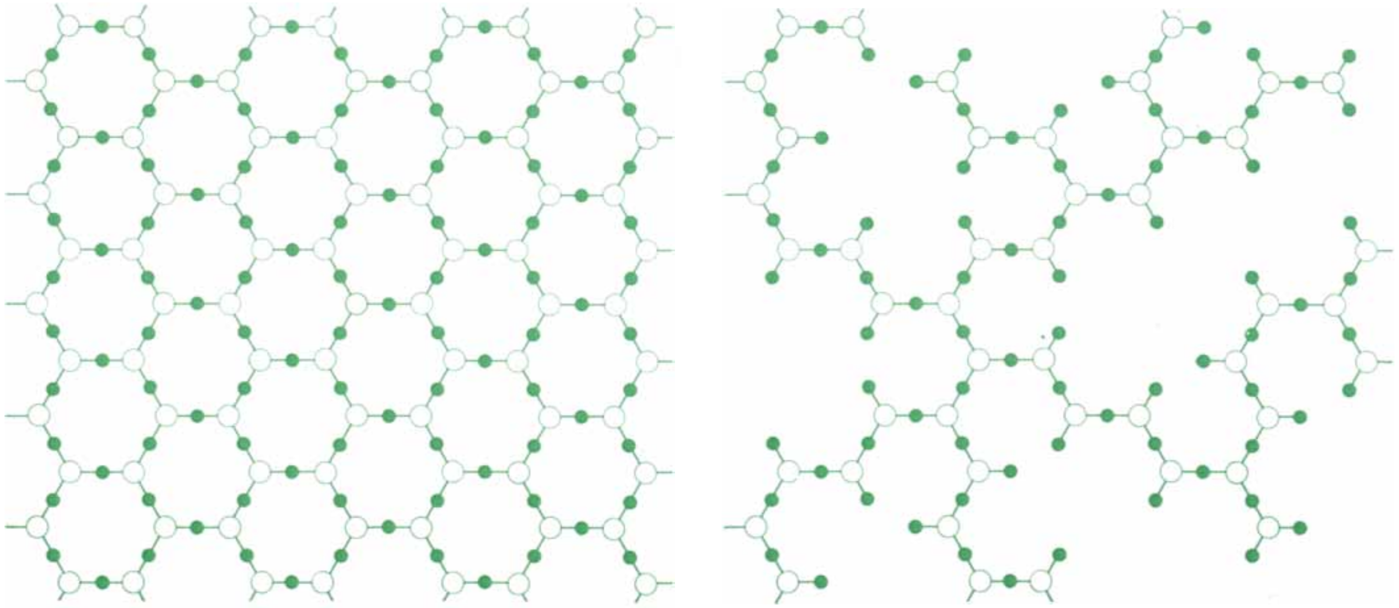
Nonetheless, a number of unexplained questions remain. Of these the major one is: What kind of mechanisms lead to the appearance of molecules of water II when vapors of water I condense on a surface of fused quartz or glass? It is obvious that here one must talk about a new type of condensation catalysis, since contact of liquid water with the same surfaces does not lead to persistent changes. At the same time, the specific role of the surface is evident from the fact that when water vapors condense on a surface of quartz or glass that is already covered by a film of ordinary water, water II does not appear. On the other hand, water II does appear on surfaces covered by adsorption films of water about one molecule thick. Apparently the catalytic action of the surface is transmitted through the adsorption layer.

The yield of molecules of water II during the time of formation of an anomalous column in capillaries with diameters of up to 100 microns (a time sometimes of the order of hours) corresponds to a layer of molecules of water II up to 100 or more angstroms thick. Therefore the surface of glass or fused quartz either has a very large radius of catalytic action or else the molecules of water II formed near it are able by thermal motion to yield their position to molecules of water I, which in turn have the possibility of being polymerized into molecules of water II. Here, however, we enter on a path of guesses and hypotheses, the choice among which will belong to experiment.

Some Remaining Questions

In conclusion I wish to answer a question that is often addressed to my colleagues and me: Why was water II not found earlier in the laboratory (since the technique for obtaining it is based mainly on the perseverance of the experimenter but not on complicated modern apparatus) or in nature (since during investigations of the isotopic composition of natural water, for example, the density is measured with great accuracy)?

One can answer the first half of the



TWO HYPOTHETICAL STRUCTURES for "polywater" were proposed in 1969 by Ellis R. Lippincott and his co-workers at the University of Maryland and the National Bureau of Standards. At left is a network of hexagonal units; at right is a highly branched polymer chain. Both arrangements are based on Lippincott's suggestion that a structure with oxygen atoms at the corner of a planar hexagon possesses particular stability. Many other possible structures have since been put forward by a number of investigators.

question by saying that water II might very well have been discovered much earlier if there had not been a tendency to ignore it because it did not fit into the generally accepted scheme of views, and if it were not for the strong, unverified prejudice that everything could be explained by impurities. Actually as long ago as 1928 the American investigator S. L. Shereshefsky observed that the condensation of vapors of water and of certain other liquids in glass capillaries takes place under vapor pressures that are smaller than should correspond to the behavior of a normal liquid. The Russian worker K. V. Chmutov arrived at a similar conclusion in 1946 by observing the formation between plane and convex surfaces of glass of a liquid ring associated with the condensation of vapors.

These experiments were not extended because it did not occur to anyone to explain them other than by a reduction of the vapor pressure due to contaminants. The discovery of water II makes it possible to explain the experiments associated with the condensation of water by the appearance of water II, which decreases the vapor pressure of water.

To the second part of the question one can answer that before natural water is examined by precision methods it is customarily purified by distilling it at 100 degrees C. Since the molecules of water II are not volatile at that temperature, they remained with the "impurities" and did not come under investigation. Thus the question of the existence of water II in nature remains open.

The Russian astrophysicist O. B. Vasil'ev has expressed the hypothesis that the noctilucent clouds consist of drops of water II, which in contrast to drops of water I may remain at a height of 90 kilometers without being evaporated and without crystallizing. Again the final proof must be supplied by direct experiment or observation. An even bolder hypothesis has been put forward by the American astrophysicist F. J. Donahoe, who has suggested the possibility that on Venus water exists mainly in the form of water II. The question of the role of water II in living organisms and plant tissues is of no less interest.

But here, following the example of Scheherazade, who invariably lapsed into silence at the most interesting place in her story, it is appropriate to end in the certainty that continued investigations of the properties of liquids will lead not only to universal acceptance of the reality of water II but also to the discovery of new and even more surprising phenomena.

Automatic Analysis of Blood Cells

Microscopic examination of white cells is laborious and expensive. An experimental computer-operated system has been developed that identifies and counts cell types and describes cells quantitatively

by Marylou Ingram and Kendall Preston, Jr.

Every day more than a million visual examinations of blood smears are performed in hospitals in the U.S. The routine microscopic blood inspection that is a universal feature of present medical practice is generally depended on as one of the most useful indicators of the state of a person's health. Its value lies in the fact that the body's production of the various types of blood cells is highly sensitive to general stress, injuries, diseases (infectious and noninfectious), poisons, ionizing radiations and other noxious stimuli. By increasing the rate of loss of or the demand for specific white blood cells, these stimuli cause the blood-cell-forming tissues to alter their production rate accordingly. The relative number of a particular type of white cell therefore becomes significant. In addition, as may happen in any production line, the change in the rate of output of the cells increases the probability that some of the products will be abnormal. The form of the blood cells tends to reflect, often very sensitively, the conditions under which they were produced. Consequently information about the cells' morphology may be as important as the numerical counts of the various cell types.

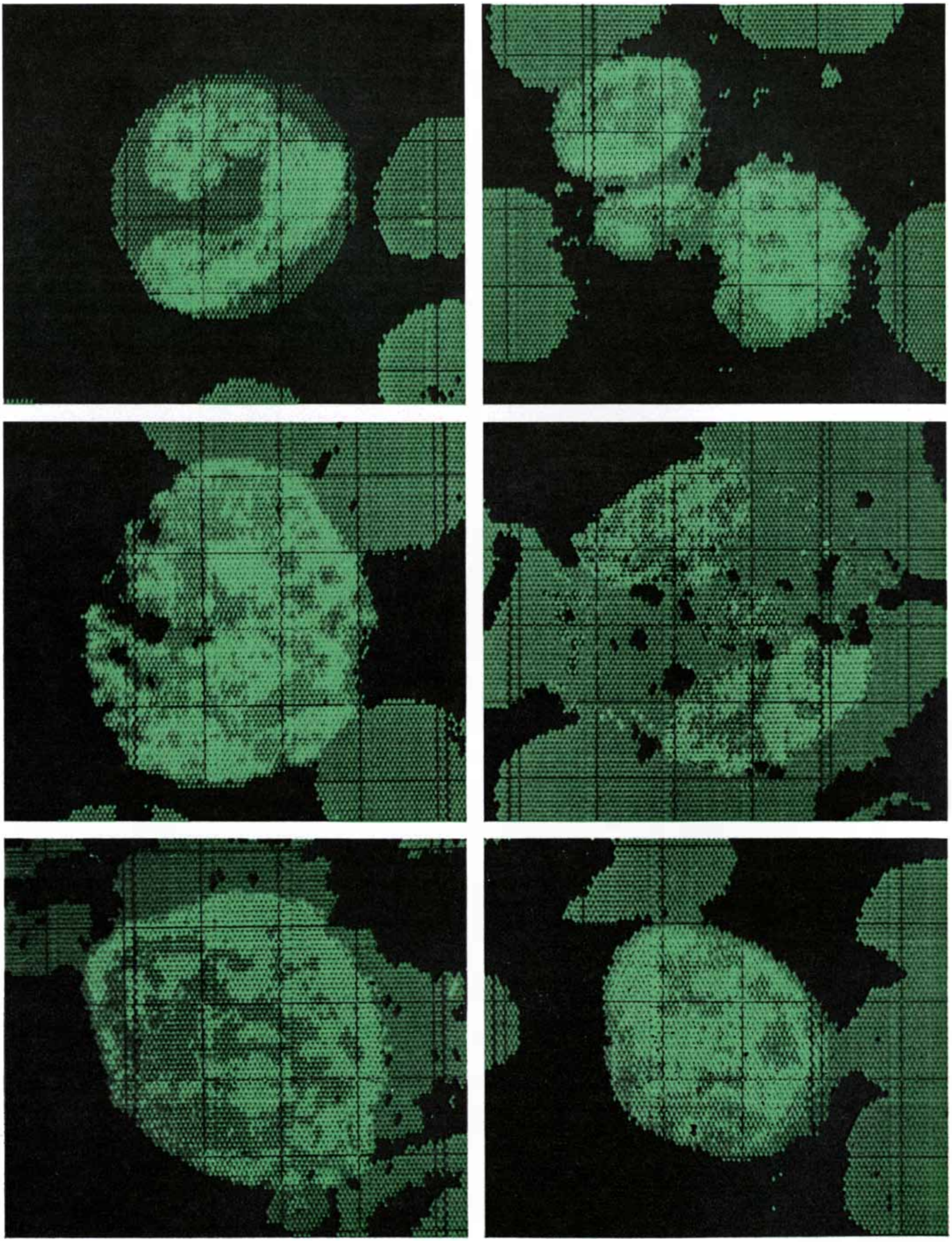
The visual examination of blood cells in present practice is carried out by toilsome human labor. Professional personnel or technicians prepare each specimen as a thin film of blood, then stain it and examine it through a microscope. The method is expensive (the daily cost in the nation's hospitals totals several million dollars and hundreds of thousands of man-hours) and often unreliable. In a recent study conducted by the Center for Disease Control it was found that, even in routine classification of blood cells in normal specimens, the performance was unsatisfactory in 40 percent of the laboratories tested. The results were even poorer when the blood samples represented certain commonly encountered abnormal conditions. As the work load of busy laboratories increases and more of the examinations are relegated to relatively unskilled technical personnel, the rate of error can be expected to rise.

Furthermore, the requirements of skill and sophistication in the examination are continually increasing with the growth of knowledge about the significance of specific characteristics of blood cells. For example, a variety of small appendages had long been observed on the nucleus of the most common type of leukocyte (the cell known from its staining properties as the neutrophilic granulocyte, or neutrophil). The significance of one of these appendages went undiscovered until 1954, when W. M. Davidson and D. R. Smith found that it represents one of the two X chromosomes that distinguish the cells of the female sex. As time goes on other specific structural features of blood cells may be identified not only with the genetics of cells but also with their biochemical and physiological processes.

The growing difficulty and massive expense of blood-cell analysis suggest that it would be highly desirable to mechanize this function. An effective system of automatic analysis could standardize the procedure, improve its reliability, reduce the cost and provide a system flexible enough to allow for the addition of new measurements as new understanding of the blood cells develops. Obviously this is a tall order. It will not be easy to create a machine that can compete in sensitivity and rapidity with the admirable system of pattern recognition represented by the human eye and brain. After several years of study and experiment, however, we have developed a computer-operated system for recording and analyzing blood-cell images that now approaches the capabilities of a human examiner.

The first requirement of such a system of course is to identify the different blood cells produced by the cell-forming tissues: bone marrow, spleen and lymph nodes. The familiar erythrocytes (red cells), which synthesize hemoglobin and transport oxygen and carbon dioxide, are marked by, among other things, the absence of a nucleus. The leukocytes (white cells) fall into several distinct classes. There are the granulocytes, which destroy or inactivate infective cells or other foreign materials by phagocytosis and for this purpose carry in their cytoplasm myriads of granules containing enzymes and other biologically active molecules. The granulocytes are identifiable in three subclasses according to their staining characteristics: eosinophilic (readily stainable by the red acidic dye eosin), basophilic (stainable by the basic dye methylene blue) and neutrophilic (stainable by both types of dye). A second class of phagocytic white cells is the monocytes, which have an irregularly oval or horseshoe-shaped nucleus and cytoplasmic granules different in size and content from those in granulocytes. Another class of white cells is the lymphocytes, cells with relatively little cytoplasm and a round nucleus, which produce antibodies and other agents involved in the body's immune responses. Finally, rounding out the list of identifiable cell components of the blood, there are the platelets, fragments of cytoplasm released by very large bone-marrow cells, which act as agents for blood clotting.

An automatic system for analyzing blood cells not only must recognize and



WHITE BLOOD CELLS are displayed as "composite cartoons" that were formed by computer processing of the microscopic images of cells. The cartoons show a dense (bright and structured) nucleus surrounded by cytoplasm and parts of red blood cells. The white cells are an unsegmented neutrophil, or "stab" (*top left*), a segmented neutrophil (*top right*), a basophil (*middle left*), an eosinophil (*middle right*), a monocyte (*bottom left*) and a lymphocyte (*bottom right*). Cartoons constitute the input for computer analysis.

count the relative numbers of these various white cells but also should give quantitative information about components of the cells' structure, such as the degree of lobulation of the nucleus, the presence of various small cell bodies and idiosyncrasies in the size or shape of the cell and its components.

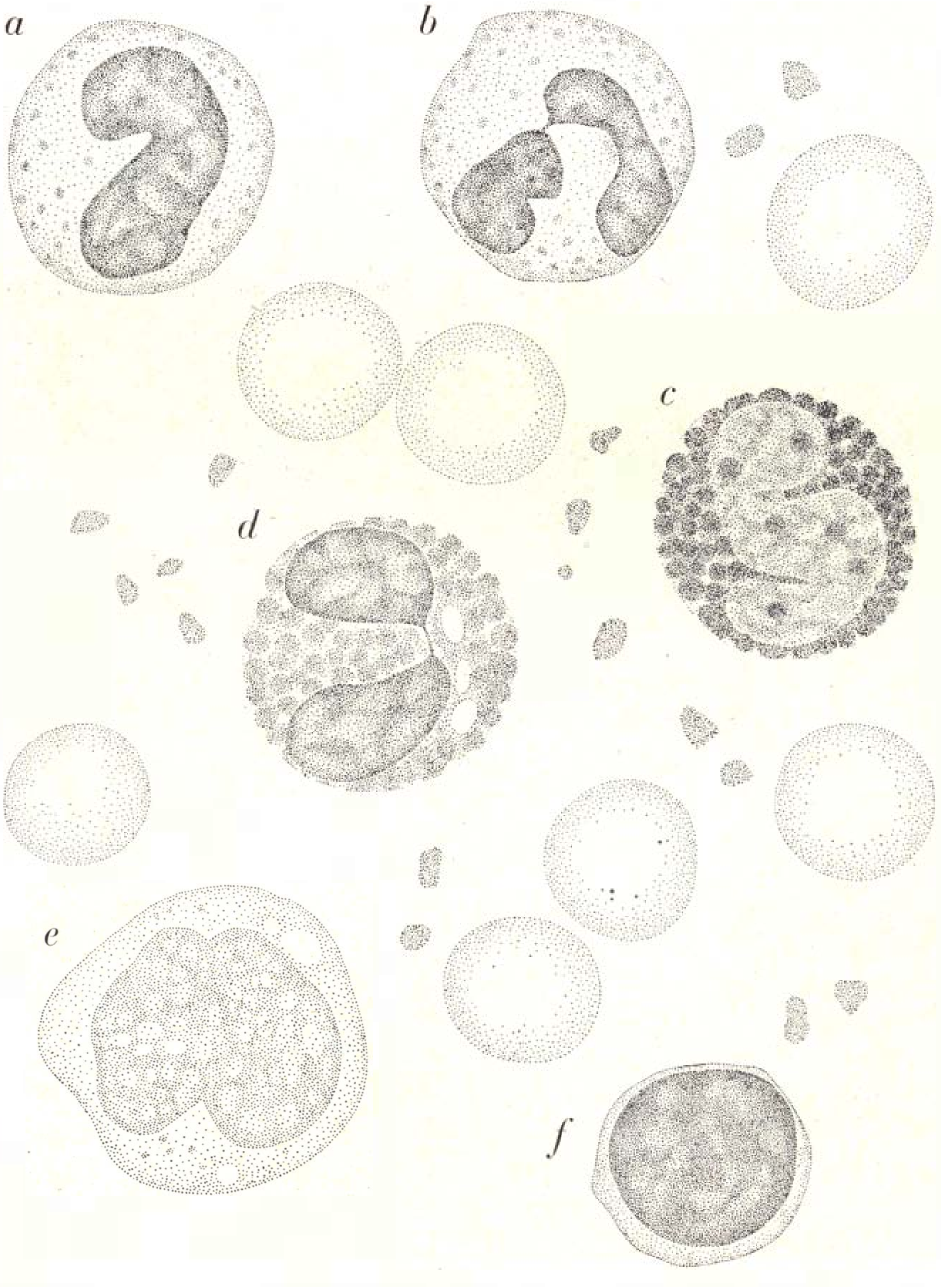
One might suppose that a task of this complexity would require an elaborate program in a large-scale, general-purpose computer. The high cost of such a regimen, however, rules it out as a practical system for general use. We decided to attack the problem in a simpler way by using a special-purpose computer system that would focus directly on the basic task of processing and analyzing images. One of the virtues of this approach is that such a system can operate at speeds that are one or two orders of magnitude faster than general-purpose computers.

Our first design was a system called Cellscan (trademarked by the Perkin-Elmer Corporation). For this system we developed a high-resolution microscope using a vidicon, a conventional television camera tube. The faceplate in the vidicon, presenting a photosensitive surface, is placed in the image plane of the microscope at the location normally occupied by the photographic film in photomicrography. The electron beam scanning this photosensitive surface reacts to the level of the light at each image point. The field of the object plane is a 20-by-20-micron square and the vidicon scans it point by point in 200 lines and converts the image into an electronic video signal. In the Cellscan system this signal consists of 40,000 image points.

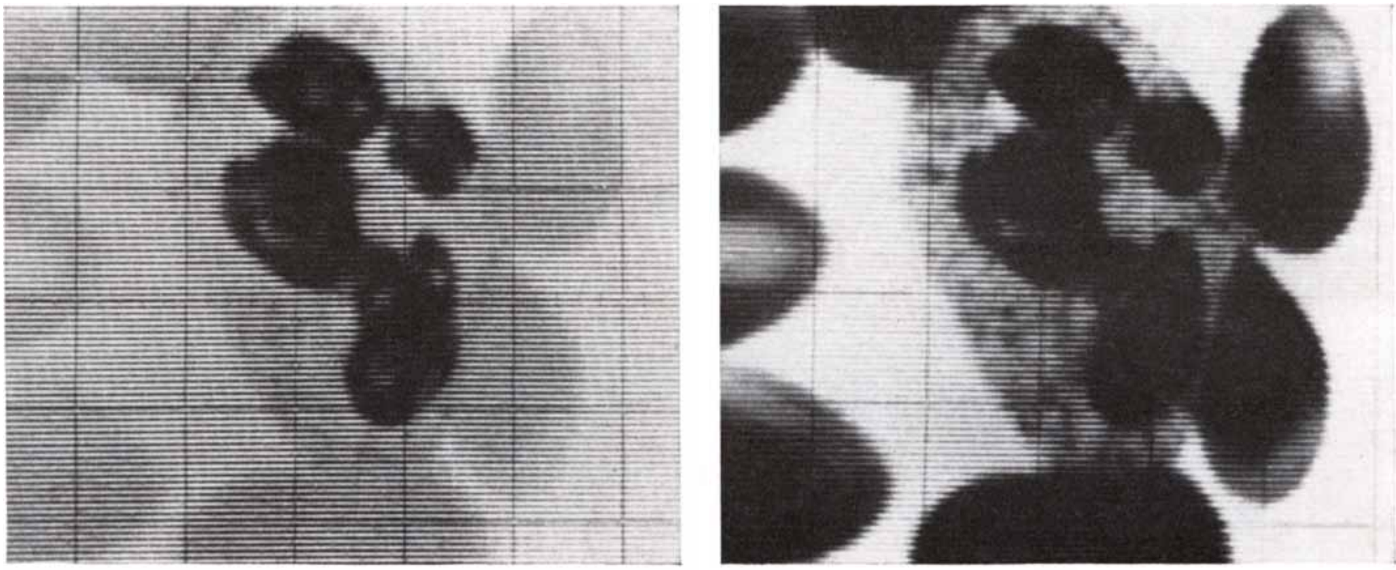
The most critical problem in mechanizing the examination of the image plane is translating the image into computer terms so that the computer can analyze it. Since speed in processing the image is essential, we reduced the number of image points by a sampling procedure. For registration in the computer the video signal is converted electronically into an image in terms of binary numbers, the digit 0 representing white and the digit 1 representing black. We call this operation "quantizing" or "cartooning" [*see illustrations on opposite page*]. Another operation, called "compression," reduces by a factor of nine the number of sample points actually recorded by the computer; if any of the nine quantized sample points in a three-by-three-point square is a binary 0, the entire square is stored as 0 (white), and if all nine points are binary 1, the value of the area is recorded as 1 (black). This sampling device causes isolated "black" areas to be ignored and highlights "white" details in the binary image stored by the computer.

The system's reliability must depend in the first instance on the accuracy and consistency of the photometric mapping by the television microscope. For quantitative evaluation of its performance we use two techniques. One is an assessment of its efficiency in showing detail of various degrees of fineness (that is, various spatial densities of the image points). Tests disclosed that the video signal reproduced images of objects one micron in diameter at essentially full contrast but that the contrast was not as good for objects half a micron or less in diameter. (The limit of the system's optical resolution is approximately a fifth of a micron.)

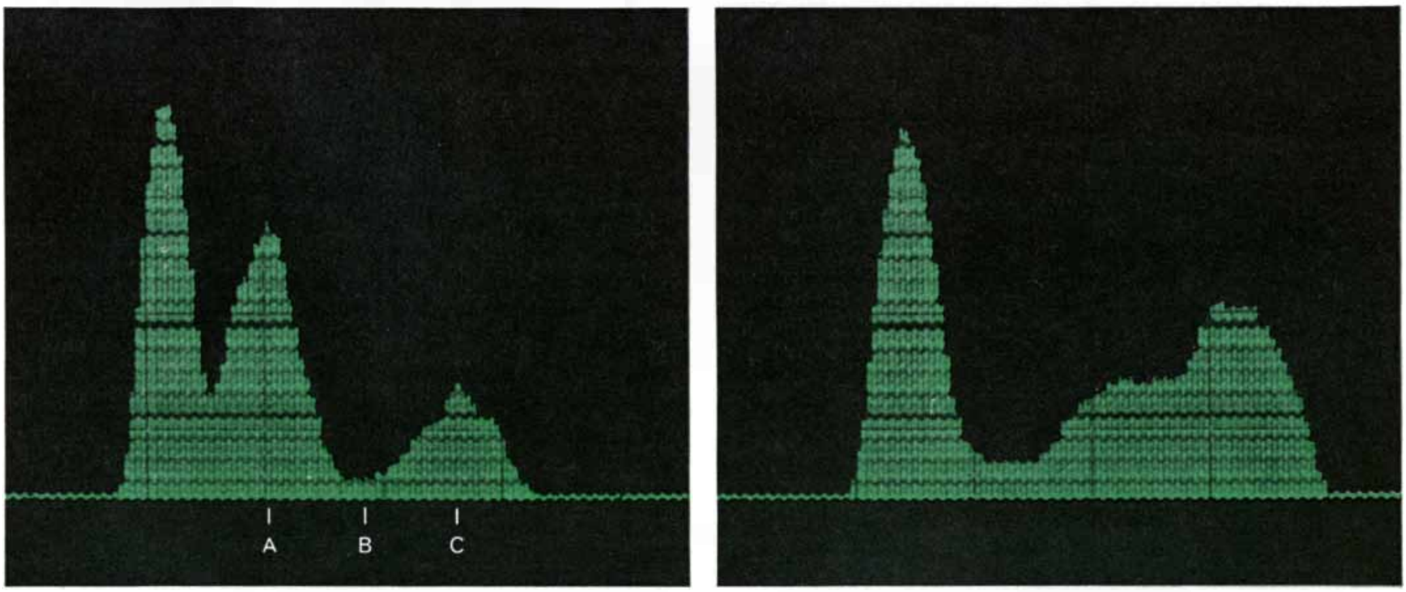
The other measurement we use for evaluation of performance is a display technique called "contourography." In the ordinary television picture tube the electron gun applies the video signal in the form of variations in the strength of the electron beam, producing a pattern of differential emissions of light from the points of phosphor on the tube's face. For the production of a contourograph, on the other hand, the stream of electrons is held constant, and the image, instead of being formed by modulation of the beam, is produced by combining the



CELL TYPES are distinguished by size, shape, texture and color when stained. Color is the least important: a moderately skilled technologist would readily identify the six white-cell types on the basis of these diagrammatic black-and-white representations. The white cells, shown here among red cells and small platelets, are unsegmented neutrophil (*a*), segmented neutrophil (*b*), basophil (*c*), eosinophil (*d*), monocyte (*e*) and lymphocyte (*f*).



TELEVISION DISPLAY shows an unprocessed image of a neutrophil and some red cells illuminated with yellow light *(left)*. Dark regions are the white cell's nucleus, lighter regions its cytoplasm and the red cells; the background is lightest. When the field is illuminated with green light *(right)*, an increase in absorption reveals granularity in the cytoplasm and darkens the red cells.

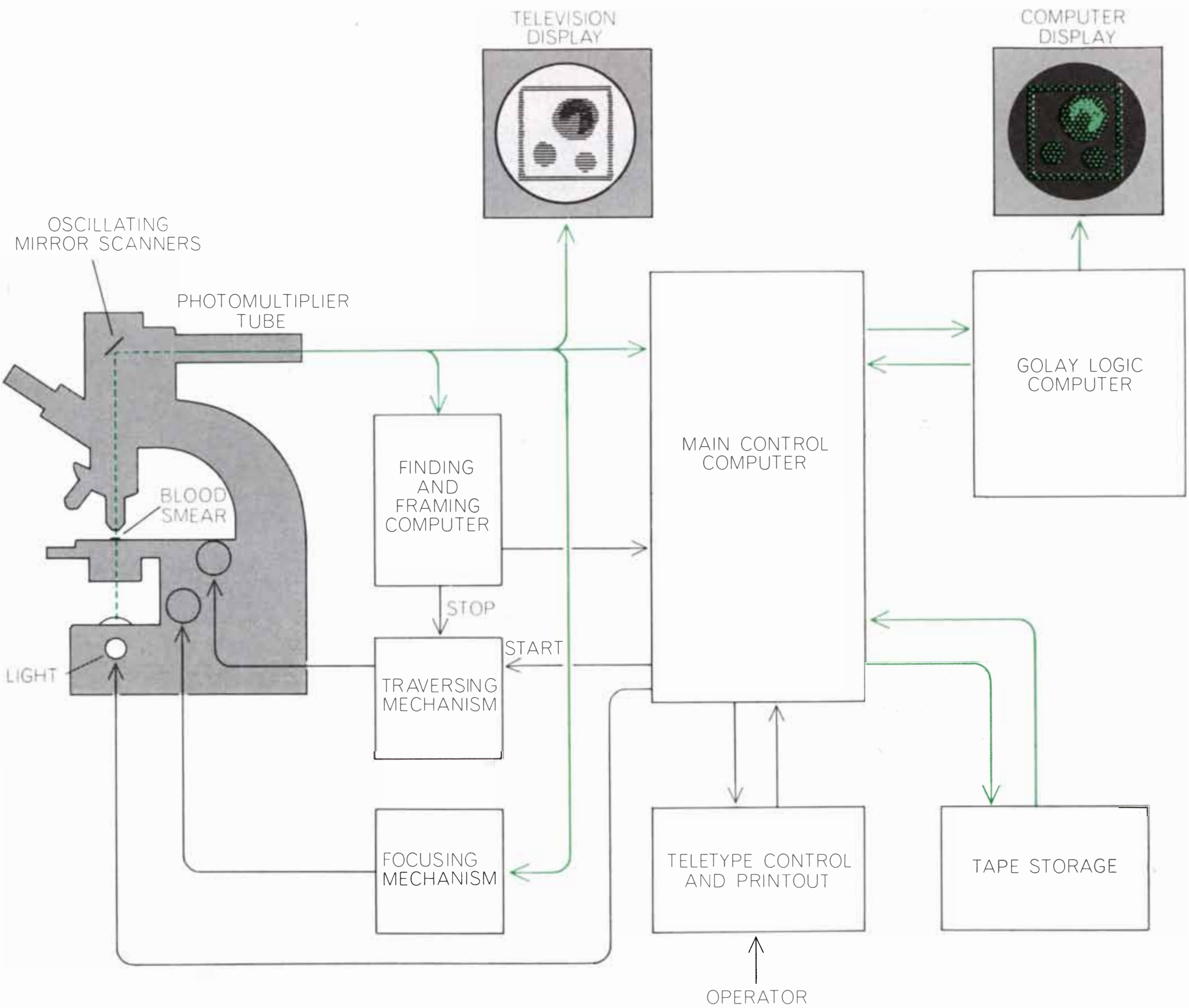


SPECTROPHOTOMETRIC HISTOGRAMS formed by the computer plot the frequency distribution of optical density values in the television images at the top of the page. (Density increases to the right in the histograms.) The peaks in the yellow-light histogram *(left)* represent, from left to right, the densities of the background, the red cells and the nucleus. The most noticeable change under green light *(right)* is an increase in the density of the red cells, which is shown by a shift to the right of the middle peak.

QUANTIZED IMAGE, or cartoon, is formed by the computer. It selects three levels of optical density *(A, B and C in middle illustration on this page)* corresponding to the average red-cell absorption, minimum nuclear absorption and average nuclear absorption respectively. With these levels as quantizing levels for translating the grays of the television image into black (binary 1) or white (binary 0), it forms three cartoons, shown here, and superposes them to form a composite cartoon *(see illustration on page 73)*.

video and sweep signals through the use of the deflection plates [*see bottom illustration on opposite page*]. When we applied this technique to test the Cellscan microscope's performance, as in the reproduction of a knife-edge image placed across the midpoint of the field, we found that the picture was considerably blurred by "noise" arising from nonuniformities in the vidicon photoconductor [*see top illustration on page 78*]. Even with the recently developed vidicon that has a silicon diode array as its photosensitive surface, the photometric error is 5 percent.

We therefore redesigned the system, replacing the vidicon with a mirror scanner and using a method of image analysis developed by Marcel J. E. Golay. This new system for blood-cell analysis is called Cellscan-Glopr (Glopr being an acronym for Golay logic processor). A pair of oscillating mirrors at right angles to each other scans the image formed by the microscope and transmits its scan to a phototube [*see top illustration on opposite page*]. At any one instant the phototube is looking at only one point in the image, as the light reaches it through a small aperture. The light from the image point floods the entire face of the tube, and its photoemissive surface emits a stream of electrons that is proportional to the intensity of the incident light. The stream is collected and amplified by a chain of electrodes, the amplification proceeding by multiplication of the electrons—a multiplication that can be as high as a million to one. This amplification is essentially noise-free, and since the electron stream, or video signal, emitted by the photoemissive face comes from the entire surface, any nonuniformities from point to point on the face are of no consequence. In fact, edge contourographs made with the Cellscan-Glopr microscope are much more accurate and invariant than those produced



AUTOMATIC ANALYSIS of blood cells is accomplished by the Cellscan-Glopr system as indicated in this schematic diagram. The substage carrying the blood smear is moved under the objective lenses by automatic traversing and focusing mechanisms and is stopped by the finding and framing computer when a white cell comes into view. The cell is scanned and the image is converted into an electronic signal by a photomultiplier. It can be displayed as a television picture or processed: quantized and "compressed" by the control computer for analysis by the Golay logic computer. The computerized image can be displayed, stored in the tape memory, identified as to cell type and counted. The entire operation can be directed through the teletype keyboard or done automatically.

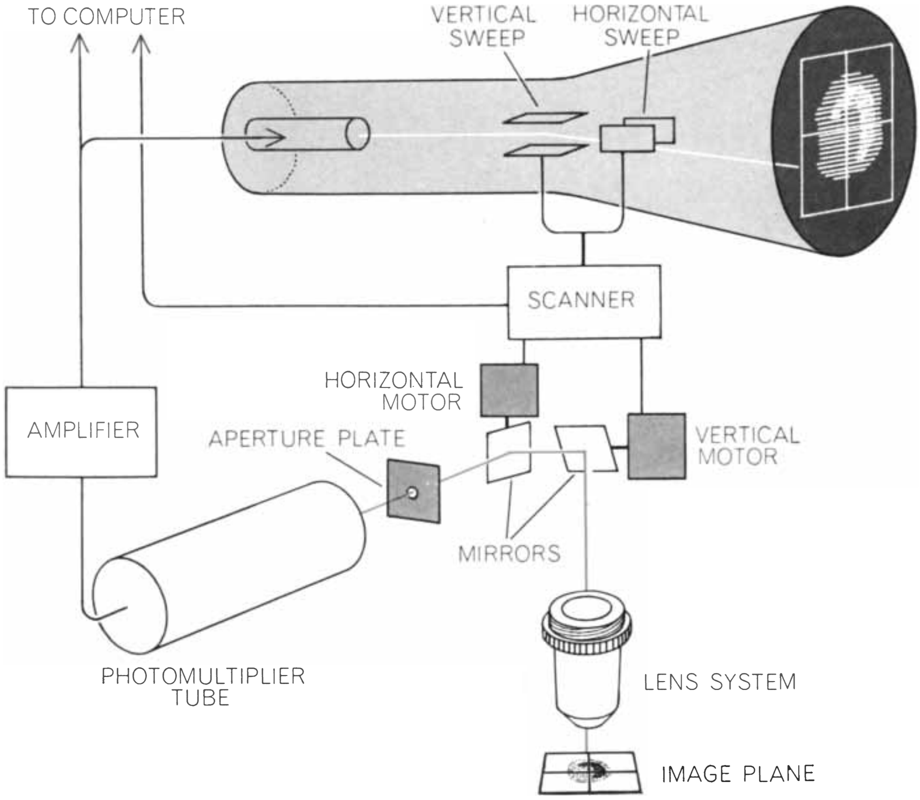
by the vidicon [*see bottom illustration on next page*].

The mirror scanning system, depending on moving mirrors, is somewhat slower than the electronic vidicon. We believe, however, that the system can be designed to oscillate the mirrors at a rate that will feed information to the image-analyzing computer as rapidly as the computer can accept it.

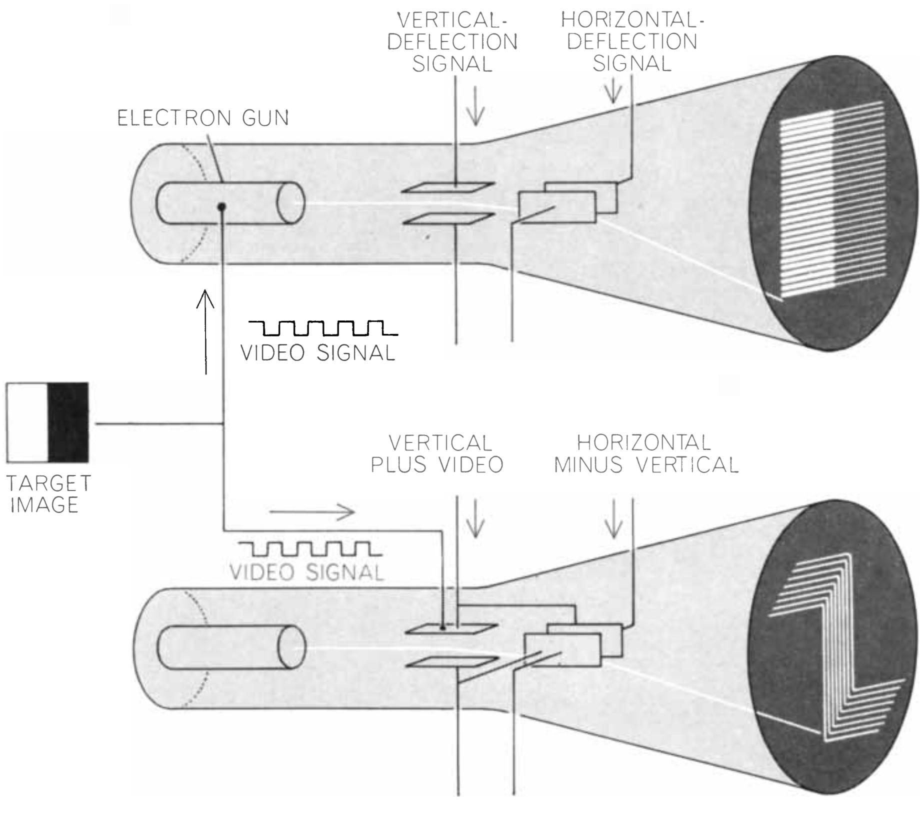
The computer's translation of the microscope's point-by-point image of blood cells into "cartoons" proceeds much as in the Cellscan system. The computer first forms a photometric histogram of the entire image, showing the frequency distribution of the various photometric values for all points in the image. The histogram is based on illumination of the object by light of a selected color. Characteristically the histogram of a white cell will show major peaks corresponding to the absorption of the light by the cell nucleus, by the cytoplasm, by adjacent red cells and by the background. In yellow light, for example, the nucleus of a neutrophilic leukocyte will appear dark and its cytoplasm, any red cells and the background will be light. Under green light the granular structure of the neutrophil's cytoplasm shows up, because the granules absorb light of this wavelength, and red cells also darken for the same reason.

After forming a histogram the computer examines it and instantly selects quantizing levels for the video signal that will be used to reproduce cell images and identify them. Examining a typical cell illuminated with yellow light, the computer selects levels representing the average absorption by the white-cell nucleus, the average absorption by red cells and an absorption level intermediate between these two values. It then superposes these three cartoons, or density measures, to form composite cartoons describing specific white cells [*see illustration on page 73*].

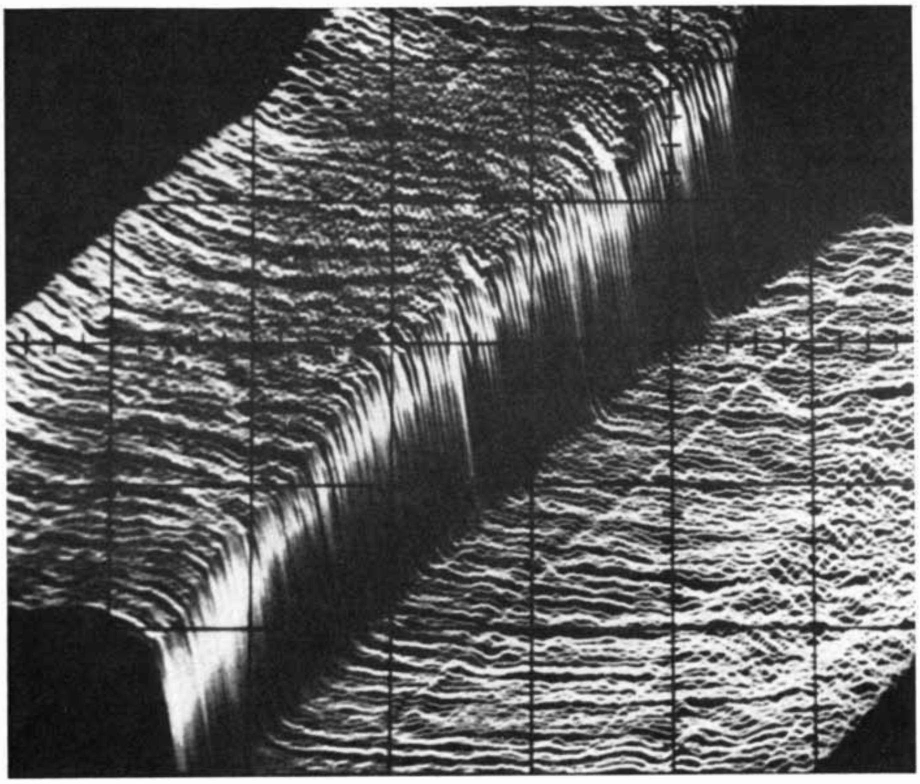
The computer now goes on to process the information stored in the composite cartoons to define and analyze the image of each white cell viewed by the television microscope. For this analysis the Cellscan-Glopr system uses hexagonal "pattern transforms" devised by Golay. The system successively examines each image point in terms of the binary states of the six neighboring points surrounding it in a hexagonal array, considering 14 nearest-neighbor patterns [*see top illustration on page 79*]. Then the system recalculates the binary state of each image point on the basis of its surround



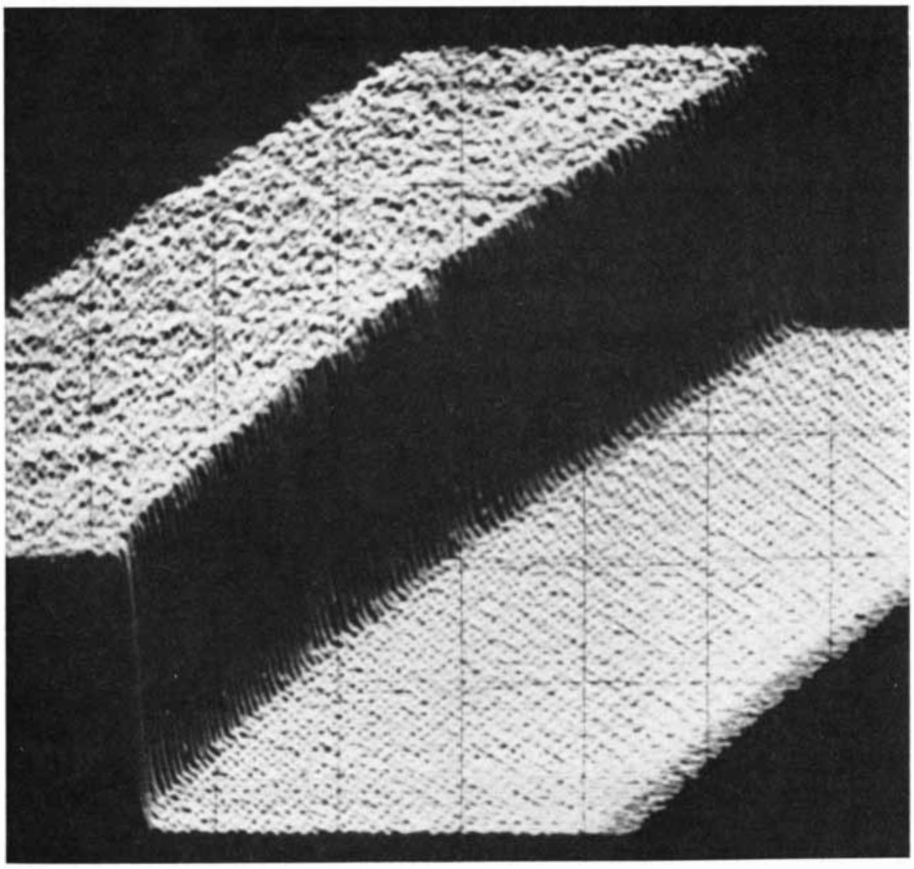
OSCILLATING-MIRROR SCANNER scans the microscope objective plane horizontally and vertically. Light from one image point at a time passes through an aperture to the face of a photomultiplier tube, giving a measure of the point-by-point optical density. The resulting electronic signal is amplified to yield the video signal, which goes to the computer or, as shown here, to a television picture tube where the original image is reconstituted.



PERFORMANCE of the system is monitored by contourography. In an ordinary television display (*top*) the video signal (*square wave form*) is scanned across the tube. Modulation of the electron beam produces a pattern of light and dark that reproduces the original image, a vertical knife-edge in this case. In contourography (*bottom*) light-dark modulations are changed into vertical deflections. This is done by subtracting the video from the vertical signal. Individual lines are offset by subtracting the vertical from the horizontal signal.



CONTOUROGRAPH of a knife-edge target was made with the vidicon tube, the type of scanner used in the authors' original Cellscan system. The waviness of the lines and their variation from one scan to the next represent electronic "noise" resulting from nonuniformities in the photosensitive surface of the vidicon on which original image was formed.



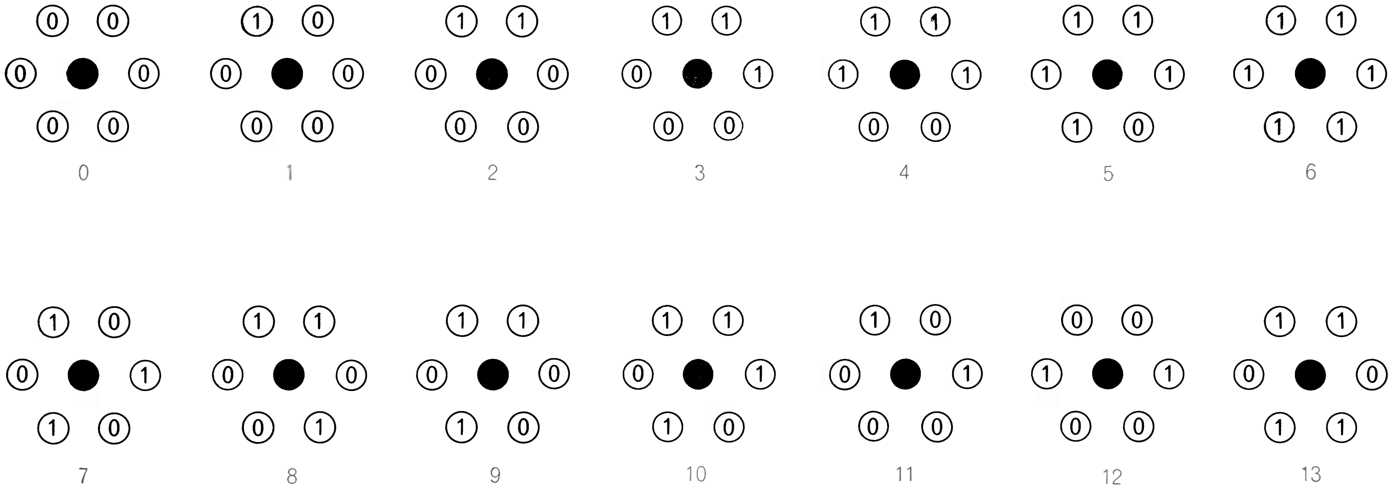
IMPROVEMENT IN ACCURACY with the oscillating-mirror scanner is demonstrated by this contourograph. Photosurface nonuniformity is no longer a problem, as indicated by the regularity of the horizontal lines, although random arrival of photons still produces noise in illuminated region. The resolution is improved, as is shown by the sharp vertical plane.

and the particular transform that is being performed. These transforms can be directed to various specific purposes, such as measuring the total area of the cell nucleus, calculating the length of its periphery, analyzing and measuring its fine structure, detecting concavities that indicate lobes or irregularities and displaying many other topological features. Thus the computer arrives at measurements of the cell's size, shape, texture and other properties.

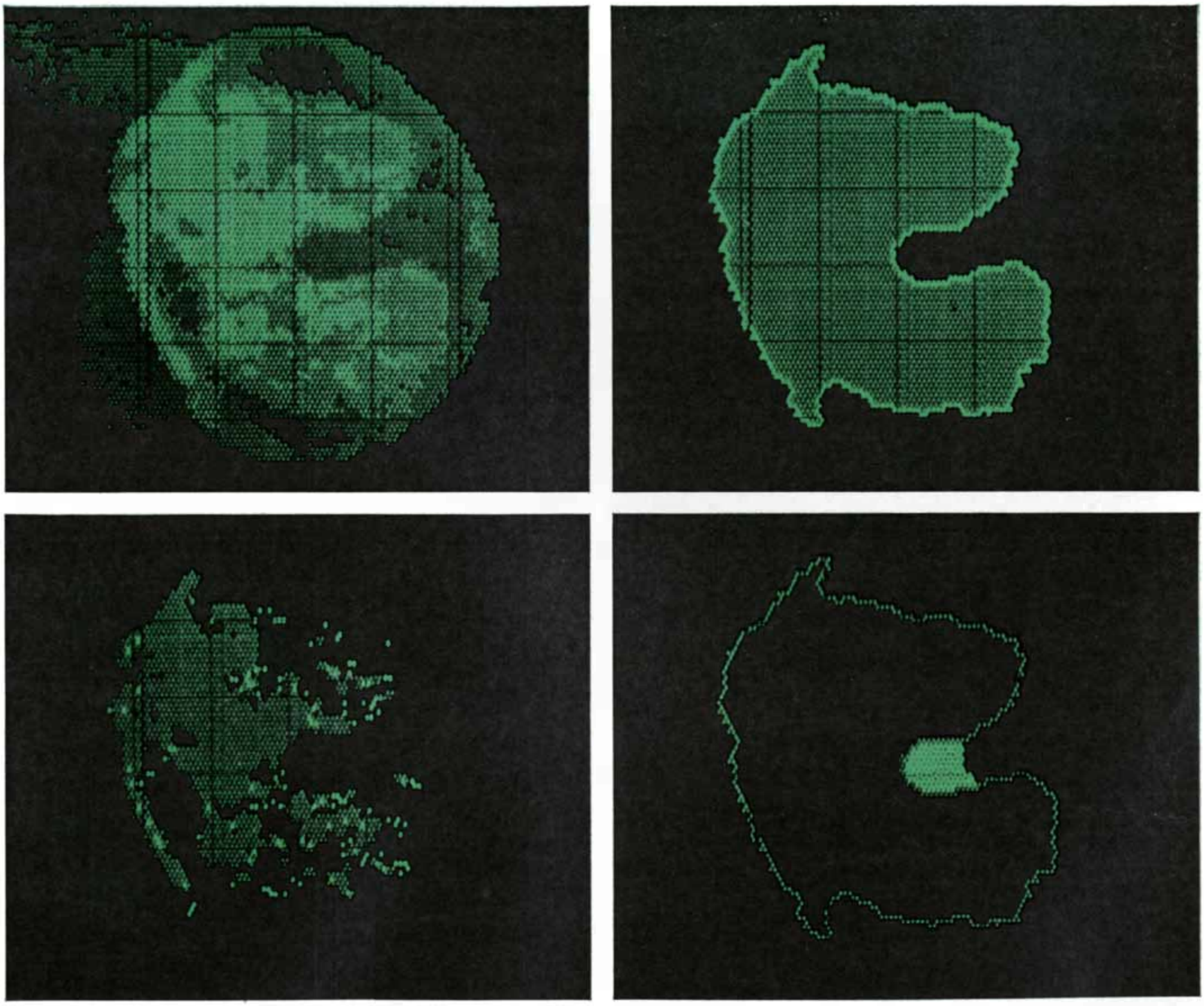
All of this is done very rapidly, although the computer logic operates on only one image point at a time. The special-purpose computer processes images at a rate 100 times higher than can be achieved by the application of general-purpose computers to this method of pattern analysis. Our present Cellscan-Glopr system can analyze a 32-by-32-point image in 1.25 milliseconds, a 64-by-64 image in five milliseconds and a 128-by-128 image in 20 milliseconds. It executes even highly complex Golay transforms within a matter of seconds.

Having obtained a set of measurements describing the appearance of a cell, the machine is finally confronted with the most difficult task of all: identifying the cell according to its type. We have explored many methods of providing the computer with the ability to make this decision, from the classical technique of statistical analysis on objects embodying many variables to some of the newer approaches taken in disciplines such as linear programming. Our most successful results have been obtained by devising models that represent the sets of measurements corresponding to specific cell classes by locations in a multidimensional space (just as one locates a point on a two-dimensional graph by measuring its distance along the two axes) and then finding boundaries that separate the classes from one another.

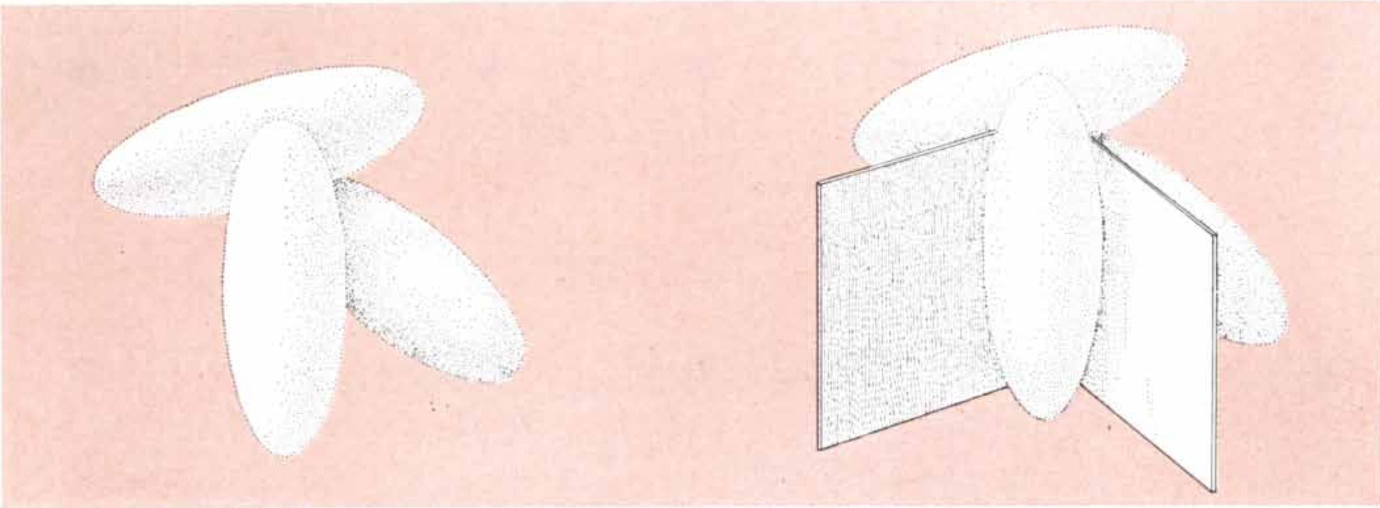
When different classes of white blood cells are considered and the positions of the individual cells are plotted in a three-dimensional measurement space (that is, on the basis of three image measurements for each cell), the sets of measurements tend to pattern themselves in clusters corresponding to the different classes. Suppose we examine such a three-dimensional diagram, showing three clusters. If we try to find a plane that will represent a boundary separating the measurements for one class from those for the other two, we discover that in general no single plane can make this separation. If, however, we take the clusters pair by pair and draw planes



GOLAY PATTERN TRANSFORMS analyze each image point in terms of the binary state (1 or 0, meaning black or white respectively) of the six other points that are nearest it in the hexagonal image-point lattice that constitutes the cartoon. There are 14 possible orientation-independent nearest-neighbor patterns, or surrounds. (They are numbered from 0 to 13 for computer processing.)



COMPOSITE CARTOON, such as the one of a monocyte (*top left*), constitutes the input to the Golay logic computer, which operates by analyzing the appropriate individual cartoon. For example, a simple transform that locates surrounds corresponding to edges identifies the periphery of the nucleus (*top right*) and calculates the nuclear circumference and area. Another transform "shrinks" elements of the cartoon of the dense nuclear regions to determine the fine structure of the nucleus (*bottom left*). Other transforms locate the large nuclear concavity and brighten it for display (*bottom right*); the size of the concavity can be measured.

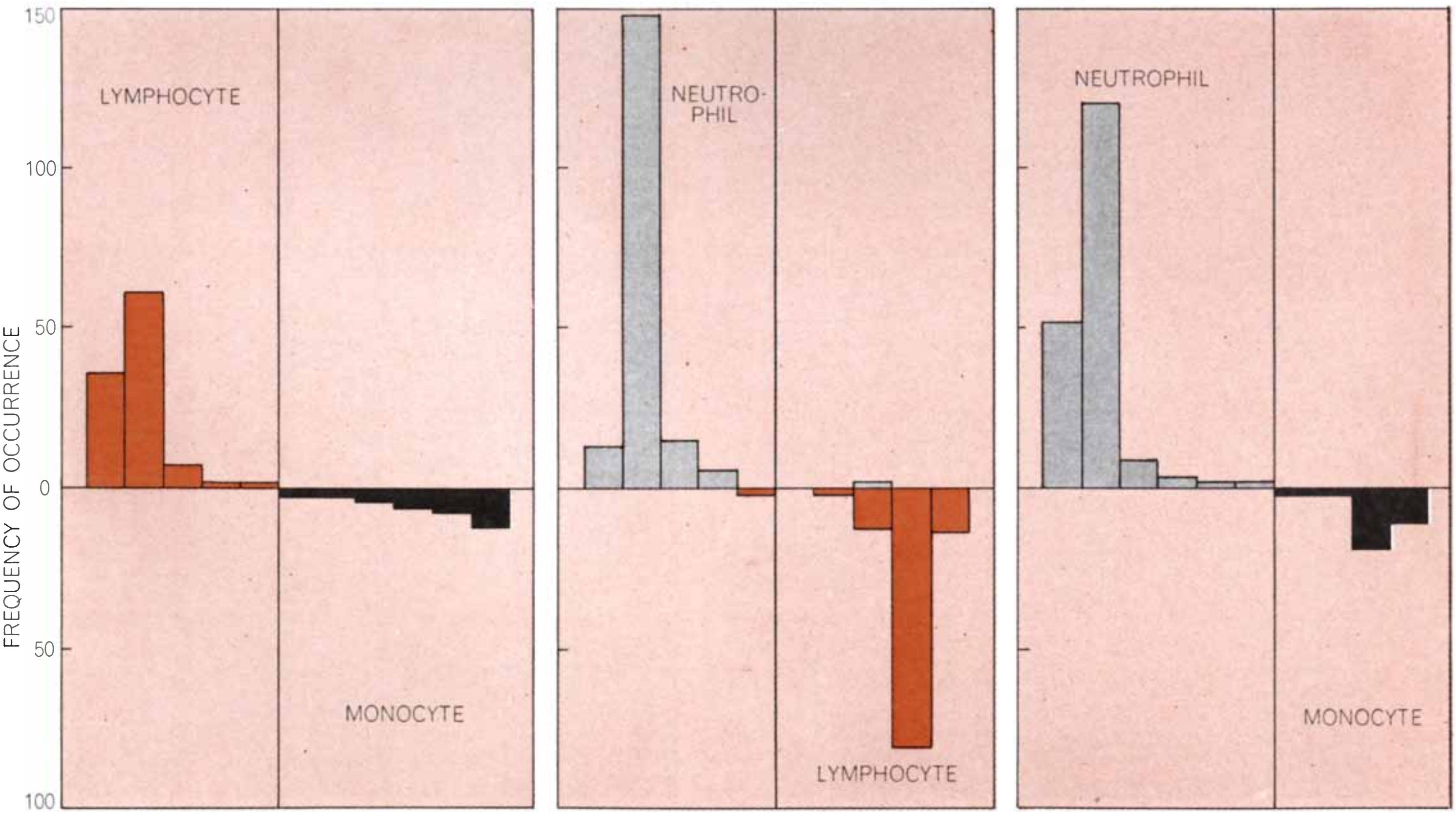


CELLS ARE IDENTIFIED by the way in which various measurements characteristic of each cell type tend to cluster in measurement space. When three measurements are made on the cartoon of each cell, a cell is defined as a point in three-dimensional space. When measurements are made on many members of a class of cells, the measurements tend to cluster. The model (*left*) shows three such clusters; the problem is to establish planes that will separate one from the others. Two planes are required in order to separate measurements corresponding to a particular cell from measurements corresponding to two other classes of cells (*right*).

separating the pair members from each other, the measurement space can be divided into compartments each of which contains only the members of one class [*see illustration above*].

When each white cell is described by more than three measurements, it is of course no longer possible to picture the separation problem with a simple visual model. We resort to a different kind of model, a distance histogram. Clusters of cells are established, on the basis of a number of measurements, by the computer, which then constructs separation planes and measures the distance of each cell from each plane.

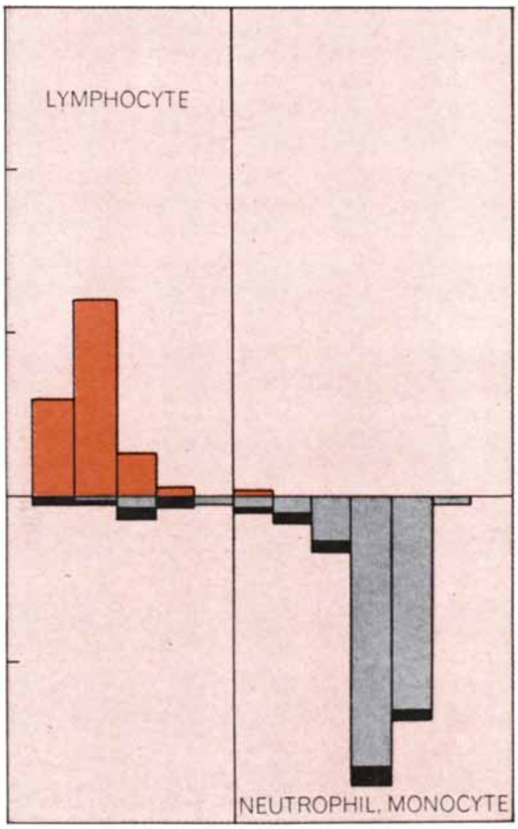
In one trial we analyzed in this way the images of representative samples of the three most common types of human white cells: lymphocytes, neutrophils and monocytes. With a computer pro-



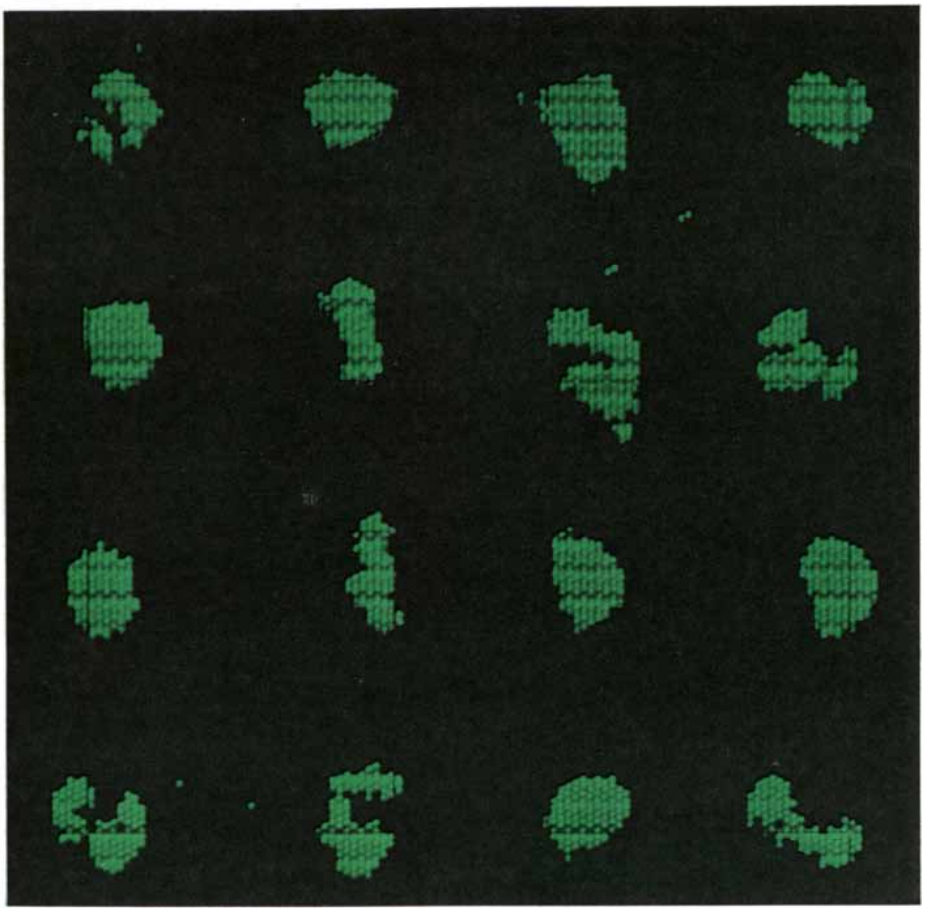
DISTANCE HISTOGRAMS can be used to evaluate the separation of clusters in a space of as many dimensions (measurements) as necessary. The height of each bar shows the number of sets of measurements, each corresponding to one cell, that fall in a given interval of distance (*horizontal axis*) from a separating plane. The best approach is to use a separating plane for each pair of cell classes, as in the first three histograms. This separation involved 107 lymphocytes (*color*), 179 neutrophils (*gray*) and 27 monocytes gram based on classical statistical analysis we first constructed the single plane that would optimally separate the lymphocytes from the other two classes. This separation attempt was unsuccessful: the measurements overlapped so that in the distance histogram six neutrophils and nine monocytes fell on the lymphocyte side of the plane and one lymphocyte fell on the neutrophil-monocyte side. Separation improved greatly when the cell types were divided pairwise, one plane separating lymphocytes from monocytes, another neutrophils from lymphocytes and a third neutrophils from monocytes. Of a total of 313 cells examined, only two (one lymphocyte and one neutrophil) fell on the wrong side of a plane [*see bottom illustration on these two pages*].

The pairwise separation of three classes of cells requires the construction of three separating planes by the computer; four classes require six planes; five classes require 10 planes, and so on. The Cellscan-Glopr system is now programmed to perform pairwise separations for as many as eight cell types, and this selectivity calls for 28 planes.

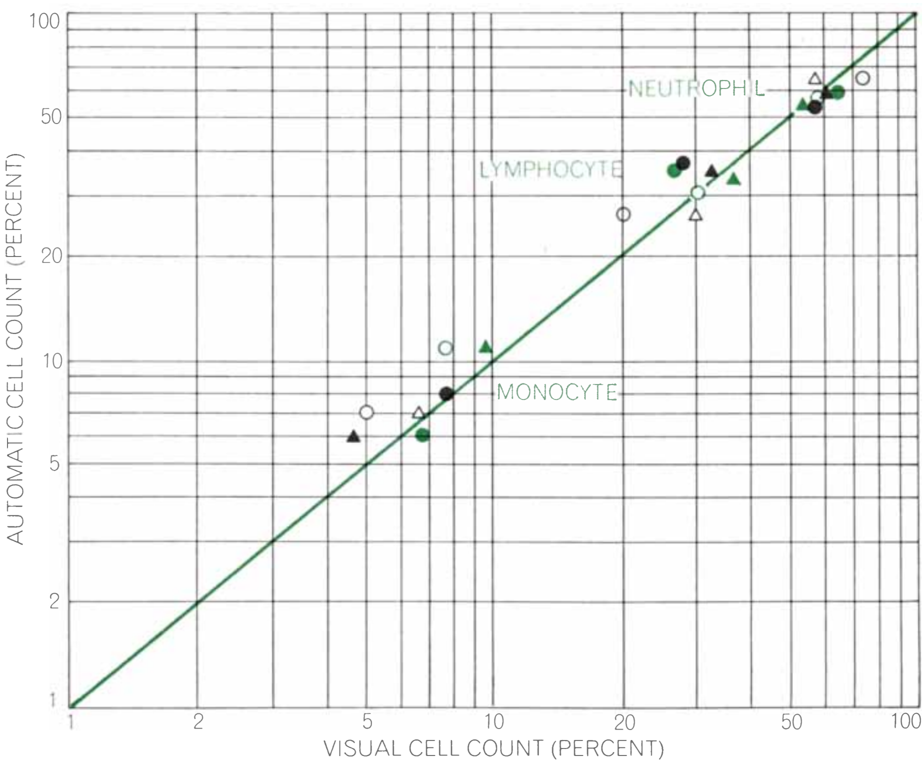
If all the cells of each class faithfully followed a stereotype for their class, the



(*black*). Only two cells are improperly separated. When just a single plane was used (*right*), six neutrophils, nine monocytes and a lymphocyte were improperly separated.



VARIABILITY among cells within a class can be almost as great as differences between classes, complicating the problem of classification. This montage formed by the computer shows cartoons of nuclei of lymphocytes and neutrophils. The former are more nearly circular, the latter more irregular, but the shapes of the two classes are not clearly stereotyped.



ACCURACY of the automatic process compares well with that of hospital technologists, as shown by the scatter diagram. The results are shown for seven blood smears, each represented by a different symbol. The average of the counts reported by each of several laboratory technologists is plotted along the horizontal scale at a height on the vertical scale that corresponds to the automatic count. (Points on the diagonal indicate exact agreement.)

separation of classes could be quite clear-cut. Actually the white blood cells within a class vary considerably in structure; this variability is almost as great as the differences among classes [*see top illustration at left*]. The variations may be due to individual differences among the many subjects, of both sexes and various ages, from whom blood samples are taken or to fortuitous differences in laboratory preparation of the cells. In developing optimal separation programs for the computer and testing their performance we have paid particular attention to the variability problem, applying our test in each instance to samples representing a realistic range of variability.

So far we have concentrated mainly on the analysis of blood specimens from normal subjects. Our present Cellscan-Glopr system can operate automatically without monitoring for a long period, such as overnight. Recently we tested it in a series of unattended overnight runs. In each run the machine scanned a single normal blood smear, screening some 200,000 to 400,000 cells in order to locate and analyze 200 to 400 white cells, with the assigned task of classifying the lymphocytes, granulocytes and monocytes. In a number of runs the system located approximately 5,000 objects that were judged to be white cells. Each object was measured, analyzed as to structure and then identified by the machine as a lymphocyte, a granulocyte, a monocyte or DK (Don't Know). All the smears were then examined visually by four skilled technologists at the Norwalk Hospital in Connecticut. The machine's differential count of the relative number of white cells in each class agreed closely with the counts by the technologists [*see bottom illustration at left*]. Besides classifying the cells, the machine in these runs measured and tabulated several details of each cell's structure, such as size and average color and the elongation, degree of texture and number of lobes of the nucleus.

Our experiments with the Cellscan-Glopr system have demonstrated that it can be programmed to perform a number of tasks other than the differential counting of white blood cells. As time allows we are exploring its capabilities in a variety of functions, such as the counting of grains in the emulsions of cell autoradiographs, the location of malarial parasites in red cells, the analysis of human chromosomes, the identification and counting of reticulated red cells and other examinations that are difficult or tedious to perform but are important in clinical medicine or in research.

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THE GREAT ALBATROSSES

The royal albatross and the wandering albatross are the largest birds in terms of wingspan. The species are so much alike that they probably evolved from a common ancestor in the recent past

by W. L. N. Tickell

By far the largest of all oceanic birds and the largest of all birds in terms of wingspan are two closely related members of the albatross family: the royal albatross and the wandering albatross. The wingspan of both birds, measured from wingtip to wingtip, has been known to exceed 11 feet. The only other bird of comparable size is the Andean condor; it can weigh more but its maximum wingspan is 10 feet. The royal and wandering albatrosses are distinct species within the albatross family, which consists of 13 species in all (11 in the genus *Diomedea* and two in the genus *Phoebetria*), but the two giant birds have been collectively known as the "great albatrosses." All the albatrosses belong to the order Procellariiformes, a group that includes the several types of petrels, the shearwaters, the fulmars and other birds adapted to an entirely marine environment.

In the 18th and 19th centuries the separate identity of the two great albatrosses was not clear; it was only in 1891 that the British ornithologist Walter L. Buller was able to demonstrate that they represent two distinct species. Both birds are white and have black wingtips. The royal albatross is the species *Diomedea epomophora*. Its nostrils are rounded and its eyelids and the cutting edges of its upper mandible are black. The wandering albatross is *D. exulans*. Its nostrils are less rounded and the eyelids and the cutting edges of the upper mandible are white. These differences are too inconspicuous to be of much help in identifying the birds at sea. Distinguishing between the species is aided somewhat by differences in the development of plumage. Young royals fledge into a white plumage like that of their parents; young wanderers are mostly dark when they leave the nest and become whiter over a period of several years. Wanderers are thus easily identified in their darker plumage phase, although almost half of the breeding male wanderers and nearly a fifth of the breeding females reach the whitish "chionoptera" condition rather quickly.

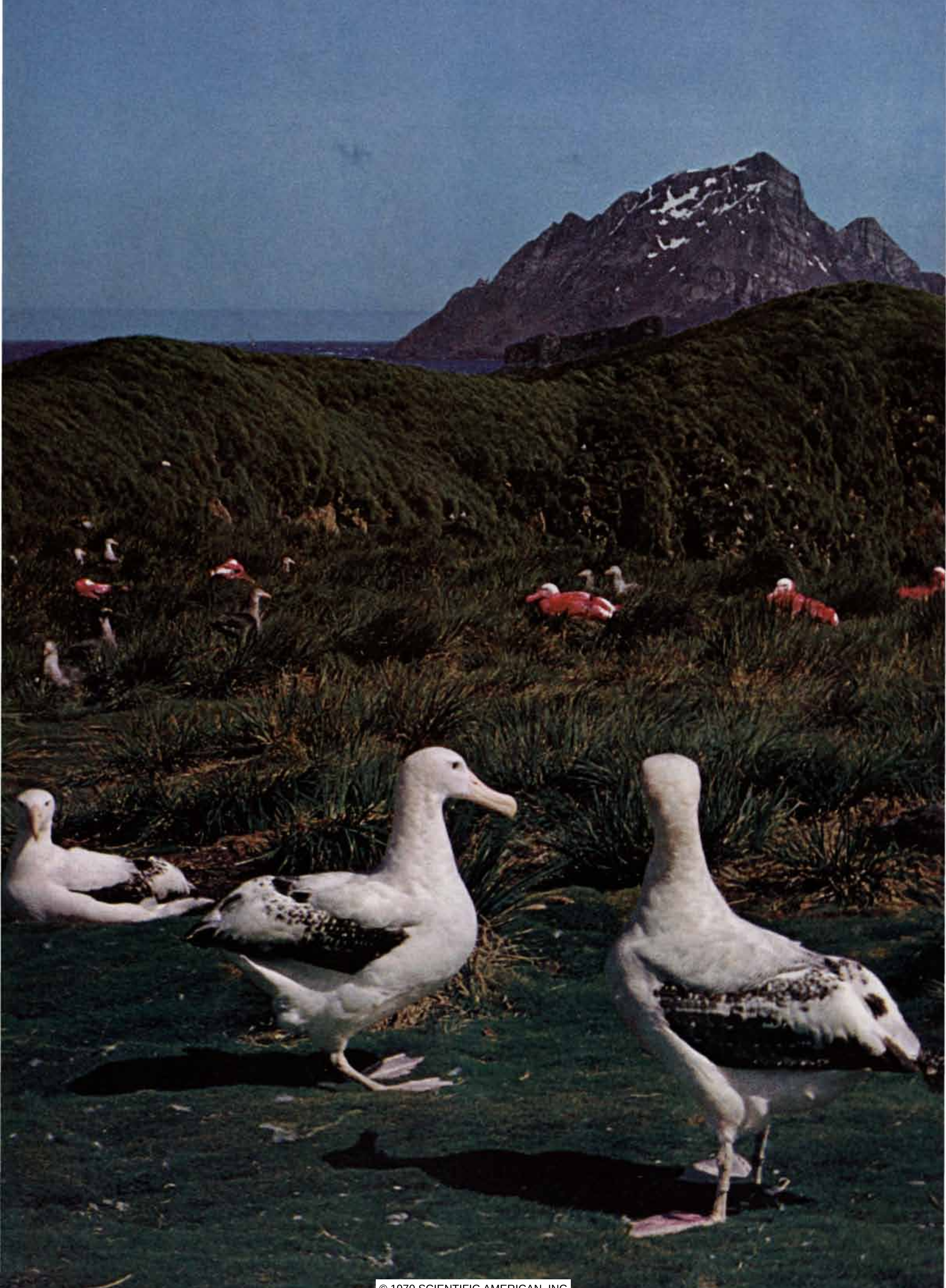
Knowledge of the royal albatross has come almost exclusively from the work of New Zealand biologists. Between 1938 and 1952 L. E. Richdale of the University of Otago studied an expanding population of royals at Taiaroa Head on the Otago Peninsula of New Zealand's South Island, and between 1942 and 1958 J. H. Sorensen of the New Zealand subantarctic expedition of 1941–1945 and K. E. Westerskov of the University of Otago observed a much larger royal population on Campbell Island, a lonely outpost in the waters between South Island and the Ross Sea.

The history of Richdale's work demonstrates that the great albatrosses are tenacious in their nesting habits. In 1920 a pair of royal albatrosses was observed nesting at Taiaroa Head; the nest was robbed of its egg by local people. The royal pair probably laid another egg in the same nest each year over the next 15 years. Only once was the nest left undisturbed long enough for a chick to be hatched, and the chick was later killed. Eventually, through Richdale's efforts and the protection of the Royal Society of New Zealand, a fledgling royal albatross was successfully reared in 1938. Richdale was able to study the birds in detail over the next 15 years. Benefiting from strict measures imposed by the Government Department of Internal Affairs and the Otago Harbor Board, the colony in the past 31 years has grown from one breeding pair to 15.

It is conceivable that royal albatrosses had bred on the New Zealand mainland before the area was populated by the Maori migrations of the 14th century. The Maori are thought to have been responsible for the demise of another remarkable bird: the gigantic, flightless moa. The albatross would have been equally good to eat, and it would probably have been just as easy to catch on land. There is, however, no evidence to support this speculation, and the recent buildup of the royal albatross population at Taiaroa Head may be no more than a successful accident. Although the Otago colony is insignificant compared with the neighboring royal albatross populations of Campbell Island, the Chatham Islands and the Auckland Islands, Taiaroa Head is the only place in the world where one of the great albatrosses nests within easy access of man: the city of Dunedin is only 20 miles away.

My own work has concerned the wandering albatross. Following a reconnaissance expedition in 1958–1959 to the subantarctic wanderer nesting area on South Georgia, a continuing study of that wanderer population was sponsored by Johns Hopkins University. In 1960–1961, 1961–1962 and 1962–

ALBATROSS NESTING GROUND on Bird Island, off the northwest tip of South Georgia in the subantarctic waters of the South Atlantic, is seen during the summer in the photograph on the opposite page. The three large birds in the foreground are wandering albatrosses (*Diomedea exulans*). The pink birds were dyed for an experiment by the author and his colleagues. Other birds in picture are giant petrels (*Macronectes giganteus*) and smaller albatrosses. The royal albatross (*Diomedea epomophora*) does not nest here.



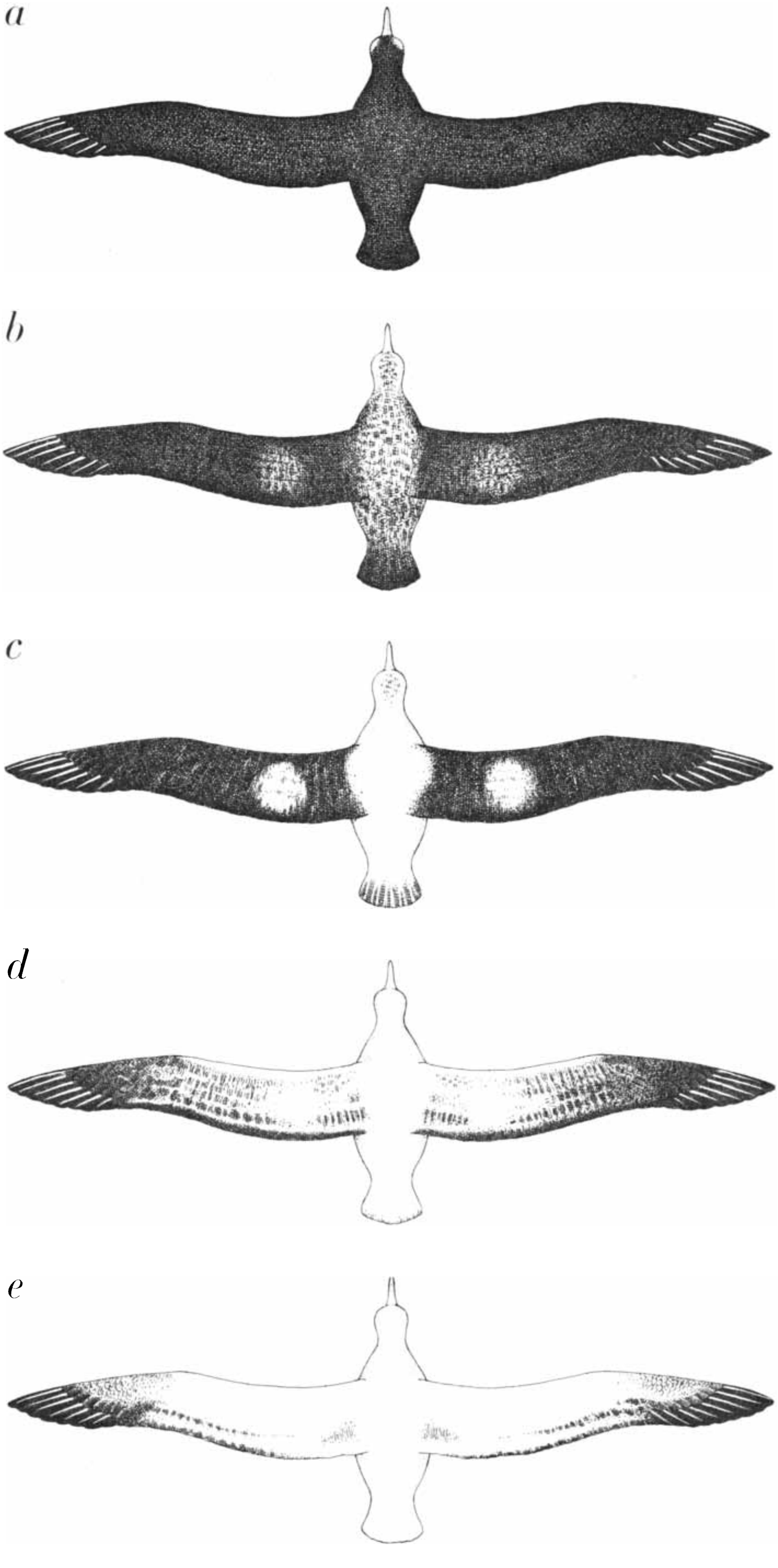
DYE IS APPLIED to one of the parent albatrosses to make its identity unmistakable and thus help to locate the feeding area used by the albatrosses from Bird Island. Ship sightings indicated that the birds fed at sea about 150 miles north of their nesting ground.

COLORED DOTS are painted on the head of an adult wanderer by one of the investigators visiting the Bird Island nesting ground. Use of the markings enabled the visitors to identify individuals in their study of the reproductive cycle of the wandering albatross.

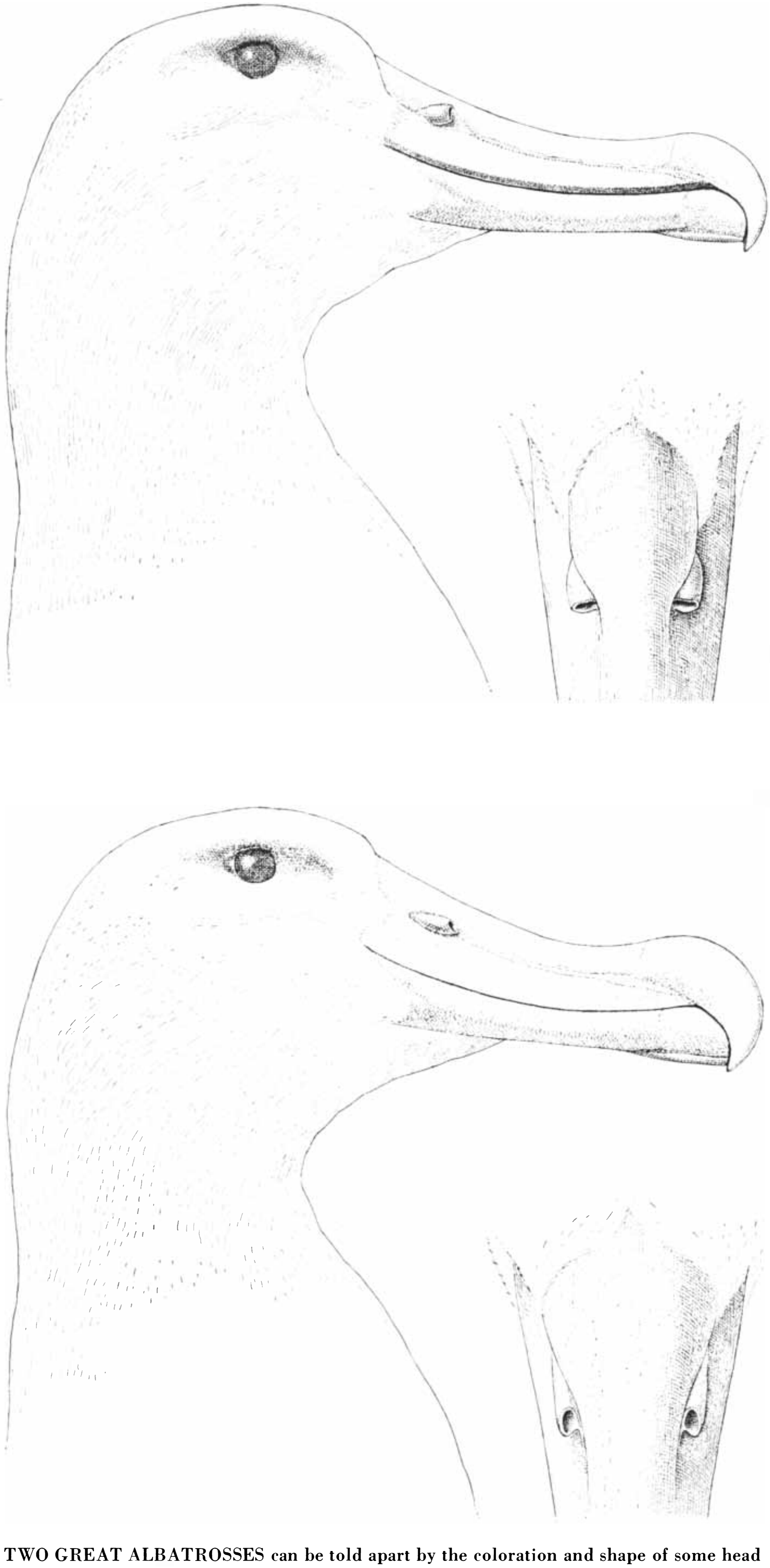
1964 the National Science Foundation financed a series of three expeditions for which the British Antarctic Survey provided logistic support. Altogether my companions and I spent a total of six summers and one winter studying a colony of some 5,000 wanderers on Bird Island, just off the northwest tip of South Georgia.

The distribution of the great albatrosses is poorly known even today. Our best information concerning their ocean range is still what was obtained by Captain C. C. Dixon, during many years at sea beginning in 1892. Dixon acknowledged that he could not distinguish between the two species at sea, but that does not detract from the value of his work. By the time he retired in 1919 he had accumulated 3,500 days of observation showing that the birds' range in the southern oceans lies generally between 30 degrees and 60 degrees south latitude. A few great albatrosses have since been reported in tropical waters as far north as 18 degrees south latitude. Individual birds have been known to cross the Equator into the North Atlantic and even to enter the Mediterranean. The southern extreme of the birds' range lies well within antarctic waters; the southernmost sighting was made by members of Admiral Byrd's second antarctic expedition, who observed one bird in the Ross Sea at 69 degrees south latitude.

At sea the abundance of the great albatrosses varies with the seasons. Dixon sighted more of the birds in the northern part of their range during the winter and more in the southern part during the summer. The movements of each species need to be worked out more precisely, and a beginning has been made by banding albatrosses in both their breeding grounds and their wintering grounds. For example, in the early 1950's several Australian ornithologists became interested in the large number of wanderers that congregate at sea off the coast of New South Wales each winter. In 1958 they began capturing birds with motorboats and banding them. The following summer (1958–1959), without knowing about the Australian tagging program, I started to work among the wanderers breeding on South Georgia, and in December I found one bird carrying a band put on in Australian waters the preceding July. The following July the reciprocal passage was recorded when a fledgling wanderer I had banded on South Georgia was recovered off Australia. The work of the next five years showed that these passages were far from rare. Of 1,477 adult wanderers caught and band-



SLOW TRANSFORMATION of the plumage of the wandering albatross from dark to light color (*a*—*d*) makes the distinction difficult between mature wanderers and all royal albatrosses, which fledge into a white plumage (*e*), when either bird is seen at a distance.



TWO GREAT ALBATROSSES can be told apart by the coloration and shape of some head parts. The royal albatross (*Diomedea epomophora*) has black eyelids and the cutting edges of its upper mandible are black; its nostril is rounded (*top*). The wanderer (*D. exulans*) has white eyelids and mandibles; its nostril is less rounded (*bottom*). Because these features are invisible at a distance the existence of the two species long went unrecognized.

ed off eastern Australia, 50 were recovered on South Georgia, most of them more than once. During the same period 6,601 wanderers were banded on South Georgia and 14 of them were recovered off Australia. In all 27 of the 64 passages between the two areas took place within six months or less; 12 birds made the passage both ways and one of them did it within a span of 12 months. It therefore appears that, far from wandering, these birds navigate regularly over long distances between nesting areas and comparatively restricted feeding grounds.

The best available information about the great albatrosses' speed of flight was obtained long before the advent of modern birdbanding. On December 30, 1847, Captain Hiram Luther of the whaler *Cachalot* shot a great albatross off the Pacific coast of South America at 43 degrees 24 minutes south latitude and 79 degrees five minutes west longitude. A vial tied to the bird's neck contained the following message: "Dec. 8th 1847. Ship *Euphrates*, Edwards, 16 months out, 2,300 barrels of oil, 150 of it sperm. I have not seen a whale for 4 months. Lat. 43 degrees south, long. 148 degrees, 40 minutes west. Thick fog with rain."

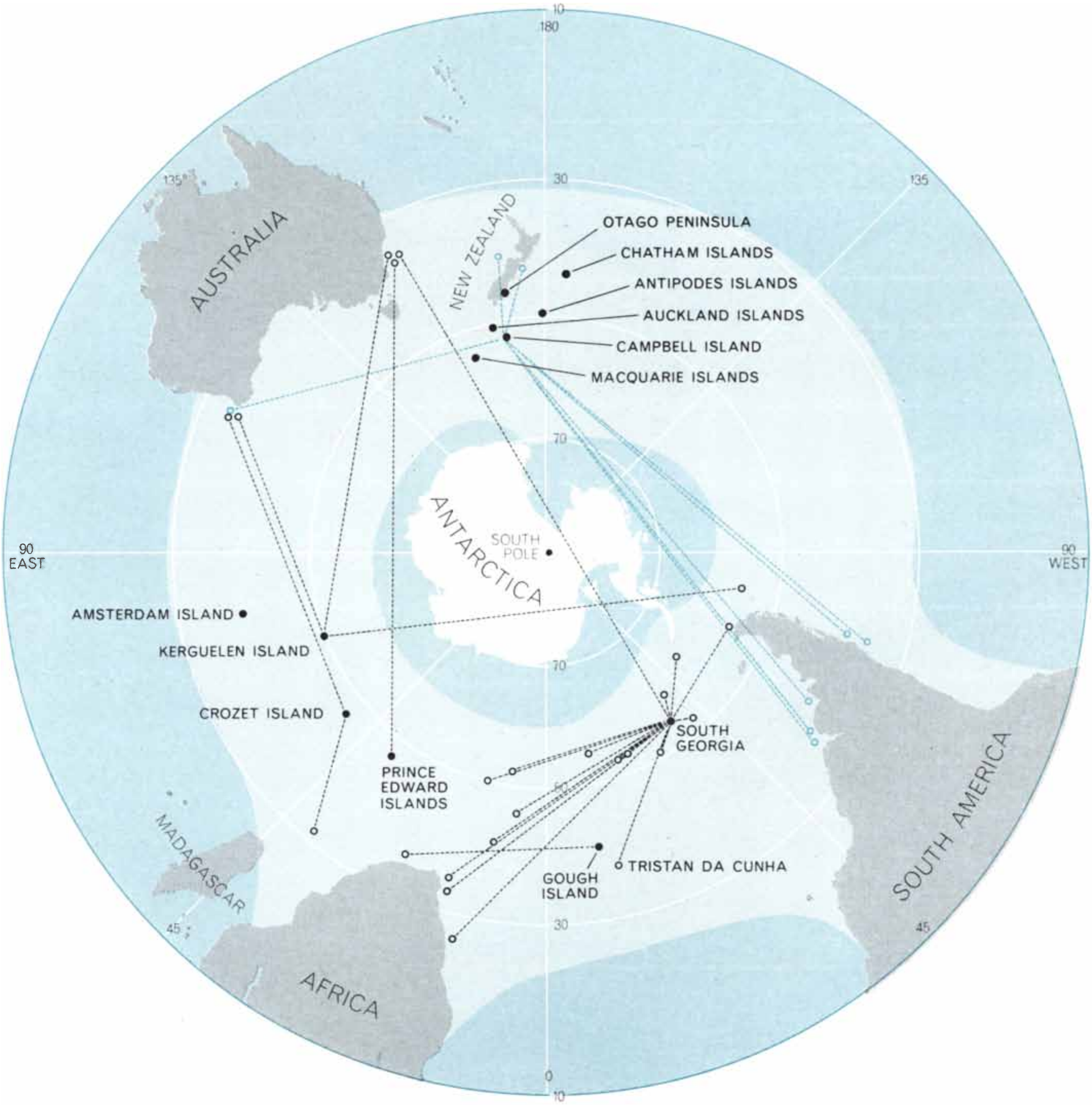
The bird had covered the 2,950 nautical miles between release and recapture in 22 days, an average of 134 miles a day. At this speed a wanderer could make the 7,000-mile flight from South Georgia to eastern Australia within eight weeks, and there is no reason the great albatrosses could not circumnavigate the Southern Hemisphere several times in a year.

The Australian observations indicate that the great albatrosses never stay long at one feeding ground but soon move to other areas. Off New South Wales the birds' arrival is associated with the appearance of shoals of large cuttlefish, which are pursued by schools of larger predators, including porpoises. The albatrosses feed on the leftover fragments of cuttlefish. The feeding grounds that have been observed attract birds from a number of different nesting grounds. Among the wanderers visiting the waters off New South Wales, in addition to those from South Georgia, were birds from the Prince Edward Islands, the Crozet Islands, Kerguelen Island and the Auckland Islands [*see illustration on opposite page*].

Although royal albatrosses rarely visit Australian waters, other feeding grounds evidently attract birds of both species. Both wanderers banded on South Georgia and royals banded on Campbell Island have been recovered among the great numbers of seabirds that gather around the boats in the large South Atlantic fishery off the coast of Argentina.

The great albatrosses have adapted to a marine environment at the expense of their agility on land. As a result a characteristic feature of their nesting grounds is a gentle slope exposed to the prevailing winds, which makes it easy for them to take off. The birds find such slopes almost exclusively on the small uninhabited islands of the subantarctic Atlantic, Indian and Pacific oceans. Their nesting islands, in addition to those already mentioned, include Tristan da Cunha, Gough Island, Amsterdam Island, the Macquarie Islands and the Antipodes Islands. The nests of both species are found together in only two places: on Campbell Island and in the Aucklands.

Because their nesting areas are so isolated the great albatrosses have no natural enemies of any consequence other than man. In the late 18th and early 19th centuries, following the discovery of their nesting grounds, British and U.S. sealing ships often visited the islands, and shipwrecked men sometimes survived on them for months or even years. On such occasions the birds and their eggs were taken for food, with the result that in some places they were all but exterminated. The caves on Macquarie Island, once occupied by sealers, have yielded wanderer skulls by the score. In 1913, when a party from Sir Douglas Mawson's Australian antarctic expedition wintered on Macquarie, only one wanderer nest could be found. In the period since World War II, however,

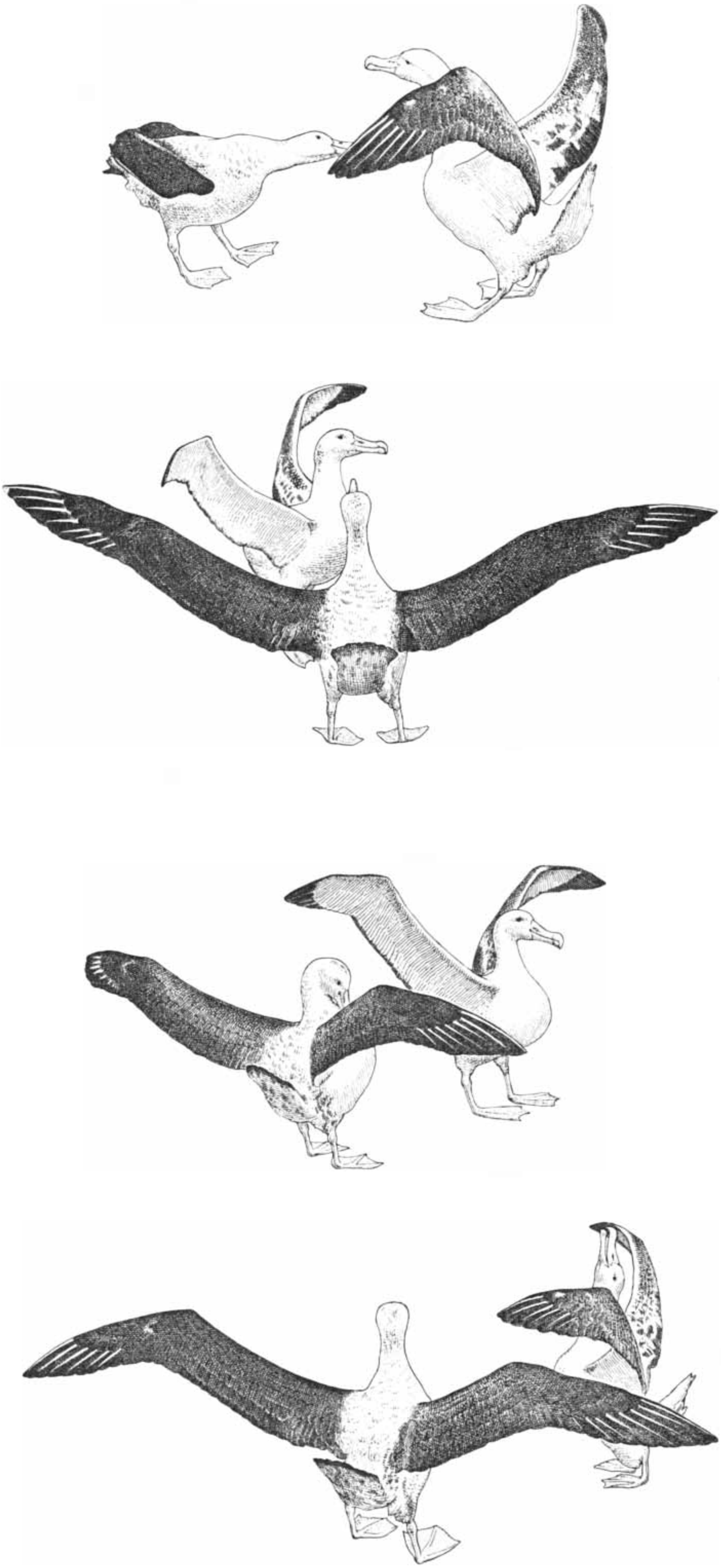


RANGE OF GREAT ALBATROSSES extends generally from 30 to 60 degrees south latitude. The nesting islands occupied by the two species are named on the map. The broken lines connecting the islands with feeding grounds indicate instances when birds banded in their nests have later been recovered at sea, or vice versa. The black lines indicate such recoveries in the case of the wandering albatross; the colored lines, instances of royal albatross recoveries. The orientation of a line does not portray the bird's flight path.

Australian visitors to Macquarie have discovered that the wanderer population somehow survived this low point, or perhaps reestablished a colony, and it is now showing an increasing rate of growth. Simultaneous study of this small but expanding population and the large and apparently stable wanderer population on South Georgia provides an excellent opportunity for examining the population dynamics of the same species at different positions on the curve of its population growth.

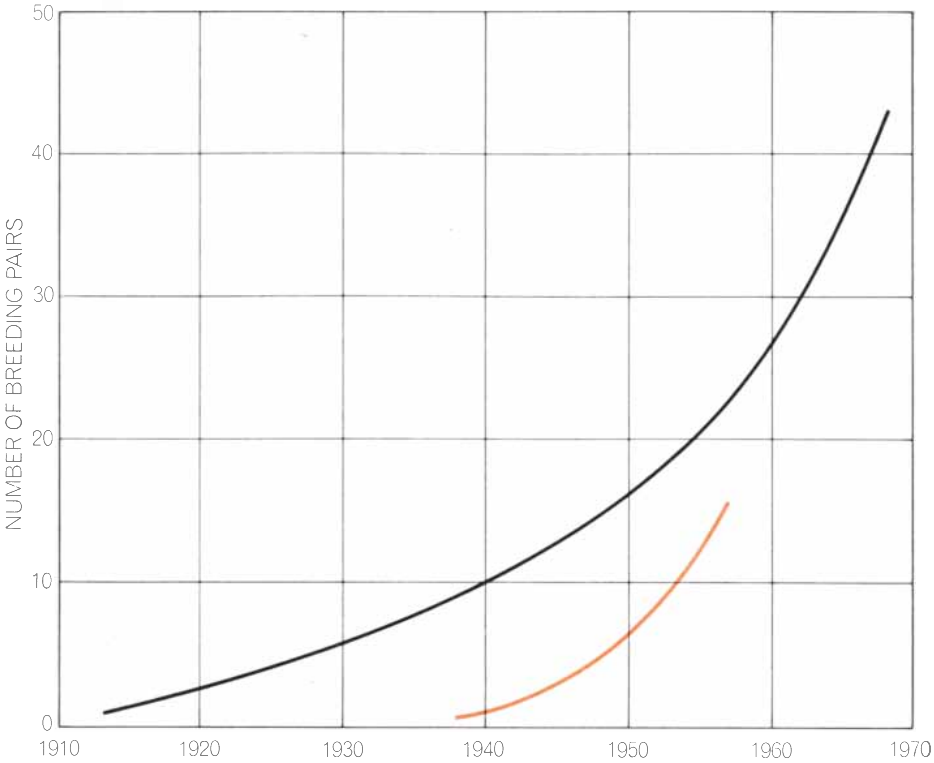
At nesting time the great albatross female lays a single egg. If the egg hatches successfully and the chick lives, the parents must feed it for an entire winter until it is able to fly and fend for itself at sea. As a result successful albatross parents reproduce only every other year. The birds' neuroendocrine apparatus can apparently respond to external stimuli to mediate an annual cycle of gonad regeneration, acceleration and culmination, but the presence of either an egg or a chick initiates a negative feedback that breaks the cycle after the usual postnuptial gonad regression and inhibits normal regeneration for 10 months. This is a nicely adapted mechanism; it gives the parents an opportunity to breed every year, removing that option only when there is a good chance that the current season's breeding will reach a successful conclusion.

Once the parents begin to care for the egg, their capacity to breed the following year gradually diminishes. The wanderer egg is usually laid in December. If some accident results in its destruction immediately after it is laid, both parents will then go to sea, returning to breed the following season. By March, when the chicks hatch, parents that then lose either an incubated egg or a young chick are less likely to breed the following December; their capacity to do so diminishes sharply the longer the chick has been in the nest. Of 19 wanderer pairs that lost their chicks on South Georgia between March and June of 1963, only 12 managed to breed the following December, and not one of 16 pairs that lost young between June and October was able to do so. It appears that males may



RITUAL "DANCE" of the wandering albatross is actually the agonistic responses of an unmated male and female that are not familiar with each other. The signals, both visual and vocal, alternately attract, repel and appease the potential partner until eventually the birds are at ease in each other's presence and a pair bond is established.

come into breeding condition more readily than females: two of the nine male parents that lost chicks in July and August returned at the beginning of December with testes showing advanced stages of spermatogenesis. Therefore in at least some pairs failure to breed may be solely the female's responsibility.



POPULATION GROWTH in the two species of great albatross appears to be quite similar. The first curve (*black*) projects the growth of the wanderer population on Macquarie Island since 1913, when only one albatross nest was found there, to the present. The second (*color*) indicates the growth of the royal population in New Zealand from 1938 to 1960.

Theoretically if every egg laid by a great albatross female produced a fledgling, then exactly half of the total population of any nesting area would breed in each successive year and the breeding pairs would always be composed of individuals from the same half-population. If, on the other hand, all the eggs produced in one summer were destroyed, the breeders in that half-population would return to breed the following year and join the other half, so that the entire breeding population would nest together in a single season. Of course neither extreme actually occurs. Among undisturbed birds the natural mortality of eggs and chicks means that some parental pairs are always moving from one half of the breeding population to the other, and the stabilized "demipopulation" is rather more than half of the total biennial breeding population. The size of the demipopulation is directly related to the magnitude of the mean annual loss of eggs and young chicks. On South Georgia 20 percent of the pairs breeding in any one year were unsuccessful and nested again the following year, so that the demipopulation was 55 percent of the total.

The population dynamics of the great albatrosses are complicated by the birds' biennial breeding cycle. One can only determine the total of nesting pairs in a population by adding two consecutive years' censuses and then subtracting the pairs that failed in the first year and bred again in the second. Therefore without knowing the survival rates for eggs and chicks at all the breeding grounds it is impossible to estimate the world population of great albatrosses with precision. Most of the nesting islands have been visited, however, and a rough calculation indicates that there are about 10,000 pairs of breeding royals, almost all of them on Campbell Island and the Chatham Islands. More than 14,000 breeding pairs of wanderers nest at nine of the 11 islands where these birds breed; when figures are obtained from Kerguelen and Amsterdam Island, it is probable that the world breeding stock of wanderers will total somewhere near 20,000 pairs, or about twice the number of royals. When we know enough to add the young and subadult birds of each species to this figure, the total will certainly be very much larger.

The life cycle of the great albatrosses is unique in the extraordinary length of the fledging period. It averages 236 days for royals and 278 days for wanderers. The difference of 42 days between species otherwise so similar is outstanding; it is almost certainly associated with the different conditions under which the two birds nest. South Georgia, being a subantarctic island, is completely covered with snow for several months during the winter. The ground is frozen and the mean air temperature is minus 2 degrees Celsius. New Zealand and its neighboring islands have a much milder winter. On the Otago Peninsula the midwinter (July) air temperature averages 7 degrees C. and there are only about five days of snow each year. As a result the metabolic demands for insulation and the generation of heat are likely to be much lower in the chicks of the New Zealand royals than in the chicks of the South Georgia wanderers. Another consequence of the difference in climate seems to be that the wanderer chicks receive more food, grow bigger and take longer to lose excess weight before their first flight than the royal chicks do. This conclusion is supported by observations of plumage development: wanderer chicks stay in down about 60 days longer than royal chicks, although the growth of the primary feathers takes about the same time in both species.

Newly hatched, a great albatross chick weighs between 10.5 and 14 ounces. The parent does not feed it during its first 24 hours out of the shell, and over the next three days it receives only small amounts of stomach oil. Thereafter its meals become progressively larger. At the end of 32 days the chick's heat-regulating mechanisms are sufficiently active for brooding to no longer be necessary. The chick has then reached a weight of about 6.5 pounds.

Once the brooding period is over both parents go to sea to forage for fish and squid, which are brought back and fed to the chick as a neatly regurgitated, partly digested mush. The chick receives one such meal roughly every third day, for an average monthly total of 20 pounds of mush and a cumulative total of nearly 180 pounds for the 250 days between end of brooding and first flight. Its body weight fluctuates widely from day to day, depending on the amount of food it receives. When averaged, however, the pooled daily weight of 24 wanderer chicks under observation at the Bird Island station showed a growth-and-weight curve that is characteristic of all procellariiform birds.

The chicks' weight plateau is reached between 80 and 40 days before their time of departure. Thereafter parental attention begins to wane, the frequency of feeding declines and the juveniles begin to lose weight. In many studies of petrel rookeries this has been called the "starvation period." It is a misleading term; although a chick may receive fewer meals than average, the parents continue to bring it food. The mean interval we observed between the last time of feeding and the time of departure for 19 wanderer chicks on Bird Island was 6.8 ± 1.4 days. All 19 had fasted much longer (as long as 14 ± 1 days) earlier in their fledging period.

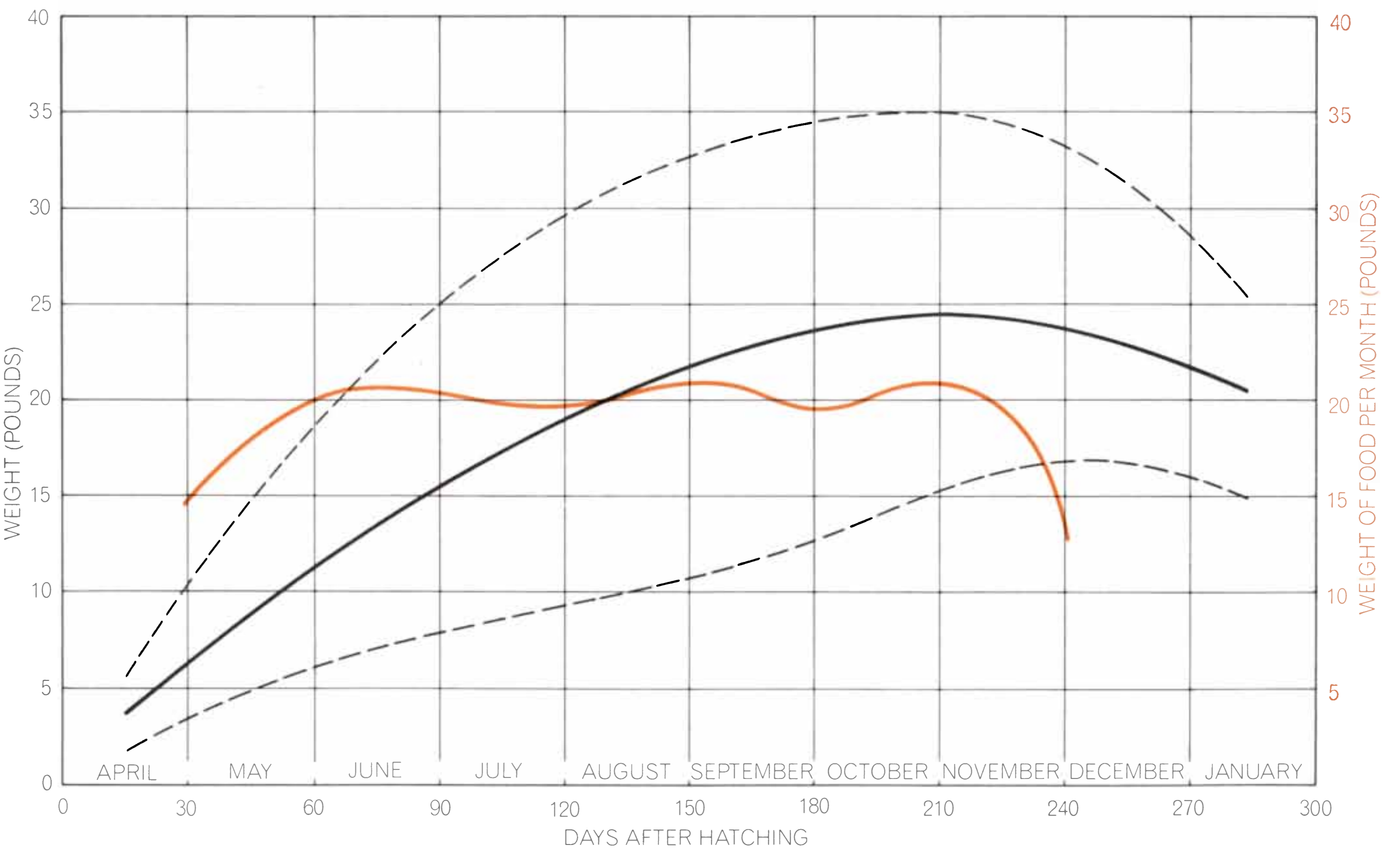
In spite of the parents' considerable powers of flight, the need to feed a chick on the average once every three days imposes a substantial limitation on the size of the ocean area where food may be sought. In effect the main supply must be available all year round within approximately 36 hours' flying time of the nest, which is equivalent to a radius of about 200 nautical miles. Where South Georgia is concerned, high concentrations of zooplankton are found not far north of the island; this is the food supply that was responsible for the former abundance of baleen whales in the vicinity. To discover if parents from the Bird Island nesting ground were feeding in this area of abundant marine life we marked several hundred nesting adults with a pink dye [*see top illustration on page 86*]. We then asked the numerous whale-catching vessels that still traversed the area, and also occasional passing antarctic expedition ships, to report any sightings of dyed birds. Enough reports were received to show that many pink albatrosses from South Georgia were in fact feeding in the plankton-rich waters within 150 miles of the island.

When the juvenile albatross leaves the nest, it goes to sea for a few years. Recoveries of banded juveniles indicate that during these early years they cover just as much territory as adult birds. The immature birds first begin to return at an age of about four years to spend the summer on the islands where they were hatched. On Bird Island some 50 percent of 656 wanderers we banded as chicks in our first season's fieldwork had returned to South Georgia by the time they were six years old. The initial period at sea seems to be longer for the royals. So far three age-marked birds are reported to have returned to Taiaroa Head; one was six years old, the others were eight.

Compared with the high mortality rate of most birds, the mortality rate of the great albatrosses is remarkably low. On Campbell Island 75 percent of royal eggs (and on Bird Island 58 percent of wanderer eggs) produced viable young. Half of the wanderers hatched on Bird Island survive to the age of six and return to the nesting ground. By the time the subadults reach the breeding age, in their 10th year, the mortality rate has dropped to a yearly level of about 4.3 percent. An equivalent figure of 3 percent is reported for adult royals.

During the early years of their summer return to home ground the subadult birds are mainly solitary. This is not true of adults in instances where one member of a breeding pair has died. The surviving partner actively seeks a new mate when it arrives the next summer. As the years pass the subadults begin to join in the "dances" that constitute the birds' courtship ritual. These dramatic displays involve a single male and one or more females. The females are attracted by the males, but the males are often reluctant to allow the females to approach too close.

The performance consists of a series of visual and vocal signals that alternately attract, repel and appease the poten-



CHICK'S WEIGHT GAIN during the nine-month period between hatching and first flight fluctuates widely from day to day but is close to the mean between the maximum and minimum values recorded (*black*) for 24 wandering albatross nestlings weighed daily on Bird Island. The average amount of food received per month (*color*) dips sharply as the fledglings prepare to leave the island.

tial partner. Gradually the male comes to spend more and more time with a particular female and the frequency of dancing diminishes. Eventually a pair bond is established; male and female recognize each other without hesitation and a confrontation no longer elicits the stereotyped, agonistic responses of the dance. Thus the young albatross spends about five years at sea, presumably learning the marine environment; this initial experience is followed by about five summers of courting and five more winters at sea.

For two distinct species the great albatrosses are remarkably similar. With two notable exceptions—the differences in length of fledging period and in fledgling plumage color—most of the detectable variations amount to no more than the variations between the races of either species. It is possible that both exceptions are a function of related responses to the environment. As I have noted, the milder winter climate of New Zealand is probably responsible for the royal fledging period's being shorter than that of the wanderer. As a result when the pairs of adult royals that are ready to breed reach Taiaroa Head to start nesting, most if not all of the previous season's royal fledglings have already left for their first summer at sea. (No data on this point are available from the colonies of royals on Campbell Island and the Chathams.)

The wanderer fledging period is so much longer that when breeding adults return to Bird Island many fledglings from the preceding season are still occupying the nesting ground. The mean date for the arrival of adult males on Bird Island is November 30. The adult females arrive around December 10, which is also the mean date of departure for the preceding season's fledglings. At that time of year the fledglings are very active and aggressive, behaving in a manner that could easily interfere with the nesting of the arriving adults. There could well be a selective value in the dark plumage that makes the wanderer fledglings recognizable at a distance to adult wanderers. In view of the royal fledglings' early departure from Taiaroa Head, however, such a ready distinction would be of no importance there.

CHICK IN MIDWINTER on Bird Island keeps to its nest, depending for warmth on a coat of down, a subcutaneous layer of fat and two pounds of fish mush brought every third day.

FLEDGED AFTER NINE MONTHS, a young wandering albatross faces into the wind on a slope on Bird Island and stretches its wings in anticipation of its impending first flight.

The wandering albatross and the royal albatross not only share part of their open-ocean habitat but also nest together on two islands. Yet the marked difference between the sizes of the two populations and the location of their major breeding grounds evidently reflects an evolution of the two species from a single ancestral stock within comparatively recent times. The cold-temperate and subantarctic regions of the Southern Hemisphere are a rigorous environment where new ecological niches rarely develop. Nonetheless, the history of glacial advances, halts and retreats that characterized the Pleistocene period of the Northern Hemisphere had its counterpart in the Southern Hemisphere, where the antarctic ice sheet and its fringe of shelf ice also advanced and retreated to some extent.

Such glacial ebbs and flows probably fragmented and altered an environment that had previously been favorable to maintenance of the single stock ancestral to the two present species of great albatrosses. Fluctuations in ice cover could have led to changes in the vegetation of the nesting islands; changes in sea temperature and salinity must have affected the availability of food organisms within easy flying distance of land. In the course of such changes some nesting islands may well have become effectively isolated. An interruption of the usual gene flow between nesting grounds would have sufficed to allow the two separate lines of great albatrosses to evolve. Subsequently the disappearance of these Pleistocene barriers probably allowed the ranges of the two species to reexpand, bringing the royal albatross and the wandering albatross back into limited contact in the seas south of New Zealand.

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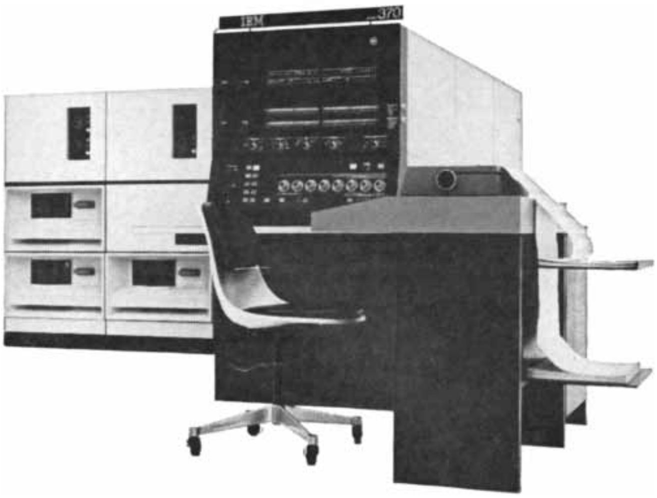

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Experiments in Intergroup Discrimination

Can discrimination be traced to some such origin as social conflict or a history of hostility? Not necessarily. Apparently the mere fact of division into groups is enough to trigger discriminatory behavior

by Henri Tajfel

Intergroup discrimination is a feature of most modern societies. The phenomenon is depressingly similar regardless of the constitution of the "ingroup" and of the "outgroup" that is perceived as being somehow different. A Slovene friend of mine once described to me the stereotypes—the common traits attributed to a large human group—that are applied in his country, the richest constituent republic of Yugoslavia, to immigrant Bosnians, who come from a poorer region. Some time later I presented this description to a group of students at the University of Oxford and asked them to guess by whom it was used and to whom it referred. The almost unanimous reply was that this was the characterization applied by native Englishmen to "colored" immigrants: people coming primarily from the West Indies, India and Pakistan.

The intensity of discrimination varies more than the nature of the phenomenon. In countries with long-standing intergroup problems—be they racial as in the U.S., religious as in Northern Ireland or linguistic-national as in Belgium—tensions reach the boiling point more easily than they do elsewhere. In spite of differing economic, cultural, historical, political and psychological backgrounds, however, the *attitudes* of prejudice toward outgroups and the *behavior* of discrimination against outgroups clearly display a set of common characteristics. Social scientists have naturally been concerned to try to identify these characteristics in an effort to understand the origins of prejudice and discrimination.

The investigative approaches to this task can be roughly classified into two categories. Some workers stress the social determinants of prejudice and discrimination. Others emphasize psychological causation. In *The Functions of Social Conflict*, published in 1956, Lewis A. Coser of Brandeis University established a related dichotomy when he distinguished between two types of intergroup conflict: the "rational" and the "irrational." The former is a means to an end: the conflict and the attitudes that go with it reflect a genuine competition between groups with divergent interests. The latter is an end in itself: it serves to release accumulated emotional tensions of various kinds. As both popular lore and the psychological literature testify, nothing is better suited for this purpose than a well-selected scapegoat.

These dichotomies have some value as analytical tools but they need not be taken too seriously. Most cases of conflict between human groups, large or small, reflect an intricate interdependence of social and psychological causation. Often it is difficult, and probably fruitless, to speculate about what were the first causes of real present-day social situations. Moreover, there is a dialectical relation between the objective and the subjective determinants of intergroup attitudes and behavior. Once the process is set in motion they reinforce each other in a relentless spiral in which the weight of predominant causes tends to shift continuously. For example, economic or social competition can lead to discriminatory behavior; that behavior can then in a number of ways create attitudes of prejudice; those attitudes can in turn lead to new forms of discriminatory behavior that create new economic or social disparities, and so the vicious circle is continued.

The interdependence of the two types of causation does not manifest itself only in their mutual reinforcement. They actually converge because of the psychological effects on an individual of his sociocultural milieu. This convergence is often considered in terms of social learning and conformity. For instance, there is much evidence that children learn quite early the pecking order of evaluations of various groups that prevails in their society, and that the order remains fairly stable. This applies not only to the evaluation of groups that are in daily contact, such as racial groups in mixed environments, but also to ideas about foreign nations with which there is little if any personal contact.

In studies conducted at Oxford a few years ago my colleagues and I found a high consensus among children of six and seven in their preference for four foreign countries. The order was America, France, Germany and Russia, and there was a correlation of .98 between the preferences of subjects from two different schools. As for adults, studies conducted by Thomas F. Pettigrew in the late 1950's in South Africa and in the American South have shown that conformity is an important determinant of hostile attitudes toward blacks in both places (above and beyond individual tendencies toward authoritarianism, which is known to be closely related to prejudice toward outgroups).

These studies, like many others, were concerned with attitudes rather than behavior, with prejudice rather than discrimination. Discrimination, it is often said, is more directly a function of the objective social situation, which sometimes does and sometimes does not facilitate the expression of attitudes; the attitudes of prejudice may be socially learned or due to tendencies to conform, but they are not a very efficient predictor of discriminatory behavior. According to this view, psychological considerations are best suited to explaining and predict-

A

MATRIX 1

−19	−16	−13	−10	−7	−4	−1	0	1	2	3	4	5	6
6	5	4	3	2	1	0	−1	−4	−7	−10	−13	−16	−19

MATRIX 2

12	10	8	6	4	2	0	−1	−5	−9	−13	−17	−21	−25
−25	−21	−17	−13	−9	−5	−1	0	2	4	6	8	10	12

B

MATRIX 3

1	2	3	4	5	6	7	8	9	10	11	12	13	14
14	13	12	11	10	9	8	7	6	5	4	3	2	1

MATRIX 4

18	17	16	15	14	13	12	11	10	9	8	7	6	5
5	6	7	8	9	10	11	12	13	14	15	16	17	18

C

MATRIX 5

−14	−12	−10	−8	−6	−4	−2	−1	3	7	11	15	19	23
23	19	15	11	7	3	−1	−2	−4	−6	−8	−10	−12	−14

MATRIX 6

17	14	11	8	5	2	−1	−2	−3	−4	−5	−6	−7	−8
−8	−7	−6	−5	−4	−3	−2	−1	2	5	8	11	14	17

FIRST EXPERIMENT conducted by the author and his colleagues utilized these six matrices. The numbers represented points (later translated into awards or penalties in money) to be assigned by a subject to other individuals; by checking a box the subject assigned the number of points in the top of the box to one person and the number in the bottom of the box to another person; he did not know the identity of these people but only whether each was a member of his own group or "the other group." (The groups had been established by the experimenters on grounds that were artificial and insignificant.) Each matrix appeared three times in a test booklet with each row of numbers labeled to indicate whether the subject was choosing between two members of his own group (ingroup) other than himself, two members of the outgroup or one member of the ingroup and one member of the outgroup. Choices were scored to see if subjects chose for fairness, maximum gain to their own group or maximum difference in favor of the ingroup.

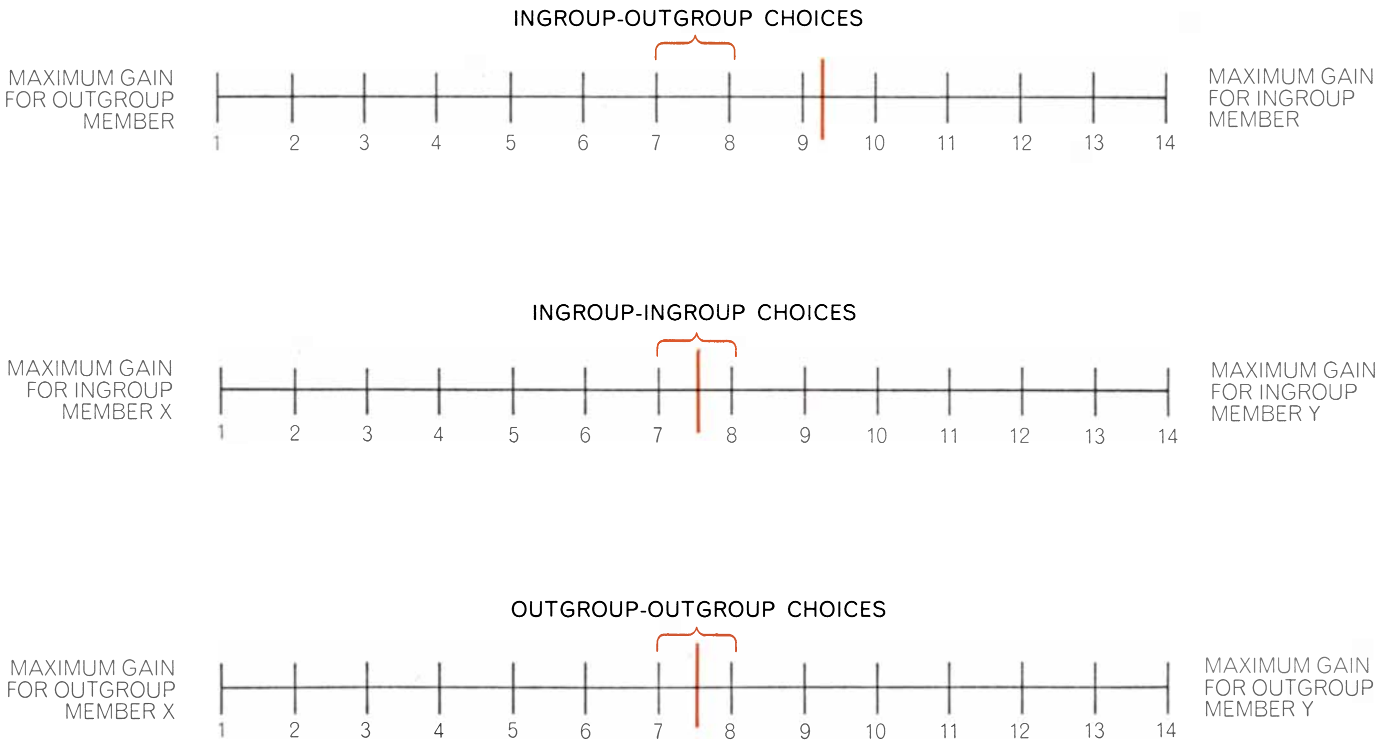
ing the genesis and functioning of attitudes; the facts of intergroup discrimination are best related to, and predicted from, objective indexes of a social, economic and demographic nature.

Although I have no quarrel with this view, I am left with a nagging feeling that it omits an important part of the story. The fact is that behavior toward outgroups shows the same monotonous similarity as attitudes do, across a diversity of socioeconomic conditions. This apparent diversity may, of course, obscure an underlying common factor of "rational" conflict, of struggle to preserve a *status quo* favorable to oneself or to obtain an equitable share of social opportunities and benefits. Another kind of underlying regularity is nonetheless common to a variety of social situations and is an important psychological effect of our sociocultural milieu. It is the assimilation by the individual of the various norms of conduct that prevail in his society.

For the purposes of this article I shall define social norms as being an individual's expectation of how others expect him to behave and his expectation of how others will behave in any given social situation. Whether he does or does not behave according to these expectations depends primarily on his understanding of whether or not and how a situation relates to a specific set of expectations. If a link is made between the one and the other—if an individual's understanding of a situation in which he finds himself is such that in his view certain familiar social norms are pertinent to it—he behaves accordingly.

There is nothing new to this formulation; it is inherent in most studies and discussions of intergroup prejudice and discrimination that stress the importance of conformity. The point I wish to make is broader. Conformity contributes to hostile attitudes and behavior toward specified groups of people in situations that are usually characterized by a history of intergroup tensions, conflicts of interest and early acquisition by individuals of hostile views about selected outgroups. We are dealing, however, with a process that is more general and goes deeper than the learning of value judgments about a specific group and the subsequent acting out of accepted patterns of behavior toward that group. The child learns not only whom he should like or dislike in the complex social environment to which he is exposed but also something more basic. An individual constructs his own "web of social affiliations" by applying principles of order and simplification that reduce the complexity of crisscrossing human categorizations. Perhaps the most important principle of the subjective social order we construct for ourselves is the classification of groups as "we" and "they"—as ingroups (any number of them to which we happen to belong) and outgroups. The criteria for these assignments may vary according to the situation, and their emotional impact may be high or low, but in our societies this division into groups most often implies a competitive relation between the groups. In other words, intergroup categorizations of all kinds may bring into play what seems to the individual to be the appropriate form of intergroup behavior.

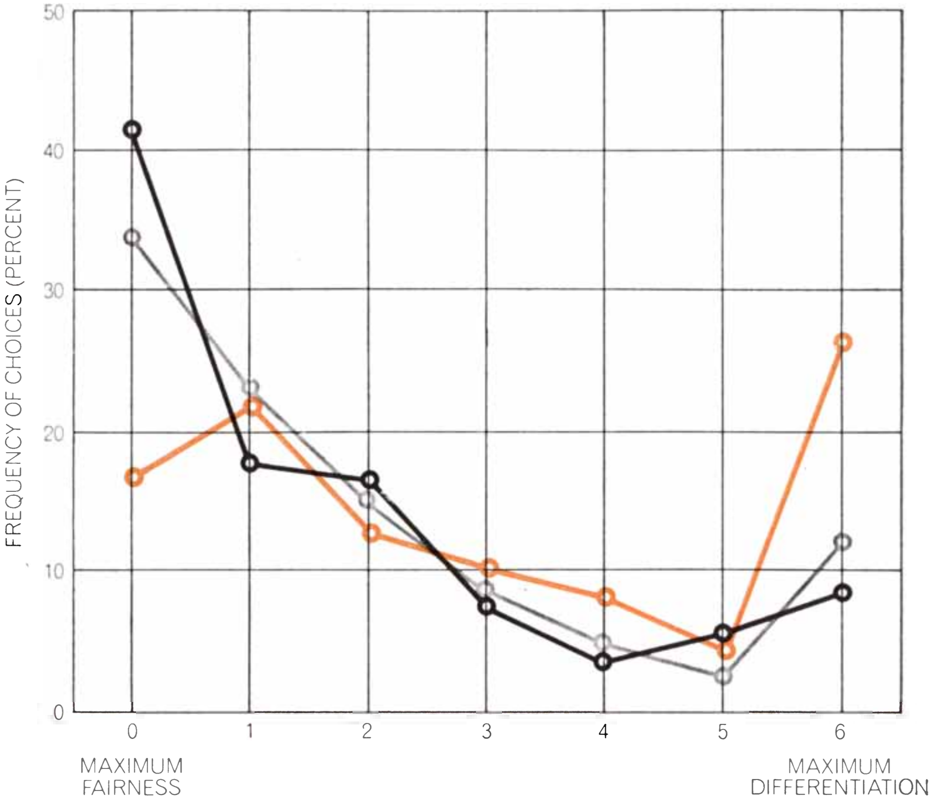
What this essentially means is that the need to bring some kind of order into our "social construction of reality" (a term recently used by Peter L. Berger of the New School for Social Research and Thomas Luckmann of the University of Frankfurt) combines with the hostility inherent in many of the intergroup categorizations to which we are continually exposed to develop a "generic norm" of behavior toward outgroups. Whenever we are confronted with a situation to which some form of intergroup categorization appears directly relevant, we are likely to act in a manner that discrimi-



RESULTS WERE SCORED by ranking the choices from 1 to 14 depending on which box was checked. The end of the matrix at which the ingroup member got the minimum number of points (and the outgroup member the maximum) was designated 1; the other end, giving the ingroup member the maximum, was 14. The mean choices (*colored vertical lines*) are shown here. In the intergroup situation the subjects gave significantly more points to members of their own group than to members of the other group. In the intragroup situations, however, the means of the choices fell at Rank 7.5, between the choices of maximum fairness (*brackets*).

nates against the outgroup and favors the ingroup.

If this is true, if there exists such a generic norm of behavior toward outgroups, several important consequences should follow. The first is that there may be discrimination against an outgroup even if there is no reason for it in terms of the individual's own interests—in terms of what he can gain as a result of discriminating against the outgroup. The second consequence is that there may be such discrimination in the absence of any previously existing attitudes of hostility or dislike toward the outgroup. And the third consequence, following directly from the second, is that this generic norm may manifest itself directly in behavior toward the outgroup before any attitudes of prejudice or hostility have been formed. If this reasoning is correct, then discriminatory intergroup behavior can sometimes be expected even if the individual is not involved in actual (or even imagined) conflicts of interest and has no past history of attitudes of intergroup hostility.



INTERGROUP DISCRIMINATION was a deliberate strategy in the ingroup-outgroup choices (*colored curve*) and fairness a deliberate strategy in the ingroup-ingroup (*gray*) and outgroup-outgroup (*black*) choices. This is indicated by the fact that the frequencies of intergroup choices differed significantly from those of the intragroup choices only at the extreme points of the distribution, the points of maximum fairness and of maximum discrimination. (For this analysis the two fairest choices in each matrix, the two middle ones, were ranked together as 0 and departures in either direction were scored from 1 to 6.)

At the University of Bristol, in collaboration with Claude Flament of the University of Aix-Marseille, R. P. Bundy and M. J. Billig, I have conducted experiments designed to test this prediction and others that follow from it. The main problem was to create experimental conditions that would enable us to assess the effects of intergroup categorization per se, uncontaminated by other variables, such as interactions among individuals or preexisting attitudes. We aimed, moreover, to look at the behavior rather than the attitudes of the subjects toward their own group and the other group, to ensure that this behavior was of some importance to them and to present them with a clear alternative to discriminating against the outgroup that would be a more "sensible" mode of behavior.

Perhaps the best means of conveying the way these criteria were met is to describe the procedure we followed in the first experiments and its variants in subsequent ones. Our subjects were 64 boys 14 and 15 years old from a state, or "comprehensive," school in a suburb of Bristol. They came to the laboratory in separate groups of eight. All the boys in each of the groups were from the same house in the same form at the school, so that they knew each other well before the experiment. The first part of the experiment served to establish an intergroup categorization and in the second part we assessed the effects of that categorization on intergroup behavior.

In the first part the boys were brought together in a lecture room and were told that we were interested in the study of visual judgments. Forty clusters of varying numbers of dots were flashed on a screen. The boys were asked to estimate the number of dots in each cluster and to record each estimate in succession on prepared score sheets. There were two conditions in this first part of the experiment. In one condition, after the boys had completed their estimates they were told that in judgments of this kind some people consistently overestimate the number of dots and some consistently underestimate the number, but that these tendencies are in no way related to accuracy. In the other condition the boys were told that some people are consistently more accurate than others. Four groups of eight served in each of the two conditions.

After the judgments had been made and had been ostentatiously "scored" by one of the experimenters, we told the subjects that, since we were also interested in other kinds of decision, we were going to take advantage of their presence to investigate these as well, and that for ease of coding we were going to group them on the basis of the visual judgments they had just made. In actuality the subjects were assigned to groups quite at random, half to "underestimators" and half to "overestimators" in the first condition, half to "better" and half to "worse" accuracy in the second one.

Instructions followed about the nature of the forthcoming task. The boys were told that it would consist of giving to others rewards and penalties in real money. They would not know the identity of the individuals to whom they would be assigning these rewards and penalties since everyone would have a code number. They would be taken to another room one by one and given information as to which group they were in. Once in the other room they were to work on their own in separate cubicles. In each cubicle they would find a pencil and a booklet containing 18 sets of ordered numbers, one to each page. It was stressed that on no occasion would the boys be rewarding or penalizing themselves; they would always be allotting money to others. At the end of the task each boy would be brought back into

A

MATRIX 1

19	18	17	16	15	14	13	12	11	10	9	8	7
1	3	5	7	9	11	13	15	17	19	21	23	25

MIP
MD

MJP

MJP
MIP
MD

MATRIX 2

23	22	21	20	19	18	17	16	15	14	13	12	11
5	7	9	11	13	15	17	19	21	23	25	27	29

B

MATRIX 3

7	8	9	10	11	12	13	14	15	16	17	18	19
1	3	5	7	9	11	13	15	17	19	21	23	25

MIP
MJP

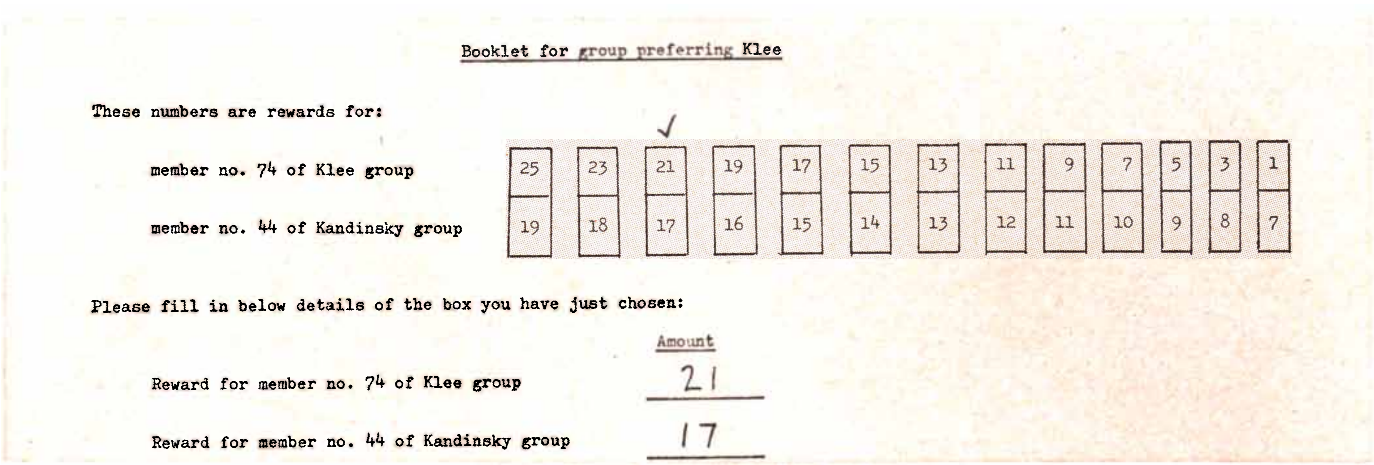
MD

MIP
MJP
MD

MATRIX 4

11	12	13	14	15	16	17	18	19	20	21	22	23
5	7	9	11	13	15	17	19	21	23	25	27	29

SECOND EXPERIMENT involved new matrices. Each was presented in four versions labeled (as in the illustration at the bottom of this page) to indicate whether the choice was between members of different groups or between two members of the same group; the intergroup choices sometimes had the ingroup member's points in the top row and sometimes had them in the bottom row. The objective now was to analyze the influence of three variables on the subjects' choices: maximum ingroup profit (*MIP*), maximum joint profit (*MJP*) and maximum difference in favor of the ingroup member (*MD*). These varied according to different patterns in the Type *A* and Type *B* matrices and in the different versions; in some cases the maxima were together at one end of the matrix and in other cases they were at opposite ends. For example, in the ingroup-over-outgroup version of Type *A* matrices the maximum ingroup profit and maximum difference were at one end and the maximum joint profit at the other end (*colored type*); in the outgroup-over-ingroup version of the same matrices the three maxima were together at the right-hand end of the matrices (*black type*). Type *B* ingroup-over-outgroup versions, on the other hand, distinguish the difference in favor of ingroup from the other two gains (*color*).


Booklet for group preferring Klee

These numbers are rewards for:

member no. 74 of Klee group	25	23	21 ✓	19	17	15	13	11	9	7	5	3	1
member no. 44 of Kandinsky group	19	18	17	16	15	14	13	12	11	10	9	8	7

Please fill in below details of the box you have just chosen:

	Amount
Reward for member no. 74 of Klee group	21
Reward for member no. 44 of Kandinsky group	17

PAGE OF BOOKLET, presenting a single matrix, is reproduced as a subject might have marked it. In addition to checking a box, the subject filled in the blanks below it to confirm his choice. The page heading reminded him which group he was in. The awards were made to persons identified only by number and group; the subject did not know who they were but only their group identification.

the first room and would receive the amount of money the other boys had awarded him. The value of each point they were awarding was a tenth of a penny (about a tenth of a U.S. cent). After these instructions were given, the boys were led individually to their cubicles to fill out their booklets.

On each page in the booklet there was one matrix consisting of 14 boxes containing two numbers each. The numbers in the top row were the rewards and penalties to be awarded to one person and those in the bottom row were those to be awarded to another. Each row was labeled "These are rewards and penalties for member No. ___ of your group" or "...of the other group." The subjects had to indicate their choices by checking one box in each matrix. On the cover of each booklet and at the top of each page was written: "Booklet for member of the ___ group."

There were six matrices [*see illustration on page 97*] and each of them appeared three times in the booklet—once for each of three types of choice. There were ingroup choices, with the top and the bottom row signifying the rewards and penalties to be awarded to two members of the subject's own group (other than himself). Then there were outgroup choices, with both rows signifying the rewards and penalties for a member of the other group. Finally there were intergroup, or "differential," choices, one row indicating the rewards and penalties to be awarded to an ingroup member (other than himself) and the other the points for an outgroup member. (The top and bottom positions of ingroup and outgroup members were varied at random.)

The results for the intergroup choices were first scored in terms of ranks of choices. In each matrix Rank 1 stood for the choice of the term that gave to the member of the ingroup the minimum possible number of points in that matrix; Rank 14, at the opposite extreme of the matrix, stood for the maximum possible number of points. Comparable (but more complex) methods of scoring were adopted for the other two kinds of choice, the ingroup choices and the outgroup ones, and for comparison of these choices with those made in the differential situation.

The results were striking. In making their intergroup choices a large majority of the subjects, in all groups in both conditions, gave more money to members of their own group than to members of the other group. All the results were—at a very high level of statistical significance—above both Rank 7.5, which represents the point of maximum fairness, and the mean ranks of the ingroup and outgroup choices. In contrast the ingroup and outgroup choices were closely distributed about the point of fairness. Further analysis made it clear that intergroup discrimination was the deliberate strategy adopted in making intergroup choices.

Before continuing, let us review the situation. The boys, who knew each other well, were divided into groups defined by flimsy and unimportant criteria. Their own individual interests were not affected by their choices, since they always assigned points to two other people and no one could know what any other boy's choices were. The amounts of money were not trivial for them: each boy left the experiment with the equivalent of about a dollar. Inasmuch as they could not know who was in their group and who was in the other group, they could have adopted either of two reasonable strategies. They could have chosen the maximum-joint-profit point of the matrices, which would mean that the boys as a total group would get the most money out of the experimenters, or they could choose the point of maximum fairness. Indeed, they did tend to choose the second alternative when their choices did not involve a distinction between ingroup and outgroup. As soon as this differentiation was involved, however, they discriminated in favor of the ingroup. The only thing we needed to do to achieve this result was to associate their judgments of numbers of dots with the use of the terms "your group" and "the other group" in the instructions and on the booklets of matrices.

The results were at a very high level of statistical significance in all eight separately tested groups of eight boys. In view of the consistency of the phenomenon we decided to analyze it further and also to validate it with a different criterion for intergroup categorization. We tested three new groups of 16 boys each, this time with aesthetic preference as the basis of the division into two groups. The boys were shown 12 slides, six of which were reproductions of paintings by Paul Klee and six by Wassily Kandinsky, and they were asked to express their preference for one or the other of these two "foreign painters." The reproductions were presented without the painter's signature, so that half of the subjects could be assigned at random to the "Klee group" and half to the "Kandinsky group."

The matrices that confronted the boys subsequently in their individual cubicles were different from those in the first experiment. We were now interested in assessing the relative weights of some of the variables that may have pulled their decisions in one direction or the other. In this experiment we looked at three variables: maximum joint profit, or the largest possible joint award to both people; maximum ingroup profit, or the largest possible award to a member of the ingroup, and maximum difference, or the largest possible difference in gain between a member of the ingroup and a member of the outgroup in favor of the former.

There were four different matrices [*see top illustration on opposite page*]. As in the first experiment, there were three types of choice: between a member of the ingroup and a member of the outgroup, between two members of the ingroup and between two members of the outgroup. In the outgroup-over-ingroup version of Type *A* matrices (that is, where the numbers in the top row represented amounts given to a member of the outgroup and in the bottom row to a member of the ingroup) the three gains—joint profit, ingroup profit and difference in favor of the ingroup—varied together; their maxima (maximum joint profit, maximum ingroup profit and maximum difference) were all at the same end of the matrix. In the ingroup-over-outgroup version, ingroup profit and difference in favor of ingroup went together in one direction and were in direct conflict with choices approaching maximum joint profit. In the Type *B* matrices outgroup-over-ingroup versions again represented a covariation of the three gains; in the ingroup-over-outgroup versions, difference in favor of ingroup varied in the direction opposite to joint profit and ingroup profit combined.

A comparison of the boys' choices in the various matrices showed that maximum joint profit exerted hardly any effect at all; the effect of maximum ingroup profit and maximum difference combined against maximum joint profit was strong and highly significant; the effect of maximum difference against maximum joint profit and maximum ingroup profit was also strong and highly significant. In other words, when the subjects had a choice between maximizing the profit for all and maximizing the profit for members of their own group, they acted on behalf of their own group. When they had a choice between profit for all and for their own group combined, as against their own group's winning *more* than the outgroup at the sacrifice of both of these utilitarian advantages, it was the maximization of *difference* that seemed more important to them.

Evidence leading in the same direction emerged from the other two types of choice, between two members of the ingroup and between two members of the outgroup: the ingroup choices were consistently and significantly nearer to the maximum joint profit than were the outgroup ones—and this was so in spite of the fact that giving as much as possible to two members of the outgroup in the choices applying solely to them presented no conflict with the ingroup's interest. It simply would have meant giving more to "the others" without giving any less to "your own." This represented, therefore, a clear case of gratuitous discrimination. We also included in the second experiment some of the original matrices used in the first one, with results much the same as before. Again all the results in this experiment were at a high level of statistical significance.

In subsequent experiments we tested the importance of fairness in making the choices, the effect on the choices of familiarity with the situation and the subjects' ideas about the choices that others were making. Fairness, we found, was an important determinant; most of the choices must be understood as being a compromise between fairness and favoring one's own group. We found that discrimination not only persisted but also increased when the entire situation became more familiar to the subjects. With familiarity there was also an increase (when the boys were asked to predict the other subjects' behavior) in their expectation that other boys were discriminating.

Much remains to be done to analyze the entire phenomenon in greater detail and to gain a fuller understanding of its determining conditions, but some clear inferences can already be made. Outgroup discrimination is extraordinarily easy to trigger off. In some previous studies of group conflict, such as one conducted by Muzafer Sherif at the University of Oklahoma, groups had to be placed in intense competition for several days for such results to occur [see "Experiments in Group Conflict," by Muzafer Sherif; SCIENTIFIC AMERICAN, November, 1956]; in other situations behavior of this kind can occur without direct conflict if it is based on previously existing hostility. Yet neither an objective conflict of interests nor hostility had any relevance whatever to what our subjects were asked to do. It was enough for them to see themselves as clearly categorized into an ingroup and an outgroup, flimsy as the criteria for this division were—even though the boys knew one another well before the experiments, their own individual gains were not involved in their decisions and their actions could have been aimed to achieve the greatest common good.

It would seem, then, that the generic norm of outgroup behavior to which I have referred does exist and that it helps to distort what might have been more reasonable conduct. This norm determines behavior—as other social norms do—when an individual finds himself in a situation to which, in his view, the norm applies. Behavior is never motiveless, but it is a crude oversimplification to think that motives in social situations include no more than calculations of self-interest or that they can be derived from a few supposedly universal human drives such as aggression toward the outsider, the need to affiliate and so on. To behave socially is a complex business. It involves a long learning process; it is based on the manipulation of symbols and abstractions; it implies the capacity for modification of conduct when the situation changes—and social situations never remain static. To behave *appropriately* is therefore a powerful social motive, and attempting to do so means to behave according to one's best understanding of the situation. Judgments of what is appropriate are determined by social norms, or sets of expectations.

It seems clear that two such norms were understood by our subjects to apply to the situation we imposed on them: "groupness" and "fairness." They managed to achieve a neat balance between the two, and one might assume that in real-life situations the same kind of balance would apply. Unfortunately it is only too easy to think of examples in real life where fairness would go out the window, since groupness is often based on criteria more weighty than either preferring a painter one has never heard of before or resembling someone else in one's way of counting dots. Socialization into "groupness" is powerful and unavoidable; it has innumerable valuable functions. It also has some odd side effects that may—and do—reinforce acute intergroup tensions whose roots lie elsewhere. Perhaps those educators in our competitive societies who from the earliest schooling are so keen on "teams" and "team spirit" could give some thought to the operation of these side effects.

WHY THE SEA IS SALT

The sea contains more than 70 elements in addition to sodium and chlorine. The global cycles that remove and replenish them involve rainfall, volcanoes and the spreading of the ocean floor

by Ferren MacIntyre

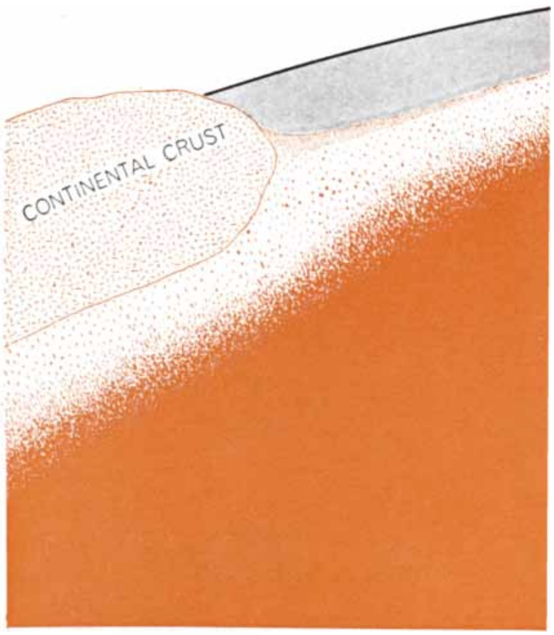
According to an old Norse folktale the sea is salt because somewhere at the bottom of the ocean a magic salt mill is steadily grinding away. The tale is perfectly true. Only the details need to be worked out. The "mill," as it is visualized in current geophysical theory, is the "mid-ocean" rift that meanders for 40,000 miles through all the major ocean basins. Fresh basalt flows up into the rift from the earth's plastic mantle in regions where the sea floor is spreading apart at the rate of several centimeters per year. Accompanying this mantle rock is "juvenile" water—water never before in the liquid phase—containing in solution many of the components of seawater, including chlorine, bromine, iodine, carbon, boron, nitrogen and various trace elements. Additional juvenile water, equally salty but of somewhat different composition, is released by volcanoes that rim certain continental margins, such as those bordering the Pacific, where the sea floor seems to be disappearing into deep trenches [*see illustration on these two pages*].

The elements most abundant in juvenile water are precisely those that cannot be accounted for if the solids dissolved in the sea were simply those provided by the weathering of rocks on the earth's surface. The "missing" elements, such as chlorine, bromine and iodine, were once called "excess volatiles" and were attributed solely to volcanic emanations. It is now recognized that juvenile water may have nearly the same chlorinity as seawater but is much more acid due to the presence of one hydrogen ion (H^+) for every chloride ion (Cl^-). In due course, as I shall explain later, the hydrogen ions are removed and replaced by sodium ions (Na^+), yielding the concentration of ordinary salt (NaCl) that constitutes 90-odd percent of all the "salt" in the sea.

The chemistry of the sea is largely the chemistry of obscure reactions at extreme dilution in a strong salt solution, where all the classical chemist's "distilled water" theories and procedures break down. The father of oceanographic chemistry was Robert Boyle, who demonstrated in the 1670's that fresh waters on the way to the sea carry small amounts of salt with them. He also made the first attempt to quantify saltiness by drying seawater and weighing the residue, but his results were erratic because some of the constituents of sea salt are volatile. Boyle found that a better method was simply to measure the specific gravity of seawater and from this estimate the amount of salt present. Since the distribution of density in the sea is important to oceanographers, the same calculation is routinely performed today in reverse: the salinity is deduced by measuring the electrical conductivity of a sample of seawater, and from this and the original temperature of the sample one can compute the density of the seawater at the point the sample was taken.

In 1715 Edmund Halley suggested that the age of the ocean and thus of the world might be estimated from the rate of salt transport by rivers. When this proposal was finally acted on by John Joly in 1899, it gave an age of some 90 million years. The quantity that Joly measured (total amount of x in ocean divided by annual river input of x) is now recognized as the "residence time" of the constituent x, which is an index of an element's relative chemical activity in the ocean. Joly's value is about right for the residence time of sodium; for a more reactive element (in the ocean environment) such as aluminum the residence time is as brief as 100 years.

Not quite 200 years ago Antoine Laurent Lavoisier conducted the first analysis of seawater by evaporating it slowly and obtaining a series of compounds by fractional crystallization. The first compound to settle out is calcium carbonate ($CaCO_3$), followed by gypsum ($CaSO_4 \cdot 2H_2O$), common salt (NaCl), Glauber's salt ($Na_2SO_4 \cdot 10H_2O$), Epsom salts ($MgSO_4 \cdot 7H_2O$) and finally the chlorides of calcium ($CaCl_2$) and mag-



MAGIC SALT MILL at the bottom of the sea, imagined in the old Norse folktale, turns out to be not so fanciful after all. The modern explanation of why the sea is salt invokes the concept of the "mid-ocean" rift and sea-floor spreading, as depicted here in cross section. The rift is a weak point be-

nesium ($MgCl_2$). Lavoisier noted that slight changes in experimental conditions gave rise to large shifts in the relative amounts of the various salts crystallized. (In fact, some 54 salts, double salts and hydrated salts can be obtained by evaporating seawater.) To get reproducible results for even the total weight of salt one must remove all organic matter, convert bromides and iodides to chlorides, and carbonates to oxides, before evaporating. The resulting weight, in grams of salt per kilogram of seawater, is the salinity, S‰. (The symbol ‰ is read "per mil.")

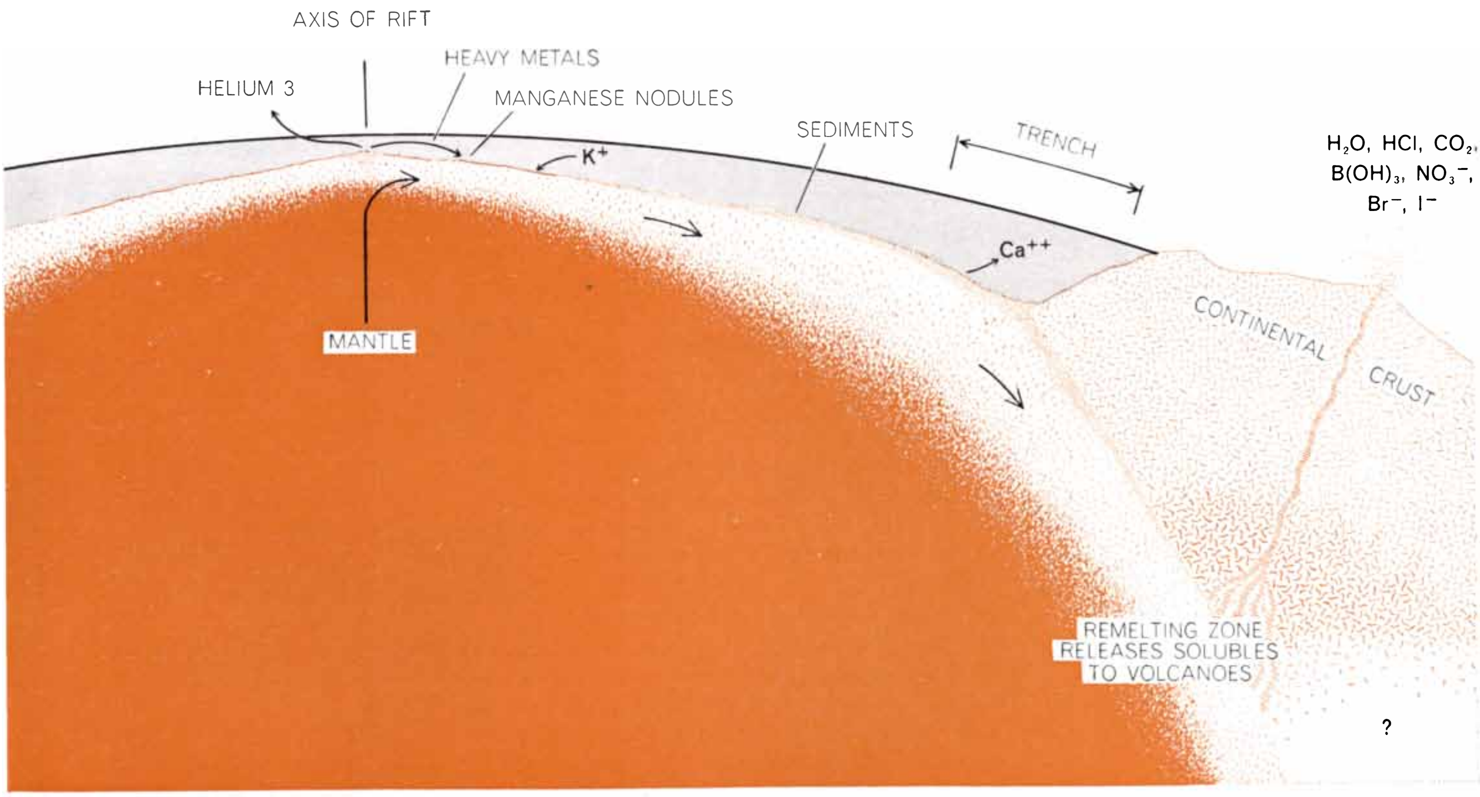
In actual practice the total weight of salt in seawater is nowadays never determined. Instead the amount of chloride ion is carefully measured and a total for all other ions is computed by applying the "constancy of relative proportions." This concept dates back to the middle of the 19th century, when John Murray eliminated confusion about the multiplicity of salts by observing that individual ions are the important thing to talk about when analyzing seawater. Independently A. M. Marcet concluded from many measurements that various ions in the world ocean were present in nearly constant proportions, and that only the absolute amount of salt was variable. This constancy of relative proportions was confirmed by Johann Forchhammer and again more thoroughly by Wilhelm Dittmar's analysis of 77 samples of seawater collected by H.M.S. *Challenger* on the first worldwide oceanographic cruise. These 77 samples are probably the last ever analyzed for all the major constituents. Their average salinity was close to 35‰, with a normal variation of only ±2‰.

In the 86 years since Dittmar reported eight elements, 65 more elements have been detected in seawater. It was recognized more than a century ago that elements present in minute amounts in seawater might be concentrated by sea organisms and thereby raised to the threshold of detectability. Iodine, for example, was discovered in algae 14 years before it was found in seawater. Subsequently barium, cobalt, copper, lead, nickel, silver and zinc were all detected first in sea organisms. More recently the isotope silicon 32, apparently produced by the cosmic ray bombardment of argon, has been discovered in marine sponges.

There are also inorganic processes in the ocean that concentrate trace elements. Manganese nodules (of which more below) are able to concentrate elements such as thallium and platinum to detectable levels. The cosmic ray isotope beryllium 10 was recently discovered in a marine clay that concentrates beryllium. In all, 73 elements (including 13 of the rare-earth group) apart from hydrogen and oxygen have now been detected directly in seawater [*see illustration on page 107*].

It is only in the past 40 years that geochemists have become interested in the chemical processes of the sea for what they can tell us about the history of the earth. Conversely, only as geophysicists have pieced together a comprehensive picture of the earth's history has it been possible to bring order into marine chemistry.

The earth's present atmosphere and ocean are not primordial but have been liberated from chemical and mechanical entrapment in solid rock. Perhaps four billion years ago, or a little less, there was (according to many geophysicists) a "grand catastrophe" in which the earth's core, mantle, crust, ocean and atmo-



tween rigid plates, or segments, in the earth's crust. Although the driving mechanism is not yet understood, the plates move apart a few centimeters a year as fresh basalt from the plastic mantle flows up between them. The new basalt releases "juvenile" water (water never before in liquid form) and a variety of elements, including heavy metals that become incorporated in manganese nodules and the rare isotope helium 3, which escapes finally into space. At the continental margin (*right*) the lithospheric plate is subducted, forming a trench and carrying accumulated sediments with it. (The plate apparently thickens en route as plastic basalt "freezes" to its underside.) As it descends the plate remelts and releases soluble elements and ions that are ejected into the atmosphere by volcanoes. They maintain the saltiness of the sea and together with weathered crustal rock, such as granite, provide the stuff of sediments.

sphere were differentiated from an original homogeneous accumulation of material. Estimates of water released during the catastrophe range from a third to 90 percent of the present volume of the ocean. The catastrophe is not finished even yet, since differentiation of the mantle continues in regions of volcanic activity. Most of the exhalations of volcanoes and hot springs are simply recycled ground water, but if only half of 1 percent of the water released is juvenile, the present production rate is sufficient to have filled the entire ocean in four billion years.

There is evidence that the salinity of the ocean has not changed greatly since the ocean was formed; in any event the salinity has been nearly constant for the past 200 million years (5 percent of geologic time). The composition of ancient sediments suggests that the ratio of sodium to potassium in seawater has risen from about 1 : 1 to its present value of about 28 : 1. Over the same period the ratio of magnesium to calcium has risen from roughly 1 : 1 to 3 : 1 as organisms removed calcium by building shells of calcium carbonate. It is significant, however, that the total amount of each pair of ions varied much less than the relative amounts.

If we look at rain as it reaches the sea in rivers, we find a distinctly nonmarine mix to its ions. If we catch it even earlier as it tumbles down young mountains, the differences are even more pronounced. This continual input of water of nonmarine composition would eventually overwhelm the original composition of the ocean unless there were corrective reactions at work.

The overall geochemical cycle that keeps the marine ions closely in balance involves a complex interchange of material over decades, centuries and millenniums among the atmosphere, the ocean, the rivers, the crustal rocks, the oceanic sediments and ultimately the mantle [*see "a" in illustration on page 108*]. Because this overall picture is too general to be of much use, we abstract bits from it and call them thalassochemical models (*thalassa* is the Greek word for "sea"). One model involves simply the cyclic exchange of sea salt between the rivers and the sea; the cycle includes the transport of salt from the sea surface into the atmosphere, where salt particles act as condensation nuclei on which raindrops grow [*see "b" in illustration on page 108*]. This process accounts for more than 90 percent of the chloride and about 50 percent of the sodium carried to the sea by rivers.

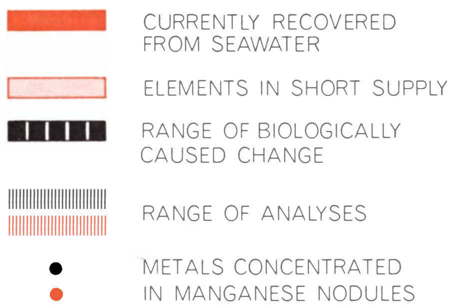
Another useful abstraction is the "steady state" thalassochemical model. If the ocean composition does not change with time, it must be rigorously true that whatever is added by the rivers must be precipitated in marine sediments [*see "c" in illustration on page 108*]. Oceanic residence times computed from sedimentation rates, particularly for reactive trace metals, agree well with the input rates from rivers. Unfortunately residence times do not reveal the mechanism by which an element is removed from seawater. For residence times greater than a million years it is often helpful to invoke the "equilibrium" model, which deals only with the rate of exchange between the ocean and its sediments [*see "d" in illustration on page 108*].

To understand how the earth maintains its geochemical poise over a billion-year time scale we must return to the circle of arrows—the weathering and "unweathering" processes—of the geochemical cycle. This circle starts with primordial igneous rock, squeezed from the mantle. Ignoring relatively minor heavy metals such as iron, we can assume that the rock consists of aluminum, silicon and oxygen combined with the alkali metals: potassium, sodium and calcium. The resulting minerals are feldspars (for example $KAlSi_3O_8$). Rainwater picks up carbon dioxide from the air and falls on the feldspar. The reaction of water, carbon dioxide and feldspar typically yields a solution of alkali ions and bicarbonate ions (HCO_3^-) in which is suspended hydrated silica (SiO_2). The residual detrital aluminosilicate can be approximated by the clay kaolinite: $Al_2Si_2O_5(OH)_4$ [*see Step 1 in illustration on page 109*]. A mountain stream carries off the ions and the silica. The kaolinite fraction lags behind, first as a friable surface on weathering rock, then as soil material and finally as alluvial deposits in river valleys. If the stream evaporates in a closed basin, such as one finds in the western U.S., the result is a "soda lake" containing high concentrations of carbonates and amorphous silica.

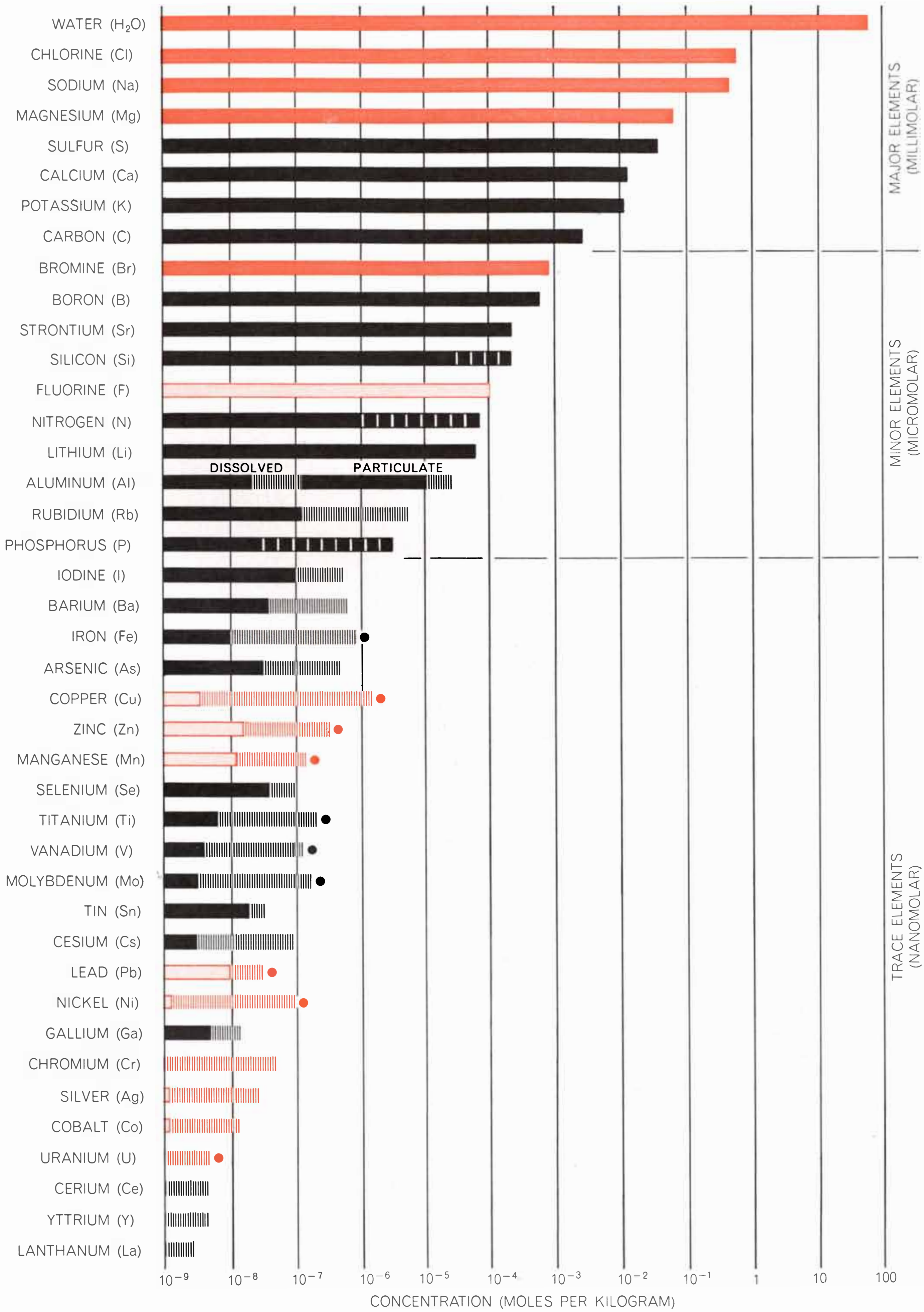
In mature river systems the kaolinite fraction reaches the sea as suspended sediment. Encountering an ion-rich environment for the first time, the aluminosilicate must reorganize itself into new minerals. One such mineral, which seems to be forming in the ocean today, is the potassium-containing clay illite [*see Step 2 in illustration on page 109*]. These "clay cation" reactions may take decades or centuries. They are poorly understood because graduate students who study them invariably leave before the reactions are complete. The net effect of such reactions is to tie up and remove some of the potassium and bicarbonate ions, along with aluminum, silicon and oxygen.

A biologically important reaction, usually confined to shallow water, allows marine organisms to build shells of calcium carbonate, which precipitates when calcium (Ca^{++}) and bicarbonate ions react. If dilute hydrochloric acid is present (it is released by volcanoes), it reacts even more rapidly with bicarbonate, forming water and carbon dioxide and leaving free the chloride ion. When marine organisms die and sink to about 4,000 meters, they cross the "lysocline," below which calcium carbonate redissolves because of the high pressure. We have now traced the three metallic ions removed from igneous rock to three separate niches in the ocean. Sodium remains dissolved, potassium precipitates in clays on the deep-sea floor and calcium precipitates in shallow water as biogenic limestone: coral reefs and calcareous oozes.

Ages pass and the geochemical cycle rolls on, converting ocean-bottom clay into hard rock such as granite. When old sea floor finally reaches a region of high pressure and temperature under a continental block, it still contains some free ions that can react with the clay to reconstitute hard rock. A score of reaction



COMPOSITION OF SEAWATER has been a challenge to chemists since Antoine Laurent Lavoisier made the first analyses. The logarithmic chart on the opposite page shows in moles per kilogram the concentration of 40 of the 73 elements that have been identified in seawater. A mole is equivalent to the element's atomic weight in grams; thus a mole of chlorine is 35 grams, a mole of uranium 238 grams. Only four elements are now recovered from the sea commercially: chlorine, sodium, magnesium and bromine. Recovery of other scarce elements is not promising unless biological concentrating techniques can be developed. Manganese nodules are a potential source of scarce metals but gathering them from the deep-sea floor may not be profitable in this century.


WATER (H_2O)
CHLORINE (Cl)
SODIUM (Na)
MAGNESIUM (Mg)
SULFUR (S)
CALCIUM (Ca)
POTASSIUM (K)
CARBON (C)
BROMINE (Br)
BORON (B)
STRONTIUM (Sr)
SILICON (Si)
FLUORINE (F)
NITROGEN (N)
LITHIUM (Li)
ALUMINUM (Al)
RUBIDIUM (Rb)
PHOSPHORUS (P)
IODINE (I)
BARIUM (Ba)
IRON (Fe)
ARSENIC (As)
COPPER (Cu)
ZINC (Zn)
MANGANESE (Mn)
SELENIUM (Se)
TITANIUM (Ti)
VANADIUM (V)
MOLYBDENUM (Mo)
TIN (Sn)
CESIUM (Cs)
LEAD (Pb)
NICKEL (Ni)
GALLIUM (Ga)
CHROMIUM (Cr)
SILVER (Ag)
COBALT (Co)
URANIUM (U)
CERIUM (Ce)
YTTRIUM (Y)
LANTHANUM (La)
DISSOLVED
PARTICULATE
MAJOR ELEMENTS (MILLIMOLAR)
MINOR ELEMENTS (MICROMOLAR)
TRACE ELEMENTS (NANOMOLAR)
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
100
CONCENTRATION (MOLES PER KILOGRAM)

schemes are possible. In Step 3 in the illustration on the opposite page I have chosen to build a "granite" from equal parts of potassium feldspar, sodium feldspar, potassium mica and quartz. (Notice that calcium is missing because it has dissolved from the sediments during their descent into the deep-ocean trenches that carry the sediments under the continental blocks.) The reaction written in Step 3 uses up all the silica formed in Step 1.

The goal of this geochemical exercise has now been reached. First, we have shown that of all the substances that enter the ocean, only sodium and chlorine remain abundantly in solution. Of the other elements, the amount remaining in solution is less than a hundredth of the amount delivered to the ocean and precipitated from it. Second, we have made a start at explaining the observed sodium-potassium ratios: in basalt this ratio is about 1 : 1, in seawater 28 : 1 and in granite 1 : 1.2. If the weight of sodium tied up in granite were about 140 times as great as the weight of sodium dissolved in the sea, the slight excess of potassium over sodium in granite would explain the sea's deficiency in potassium.

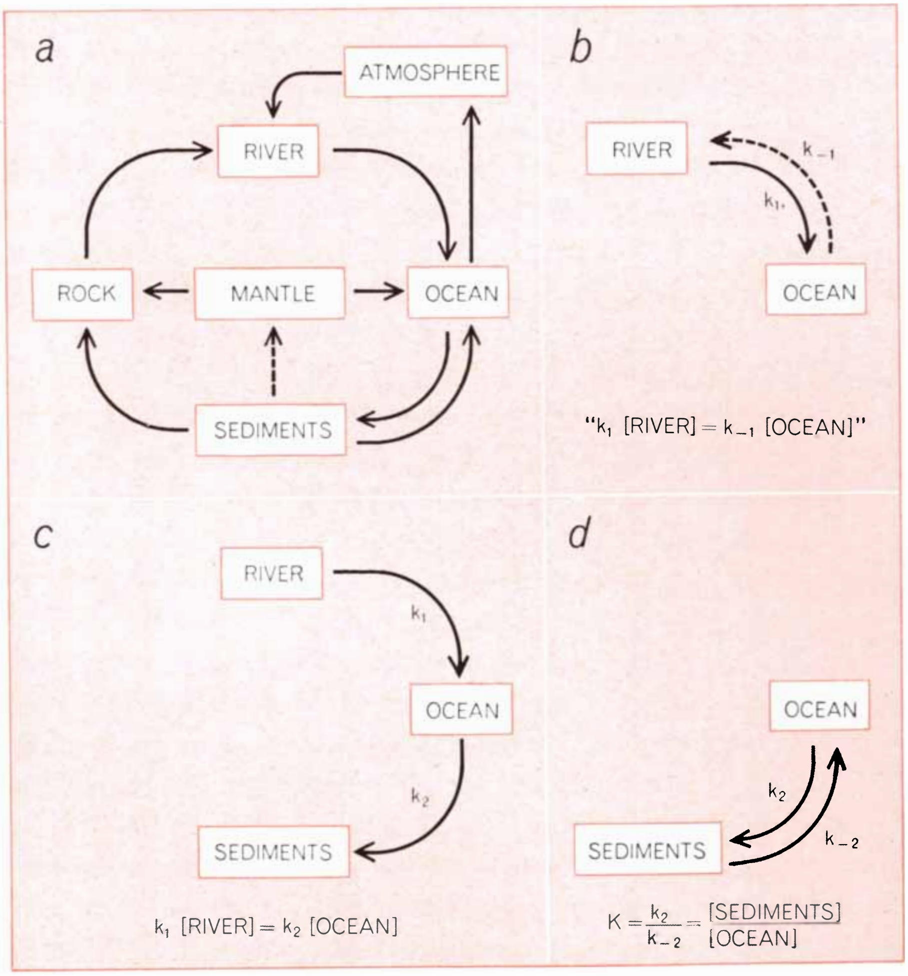
We now have working models for thinking about the circulation of the major elements, but we have barely scratched the true complexity and subtlety of seawater. The sources and sinks of the minor elements are now being explored. In many cases we can only guess at what the natural marine form of an element is because our detection techniques either convert all forms to a common form for analysis or miss some forms completely. Moreover, certain ions seem to behave capriciously in the ocean. For example, at the *p*H (hydrogen-ion concentration) of seawater, vanadium should appear as $VO_2(OH)_3^{--}$, an ion with a double negative charge; instead it seems to exist in positively charged form, perhaps as VO_2^+.

Much of what is known about elements in the sea can be summarized in an oceanographer's periodic table [*see illustration on page 110*]. The usefulness of the usual kind of periodic table to the chemist is that it arranges chemically similar elements in vertical columns and presents behavioral trends in horizontal rows. The oceanographer's table shows how these regularities are disrupted in the ocean environment.

First of all, more than a dozen elements have never been detected in seawater, although two of them (palladium and iridium) exist in parts per billion in marine sediments and another (platinum) is present in manganese nodules. The second interesting feature of the oceanographer's table is the tendency for the "upper" and "outer" elements, those in the raised wings, so to speak, to be the most plentiful in the sea. The "upper" tendency simply reflects the greater cosmic abundance of light elements. (Lithium, beryllium and boron, however, are fairly scarce even cosmically.)

The "outer" trend can be explained in quantum-mechanical terms by the presence or absence of electrons in *d* orbitals, the electron shells principally involved in forming complexes. Elements in the first three columns at the left have no *d* orbitals; those in the last four columns at the right have full *d* orbitals. Both characteristics favor weak chemical bonds, with the result that these two groups of elements tend to ionize readily and remain in solution, either by themselves or in simple combination with oxygen and hydrogen. In contrast, the elements in the center of the table with partially filled *d* orbitals form strong chemical bonds and compounds that precipitate readily; thus they can exist only at low concentration in solution. For silver and the surrounding group of metals the most stable complexes are formed with the most abundant seawater ion: chloride. Most of the other elements that are hungry for *d* electrons form their complexes with oxygen, or oxygen plus some protons (hydrogen nuclei).

Ordinarily the oxidation state of metals



GRAND GEOCHEMICAL CYCLE (*a*) summarizes the global pathways taken sooner or later by the three-score elements that pass through the ocean and maintain its saltiness. The three "thalassochemical" models (*b, c, d*) abstracted from it are more helpful when trying to understand the rate laws governing the transport of specific elements. The rate constants, *k*, are expressed as a fraction: one over some number of years. The brackets enclose concentrations of the element being studied, specified according to its environment. The "cyclic" model (*b*) accounts for 90 percent of the chloride in river water. Its rate law is in quotation marks because extra factors, such as the area of the ocean, must be incorporated. The "steady state" model (*c*) works well for reactive trace metals; the reciprocal of k_2 is simply the residence time in the ocean. The "equilibrium" model (*d*) seems the most appropriate for the hydrogen ion (H^+) and the ions of the major metals, such as sodium.

STEP 1: WEATHERING OF IGNEOUS ROCK

$$\left\{\begin{array}{c} CaAl_2Si_2O_8 \\ \text{ANORTHITE} \\ 2KAlSi_3O_8 \\ \text{POTASSIUM FELDSPAR} \\ 2NaAlSi_3O_8 \\ \text{SODIUM FELDSPAR} \end{array}\right\} + 9H_2O + 6CO_2 \longrightarrow \left\{\begin{array}{c} Ca^{++} \\ 2K^{+} \\ 2Na^{+} \\ 6HCO_3^{-} \end{array}\right\} + 8SiO_2(aq) + \underset{\text{"KAOLINITE"}}{3Al_2Si_2O_5(OH)_4}$$

IGNEOUS ROCK + RAINWATER ⟶ STREAM WATER + DETRITUS

STEP 2: EQUILIBRATION IN OCEAN

$$3Al_2Si_2O_5(OH)_4 + 2K^{+} + 2HCO_3^{-} \longrightarrow 2K(AlSiO_4)Al_2(OH)_2O_2(Si_2O_4) + 5H_2O + 2CO_2\uparrow \quad \text{(DEEP WATER)}$$

"KAOLINITE" + SEAWATER ⟶ CLAY (ILLITE)

$$Ca^{++} + 2HCO_3^{-} \xrightarrow{\text{ORGANISMS}} CaCO_3\downarrow + H_2O + CO_2\uparrow \quad \text{(SHALLOW WATER)}$$

$$2HCl + 2HCO_3^{-} \xrightarrow{\text{VULCANISM}} 2Cl^{-} + 2H_2O + 2CO_2\uparrow$$

STEP 3: METAMORPHOSIS OF SHALE (CLAY)

$$2K(AlSiO_4)Al_2(OH)_2O_2(Si_2O_4) + Na^{+} + Cl^{-} + 8SiO_2 \xrightarrow[\text{PRESSURE}]{\text{HEAT}} \left\{\begin{array}{c} KAlSi_3O_8 \\ \text{POTASSIUM FELDSPAR} \\ NaAlSi_3O_8 \\ \text{SODIUM FELDSPAR} \\ KAl_2(AlSi_3O_{10})(OH)_2 \\ \text{POTASSIUM MICA} \\ SiO_2 \end{array}\right\} + HCl + 2SiO_2 + AlSi_2O_5(OH)$$

CLAY + INTERSTITIAL WATER ⟶ "GRANITE" + VOLCANIC GAS + QUARTZ + PYROPHYLLITE

STEP 4: LEFT BEHIND IN OCEAN

$$Na^{+} + Cl^{-}$$

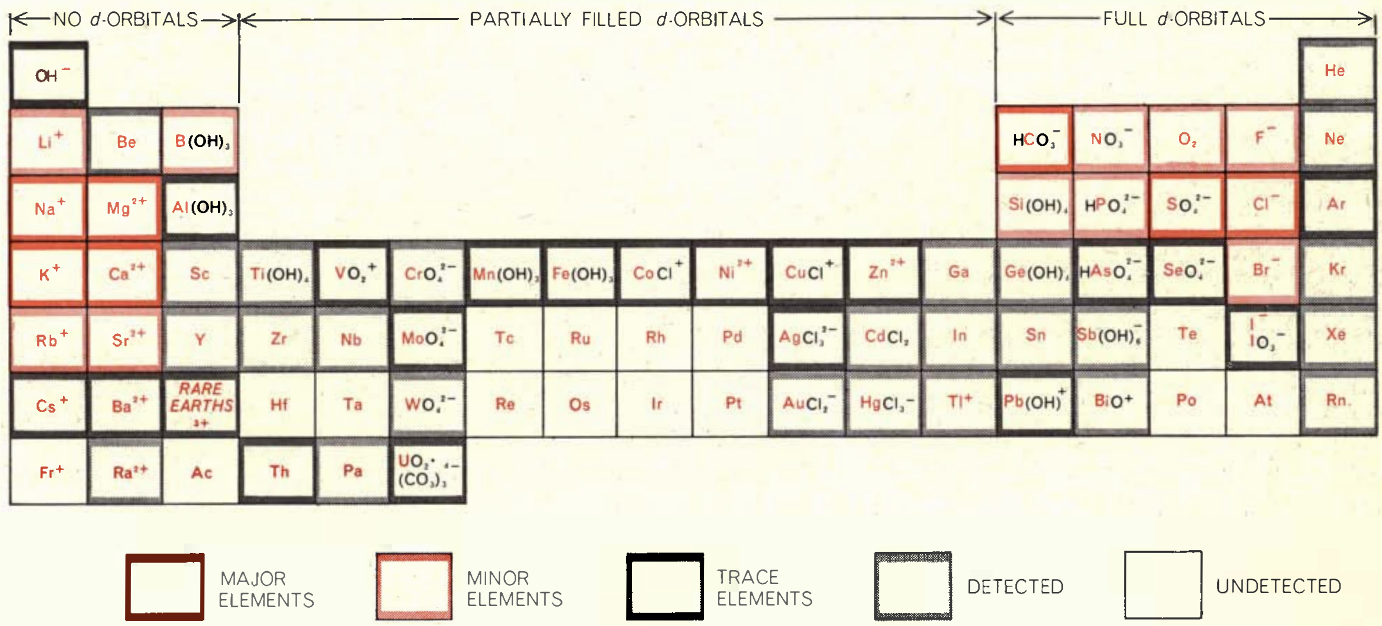
ONLY SALT REMAINS after the ocean "laboratory" has finished processing the complex of chemicals removed from igneous rock by rainwater containing dissolved carbon dioxide. Step 1 yields a solution of alkali ions and bicarbonate (HCO_3^-) ions in which hydrated silica (SiO_2) and aluminosilicate detritus are suspended. In crystalline form the aluminosilicate would be kaolinite. In the ocean (*Step 2*) the "kaolinite" is complexed with potassium ions (K^+) to form illite clay. Marine organisms use the calcium ion (Ca^{++}) to make calcium carbonate shells, which form sediments in shallow water. Hydrochloric acid (HCl), injected by undersea volcanoes, reacts with bicarbonate ions, returning some carbon dioxide to the atmosphere. In Step 3 clay is metamorphosed into "granite." Sodium chloride (*Step 4*) remains. Although some of this sequence is hypothetical, something very similar seems to take place.

avid for *d* electrons would be determined by the oxidation potential of seawater, which is a measure of its ability to extract electrons from a substance just as its *p*H is a measure of its ability to extract protons. The oxidation potential of seawater has the high value of .75 volt, enabling it to extract the maximum possible number of electrons from nearly all elements except the noble metals (platinum group) and the halogens (fluorine family).

Surprisingly, however, the oxidation potential of seawater does not seem to control the oxidation states of many metals that have partially filled *d* shells. One reason is that most reactions proceed by a mechanism in which only a single electron is transferred at a time. Such transfers occur most readily when the reactants are adsorbed on surfaces where atomic geometry and electric-charge distribution are able to expedite the redistribution of electrons (hence the utility of catalysts, which provide such surfaces). But surfaces of any kind are few and far between in the ocean, and (with the exception of manganese nodules) those that do exist are poor catalysts. A second reason for the failure of the sea's oxidation potential to control valence states is that organisms sometimes excrete electron-rich substances, which then remain in that reduced state in spite of seawater's apparent capacity to oxidize them.

Manganese nodules are porous chunks of metallic oxides up to several centimeters in diameter, widely distributed over the ocean floor. They evidently exist because they are autocatalytic for the reaction that produces them. Because of their porous structure, nodules have a surface area of as much as 100 square meters per gram. The autocatalytic property seems to extend to an entire suite of metals that coprecipitate with manganese: iron, cobalt, nickel, copper, zinc, chromium, vanadium, tungsten and lead. Nodules found on the flanks of oceanic ridges contain significant concentrations of metals, such as nickel, that are scarce in seawater itself. This suggests that the nodules are collecting juvenile metals as the metals leak from the mantle at the fissure of the ridge. One would like to know why the nodule metals are present in oxide form rather than, as one would expect, in carbonate form.

The level of the discussion so far might best be called thalassopoetry. The discussion can be made more serious in two ways. One approach—the "geochemical balance"—has employed a computer to follow in detail as many as 60 elements as they move through the geochemical cycle, from igneous rock back



PERIODIC TABLE, as prepared by the "thalassochemist," shows the form in which the detectable elements appear in seawater. In each box the element normally found in that place in the usual periodic table is shown in color; the elements associated with it are in black. Thus carbon appears predominantly as HCO_3^-, arsenic as $HAsO_4^{2-}$ and so on. The superscripts show the number of positive or negative charges carried by each ion. Iodine's two forms, I^- and IO_3^-, are about equally common. Except for the noble gases (*last column at right*), all the elements dissolved in the sea must be present as ions. When an element (other than a noble gas) is shown by itself, without a plus or minus charge, it means that its preferred ionic form in seawater is not yet established.

to metamorphosed sediments. In the second approach the actual chemistry of each element is followed by applying the thermodynamic methods of Josiah Willard Gibbs to systems regarded as being near equilibrium. This effort was launched by Lars Gunnar Sillén of Sweden and has been pursued by Robert M. Garrels of Northwestern University and by Heinrich D. Holland of Princeton University.

Of course no chemist in his right mind would talk seriously about equilibria in a system of variable temperature, pressure and composition that was poorly stirred, had variable inputs and contained living creatures. On the other hand, the observed uniformity of the ocean and the long periods available for reacting suggest that at least the major components are sufficiently close to equilibrium to make an investigation worthwhile. (We *know* the minor constituents are not in equilibrium.)

The equilibrium approach is based on Gibbs's phase rule, which states that the number of phases (P) possible in a system of C components at equilibrium is given by the equation $P = C + 2 - F$, where F is the number of "degrees of freedom," or quantities that may be independently varied without changing the number of phases or their composition (although F may change their relative proportions). The 2 enters the equation because only two variables, temperature and pressure, are important in most chemical reactions.

One of Sillén's most comprehensive ocean models has nine components: water, hydrochloric acid, silica, three hydroxides (aluminum, sodium and potassium), carbon dioxide and the oxides of magnesium and calcium. Observation of sea-floor sediments, aided by laboratory studies, suggests that a nine-phase ocean will result [*see illustrations on opposite page*]. If C and P both equal nine, the phase rule states that the number of degrees of freedom (F) must equal two. Logically these are temperature (which can vary over the oceanic range from −2 degrees Celsius to 30 degrees) and the chloride ion concentration (which can shift over the normal oceanic range without changing the composition of the stable phases).

A diagrammatic view of how the nine components sort themselves into phases is shown in the bottom illustration on the opposite page. Note that the liquid phase contains ions not listed either as components or as phases (for example H^+ and OH^-). Thermodynamics need not consider them explicitly because they do not vary independently; their concentrations are fixed by the equilibrium constants that connect the observed phases. Thus $H_2O = H^+ + OH^-$. Moreover, one knows that the product of H^+ and OH^- is a thermodynamic constant, which equals 10^{-14} mole per liter. Similar relations tie the entire system into a comprehensible whole, so that when all the calculations are performed one has discovered the equilibrium concentrations of five cations (H^+, Na^+, K^+, Mg^{++} and Ca^{++}) and four anions (Cl^-, OH^-, HCO_3^- and CO_3^{--}).

It may seem peculiar to discuss an "atmosphere" containing only water vapor and carbon dioxide. One could easily add oxygen and nitrogen to the list of components. Since they would add no new phases, they would raise the number of degrees of freedom from two to four ($9 = 11 + 2 - 4$). The two new F's would be the total atmospheric pressure and the ratio of oxygen to nitrogen. In the study of the ocean, however, the partial pressure due to carbon dioxide is more significant than the total pressure of the atmosphere. Moreover, the presence of gaseous oxygen and nitrogen has little importance for the inorganic environment of the ocean, so that it is simpler to omit them and just as "real."

Suppose now we perturb the equilibrium of the model ocean by assuming that a submerged volcano has suddenly released enough hydrochloric acid (HCl) to double the amount of chloride ion (Cl^-). The dissociation of hydrochloric acid releases enough H^+ ions to raise the total number of hydrogen ions in the ocean from the former equilibrium value of 10^{-8} mole per liter to $10^{+.3}$. This excess of hydrogen ions almost immediately pushes all the available carbonate ions (CO_3^{--}) to bicarbonate ions (HCO_3^-) and the latter to carbonic acid (H_2CO_3). These shifts, however, only slightly depress the pH, which remains high until the slow circulation of the ocean brings the hydrogen ions in direct contact with the clay sediments on the sea floor.

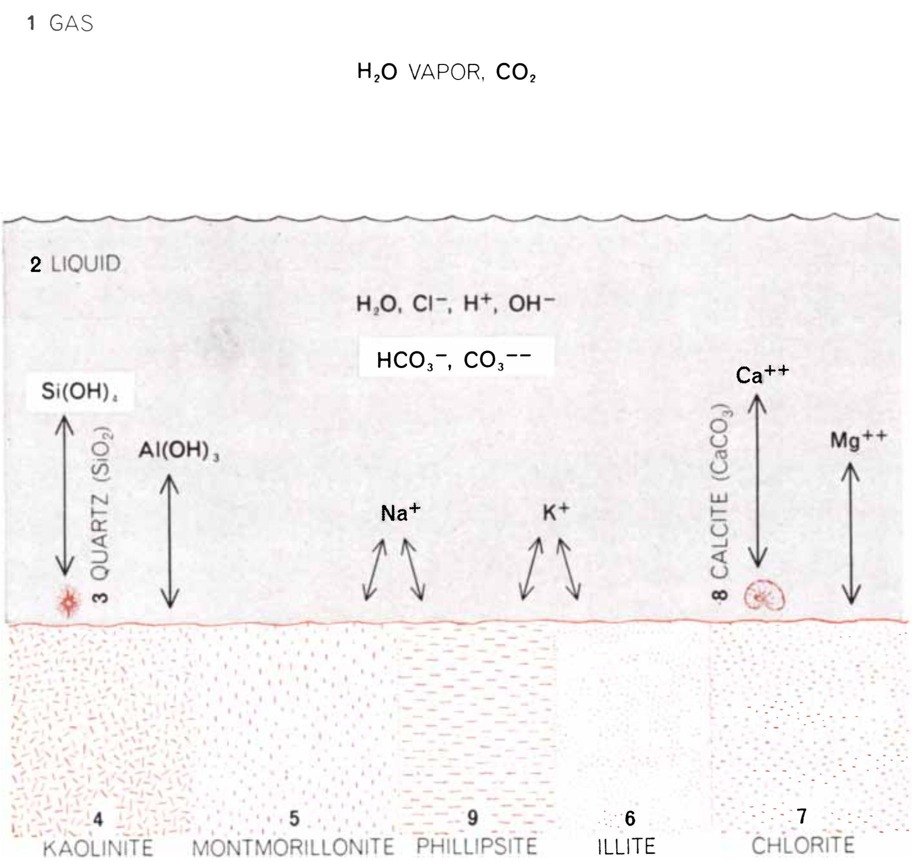
The structure of clay is such that oxygen atoms at the free corners of polyhedrons carry unsatisfied negative charges, which attract positive ions [*see top illustration on next page*]. Because the ocean is so rich in sodium ions (Na^+), they occupy most of the corners of clay polyhedrons. When the excess hydrogen ions come in contact with the clay, they quickly replace the sodium ions and set them adrift. This fast reaction is limited in scope because the surface and interlayer ion-exchange capacity of clay is not very great. Much more capacity is provided when the structure of the clay is rearranged; for example, the conversion of montmorillonite to kaolinite also consumes hydrogen atoms and releases sodium. Given sufficient time—centuries—such rearrangements inexorably take place, and the *p*H of the ocean slowly drifts back to its equilibrium value. The charge on the excess chloride introduced by the volcano will then be balanced not by H^+ but by Na^+. This slow equilibration mechanism can be regarded as the ocean's "*p*H-stat" (in analogy with "thermostat"). This clay-cation model suggests that the *p*H of the ocean has been constant over the span of geologic time and that hence the carbon dioxide content of the atmosphere has been held within narrow limits.

If only the *p*H-stat were available for leveling surges in *p*H, the ocean might be subjected to violent local fluctuations. For fast response *p*H control is taken over by a carbonate buffer system [*see bottom illustration on next page*]. In fact, until recently oceanographers neglected the clay-cation reactions and assumed that the carbonate-buffer system almost completely determined the *p*H of the ocean.

One might think that if the carbon dioxide content of the atmosphere were to decrease, carbon dioxide would flow from the sea into the atmosphere, leading to a general depletion of all carbonate species in the ocean and eventually to the dissolution of some carbonate sediments. In actuality something quite different happens because the carbonate system is its own source of hydrogen ions. Removal of carbon dioxide from water reduces the concentration of carbonic acid (H_2CO_3), the hydrated form of carbon dioxide. Replacement of this acid from bicarbonate ions requires a hydrogen ion, which can only be obtained by converting another bicar-

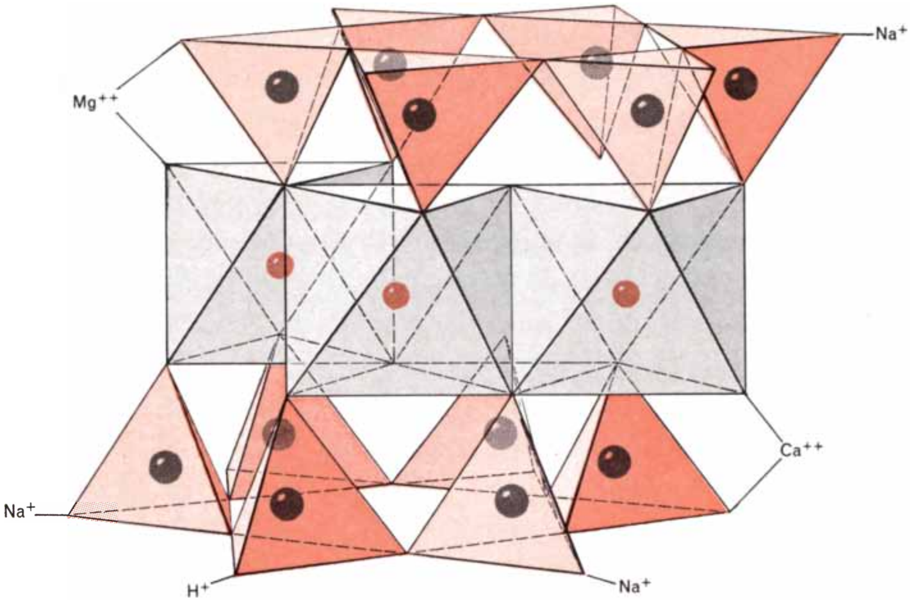
COMPONENTS (C)	PHASES (P)	VARIABLES (F)
H_2O	1 GAS	TEMPERATURE
HCl	2 LIQUID	Cl^-
SiO_2	3 QUARTZ (SiO_2)	
$Al(OH)_3$	4 KAOLINITE (t-o CLAY)	
NaOH	5 MONTMORILLONITE (Na-t-o-t CLAY)	
KOH	6 ILLITE (K-t-o-t CLAY)	
MgO	7 CHLORITE (Mg-t-o-t CLAY)	
CO_2	8 CALCITE ($CaCO_3$)	
CaO	9 PHILLIPSITE (Na-K FELDSPAR)	

NINE MAJOR COMPONENTS IN SEA can, to a first approximation, be combined into nine distinctive phases to satisfy the "phase rule" that governs systems in equilibrium. The rule, formulated in the 19th century by Josiah Willard Gibbs, prescribes the number of phases *P*, components *C* and degrees of freedom *F* in such a system: $P = C + 2 - F$. When the number of phases and components are equal, the number of degrees of freedom, *F*, must be two, which allows both the temperature and the chloride-ion concentration to vary without altering the number of phases. In the clay-containing phases (*4, 5, 6, 7*) the letter "t" stands for a tetrahedral crystal structure; the letter "o" stands for an octahedral structure.

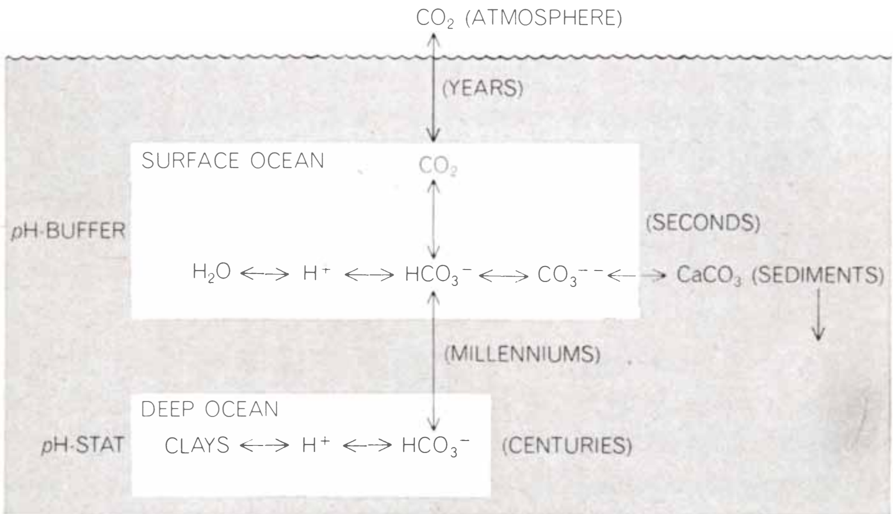


EQUILIBRIUM OCEAN MODEL, consisting of nine phases and nine components, shows how the principal constituents of the ocean distribute themselves among the atmosphere, the ocean and the sediments. Three of the constituents (HCO_3^-, CO_3^{--} and $Si(OH)_4$) are not included among nine listed components but appear as equilibrium products of those that are listed, as do seven ions (H^+, K^+, Na^+, Ca^{++}, Mg^{++}, Cl^-, OH^-). Two of the solids are shown as biological "precipitates": "quartz" (*3*) in the form of silicate structures built by radiolarians and "calcite" (*8*) in the form of calcium carbonate chambers built by foraminifera. The method of precipitation is unimportant as long as the product is stable. The equilibrium model goes far to explain why the ocean has the composition it does.

bonate ion to carbonate. The overall reaction is $2HCO_3^- \rightarrow H_2CO_3 + CO_3^{--}$. Thus instead of dissolving existing sediments, removing carbon dioxide from the sea may actually precipitate carbonate. This reaction can be seen in the "whitings" of the sea over the Bahama Banks, where cold deep water, rich in dissolved carbon dioxide and calcium, is forced to the surface and warmed. As carbon dioxide escapes into the air, the *p*H drops and aragonite ($CaCO_3$) precipitates, turning large areas of the ocean white with a myriad of small crystals.



THREE-LAYER CLAY PARTICLE has a layer of octahedrons sandwiched between two layers of tetrahedrons. Each octahedron consists of an atom of silicon surrounded by eight closely packed atoms of oxygen. Each tetrahedron consists of an aluminum atom surrounded by four atoms of oxygen. The polyhedrons are tied into layers at shared corners where a single oxygen atom is bonded to a silicon atom on one side and to an aluminum atom on the other. At the free corners the oxygen atoms bear unsatisfied negative charges that attract cations such as sodium (Na^+) and potassium (K^+). If the hydrogen-ion concentration should rise in the vicinity of clay, free hydrogen ions tend to be exchanged for sodium ions, which are released. In addition, many doubly charged metal ions can replace Al^{3+} at the centers of tetrahedrons and Al^{3+} can replace Si^{4+} in the octahedrons. Whenever this occurs, another cation is bound to the structure to conserve charge. Such reactions apparently exert considerable control over the ocean's composition and hydrogen-ion concentration.



HYDROGEN-ION CONCENTRATION, or *p*H, of the ocean is controlled by two mechanisms, one that responds swiftly and one that takes centuries. The first, the "*p*H-buffer," operates near the surface and maintains equilibrium among carbon dioxide, bicarbonate ion (HCO_3^-), carbonate ion (CO_3^{--}) and sediments. The slower mechanism, the "*p*H-stat," seems to exert ultimate control over *p*H; it involves the interaction of bicarbonate ions and protons (H^+) with clays. Clay will accept protons in exchange for sodium ions (primarily).

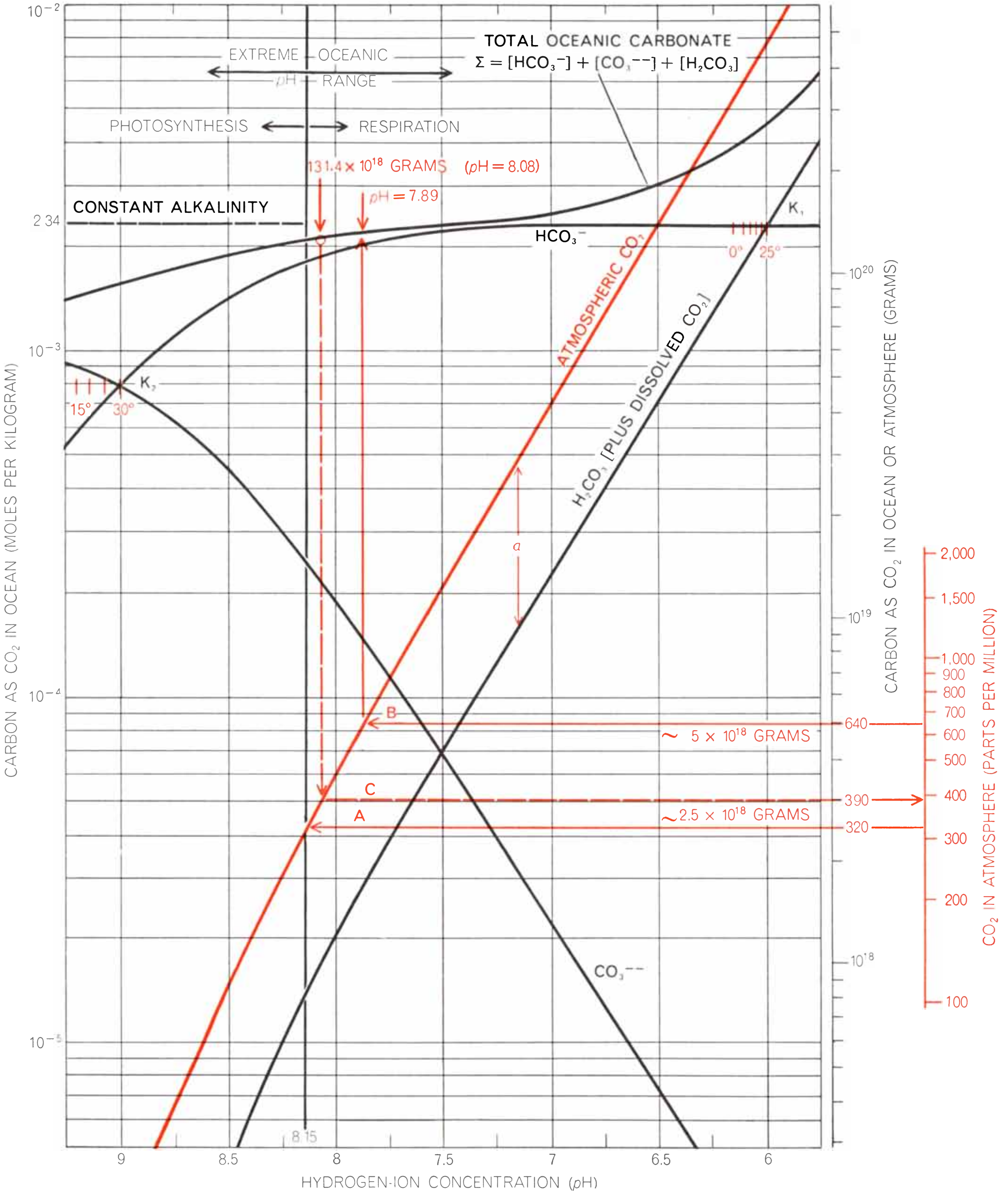
The reaction above conserves charge, which means that the "alkalinity"—the traditional name for the concentration of sodium ion ("alkali") needed to balance this negative charge—is also conserved. The "carbonate alkalinity," defined as the bicarbonate concentration plus twice the carbonate concentration, is useful because it remains fixed even when the relative amounts of the two species vary.

The system can be visualized with the help of the illustration on the opposite page, which is the "Bjerrum plot" for carbonic acid at constant alkalinity. It takes its name from Niels Bjerrum, who introduced such plots in 1914; it shows the interrelations between the various compounds in the world carbonate system as a function of *p*H. Although the diagram ignores variations of pressure, temperature and salinity, it displays the essential features of the system.

The Bjerrum plot facilitates a semiquantitative discussion of the relation of atmospheric carbon dioxide to oceanic carbon dioxide. Over the next 20 years we shall burn enough fossil fuel to double the amount of carbon dioxide in the atmosphere from 320 parts per million to 640. On the plot this is indicated by shifting the line *A*, corresponding to 320 parts per million, to position *B*, 640 parts per million.

To produce this shift some 2.5×10^{18} grams of carbon dioxide must be added to the atmosphere. If the altered atmosphere were to come to equilibrium with the ocean, the *p*H of the ocean would drop from its present value of 8.15 to 7.89—still well within the range tolerated by marine organisms. This cannot happen, however, because the total mass of carbon dioxide in the ocean (Σ in the Bjerrum plot) plus the carbon dioxide in the atmosphere would have to increase from its present value, 128.9×10^{18} grams, to 138.3×10^{18} grams. The difference, 9.4×10^{18} grams, is nearly four times the amount added to the atmosphere.

The long-term equilibration process for such an atmospheric doubling can be broken down into two steps. First the *p*H-buffer system operates: 2.5×10^{18} grams, or 2 percent of the total mass, is added to the world system at constant alkalinity. The result of this step is the line *C* in the diagram, corresponding to a total mass of 131.4×10^{18} grams, an atmospheric carbon dioxide content of 390 parts per million and an oceanic *p*H of 8.08. Next, if the ocean has time to equilibrate with its sediments, the *p*H-stat will operate, returning the system to *p*H 8.15 at a constant total mass. The re-



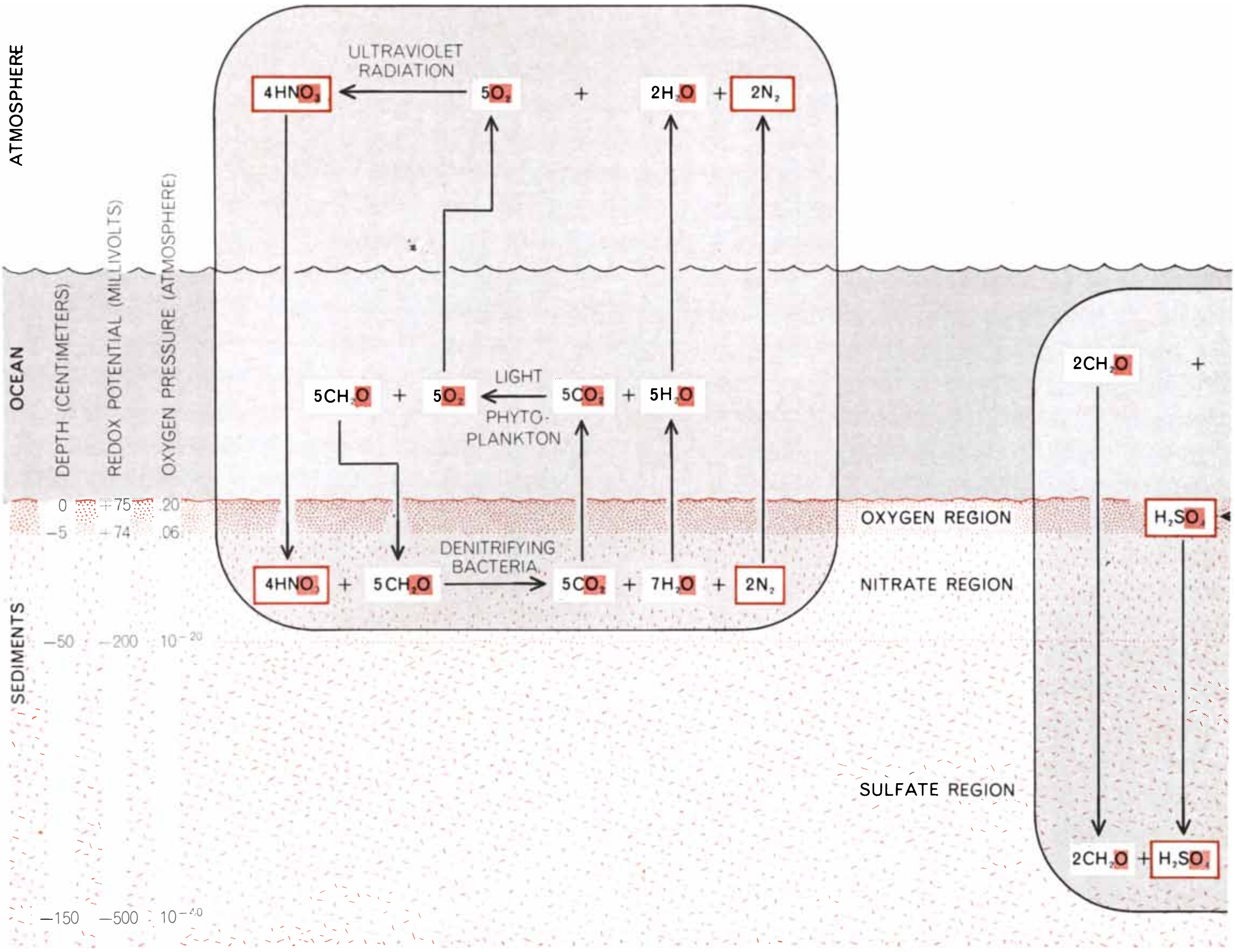
OCEANIC CARBONATE SYSTEM can be represented by a "Bjerrum diagram" that shows how carbonate in its several forms varies with the ocean's *p*H, or hydrogen-ion concentration. The diagram is plotted for a constant "carbonate alkalinity" of 2.34×10^{-3} moles of carbonate per kilogram of seawater (*scale at left*). "System point" K_1 shows where the concentrations of bicarbonate ion (HCO_3^-) and carbonic acid (H_2CO_3) are equal. At K_2 the concentrations of bicarbonate and carbonate (CO_3^{--}) are equal. The exact locations of K_1 and K_2 are shown for a range of temperatures (in degrees Celsius) at constant conditions of salinity and pressure. The top curve, Σ, is the sum of oceanic carbonate in all its forms. The normal *p*H of the ocean is 8.15. The two short arrows at top mark the normal biological limits: at 7.95 the available oxygen has been consumed by respiration; at 8.35 photosynthesis has removed so much carbon dioxide that absorption from the atmosphere rises sharply. The limits of oceanic *p*H lie between 7.45 and 8.6. The amount of carbon dioxide in the atmosphere (*colored curve and scale at far right*) is related to the amount of carbon dioxide dissolved in the ocean by alpha (α), the average worldwide solubility of carbon dioxide in seawater. The consequences of doubling the carbon dioxide in the atmosphere from 320 parts per million (*A*) to 640 parts (*B*) are discussed in the text of the article, as is line *C*.

sult of this step is that the alkalinity rises by 2 percent, which in terms of the Bjerrum plot means that the system will return to normal except that all the numbers on the concentration axes will be multiplied by 1.02. The long-range effect of a sudden doubling of the atmosphere's carbon dioxide, therefore, is to increase the ultimate value 2 percent, from 320 parts per million to 326, and some of that increase will ultimately find its way into vegetation and humus.

It is obvious that rates are crucial in the global distribution of carbon dioxide. The wind-stirred surface layer of the sea exchanges carbon dioxide rapidly with the atmosphere, requiring less than a decade for equilibration. Because this layer is only about 100 meters deep it contains only a tiny fraction of the ocean's total volume. Large-scale disposal of atmospheric carbon dioxide therefore requires that the gas be dissolved and transported to deep water.

Such vertical transport takes place almost exclusively in the Weddell Sea off the coast of Antarctica. Every winter, when the Weddell ice shelf freezes, the salt excluded from the newly formed ice increases the salinity and hence the density of the water below. This ice-cold water, capable of containing more dissolved gas than an equal volume of tropical water, cascades gently down the slope of Antarctica to begin a 5,000-year journey northward across the bottom of the ocean. The carbon dioxide in this "antarctic bottom water" has plenty of time to come to equilibrium with clay sediments.

Enough fossil fuel has been burned in the past century to have raised the carbon dioxide content of the atmosphere from about 290 parts per million to 350 parts. Since the actual level is now 320 parts per million, about half of the carbon dioxide put into the air has been removed. Although proof is lacking, a principal removal agent is undoubtedly antarctic bottom water. The process is so slow, however, that the carbon dioxide content of the atmosphere may reach 480 parts per million before the end of the century. By then it should be clear



BACTERIA IN MARINE SEDIMENTS, although scarce by terrestrial soil standards, play a major role in replenishing the oxygen of the atmosphere and in limiting the accumulation of organic sediments. The bacteria concerned are buried in fine-grained sediments from several centimeters to several tens of centimeters below the ocean floor, with limited access to free oxygen for respiration. Thus deprived, they use the oxygen in nitrates and sulfates to oxidize organic compounds, represented by CH_2O. The actual reactions are far more complex than indicated here. The net result, however, is that denitrifying bacteria (*left*) release free nitrogen and convert carbon to a form (carbon dioxide) that can be reutilized by phytoplankton. These organisms, in turn, release free oxyif man's inadvertent global experiment (altering the atmosphere's carbon dioxide content) will have the predicted effect of changing the earth's climate. In principle an increase in atmospheric carbon dioxide should reduce the amount of long-wavelength radiation sent back into space by the earth and thus produce a greenhouse effect, slightly raising the average world temperature.

Having described an equilibrium model of the ocean that neglected the atmosphere's content of nitrogen and oxygen, I should not leave the reader with the impression that the continued presence of these two gases in the atmosphere is independent of the ocean. If the ocean were truly in equilibrium with the atmosphere, it would long since have captured all the atmospheric oxygen in the form of nitrates, both in solution and in sediments. This catastrophe has apparently been averted by the intervention of certain marine bacteria that have the happy faculty of releasing nitrogen gas from nitrate compounds and of converting the oxygen to a form that can later be liberated by phytoplankton.

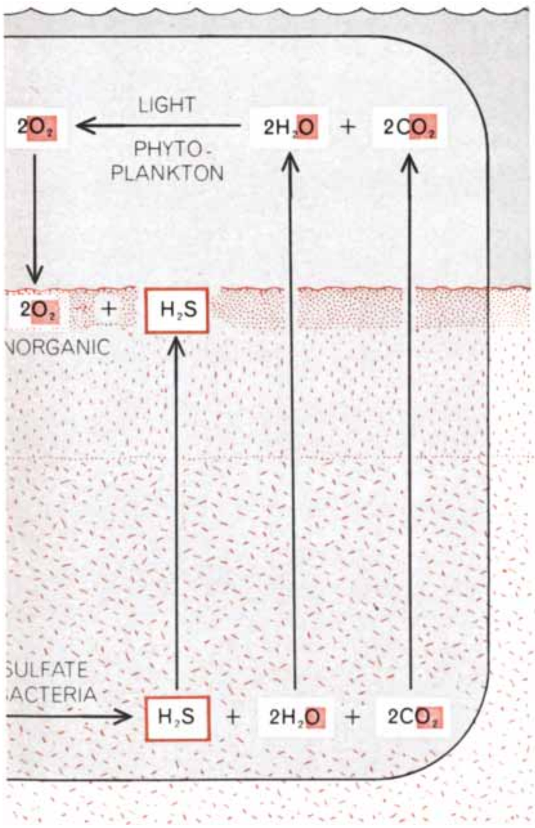
The story is this. A variety of high-energy processes in the atmosphere continuously break the triple chemical bond that holds two nitrogen atoms together in a nitrogen molecule (N_2). The bonds can be broken by ultraviolet photons, by cosmic rays, by lightning and by the explosions in internal-combustion engines. Once dissociated, nitrogen atoms can react with oxygen to form various oxides, which are then carried to the ground by rainfall. In the soil these oxides are useful as fertilizer. Ultimately large amounts of them reach the sea. They do not, however, accumulate there and no one is really sure why.

The best guess is that denitrifying bacteria in oceanic sediments use the oxygen of nitrate to oxidize organic molecules when they run out of free oxygen [*see left half of illustration on these two pages*]. The nitrogen is released directly as a gas, which goes into solution but is available for return to the atmosphere. The oxygen emerges in molecules of water and carbon dioxide. The carbon dioxide is assimilated by phytoplankton, which build the carbon into organic compounds and release the oxygen as dissolved gas, also available for return to the atmosphere. Without these coupled biological processes the atmospheric fixation of nitrogen would probably exhaust the world's oxygen supply in less than 10 million years. Nevertheless, the amount of nitrogen returned to the atmosphere from the sediments is so small that we may never be able to measure it directly: the yearly return is less than one two-thousandth of the total nitrogen dissolved in the sea.

Another little-known epicycle in the global oxygen cycle probably has the effect of limiting the net accumulation of carbon in the form of oil-bearing shale, tar sands and petroleum. After denitrifying bacteria have consumed the nitrate in young sediments, sulfate bacteria begin oxidizing organic matter with the oxygen contained in sulfates [*see right half of illustration on these two pages*]. The product, in addition to water and carbon dioxide, is hydrogen sulfide, the foul-smelling compound that characterizes environments deficient in oxygen. In undisturbed mud the hydrogen sulfide never reaches the surface because it is inorganically reoxidized to sulfate as soon as it comes in contact with free oxygen. It seems likely that the bacterial turnover of oxygen in sulfate is so rapid that half of the world's oxygen passes through this epicycle in about 50,000 years.

The global activities of man have now reached such a scale that they are beginning to have a profound effect on marine chemistry and biology. We are learning that even the ocean is not large enough to absorb all the waste products of industrial society. The experiment involving the release of carbon dioxide is now in progress. DDT, only 25 years on the scene, is now found in the tissues of animals from pole to pole and has pushed several species of birds close to extinction. The concentration of lead in plants, animals and man has increased tenfold since tetraethyl lead was first used as an antiknock agent in motor fuels. And high levels of mercury in fish have forced the abandonment of some commercial fisheries. (Lead and mercury are systemic enzyme poisons.) Of the total petroleum production some .2 percent gets slopped into the sea in half a dozen major accidents each year. (At least six of the rare gray whales died last year after migrating through the oil slick off Santa Barbara caused by the blowout of a well casing belonging to the Union Oil Company.) Conceivably a persistent oil film could change the surface reflectivity of the ocean enough to alter the world's energy balance. The rapid increase in the use of nitrogen fertilizers leaves a nitrate excess that runs into rivers, lakes and ultimately reaches the sea. The sea can probably tolerate the runoff indefinitely but along the way the nitrogen creates algal "blooms" that are hastening the dystrophication of lakes and estuaries.

It is fashionable today to view the ocean as the last global frontier, waiting only technological "development." Thermodynamically it is easier to extract fresh water from sewage than from seawater. Ecologically it is wiser to keep our concentrated nutrients on land than to dilute them beyond recall in the ocean. Sociologically, and probably economically, it makes more sense to process our junkyards for usable metals than to mine the deep-sea floor. The task is to persuade our engineers and business companies that working with sewage and junk is just as challenging as oceanography and thalassochemistry.



gen. Without the cooperative effort of these two groups of organisms the oxygen in the atmosphere might all be fixed by high-energy processes within some 10 million years. The sulfate bacteria (*right*) play a role in the recycling of sulfur and oxygen.

MATHEMATICAL GAMES

A new collection of short problems and the answers to some of "life's"

by Martin Gardner

Here is a collection of varied short problems, unrelated to one another. They will be answered in next month's department.

1. Enormously long chainlike molecules (long in relation to their breadth) have been discovered in living organisms. The question has arisen: Can such molecules have knotted forms? Max Delbrück of the California Institute of Technology, who received a Nobel prize last year, proposed the following idealized problem (in a paper that I shall identify next month):

Assume that a chain of atoms, its ends joined to form a closed space curve, consists of rigid, straight-line segments each one unit long. At every node where two such "links" meet, a 90-degree angle is formed. At each end of each link, therefore, the next link may have one of four different orientations. The entire closed chain could be traced along the edges of a cubical lattice, with the proviso that at each node the joined links form a right angle [*see illustration below*]. At no point is the chain allowed to touch or intersect itself; that is, two and only two links meet at every node.

What is the shortest chain of this type that is tied in a single overhand (trefoil) knot? Next month I shall reproduce the shortest chain Delbrück has found. It has not been proved minimal; perhaps a reader will discover a shorter one. (I wish to thank John McKay for calling this problem to my attention.)

2. The old problem of expressing integers with four 4's (discussed in an earlier column reprinted as Chapter 5 of my *Numerology of Dr. Matrix*) has been given many variations. In an intriguing new variant proposed by Fitch Cheney one is allowed to use only pi and symbols for addition, subtraction, multiplication, division, square root and the "round-down function." In the last operation, indicated by brackets, one takes the greatest integer that is equal to or less than the value enclosed by the brackets. Parentheses also may be used, as in algebra, but no other symbols are allowed. Each symbol and pi may be repeated as often as necessary, but the desideratum is to use as few pi symbols as possible. For example, 1 can be written $[\sqrt{\pi}]$ and 3 even more simply as $[\pi]$.

The reader is invited to do his best to express the integers from 1 through 20 according to these rules, and to compare them next month with the best Cheney was able to achieve.

3. L. Vosburgh Lyons contributed a fiendish dissection problem to a magic magazine in 1969 [*see top illustration on opposite page*]. The polygon [*at left in illustration*] can be dissected into four congruent polygons [*at right*]. Can the reader discover the only way in which the same polygon can be cut into *five* congruent polygons?

4. A full set of 32 chessmen is placed on a chessboard, one piece to a cell. A "move" consists in transferring a piece from the cell it is on to any empty cell. (This has nothing to do with chess moves.) Gilbert W. Kessler, a mathematics teacher in a Brooklyn high school, thought of the following unusual problem: How can you place the 32 pieces so that a maximum number of transfer moves are required to arrange the pieces in the correct starting position for a game of chess?

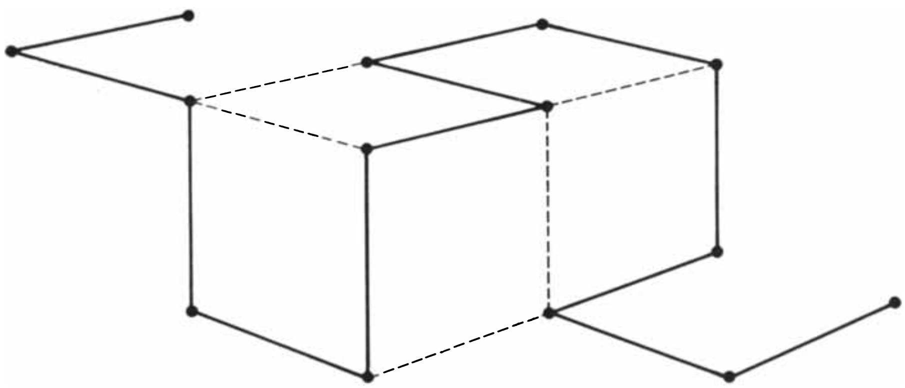
It is not specified which side of the board is the black side, but the playing sides must, as in regulation chess, be sides with a white square in the bottom right corner, and of course the queen must go on a square matching her own color. One is tempted at first to think that the maximum is 33 moves, but the problem is trickier than that.

5. A Texas oilman who was an amateur number theorist opened a new bank account by depositing a certain integral number of dollars, which we shall call x. His second deposit, y, also was an integral number of dollars. Thereafter each deposit was the sum of the two previous deposits. (In other words, his deposits formed a generalized Fibonacci series.) His 20th deposit was exactly a million dollars. What are the values of x and y, his first two deposits? (I am indebted to Leonard A. Monzert of West Newton, Mass., for sending me the problem of which this is a version.)

The problem reduces to a Diophantine equation that is somewhat tedious to solve, but a delightful shortcut using the golden ratio becomes available if I add that x and y are the two positive integers that begin the longest possible generalized Fibonacci chain ending in a term of 1,000,000.

6. A deck of 52 playing cards is shuffled and placed face down on the table. Then, one at a time, the cards are dealt face up from the top. If you were asked to bet in advance on the distance from the top of the first black ace to be dealt, what position (first, second, third, . . .) would you pick so that if the game were repeated many times, you would maximize your chance in the long run of guessing correctly? In other words, what is the most probable position of the first black ace?

7. John Horton Conway, whose game "life" was last month's topic, defines a "quintomino" as a regular pentagon



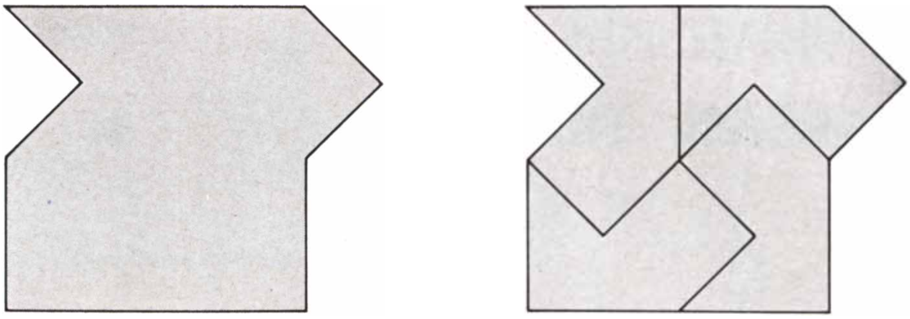
Example of a 13-link chain

whose edges (or triangular segments) are colored with five different colors, one color to an edge. Not counting rotations and reflections as being different, there are 12 distinct quintominoes. Letting 1, 2, 3, 4, 5 represent the five colors, the 12 quintominoes can be symbolized as follows:

A. 12345	G. 13245
B. 12354	H. 13254
C. 12435	J. 13425
D. 12453	K. 13524
E. 12534	L. 14235
F. 12543	M. 14325

The numbers indicate the cyclic order of colors going either clockwise or counterclockwise around the pentagon [*see illustration at left below*]. In 1958 Conway asked himself if it was possible to color the edges of a regular dodecahedron [*middle illustration below*] in such a way that each of the 12 quintominoes would appear on one of the solid's 12 pentagonal faces. He found that it was indeed possible. Can readers find a way to do it?

Those who like to make mechanical puzzles can construct a cardboard model of a dodecahedron with small magnets glued to the inside of each face. The quintominoes can be cut from metal and colored on both sides (identical colors opposite each other) so that any piece can be "reflected" by turning it over. The magnets, of course, serve to hold the quintominoes on the faces of the solid while one works on the puzzle. The problem is to place the 12 pieces in such a way that the colors match across every edge.



L. Vosburgh Lyons' dissection problem

Without such a model, the Schlegel diagram of a dodecahedron [*illustration at right below*] can be used. This is simply the distorted skeleton of the solid, with its back face stretched to become the figure's outside border. The edges are to be labeled (or colored) so that each pentagon (including the one delineated by the pentagonal perimeter) is a different quintomino.

8. Letters in the sentence "Roses are red, violets are blue" are scrambled by the following procedure. The words are written one below the other and flush at the left:

ROSES
ARE
RED
VIOLETS
ARE
BLUE

The columns are taken from left to right and their letters from the top down, skipping all blank spaces, to produce this ordering:

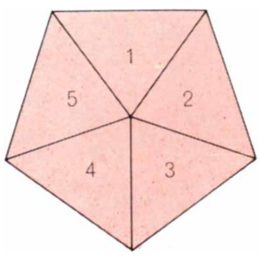
RARVABOREIRLSEDOEUELESETS.

The task is to find the line of poetry that, when scrambled by this procedure, becomes

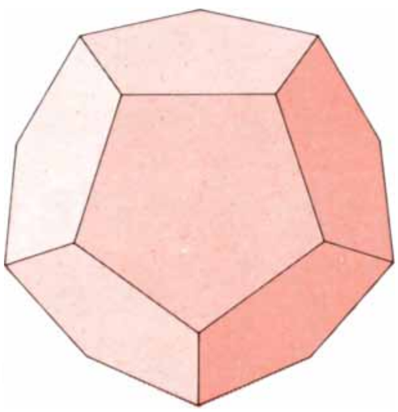
TINFLABTBULAHSORIOOESAWEIKOANARG-EKRDYEASTE.

Walter Penney of Greenbelt, Md., contributed this novel word problem to the February 1970 issue of *Word Ways: The Journal of Recreational Linguistics*. That lively quarterly, now in its third year, is currently being published privately by A. Ross Eckler, Spring Valley Road, Morristown, N.J. 07960. A subscription is $7 per year.

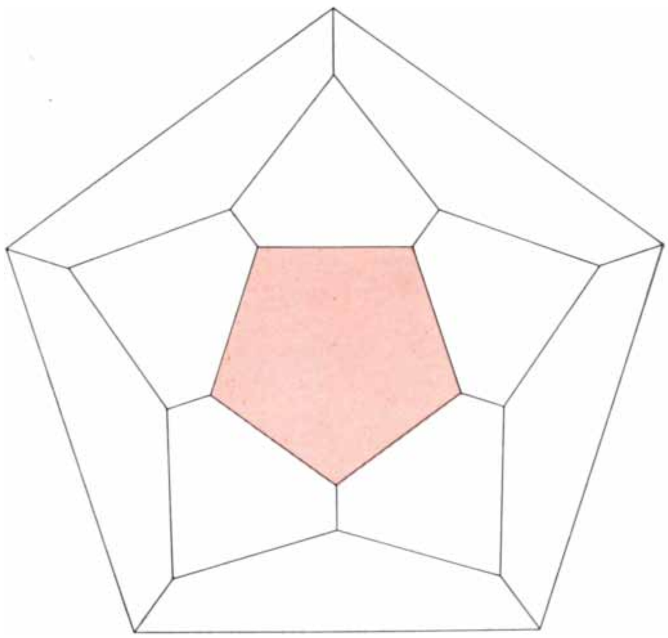
9. A secretary, eager to try out a new typewriter, thought of a sentence shorter than one typed line, set the controls for the two margins and then, starting at the



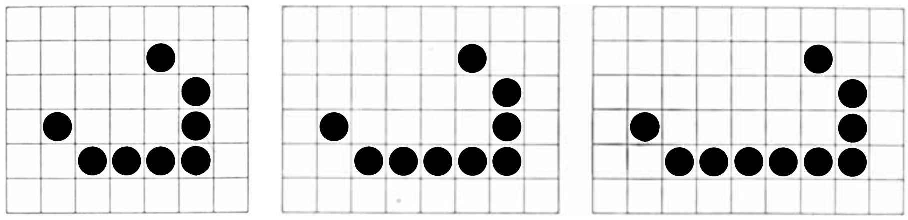
The A quintomino



The dodecahedron



Schlegel diagram of dodecahedron



Lightweight (left), *middleweight* (center) *and heavyweight* (right) *spaceships*

left and near the top of a sheet of paper, proceeded to type the sentence repeatedly. She typed the sentence exactly the same way each time, with a period at the end followed by the usual two spaces. She did not, however, hyphenate any words at the end of a line: when she saw that the next word (including whatever punctuation marks may have followed it) would not fit the remaining space on a line, she shifted to the next line. Each line, therefore, started flush at the left with a word of her sentence. She finished the page after typing 50 single-spaced lines.

Without experimenting on a typewriter, answer this question: Is there sure to be at least one perfectly straight column of blank spaces on the sheet, between the margins, running all the way from top to bottom? (T. Robert Scott originated this problem, which was sent to me by his friend W. Lloyd Milligan of Columbia, S.C.)

10. *A:* "What are the ages, in years only, of your three children?"

B: "The product of their ages is 36."

A: "Not enough information."

B: "The sum of their ages equals your house number."

A: "Still not enough information."

B: "My oldest child—and he's at least a year older than either of the others—has a wart on his left thumb."

A: "That's enough, thank you. Their ages are. . . ."

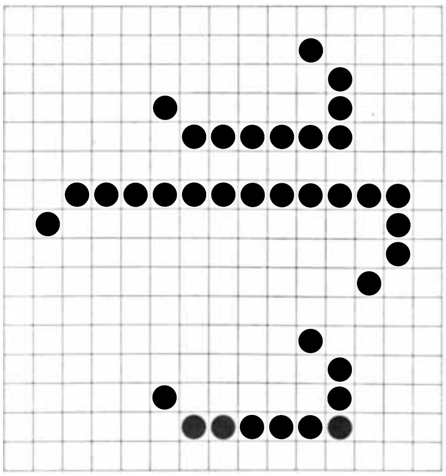
Complete *A*'s sentence. (Mel Stover of Winnipeg was the first of several readers to send in this problem, the origin of which I do not know.)

Last month's exercises, involving John Horton Conway's game "life," are answered as follows:

The Latin cross dies on the fifth move. The swastika turns into traffic lights (four blinkers) on the third move. The letter *H* dies on the sixth move. The next three figures are flip-flops: as Conway writes, "The toad pants, the clock ticks and the beacon flashes, with period 2 in every case." The pinwheel's interior rotates 90 degrees clockwise on each move, the rest of the pattern remaining stable. Periodic figures of this kind, in which a fixed outer border is required to move the interior, Conway calls "billiard-table configurations" to distinguish them from "naturally periodic" figures such as the toad, clock and beacon.

The three known spaceships (in addition to the glider, or "featherweight spaceship," given last month) are shown in the illustration above. All three travel horizontally to the right with half the speed of light. As they move they throw off sparks that vanish immediately as the ships continue on their way. Unescorted spaceships cannot have bodies longer than six counters without giving birth to objects that later block their motion. Conway has discovered, however, that longer spaceships, which he calls "overweight" ones, can be escorted by two or more smaller ships that prevent the formation of blocking counters. The illustration below shows the longest spaceship that can be escorted by as few as two smaller ships; still longer ships require a flotilla of more than two companions. A spaceship with a body of 100 counters, Conway finds, can be escorted safely by a flotilla of 33 smaller ships.

I shall report later on any success readers have in finding new spaceships or oscillators or in meeting Conway's challenge to settle his conjecture about the game.



Overweight spaceship with two escorts

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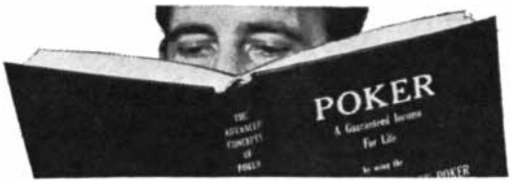

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THE AMATEUR SCIENTIST

A modulator is constructed for laser light, and phase-contrast microscopy is simulated

Conducted by C. L. Stong

Laser light has an immense capacity for carrying signals. The beam of a helium-neon laser, even if it is loaded to less than 10 percent of its capacity, can in theory transmit a million television programs and 100 times the world's present radio traffic while simultaneously enabling every person on the earth to have a private telephone. The use of the laser for mass communication, however, awaits the development of a practical modulator: an apparatus for impressing multiple signals on the light beam.

Several modulation schemes have been proposed, including a device based on the effect first described in 1845 by Michael Faraday. He observed that a block of lead glass, when it is immersed in a strong magnetic field, rotates the plane of vibration of light waves. Other experimenters demonstrated the Faraday effect in various solids and in gases and liquids. Recently Don Smith, a Mobile, Ala., high school student, used the Faraday effect for modulating both laser light and ordinary light. He describes the experiment as follows:

"Essentially the apparatus consists of a tubular glass cell of fluid that forms the core of a solenoid (a cylindrical coil of magnet wire). The solenoid, when it is energized by electrical signals, sets up a magnetic field in the fluid. The strength of the field varies in proportion to the amplitude of the signal current.

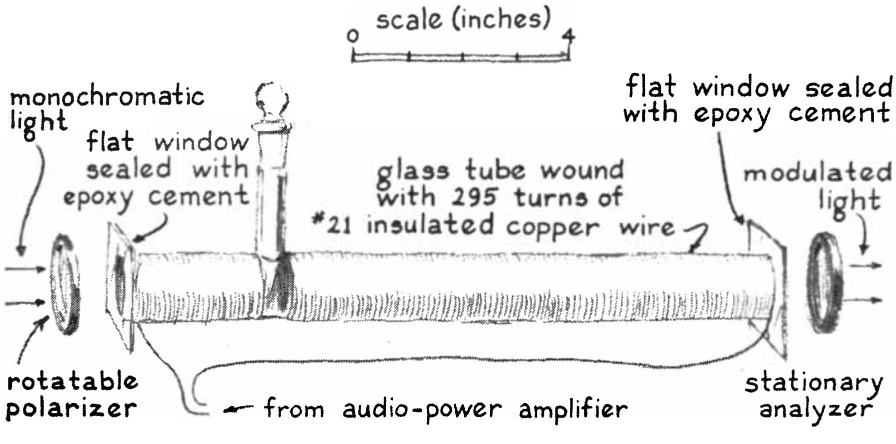
"The light to be modulated enters the cell through a polarizing filter, commonly known as the polarizer, that restricts the vibration of the light waves to a single plane. As the waves proceed through the fluid the plane in which they vibrate is rotated by an amount that varies with the strength of the magnetic field and hence with the strength of the signals. Light waves that emerge from the cell encounter a second polarizing filter, called the analyzer, that is relatively transparent to waves that vibrate in one plane, opaque to waves that vibrate at right angles to this plane and of proportionate transparency to waves that vibrate in planes between these extremes. The analyzer is adjusted to the position of maximum transparency for light waves that are rotated through the largest angle. With the apparatus so adjusted, variations in the strength of signals are reproduced as variations in the brightness of the emerging light. The electrical signal can be reproduced at a distant point by inserting a photoelectric cell in the modulated beam.

"The amount of information that can be impressed on light by the Faraday effect is limited primarily by the loss of energy in the cell. The solenoid functions as an induction furnace as well as a modulator. It can melt lead glass if it is energized by high-frequency current of sufficient strength. Other materials, including certain liquids and gases, absorb less energy. Most of my experiments have been done with carbon disulfide, although I have also used water and nitrobenzene.

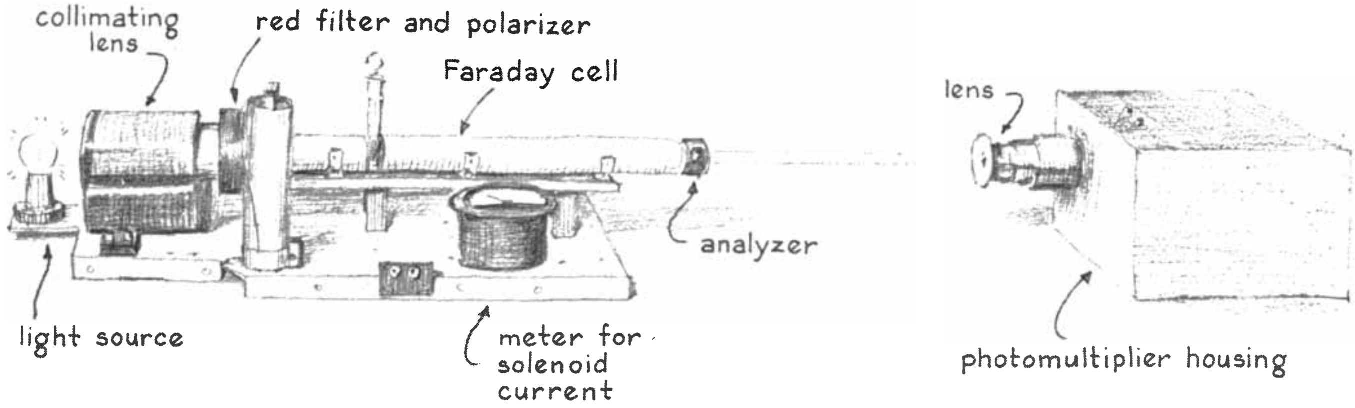
"The cell of my apparatus consists of a glass tube about 2.5 centimeters in diameter and 30 centimeters long closed at the ends by flat glass windows. Fluid is admitted to the cell through a port near one end. A short length of 1/4-inch tubing is sealed to the port. The windows can be made of cover glasses of the kind used for protecting 35-millimeter photographs. Affix them to the ends of the tube with epoxy cement. The solenoid, consisting of 295 turns of No. 21 enameled copper wire in a single layer, was wound directly on the glass tube.

"The solenoid is powered by an audio-frequency amplifier that develops an output of some 200 watts and a maximum current in the winding of 12.6 amperes. The amplifier consists of two stages of speech amplification; they drive a pair of beam-power tubes in the output stage. The construction is conventional except for the output transformer. Most commercial output transformers are designed to match the impedance of loudspeakers, which ranges from four to 16 ohms. The impedance of my solenoid is only 1.2 ohms.

"I solved the matching problem by using for the output transformer a 100-watt power transformer that happened to be on hand. It is designed to operate from a 117-volt power line and has three secondary windings. One winding is center-tapped and rated at 800 volts. Two are 6.3-volt windings rated for an output current of 15 amperes each. I reversed the transformer, using the center-tapped 800-volt winding as the input and the two 6.3-volt windings in series as the output [*see bottom illustration on opposite page*].



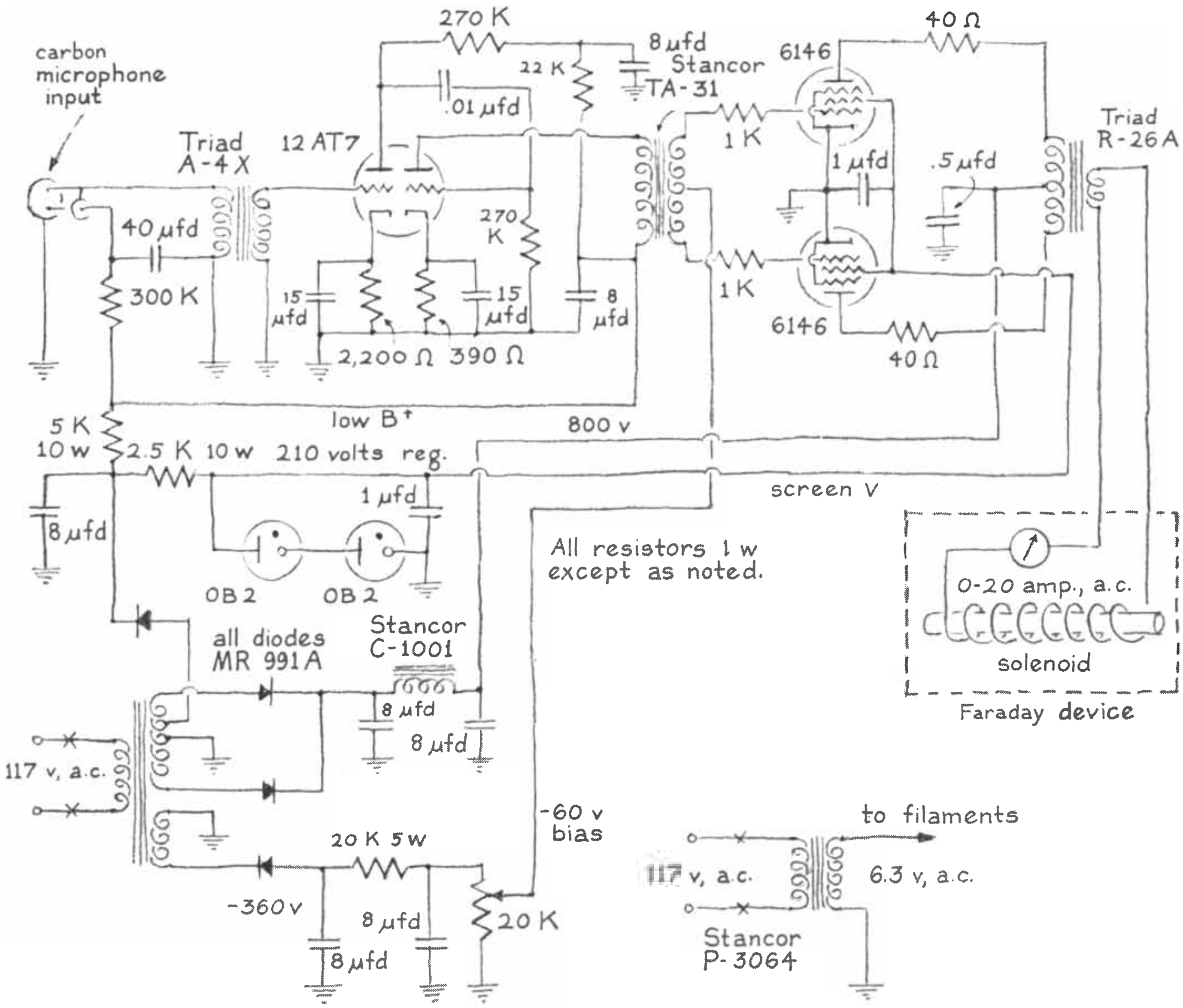
Faraday cell of Don Smith's laser-light modulator



Components of the modulator

"Although the transformer is rated at only half of the peak power that the amplifier can develop, it is adequate because the average power of an audio signal rarely exceeds 30 percent of the peak power. The match between the secondary winding and the solenoid appears to be reasonably good. An experimenter could easily substitute any comparable transformer, such as the Triad Type R-26A.

"I also had another transformer of unconventional design that I used for the power supply. One of the secondary windings develops about 600 volts and the other 250 volts. When rectified and filtered, these potentials become 800 volts and 360 volts. They are respectively used for the plate voltage and the grid-bias voltage of the output stage. A pair of transformers such as the Stancor



Circuitry of the modulator

PC-8405 and PS-8416 would develop the required voltages. Plate voltage for the input stage can be on the order of 100 to 120 volts and, with rectification, can be taken directly from the power line.

"The receiver that I use for picking up the modulated light and converting it into sound consists of a Type 931 photomultiplier tube, a power supply for energizing the photocell and a conventional audio amplifier of the kind used in record players. A simple lens, which can be an ordinary reading glass, focuses the modulated light on the photocathode of the photomultiplier. Incidentally, the light source must be monochromatic because the amount by which the Faraday cell rotates the plane of polarization varies with wavelength. In the case of white light some component colors would be rotated more than others, thus lowering the effectiveness of the cell. An incandescent lamp can be used as the light source by including in the lamp housing a simple lens for bending the rays into a parallel beam and by inserting a color filter, such as a sheet of red transparent plastic, just ahead of the polarizer. An ideal light source is a helium-neon laser with Brewster windows. The laser beam is both monochromatic and polarized, eliminating the need for the collimating lens, the color filter and the polarizer.

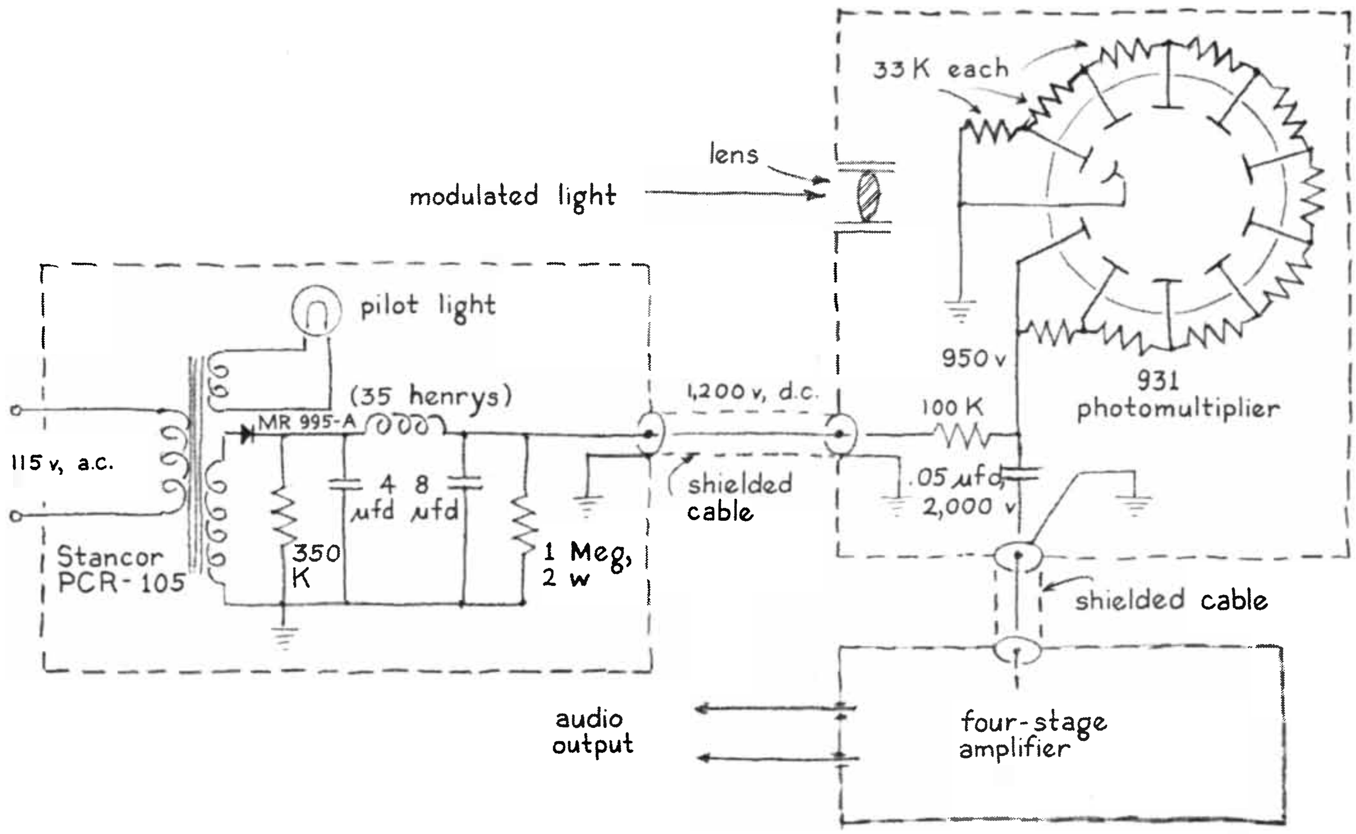
"To test the system initially I placed the transmitter at one end of my workbench and the receiver at the other end. After applying power to the lamp I located the beam of light at the distant end of the bench with a white card and adjusted the position of the transmitter so that the beam entered the lens of the receiver. Power was then applied to both the transmitter and the receiver, an audio signal was applied to the input of the transmitter and the volume of the signal was adjusted so that the pointer of an ammeter in the solenoid circuit swung to about 10 amperes every five seconds. The analyzer was now rotated to the position where the signal was reproduced at maximum volume.

"The alignment of the light beam becomes increasingly difficult as the transmitter and the receiver are operated at greater separations. The beam from an incandescent lamp diverges so much that at a distance of 100 feet or more it cannot be detected on a screen. You can locate the beam by looking toward the source and maneuvering the position of your eye until the light appears brightest. The receiver is moved to this position.

"*Never look at the source when aligning a laser beam.* Laser light can permanently damage the eye. When a laser is used, fit the transmitter with an alignment telescope of the kind used on guns and rifles. To collimate the telescope and the transmitter, intercept the laser beam with a white screen at a distance of about 30 feet and adjust the position of the telescope so that the distant spot of laser light is centered on the cross hairs. The line of sight and the light beam now converge because the telescope is situated above or toward one side of the laser.

"Measure the separation and note the radial position of the telescope with respect to that of the laser. Assume that the telescope is five inches directly above the laser at the 12 o'clock position. With a pencil make a small dot on the white screen five inches from the light spot and directly above it. Readjust the position of the telescope to center the cross hairs on the pencil dot. The line of sight and the laser beam are now parallel. Thereafter the light beam will be located just five inches below any object on which the cross hairs are centered, regardless of the distance. The lens of the receiver can be positioned accordingly.

"The apparatus works splendidly and the quality of the transmitted sound is excellent. I have not attempted to transmit multiple signals because the electronic gear required for setting up even two or three carrier channels is both complex and costly. On the other hand,



The receiver circuit

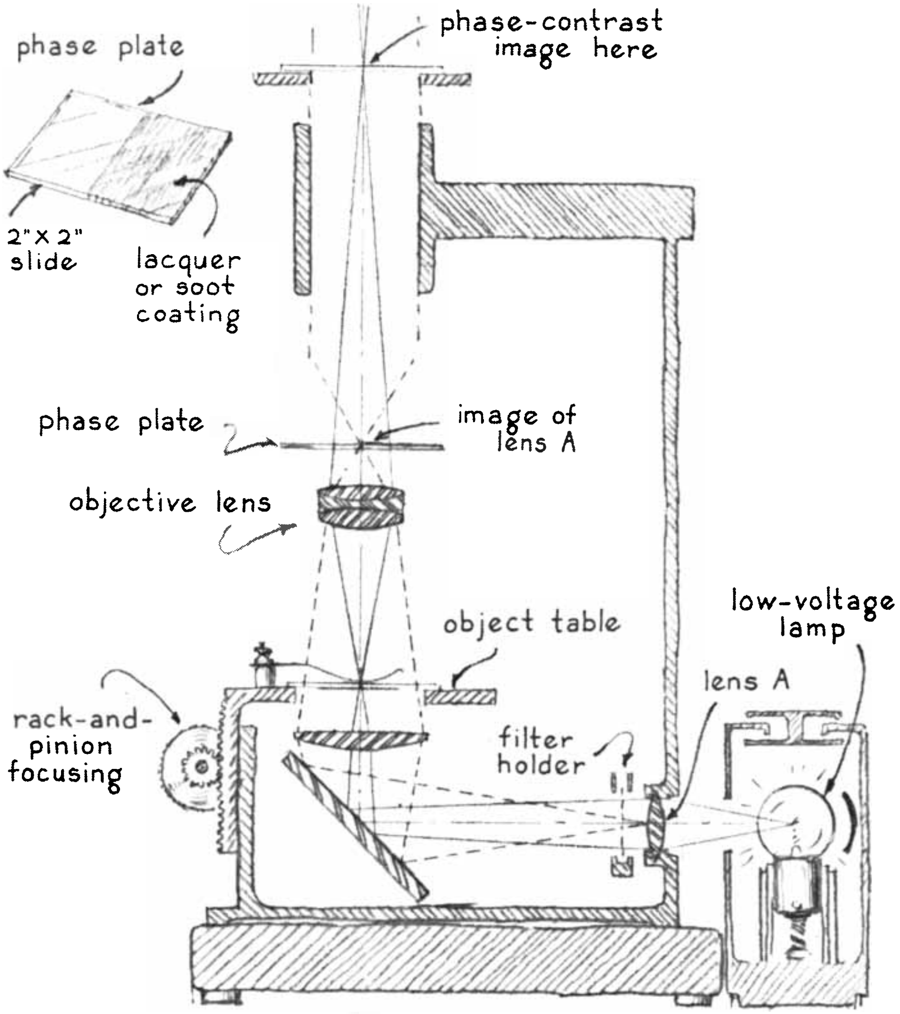
I have experimented with various fluids in the Faraday cell.

"As I have mentioned, the rotation of the plane of polarization varies directly with the strength of the magnetic field and with the wavelength of the light. It also varies with temperature, the length of the magnetized medium and the nature of the medium. Assuming polarized monochromatic light at the wavelength of the yellow hue emitted by sodium, the rotation in minutes of arc is equal to the product of the length of the magnetized path in centimeters, multiplied by the strength of the magnetic field in gauss and by a constant of proportionality that is characteristic of each substance.

"Many of the constants were determined experimentally during the 19th century by the French physicist Marcel Emile Verdet. They bear his name and specify the rotation of the plane of polarization in minutes of arc produced when light traverses one centimeter of a substance immersed in a magnetic field of one gauss. Typical Verdet constants (at 20 degrees Celsius) are rock salt, .035; lead glass, .031; zinc sulfide (beta), .225; water, .013; carbon disulfide, .042; atmospheric air, .006. Carbon disulfide works nicely but is volatile and extraordinarily toxic. Inhaling even a small quantity of the vapor can result in chronic illness.

"The plane of polarization rotates in the direction opposite to the flow of electrons in the solenoid. For this reason the amount of rotation can be doubled by reflecting modulated light back through the cell. Indeed, if the inner surfaces of both windows were aluminized and clear openings were left in the coating for the entrance and exit beams, multiple passes would be made and the amount of rotation would be increased several times (at the cost of some loss of brightness). Aluminum coatings absorb about 10 percent of the incident light, and some energy is also absorbed by the modulating medium. I intend to experiment with reflective coatings in the near future.

"Frequencies of up to 50 kilocycles can be modulated by a solid rod of lead glass of the kind used in neon signs. The ends should be ground flat at right angles to the axis of the rod and either polished or capped by microscope cover glasses cemented in place with Canada balsam. If the light source is a helium-neon laser, the diameter of the glass rod need be no larger than five millimeters. The solenoid can be wound directly on the rod.



P. C. Diegenback's phase-contrast apparatus

"The efficiency of the apparatus in terms of power consumed for modulation varies inversely with the diameter of the solenoid. A solenoid with a radius of 2.5 millimeters is substantially more efficient than one with a radius of 12.5 millimeters. On the other hand, the impedance of the solenoid is lowered proportionately with the radius, which complicates the problem of matching the output of the amplifier to the load. The impedance of a 300-turn coil of No. 21 gauge magnet wire, a radius of 2.5 millimeters and a length of 300 millimeters is about .4 ohm."

An experiment for demonstrating on a large scale and with inexpensive materials optical phenomena similar to those involved in phase-contrast microscopy is submitted by P. C. Diegenback of the Zoological Laboratory of the University of Amsterdam. The apparatus that Diegenback has designed and built could be used for large-scale phase-contrast photography, although no subjects have been found for which the technique would have an advantage over existing photographic methods. Diegenback writes:

"The correct use of the microscope implies some insight into the theories of microscopical image formation. In the case of the phase-contrast microscope such insight is absolutely necessary. One need not own a phase-contrast microscope, however, to gain experience with the phenomenon. The principles can be demonstrated by using a larger apparatus. I do the experiments with a commercial optical bench, but a bench of comparable usefulness can be improvised largely of wooden parts [*see illustration above*].

"The optical bench includes an incandescent lamp whose rays are directed through the specimen by a pair of condenser lenses. An image of the specimen is focused by an objective lens on a ground-glass screen. In the case of my optical bench a front-surface mirror between the condenser lenses deflects the rays through a right angle, but this feature is not essential. The focal length of the objective lens is 12 centimeters, but it too is not critical. The simple lenses can be of any convenient focal length, since the dimensions of the optical bench can be altered to accommodate any lenses that are available.

"The great virtue of the phase-contrast microscope is its ability to form a black-and-white image of differences in the refractive properties of a transparent specimen that appears perfectly uniform and clear to the unaided eye. Typical specimens are bacteria, but specimens of this kind large enough for use in my apparatus are rare in nature. Demonstration specimens are easy to make. For example, put a streak of Canada balsam on a conventional microscope slide with a toothpick and let it dry in a dust-free enclosure.

"In the phase-contrast microscope a portion of the light that is diverted by the specimen reaches the eye in the same way that it does in a conventional microscope. Another portion, in addition to passing through the specimen, also traverses a transparent material, called the phase plate, that retards the light waves by a quarter of a wavelength. The waves are thus divided into two portions, which combine in the eye to create the black-and-white image.

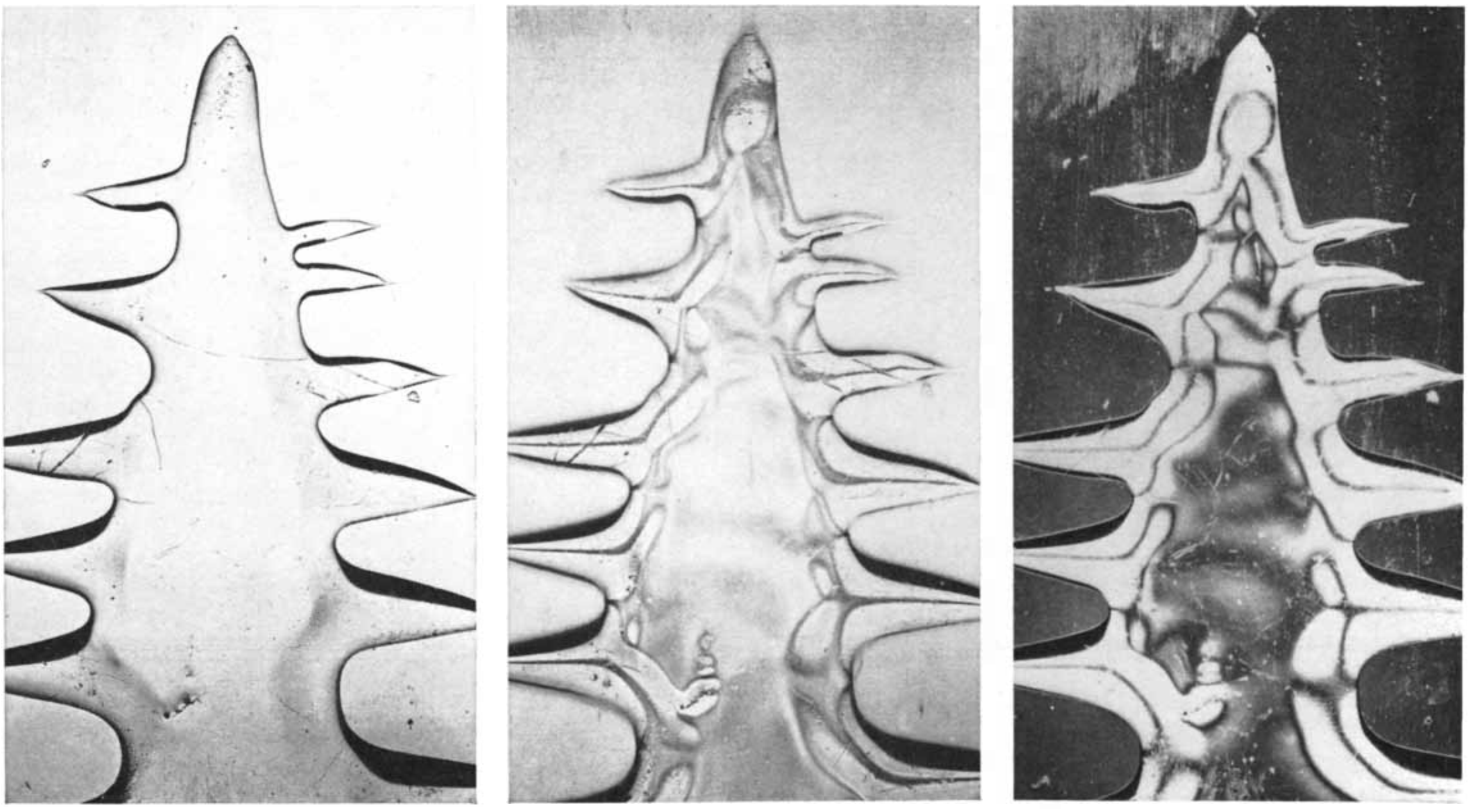
"These features are simulated by the optical bench. A support is devised for a phase plate about two centimeters above the objective lens. The phase plate consists of a clear glass plate, such as the cover glass of a 35-millimeter photograph slide, coated with a thin strip of clear lacquer.

"To make the phase plate put a length of adhesive cellophane tape across the center of the cover glass. With a razor blade cut a thin strip about a millimeter wide from the center of the tape. Spray the tape lightly with transparent lacquer, such as Krylon spray coating No. 1301. When the lacquer dries, remove the tape.

"An aperture of identical proportions is needed for masking the light source. I made the aperture by covering a second clear glass plate with opaque plastic tape and cutting in it a slit proportioned so that when the aperture was inserted in the filter holder, rays from the lamp came to focus only on the plastic strip of the phase plate. The focal length and spacing of the condenser lenses determine the size of the image made by the aperture and must be taken into account when the aperture is made.

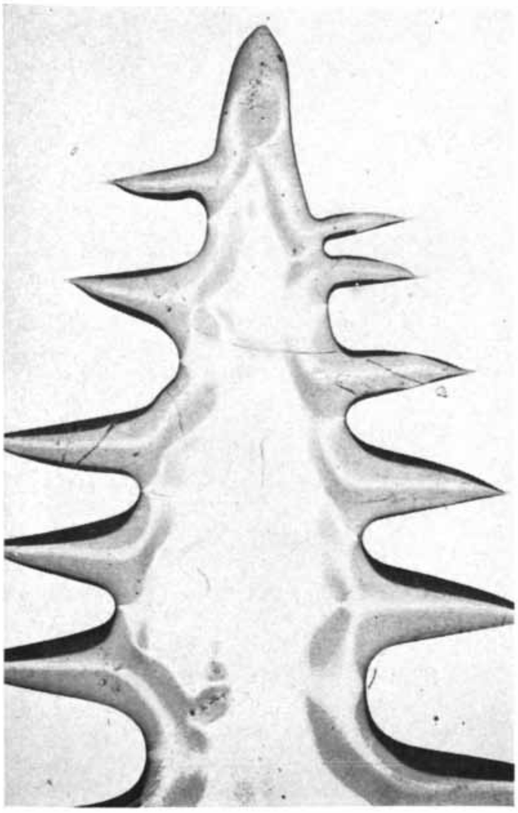
"To adjust the optical bench initially, put the aperture plate in the filter holder. Transfer the ground-glass screen at the top of the optical bench to the holder that will be used for supporting the phase plate about two centimeters above the objective lens. With the condensers and the deflecting mirror in place, but without a specimen on the object table, adjust the position of the condenser to focus the aperture on the ground glass. Return the ground glass to the top of the optical bench, place a specimen on the object table and focus it on the ground glass. (A photograph of a typical specimen—a streak of Canada balsam—thus made with conventional illumination appears at left below.) Next, remove the specimen, insert the phase plate in its holder above the objective lens and align it so that only the strip of lacquer is illuminated. Return the specimen to the object table and focus it on the ground glass. (A photograph of the same streak made by phase-contrast illumination appears second from left below.)

"The image can be further improved by reducing light from the phase plate by means of a neutral-density filter that covers the strip of lacquer. To make the filter, pass one side of a cover glass through the flame of a candle to coat it lightly with a film of soot. Wipe off all soot except a thin band that matches the strip of lacquer. Place the filter directly above the lacquer strip. If the density of the soot is optimum, a distinct improvement will be observed in the resulting image of the specimen. One can also make a filter for reducing the un-



Streak of Canada balsam photographed in normal light (left) *and three types of phase contrast* retarded light by cleaning soot only from the area of the lacquer strip. This lighting is known as negative phase contrast. It is not a desirable kind of illumination because information in the specimen is lost by absorption. (The third and fourth photographs below respectively show the streak in balanced phase contrast and in negative phase contrast.)

"An apparatus of this design is azimuth-dependent, meaning that the aperture and the lacquer strip must be parallel or the phase-contrast effect will be diminished. Manufacturers of phase-contrast instruments solve the problem of phase dependency by using an annular aperture and a phase plate in the form of a matching ring. Either element can be rotated without disturbing the optical configuration. I made an annular set of elements for the large-scale demonstration. A photograph of the resulting image contains somewhat more information than photographs made with linear elements do. Still other improvements can be achieved by using polarizing filters in the direct rays as well as those that pass through the phase plate. Indeed, the apparatus enables the experimenter to investigate all forms of microscopic lighting, including both dark-field and Rheinberg illumination" [see "The Amateur Scientist," SCIENTIFIC AMERICAN; April, 1968].



BOOKS

Population genetics, particularly the human kind, and other matters

by Philip Morrison

SPECIATION IN TROPICAL ENVIRONMENTS, edited by R. H. Lowe-McConnell. Academic Press ($11.50). AN INTRODUCTION TO POPULATION GENETICS THEORY, by James F. Crow and Motoo Kimura. Harper & Row, Publishers ($13.95). SERENDIPITY IN ST. HELENA: A GENETICAL AND MEDICAL STUDY OF AN ISOLATED COMMUNITY, by Ian Shine, with the assistance of Reynold Gold. Pergamon Press ($10). Darwin and Wallace started it all. Under the remote sovereignty of thermodynamics and of the possible bonds among the lighter atoms, the great generalization of inherited variation and natural selection has to explain the whole skein of plants, beasts and men. These three books display the diversity with which men's knowledge in this field has itself evolved.

The first book, in which maps abound but not one formula appears, is the report of a London symposium where species groups of ferns and fishes, orchids and snails are described by men who have long studied life in the Tropics. Our little lemur cousins who dwell in the Madagascar forests, for example, show a remarkable diversity of races and varieties. They were called species by their fond first classifiers a century ago, but the "species" can bear fertile offspring, gray head like mother but reddish whiskers like father, say. (One color plate shows a set of lemur family portraits.) There is nonetheless a swarm of species in most tropical environments, whether pond or savanna or dense forest. Why this is so has no certain answer; only a quantitative one could be satisfying, and the subject is too complex for a single result to suffice. The environment is an old one, unshocked by the glaciations of recent times; even a dry season does not halt life as the grip of the ice does. Our Temperate Zone biota is the immature and impoverished exception; the tropical richness is the normal product of undisturbed evolution. The rise of special ways of making a living becomes cumulative, because it is the very presence of the competing and predating species themselves that becomes the chief source of selection. Life molds life. In the Tropics there is no winter to act as the chief gate, passing a few species of generalized competence, able to act in many ways to make a living. The tropical test is living with a cluster of neighbor species, a task far more complex than beating the cold. Not all the expert contributors agree; some tropical botanists express doubt even in Darwin! Surely this is a transient consequence of the incomplete state of the theory, which still cannot give a full account of the bigger evolutionary changes.

An Introduction to Population Genetics Theory is a modern text for graduate students, written by two very active contributors to the subject. The expression of the ideas of Darwin in precise language is a taxing domain of applied mathematics whose intrinsic difficulty is the inherent complexity of the phenomena it must describe. Consider population growth alone: four models are presented in the opening chapter of the book. They describe, by difference equations or differential equations, none very difficult in itself, the growth by discrete generations that never overlap in time, such as annual flowers, or by discrete generations that do overlap, such as man; they also take up populations that can be treated as continuously changing, such as bacteria. All these populations have their own parameters to conveniently describe the situation. On this base is then set the problem of studying the varieties of organisms with mating patterns, gene frequencies, differential survival and a store of undealt genetic cards made possible by sex. A fully deterministic theory of the statics and dynamics of evolving populations is built first. The text comes equipped with many sets of problems (they are not easy) but without much empirical material. The aim is utility and clarity, not mathematical rigor. A mathematical appendix helps to make the book accessible to readers who know calculus.

It is interesting to see in how simple a model it can be shown that increase in fitness, which is defined merely as the reproductive rate of a given characteristic, is equal to the mean square fluctuation in the fitness itself. This "fundamental theorem of natural selection," which is retained even in quite realistically complicated models, leads to a maximal principle that is quite reminiscent of classical mechanics. The principle asserts that under a given degree of fluctuation the gene frequencies will change in such a way as to maximize the average fitness of the population.

The extension of these theories beyond the assumption of an essentially infinite population, to take account of the role of mere chance in favoring or ending initial gene changes, which must always involve only a few individuals, is the topic of the last third of the book. The topic is a part of diffusion theory, broadly viewed; the treatment is quite extensive, but it does not easily enhance the qualitative insight, given by many writers, of a representative point standing for a given genetic population diffusing here and there over an "adaptive surface" whose slowly changing peaks and valleys of fitness represent the successful and the failing forms we call species. The gain this book offers is quantitative, and it lies deep.

One author works at the University of Wisconsin, the other at the National Institute of Genetics in Japan. For 15 years theirs has been an intimate collaboration in teaching and research, to which distance, language and culture have plainly set no barriers.

Young Dr. Shine and Mr. Gold, the authors of *Serendipity in St. Helena,* were for a few years the entire medical profession on that beautiful high heather island, where a ship calls only about once a month. The 5,000 isolated islanders (who count about an equal number of compatriots living abroad in Cape Town and London) form the topic of this charmingly presented and remarkably interesting study. Personal and ingenious, the narrative belongs to the great tradition of studies of evolution in isolation. Here, however, it is not Darwin's finches we examine; it is the flaxgrowers and craftsmen of the island (some islanders work at a cable station and a U.S. base 700 miles north on Ascension Island) and their cheerful and winning families. Nearly all immigration to the island had ceased by 1820; the dark-eyed and handsome people are the joint descendants of the African freedmen, the British garrison and the Chinese laborers who had come to the island by that time. Their speech is a lively English. ("I worry a bit against the hill when I fetch water." "She couldn't pick the meaning of it.") Their style is modest but not simple. Not many of them pass the secondary school examinations, but "most men are able to farm, fish, play the guitar, cut hair, make an efficient watering can from a margarine tin, mend shoes and build their own houses."

Dr. Shine is a pretty good improviser himself. He had to be; he tried to carry out a medical examination of every person on the island, and actually saw about 90 percent of them. Walking a couple of hours over the heath to reach a home, he could carry little equipment. Medical gear and a weighing scale in a rucksack, a transistorized electrocardiograph in one hand and a camera in the other, Dr. Shine went out to the back-country cottages for his data. The people tested him, and once they had confidence in the tact and goodwill of their new doctor he was in a position to conduct the best-controlled genetic-medical survey yet made. No such study of inbreeding had existed before; Dr. Shine followed his sample pedigrees, each verifiably, back through 50 matings. To do so he assembled more than 1,000 individual pedigrees. ("Few investigators are fortunate enough to be well-established general practitioners when they are about to begin their research.") Good data require intimate familiarity with the people, a full sample of examinations and stringently evaluated pedigrees. ("People are nicer when isolated, they generally know more pedigree information and they have a more co-operative attitude to investigators and, finally, the family are generally accessible.")

St. Helenians have an entire catalogue of rare disorders. At least three new such conditions were discovered. Inbreeding was obvious and verifiable. It contributes its share of deaf mutes, albinos and stillbirths wherever the double dose of the damaging recessive gene is administered by heredity. On St. Helena, however, there is a much greater incidence of recessives than inbreeding alone can quantitatively account for. The founders of St. Helena must almost surely have brought in a few rare genes, which at once lost their rarity—they now belonged to the gene pool not of a million Englishmen but of a hundred islanders. This direct effect of small numbers is the phenomenon of genetic drift written plainly. Alternative mutation and selection hypotheses can be pretty well refuted by the data.

The St. Helenians are a healthy lot. The recessive defects are individual tragedies, but they remain at a level below public importance. Infant mortality is low. Cardiovascular disease is the major cause of death, just as it is in Britain and the U.S. The mortality from coronary failure rises year by year exactly parallel to the curve for England and Wales, except that it is about eight years delayed. This is in spite of the fact that smoking is infrequent, exercise plentiful and stress low. The St. Helenians are "an easy-going, delightful and gentle people," just as they were described by Captain Cook in 1775. They do not eat much fat, and some of what they do eat is unsaturated. If the effect is to be understood, it is tempting to blame it on sugar. This they now consume about as much as the English do, and their consumption increases year by year as they become more prosperous. Busy Dr. Shine collected his careful diet data anonymously, and so we cannot check individual diet on St. Helena against health.

It was as an army physician in 1960 that Dr. Shine volunteered for St. Helena, where the only doctor was due to leave by the next boat. "Believing St. Helena to be in the Pacific Ocean which I had always hoped to visit, I asked Colonel Ian Milne, my commanding officer ... and three weeks later I sailed." His two-and-a-half-year stay made a young doctor into a first-class clinical geneticist, revealed a warm and insightful man with a genius for fieldwork and brought human genetics data of real value. It is a pleasure to be able to infer from a few remarks and from the bibliography that he has since made his way to some real Pacific islands.

The book cannot be enjoyed fully without access to a medical dictionary and some formulas of quantitative genetics, but it is a delight all the same, a find worthy of the princes of Serendip.

The Discovery of Radioactivity and Transmutation, edited and with commentary by Alfred Romer. Dover Publications, Inc. ($2.25). Radiochemistry and the Discovery of Isotopes, edited, with commentary and an introductory historical essay, by Alfred Romer. Dover Publications, Inc. ($3.50). "Modern nuclear physics had its beginning in radioactivity." Those are the first words of the first of these two absorbing anthologies of early papers, reprinted (not in facsimile, unfortunately), translated where necessary, and accompanied with connective matter and helpful appraisals by their skillful and knowing editor. "Science is always most completely assimilated when it is in the nascent state," wrote James Clerk Maxwell. His comment is cited by the general editor of this series. (The two books belong to the continuing series called Classics of Science, which so far includes volumes on topics in physics and chemistry.) Nascent nuclear physics is a powerful reagent all right. It glows in the darkness, dazzling the mind.

The first and older of these volumes is an epic out of a heroic age of physics. Its hero is Ernest Rutherford, whose energy and clarity of mind led the world to the full transformation theory, the spontaneous and unchanging intrinsic rates of chains of atomic transmutations, quantitatively described, by 1904. That was just eight years from the spring of 1896, when Henri Becquerel (whose photograph appears here, the handsome young professor wearing the golden weskit and fancy sword hilt of the Académie des Sciences) made his accidental discovery of the blackening of photographic plates by the "crystalline lamellas" of a uranium salt.

The second volume, published in 1970, tells a more complex story. Its drama is more collective; many of the names are half-forgotten or little known today. This chemical volume spans the time from the Curies' first work (the word "radio-active" first occurs in their paper in the summer of 1898) to Frederick Soddy's use of "isotope" late in 1914, when the physical and chemical circle had at last closed, the new Bohr atom and the Moseley X-ray spectra showing the dominant role of nuclear charge. The neutron was not yet in view, of course; Soddy plainly thinks of the nucleus as an intimate mixture of protons and electrons.

The story begins with Röntgen, as does the rest of modern physics. Becquerel saw a photograph of the bones of the living hand at the Académie on January 20, 1896, less than a month after the announcement of X rays. Henri Poincaré had Röntgen's paper; he explained to Becquerel that the new rays came from the fluorescent spot on the glass bulb of a Crookes tube, where the beam struck the wall. Fluorescence was a kind of family study in the Becquerel household, and Henri tried to see if short-lived phosphors exposed to sunlight would blacken a photographic plate through two sheets of opaque paper. Uranium salts could. By the following week (the *Comptes Rendus* gladly published short notes by academicians every week) he had developed plates prepared earlier with the salts on them but never exposed to sunshine, because "on those days the sun appeared only intermittently," and reported that "the silhouettes appeared with great intensity." By May he had shown that the effect was present even if he crystallized the salt newly in the dark, and that it was produced even more strongly by uranium metal; it was no molecular phenomenon but an atomic one. Then the field outstripped him.

Consider the problems these pioneers faced. The electroscope and the photographic plate were their two detectors. Yet substances turned up that blackened plates but produced no current in the electroscope. Then they knew that some elements gave out alpha rays, some beta rays and some both. (The gammas recorded weakly.) That had fooled Soddy for a while. Thorium was radioactive; however, "the opening or closing of a door at the end of the room" affected the measured rate of discharge for thorium, although not for uranium. So did Rutherford and Soddy come to learn about the radioactive gas emanating from thorium. Thorium radioactivity could be "induced" on other solid surfaces; thus they learned about the active deposit of the product of emanation. Chemistry became haphazard, since results depended on the dates and the order of acts of separation. The vagaries of "weightless" chemistry were new and strange. Charcoal would absorb out nearly all the activity from a solution of uranium X. The slightest trace of added thorium sulfate, however, could prevent that absorption completely. So did they realize—Soddy by 1911—what specific activity meant: the rare active atom was swamped by the isotopic inactive thorium on the charcoal surface.

Two facts became clear very early to Rutherford and his chemist associate Soddy. Radioactivity, they said, is a "manifestation of subatomic chemical change." It had to be so, because it was atomic and yet it produced new kinds of matter. More than that, the energy release took place, atom by atom, at the very moment of the change; it did not simply follow after it. Then the exponential decay became natural. That was by 1902; the isolated nature and apparent causelessness of atomic change appeared in this result. The quantum theory was there in embryo.

The Curies thought the energy that heated their samples might stream through space and be absorbed by specific atoms. But Rutherford and a calorimetric colleague, H. T. Barnes, showed that the sum of the heat from radium and from separated emanation was just what one expected from the unseparated mix. An outside source would require a special set of assumptions. The energy was there, and it was very large. By 1904 they were sure: the atomic energy was a million times or so as great per unit of mass as any molecular energy, with "no reason to assume that this enormous store of energy is possessed by the radioelements alone." Nearly the entire complex pedigree of the natural radioactivities was worked out by the chemists by 1913 or 1914 and reported by Soddy, the reactions sliding across his isotopic table quite in the modern manner.

The way was open to the nuclear era. Of 18 authors of the 42 papers given in the two volumes, only Otto Hahn (who gives a footnote to his colleague Lise Meitner) took direct part in the large-scale release of that "enormous store of energy." Here is a paradigm-setting era much clearer than the days of Kepler and Galileo and less tangled in Kant's categories than the space-time puzzles of Einstein. These books should set off many a reader, many a class and some students of the history of ideas. The volumes are impeccably edited; one only misses a few dates on the photographs and longs for two more papers, one on the theme of radioactive dating and one on the origin of the energy of stars.

THE INTELLIGENT EYE, by Richard L. Gregory. McGraw-Hill Book Company ($7.95). The flood of solar photons nourishes all life. Yet the most remarkable optical side effect, an image-forming eye used as an early-warning and pattern-recognition system, is known to no plant, although it is found in most animals of at least the complexity and modernity of the higher mollusks. It is instructive to consider the eyes of the machine. Almost no machines can yet use images to affect their behavior. The familiar elevator door, like most industrial photoelectric devices, merely has a primitive light spot, such as no self-respecting protozoon lacks. The camera and even the up-to-date television chain are not properly eyes: they are only means of transferring images to human eyes. What the machine lacks is certainly not a lens or a retina or many amplifiers; it lacks the subtle circuitry that makes sense out of an image—the intelligence of the eye.

Our eyes are not mere passive image-formers. The retinal image for them is merely a raw input. Their marvel lies in our profound faculty of data processing. The eye-brain-hand system actively uses the incoming image to guide its powerful but quite unconscious selection of the most probable external cause of the image. "Perception must, it seems, be a matter of seeing the present with stored objects from the past." How far that past is experiential and how far innate is not clear. Such is the theme of this compact, attractive, important and fresh volume.

The main topic is the viewing of pictures. Pictures are human artifacts, always seized of an "extraordinary double reality . . . an essential paradox." Here they are, those puzzling constructions, in their most problematic forms: stereoscopic pictures for three-dimensional viewing, varied perspectives, impossible objects blandly and sharply photographed, pictures of pictures, drawings by Maurits C. Escher, illusions of scale and figure ground. The analysis goes deep, but with little jargon and no mathematics.

Many photographs and drawings are shown doubled in slightly displaced red and green tone or line. These yield strong depth perception when viewed through spectacles (provided) with a red filter for one eye and a green filter for the other. Looking even with three-dimensional glasses at such a photograph of the hollow interior of a mask, however, one sees the normal face, with the nose sticking outward, not improbably inward, even though the latter is correct; the stereoscopic cues are overridden by the intelligent eye, which—like Lloyd's of London—makes its bet on experience. (Turning the book upside down may destroy familiarity enough to restore the proper stereoscopic result.) There is a step-by-step outline of what you see looking with one eye or with two at a wire-frame cube and at pictures of it. Pictures demand an acquired interpretation. It may indeed be that some statues in ancient temples were made in these ways to seem alive, their hollow heads with that ambiguous depth appearing to follow each devotee as he moved in the "gloom of the sacred place." That astrology may have arisen out of the experience that the moon and stars seem to move with the traveler is less plausible. Now that a consciously analyzed form of instrumental perception gives us the true scale of the universe, says Professor Gregory, "all reason for a close personal association with the Universe (hence astrology) is lost." That is unfair; are we not made of star stuff?

In this book Professor Gregory has expanded and deepened a splendid series of lectures he did one recent Christmas season, which were televised by the knowing and powerful science team of the British Broadcasting Corporation. It has become a well-illustrated essay that readers concerned either with perception narrowly, or with epistemology broadly, cannot allow themselves to miss. Not everyone will agree with his more general conclusions, but the results he exhibits and the views he expresses must be taken into account by everyone who would understand either the world we see or the "essentially unpredictable future . . . a world we cannot see," the world of instruments and of "pictures, symbols, thought, and language."

THE EMERGENCE OF MAN, by John E. Pfeiffer. Harper & Row, Publishers ($10). YIWARA: FORAGERS OF THE AUSTRALIAN DESERT, by Richard A. Gould. Charles Scribner's Sons ($8.95). It has been 45 years since they uncovered the Folsom find: the specialized flint spearhead in the glass case still lies among the bison ribs where it lodged 11,000 years ago in the grassy gamelands along the upper Cimarron. Men still make those elegant symmetrical fluted points to the same pattern from the same flints, but now on the banks of the Snake River to the north in Idaho. Four typical Folsom points appear in the photograph, one with the date 1965. The modern Folsom artisan is Don Crabtree of Idaho State University. He has made more than 50,000 stone tools in his career—and spoiled three times as many! Crabtree has used heat-treating to prepare the flint, as the Indians often did. An ordinary notched arrowhead takes him five or 10 minutes, but a Folsom point ("the very ultimate in . . . control") requires three hours and special implements such as a flaking tool worked by the full pressure of his chest.

To understand that old artificer our ancestor more than one such scheme of repeating his skills and sharing his life is under way. A couple of years ago Jack Harlan found "vast seas of primitive wild wheats" growing in the foothills of Anatolia. With a city man's bare hands he painfully cropped about four and a half pounds of grain an hour; then, with a sickle he made of a branch and an ancient flint blade, his yield grew about 20 percent and his hands were spared. L. S. B. Leakey, the unriddler of Olduvai Gorge, had a more ambitious plan. He wanted to spend six weeks in the bush, moving each week to a new stage of human skills: starting with bare hands, digging sticks and snares made from tree fiber and ending with the bow and arrow. He has grown too old for that, he fears: "I'd have done it long ago, but Mary wouldn't let me. She thought it was too dangerous." But the stirring is there, and plans for organized Stone Age bands of experimental campers are ripening. A proposal for artificial burials, in which bones and shards would be placed with precision to be excavated over the course of a century, suggests the growth of a new, active experimentalism among archaeologists.

John Pfeiffer has made a remarkable book, a survey of the present state of our knowledge of human origins, from the *Ramapithecus* jawbone of 15 million years ago, with its curiously small canines (signs perhaps of a new way of life), to men using Stone Age tools today, living and thinking well in the Kalahari Desert and on the boundaries of the Woomera Rocket Range. This is by no means the first excellent book of Pfeiffer's that reviews a science. He has written, and written well, on four other large topics: on the brain, cytology, evolution, even astronomy. He holds the honestly gained reputation of a first-class popular writer of good science. Now he has lost that status, probably for good. It is not that he writes less well—far from it. Rather he has been converted to a single science. He is even a professor of anthropology now, and one hopes his fortunate students can use this lively, full and sensible book. He has traveled so far and so well among the diggers and the bone men and the toolmakers and the ethnographers, seen so much of what they do and what they plan, that at last he has lost his visitor's detachment.

It is the very immediacy of the book that distinguishes it. Pfeiffer has talked to the men and women who do the best work. (Mrs. Mary Leakey, quite improbably, is the great-great-granddaughter of John Frere, who in 1797 recognized the great antiquity of some flint hand axes found deep in a Suffolk clay pit.) The book is full of asides and plans and hints for the future as well as being a clear account of knowledge already won. At Torralba in old Castile, for example, in a site first excavated 60 years ago, Clark Howell of the University of Chicago has been digging most carefully. There and nearby he has found the killing and butchering floors of a group of elephant-hunters 300,000 years dead, men who hunted in bands, used spears, admired courage (otherwise why so many elephants when other game abounded?) and painted with ocher.

The new lines of research are too numerous even to list here. Chimpanzees make stick probes for termites; baboons never do. Flint tools are found in quantity, and the statistical study thereby made possible tends to show that "kits of tools" occur—whether because several cultures were present or merely because several occupational tasks were at hand or some mixture of both we are not quite sure. An input-output analysis of the economic life of the Bushman is almost ready. The Solutrean toolmakers about 20,000 years ago made flints of a perfection and delicacy beyond any possible usefulness for hunting: hunting tools had become the tools of ritual, of art. Monkeys reared in isolation, with bath-towel surrogate mothers, cannot mother their infants—but they learn, or unlearn; given a second chance, they perform more adequately. Neanderthal man may have invented war, as pretty surely he did the afterlife.

Closeness to new ideas requires a small payment in misplaced hope and enthusiasm in a few cases, no doubt. One is glad to pay the price. The only real if minor complaint a grateful general reader might direct to the author is against the blurring of the times and sources of many ideas presented here. In the absence of footnotes, the bibliography does not always enable one to decide whether the remarks quoted are already enlarged elsewhere or stand alone as novelties.

The latest reference in the Pfeiffer book is to the 1969 book by Gould, an archaeologist of American Indian cultures who spent more than a year in the sandhills of the western Australian desert. There, in the open lands where the emu roam in large groups, man-tall birds running at Land Rover speed, he and his wife lived among the Ngatatjara people. Like the Kalahari people, these hunters and gatherers seem masterful, gentle and varied. A shy housewife—without a house—is photographed in her eucalyptus-nut headdress, her sidelong smile revealing a charmer anyone might know. The paradox of the inexorable drift of these sure hunters to live unsurely near the tobacco, knives, food, bustle, aircraft and indignities of the mission station engages Gould very deeply. His is an ethnography of genuine interest—the people explained their art and their ritual to him and theorized about the numerous evidences of their own deep past—but it remains a thin vehicle for the transmission of a small but whole, complex and ancient culture, seen perforce through only one man's eyes.

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Readers interested in further reading on the subjects covered by articles in this issue may find the lists below helpful.

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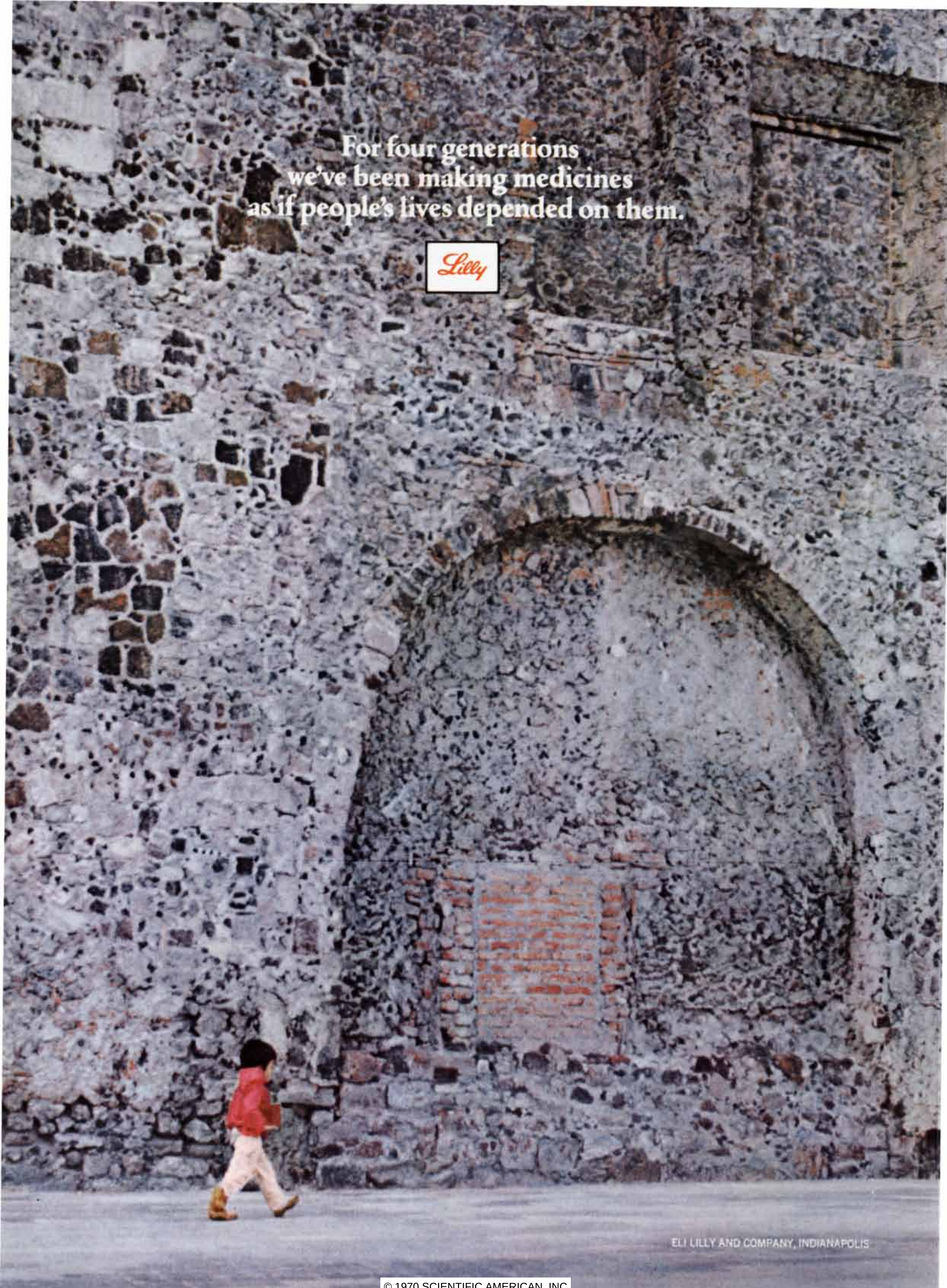
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