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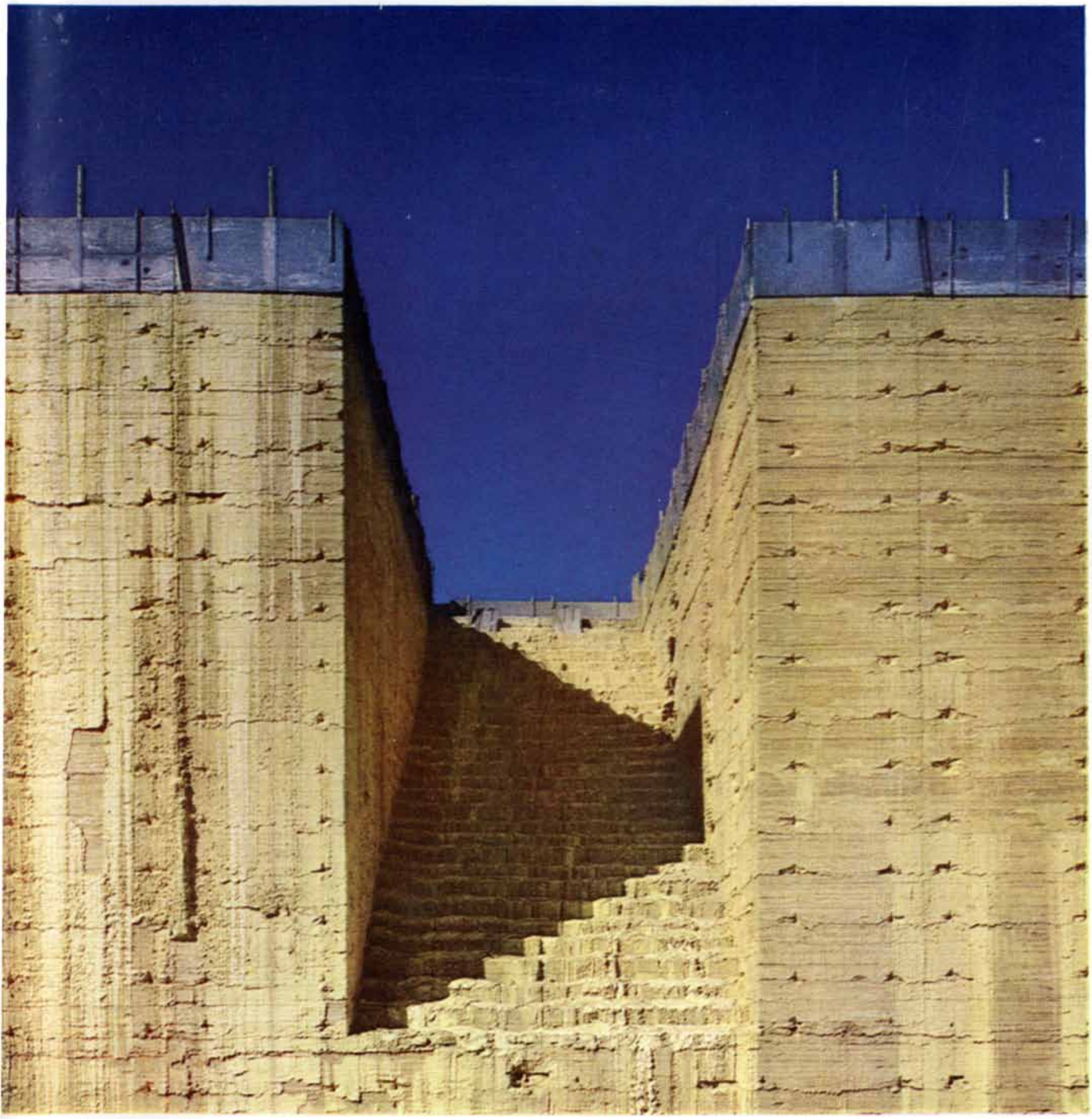

SULFUR

ONE DOLLAR

May 1970

Established 1845 **SCIENTIFIC AMERICAN** May 1970 Volume 222 Number 5

ARTICLES

DEPARTMENTS

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THE COVER

The structure in the photograph on the cover, looking for all the world like some ancient temple, is in fact a "vat" of solid sulfur at the plant of the Texas Gulf Sulphur Company in Newgulf, Tex. (see "Sulfur," page 62). The structure is called a vat because the sulfur is in molten form when it is mined, having been melted in the ground by hot water pumped down a well. Molten sulfur thus obtained is sprayed in a thin layer over the top of the vat, where it is contained by the wall of aluminum forms around the upper edge of the structure. The sulfur solidifies slowly, and from time to time the forms are raised. A completed vat may be 50 feet high. Sulfur can be stored in this way indefinitely; when it is needed, it is broken into fragments for shipment. The stairway is for driving a bulldozer to the top.

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LETTERS

Sirs:

The article by Professors G. W. Rathjens and G. B. Kistiakowsky, "The Limitation of Strategic Arms" [SCIENTIFIC AMERICAN, January], is an important contribution to the arms-control literature. I agree fully that it is of utmost urgency that the arms race be stopped and have made my own contribution by leaving the field of missile-guidance engineering for engineering work in nonmilitary fields.

The point I wish to make is that in this and other articles that discuss the vulnerability of fixed-base hardened missile silos such as those of our Minutemen I have not seen adequate discussion of questions related to the accuracy of potential first-strike weapons. I believe an appreciation of these questions will substantially strengthen the argument that our Minuteman missiles will not be vulnerable to a first strike in the foreseeable future. The questions are these:

1. What is the effect of an error in an attacker's estimate of the accuracy of his own missiles on the success of his first-strike attack on fixed-base missiles?

2. What degree of confidence can the attacker have in the accuracy of his own missiles?

The first question can be answered easily by anyone knowledgeable in probability theory. Assuming an attack on, say, 1,000 Minuteman missiles, the number remaining after the attack depends on three parameters: the number of missiles targeted on each Minuteman, the destruct radius of the bomb and the probable accuracy of the incoming missiles. Here the important point is that the number of missiles remaining depends exponentially on the square of the accuracy. Suppose, then, that the attacker determines the number of attack missiles required to destroy all but 50 of 1,000 missile silos. If the actual accuracy is worse than the figure used in the calculation by only 50 percent, the number of missiles remaining after the attack would be 263. If the actual accuracy is worse by 100 percent, the number remaining would be 472! To improve his situation by targeting more missiles on each silo would require the attacker to commit a very large number of missiles, so many, in fact, that his first-strike intentions would become obvious.

To appreciate completely the lunacy of a first-strike attempt in view of the above figures, one has to answer the second question. The accuracy of an ICBM is determined by many factors, each of which must be maintained to a precision indicated by the fact that an accuracy of half a mile (often quoted) in 5,000 miles is one part in 10,000. There are good engineering reasons to believe the accuracy may never get much better than this. Most of the errors in a guidance system can be estimated from laboratory tests on separate components, and from these data the accuracy can be computed. This is, of course, not considered adequate, and therefore test firings of complete missiles are used to verify the accuracy. The number of test firings that is practical is always limited, however, and even with attempts to use randomly chosen production missiles in these tests the test conditions are invariably different from the operational conditions. With a credible first-strike attack, the number of men who must be trained to operate in missile crews becomes exceedingly large, and hence they will never reach the level of competence of test crews. The crews must be continually checking and maintaining their missiles over a period of years and then on very short notice be ready to fire. Under these circumstances an allowance of an unknown amount must be made for deterioration of missile accuracy. Even if this deterioration were not to take place, it is simply not possible, with any confidence, to predict statistically the accuracy of a large number of missiles from a relatively small number of tests.

These considerations lead to the conclusion that the accuracy can never be known with any great confidence. The general conclusion is that the Minuteman missiles are not becoming obsolete as a deterrent to nuclear attack, and further that they are not in need of ABM protection to remain a deterrent.

J. EDWARD ANDERSON

Department of Mechanical Engineering
University of Minnesota
Minneapolis, Minn.

Sirs:

Dr. Anderson's letter raises three questions on which we should like to comment: (1) Are missile accuracies likely to improve further? (2) If they do, is either superpower likely to have enough confidence in its missiles to make rational the initiation of a counterforce attack against adversary missiles? (3) Finally, are fixed-base missiles likely to be judged by decision-makers as being obsolete?

We disagree with Dr. Anderson's contention that there may be fundamental engineering reasons that will preclude the attainment of missile accuracies of better than about half a mile. Some improvement is to be expected with normal evolution in guidance and propulsion components, with the acquisition of better geodetic information and with continuing development of reentry vehicles that are less affected by variations in meteorological conditions in impact areas. Still further improvements in accuracy are likely to result with the introduction of terminal-guidance techniques. These will be particularly important in reducing the effect of errors in alignment and boost-phase thrust termination, in compensating for variations in air density and wind conditions in impact areas and possibly in compensating for geodetic errors. Several schemes for mid-course and terminal guidance have been explored, and we see no reason to question the feasibility of their being used to achieve miss-distances ultimately of a few hundred feet or less.

With respect to the second question, we are pleased to note Dr. Anderson's agreement with our view that it is very unlikely that a would-be attacker's con-

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fidence in his ability to destroy the adversary's fixed missiles by preemptive attack could be high enough for him to initiate such an attack. It is simply not possible to have adequate confidence in performance when numbers of missile tests are small and when there are significant differences between operational and test environments.

Having said this, we would reiterate what we believe to be possibly the single most important point we tried to make in our article: that in their real but shortsighted attachment to "worst case" analyses, planners and decision-makers on both sides will impute to adversaries risk-taking proclivities that would be judged insane in one's own leaders. Thus we believe neither side will continue to have confidence in its fixed missiles if as a result of worst-case analyses it appears that all, or all but a few, such missiles can be knocked out by a first strike. The Secretary of Defense has said as much in his posture statement for 1971, saying "that the growth of Soviet forces could present a severe threat to the survival of the Minuteman and bomber forces by the mid-70's," and in his assurance that he "will not hesitate at any time to recommend accelerated development of ULMS [the Navy's undersea long-range missile system] should the nature of that threat [to Minuteman] warrant it in the future." We continue to believe that if Soviet counterforce capabilities improve significantly, Minuteman will be judged obsolete or at least obsolescent, whether rationally or not, by those with decision-making responsibilities.

G. W. Rathjens

Massachusetts Institute of Technology
Cambridge, Mass.

G. B. Kistiakowsky

Harvard University
Cambridge, Mass.

Erratum

In the article "Genetic Load" (Scientific American, March) the third sentence from the end should read: "... the balanced load would not increase directly with added heterozygosity as the mutational load does." The word "not" was inadvertently omitted in the article as it was published.

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MAY, 1920: "Conflicting statements about the nationality of Prof. Einstein, of relativity fame, have appeared in the daily press, and Einstein himself vouchsafed some facetious remarks on the subject in the London *Times* when popular interest in his theory was at its height. From a more recent interview with Einstein, published in the London *Daily Chronicle*, it appears that he is a German by birth but went to Switzerland at an early age and was naturalized in that country. For some years he was professor of physics at the Polytechnikum in Zürich and also for a short time at the University of Prague. Shortly before the late war began he was called to the University of Berlin, where he still is, being at the same time director of the Kaiser Wilhelm Institute for Physical Research. He is now little more than 40 years of age, and he conceived the outlines of his theory of relativity at the early age of 18. He was only 27 when he presented it to the world."

"Much interest has been aroused by a hypothesis that is usually called the 'electron theory.' One of the latest versions of this theory has been elaborated by Dr. Irving Langmuir. The Langmuir theory can be stated very briefly as follows: The atom of each element is composed of a nucleus and electrons. The number of electrons is in every case given by the atomic number. The nucleus is surrounded by electrons, which are arranged about it in concentric spherical shells. Each electron possesses a negative electric charge. The nucleus contains as many positive electric charges as there are electrons. The entire atom is therefore electrically neutral. With the exception of hydrogen every element has the following arrangement: its nucleus is surrounded in the first shell by two and only two electrons, the other electrons going into the outer shells. The outer layers of the electrons that go to make up an atom tend to form groups of eight; these groups, represented diagrammatically as cubes, have been given the name octets. When two octets are adjacent to each other in the architecture of a pair of atoms, the theory indicates that they may hold in common one or two *pairs* of electrons but never a *single* electron. The property which causes octets to share pairs of electrons is called covalence. Atoms unite because each one which has an insufficient number of electrons in its outer shell to form a complete octet endeavors to complete its octet by sharing pairs with the finished or unfinished octets of other atoms."

"The recent meeting of the National Academy of Sciences at Washington was marked by one astronomical announcement of exceptional interest—the success of Professor Michelson in devising and putting into use an apparatus which permits the observation of double stars so close that their double character has never previously been detected. The apparatus, which works on the principle of the interferometer, was set up under Professor Michelson's direction at Mount Wilson and turned upon Capella. The very first observations, on December 30th of last year, showed exactly such a change in the visibility of the interference fringes as had been predicted, thus fully confirming the duplicity of the star, which had been proved by the spectroscope. The angular distance between the components was calculated to be 0.″42, just too small to be resolved by direct vision in the greatest telescopes. Later observations on Capella indicated a very rapid angular motion, amounting to four or five degrees per day, and by the middle of March the pair had been followed three-quarters of the way round their orbit."

SCIENTIFIC AMERICAN

MAY, 1870: "We have, as our readers are well aware, taken strong ground in favor of the earth closet as a substitute for the water closet, and have based our opinion upon both sanitary and economic considerations. It appears to us, however, that the immense importance of this subject has not seized upon the public mind, and that it fails to be appreciated except by such as have given special attention to the subject of the disposal of sewage. We find this subject fully discussed in all its bearings in the technical journals, and numerous plans—some of them of the most impracticable character—are proposed, but the popular press in this country has been content to drop the subject after a brief discussion and leave the matter to whatever issue destiny has reserved for it. In our opinion no current topic is freighted with such import as the question of cutting off the enormous drain of fertilizing matter now permitted to wash away into the sea, and the purification of the waters that surround large cities from the pollutions now permitted to contaminate them and the atmosphere that sweeps over them."

"We are indebted to Mr. Edward Bierstadt of this city for specimens of the new process of printing invented by Professor Albert of Munich. The printing plates are produced by photographic agency, but the impressions are made with the ordinary printer's inks. A glass plate is covered with bichromatized gelatin. On this a second film of the gelatin is placed. This film, being sensitive to light, is exposed under the negative, whereby those portions of the gelatin film on which the light acts are rendered hard and insoluble in water, the remaining portion being soluble and capable of receiving moisture. The plate is then plunged into cold water, and those portions of the film which were covered and protected from light by the negative will imbibe moisture, the other parts will reject it. The plate is now rolled with fatty ink, as in lithographic printing. The moist parts will reject the ink, the other parts will receive it. The inked glass plate is then printed by pressure between rollers, and the result is marvelous, being nothing less than the production of a photograph in printing ink, with all the fidelity and delicate shadow of the finest silver-print photos. The working of the process is soon to be commenced in this country."

"Letters from Japan state that the arrangements are completed for a line of railway—the first in the country—to connect Yeddo and Osaka, the new and old capitals of the Empire, a distance of 300 miles. There are also to be branches from Yeddo to Yokohama and from Osaka to Tsuruga. The work will belong to the Japanese Government but is to be carried out under the advice of English engineers. An English loan of one million pounds sterling is to be raised to meet the costs, and this will be secured not only by the line itself but also by a mortgage on the custom duties collected at the ports. From three to five years is to be allowed for the completion of the railway."

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THE AUTHORS

MATTHEW S. MESELSON ("Chemical and Biological Weapons") is professor of biology at Harvard University. His extensive work on the subject he discusses is in addition to his activity as a molecular biologist, which has brought him wide recognition for his demonstration of how DNA duplicates itself in dividing cells, for studies of the mechanism of genetic recombination and for his invention of an ultracentrifugal method for analyzing the density of giant molecules. Meselson was graduated from the University of Chicago in 1951 and obtained his Ph.D. from the California Institute of Technology in 1957. He stayed at Cal Tech for three more years—one as a research fellow and two as assistant professor of physical chemistry—before he went to Harvard in 1960. In 1963 Meselson received the National Academy of Sciences award in molecular biology, and in 1968 he was elected to the Academy.

ROBERT B. LEIGHTON ("The Surface of Mars") is professor of physics at the California Institute of Technology, where he has spent many years, first as an undergraduate, then as a graduate student (he received his Ph.D. in 1947) and later as a research associate and member of the faculty. He worked on cosmic ray physics until about 1960, when his research interest turned to solar physics and astrophysics and particularly to infrared astronomy. He participated in infrared radiometric experiments flown past Venus and Mars and in the television experiments carried out by Mariner spacecraft. He was the author of "The Photographs from *Mariner IV*" in the April 1966 issue of SCIENTIFIC AMERICAN.

DANIEL MERRIMAN ("The Calefaction of a River") is director of the Connecticut River Survey. He received his formal education at Harvard University, the University of Washington (bachelor's and master's degrees) and Yale University (Ph.D.), where he is associate professor of biology and director of the Sears Foundation for Marine Research. Merriman notes that "much of the research outlined in this article is to be found in the semiannual reports to the Connecticut Water Resources Commission under the divisional headings: William A. Boyd (hydrography); Ronald R. Massengill (benthic fauna); Barton C. Marcy, Jr. (ichthyofauna), with earlier contributions from Sarah W. Richards and Sanford A. Moss, and William C. Leggett (adult shad), all of whom may be addressed c/o the Essex Marine Laboratory, P.O. Box 367, Essex, Conn. 06426."

CHRISTOPHER J. PRATT ("Sulfur") is manager of commercial development for the Hoechst-Uhde Corporation, the U.S. affiliate of the German engineering firm Friedrich Uhde. Born and educated in England, he studied industrial chemistry at Rutherford College of Technology and psychology and music at Goldsmiths' College. He is a chartered chemical engineer. For several years before he came to the U.S. in 1953 he was a management consultant to British process industries. In his spare time he is a freelance writer and a musician. He was the author of "Chemical Fertilizers" in the June 1965 issue of SCIENTIFIC AMERICAN, and he indulges an interest in baroque music by playing the contrabass (he played it professionally in England) and the organ.

WERNER R. LOEWENSTEIN ("Intercellular Communication") is professor of physiology at the Columbia University College of Physicians and Surgeons, where he directs the Cell Physics Laboratory. He was trained in physics and physiology and obtained his doctorate at the University of Chile in 1950. As he puts it, he "came to the U.S. in 1953 to learn the craft of the neurobiologist with Stephen Kuffler at Johns Hopkins University." Thereafter he moved to the University of California at Los Angeles, did further research at the University of Chile and returned to the U.S. in 1957 to take his present position at Columbia. In an article on "Biological Transducers" in the August 1960 issue of SCIENTIFIC AMERICAN he described his discoveries in energy conversion and nerve-impulse generation at sensory receptors. "When I wrote that article," he notes, "I had just started another love affair, about which I write now. This affair continues unabated and is now unexpectedly reviving the old one. I may have something to tell about the two combined in 1980." Loewenstein describes his avocations as "sculpting, sailing and playing tennis."

BERNARD BERTMAN and DAVID J. SANDIFORD ("'Second Sound' in Solid Helium") had a friendship and collaboration of long standing that was ended by the death of Bertman in February at the age of 36. Bertman was associate professor of physics at Wesleyan University; Sandiford is lecturer in physics at the University of Manchester. At a memorial service Sandiford described Bertman as a scientist of great creative ability and said: "Bud was a colleague and teacher whose advice one would want to seek, whose arguments one would listen to, for his intelligence and personality enabled him in all these matters to be constructive and forward-looking." Sandiford, who was graduated from the University of Cambridge in 1954, did research on semiconductors for three years and then went to Yale University, where he obtained his Ph.D. in 1960. Last year he was on leave from the University of Manchester to serve as adjunct professor of physics at Wesleyan.

RALPH NORMAN HABER ("How We Remember What We See") is professor of psychology and chairman of the department of psychology at the University of Rochester, where he has been a member of the faculty since 1964. As an undergraduate at the University of Michigan he majored in philosophy, but he took his advanced degrees (master's in 1954 at Wesleyan University and Ph.D. in 1957 at Stanford University) in psychology. He taught at Stanford, San Francisco State College and Yale University before he went to Rochester. Haber was the author of "Eidetic Images" in the April 1969 issue of SCIENTIFIC AMERICAN.

LESLIE HOLLIDAY ("Early Views on Forces between Atoms") retired in 1967 after 27 years with the Shell Company and is now adjunct professor of polymer science at Brunel University, one of the new universities in Great Britain, and an industrial consultant. He joined Shell after studying chemistry at the University of Oxford, worked in several parts of the world on matters involving ores or chemicals and at his retirement was director of the Carrington Plastics Laboratory of Shell Research Ltd. His scientific interests include polymer and materials science; he was founder of the Materials Science Club. Holliday writes: "I enjoyed my industrial career; I enjoy my present intellectual freedom. I collect pictures and books. In the latter case I specialize in the history of British India. I play the piano and am especially fond of two-piano playing. I live near the sea, as all sensible people do. This enables me to collect semiprecious pebbles, which I polish and my wife makes into jewelry. I am becoming increasingly interested in home winemaking."


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Deeply hurt, so the story goes, Ts'ai Lun spread the word of his death and staged a sham funeral. It was customary at the time to burn leather money for the recently departed, thus assuring a warm welcome in the spirit world. But Ts'ai Lun pulled a switch. He had his family burn paper money instead,

The Dow Chemical Company, Designed Products Department, Midland, Michigan 48640.

then popped out of his coffin and told his mourners that the ersatz currency had been accepted as the genuine article.

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Established 1845 SCIENTIFIC AMERICAN May 1970 Volume 222 Number 5

Chemical and Biological Weapons

The U.S. has renounced all forms of biological weapons and the first use of most chemical weapons. The issue of whether or not to include irritant gases and antiplant agents in the prohibition remains open

by Matthew S. Meselson

On November 25 of last year President Nixon announced a number of major decisions regarding chemical and biological weapons. He proclaimed that the U.S. will never be the first to use lethal or incapacitating chemical weapons and will not use biological weapons under any circumstances, even in retaliation. He also announced that he would submit to the Senate the 1925 Geneva Protocol prohibiting the use of chemical and biological weapons in warfare.

The President's statement left a question whether toxins, the poisonous but nonliving substances produced by some bacteria and other organisms, were included in the unconditional renunciation of biological weapons or only in the no-first-use pledge for chemicals. The question was resolved on February 14 when the President extended the policy for biological weapons to cover toxins as well. In order to remove a possible ambiguity, it was decided to renounce toxin weapons even if advances in chemistry should make it practicable to prepare them synthetically instead of by extraction from bacteria or other organisms.

Under the new policy the U.S. will destroy existing stocks of germ and toxin weapons and will no longer engage in their development, production or stockpiling. The U.S. biological program will be restricted to research for strictly defined defensive purposes, such as techniques of immunization.

In accord with these decisions on biological and toxin weapons, White House officials have stated that there will no longer be a need for secret work and that consideration is being given to the transfer for conversion to other purposes of our sizable biological weapons facilities at Fort Detrick, Md., and Pine Bluff, Ark., from the Department of Defense to nonsecret agencies such as the Department of Health, Education, and Welfare and the Department of Agriculture.

As to chemical weapons, the restraints are less sweeping. The U.S. reserves the right to continue the development, production and stockpiling of lethal and incapacitating chemical weapons. It pledges, however, never to use them first. The same pledge is embodied in the treaty commitment by the 84 states now party to the Geneva Protocol.

There are two types of chemical weapon whose use in war has not been renounced. They are the antiplant chemicals and the "riot control" agents, such as CS, employed by U.S. forces in Southeast Asia. The U.S. has maintained that these agents are not prohibited by the Geneva Protocol. Many nations disagree, which raises problems for U.S. ratification of that treaty. The President himself has made no statement regarding CS or herbicides. White House officials have said only that the use of these chemical weapons will continue "for the time being."

The President's decisions were based on a six-month review of U.S. policies and programs for chemical and biological weapons. The review was conducted under the auspices of the National Security Council, which coordinated the efforts of the Department of State, the Department of Defense, the Arms Control and Disarmament Agency, the Central Intelligence Agency, the Office of Science and Technology and other branches of the Government. The subject was put under searching examination. The National Security Council considered the following topics: chemical and biological weapons that were already available and those that might conceivably be developed, the possible military value of each type of weapon in relation to other weapons at our disposal, the possible consequences of proliferation, strategic questions concerning the use of such weapons for threat or deterrence, the political and moral impact of their development and possible use, the potential hazards for civilian populations, possible defenses against the various weapons, and the policies and activities of other nations.

It was obvious and became more so as the review proceeded that such a study was long overdue. The U.S. had a large factory for producing germ weapons, even though no one had ever produced a convincing "scenario" for a case in which they should be used. Shortly

HERBICIDES ARE SPRAYED by U.S. Air Force planes in South Vietnam. More than 19,000 sorties have been flown since 1962. One aircraft covers a swath nearly 300 feet wide and 10 miles long. Military officials say destruction of crops in certain areas held by Vietcong reduces food supplies for opposing forces and jungle defoliation reduces concealment.

before and during the National Security Council study, chemical weapons were involved in one disquieting incident after another, creating a political atmosphere favorable to the questioning of previous policies. A series of earthquakes that shook the city of Denver was traced to the massive subterranean disposal of chemical wastes at the Army's Rocky Mountain Arsenal. The accidental release of nerve gas in a test of an aircraft spray tank over the Dugway Proving Ground in Utah led to the death of thousands of sheep, some of them grazing as far as 40 miles away. Then there was protest against the Army's plan to ship 12,000 tons of outmoded nerve-gas bombs across the country from Colorado to be dumped in the Atlantic. Soon afterward there was an incident in which nerve gas escaped from U.S. munitions stored on Okinawa, and it was also revealed that nerve-gas munitions were stored in West Germany. Finally there had been newspaper articles to the effect that the Defense Department was testing biological weapons in the South Pacific and had conducted open-air tests of nerve gas in Hawaii without informing state officials.

The public reaction to these incidents can be gauged from the fact that the U.S. Senate voted 91 to 0 for a resolution requiring the review by the Public Health Service of any plan for the domestic transportation or open-air testing of lethal chemical agents or of any biological warfare agents. The resolution, which is now law, also requires the Defense Department to render semiannual reports to Congress on the investigation, development, testing and procurement of all agents of chemical and biological warfare.

Here I shall discuss first the nature of chemical and biological weapons (CBW) and their military implications, then the international effort that has been made to prevent their use, and finally the present situation. Although much work on CBW has been secret, the essential facts about the weapons are now in the open literature. Particularly noteworthy is the report of a United Nations group published last year and the subsequent World Health Organization report that specifically examines the potential effects on civilian populations. The UN report was prepared by a group of 14 consultant experts nominated by their respective governments. The U.S. participant was Ivan L. Bennett, Jr., director of the New York University Medical Center and former Deputy Director of the U.S. Office of Science and Technology. The American members of the WHO consultant group were Joshua Lederberg of the Stanford University School of Medicine and myself. Even more detailed than the UN and WHO reports is the forthcoming study by the Stockholm International Peace Research Institute.

Although chemical and biological weapons are linked together in the psychology, the customs and the international law that restrain their use, it is helpful to distinguish several categories for analyzing military characteristics and implications. I shall discuss five kinds of weapon: lethal biological weapons, incapacitating biological weapons, lethal chemical weapons, incapacitating chemical weapons and antiplant agents. The distinction between lethal and incapacitating is not altogether clear-cut, particularly under the extremely uncontrolled conditions of warfare. There is a continuous spectrum of agents from the highly lethal to the generally nonlethal, and even tear gas can be used together with bullets and bombs to increase casualties. Nonetheless, the arguments for and against lethal and nonlethal weapons deserve separate attention.

Let us first consider lethal biological weapons. They would operate by disseminating clouds of disease germs over the target area or upwind from it. The germs would then be inhaled by the target population. The disease anthrax is an example. Caused by the bacterium *Bacillus anthracis*, it is mainly encountered as a disease of domesticated animals that is occasionally transmitted to man. Because it is not very contagious among humans, natural cases of anthrax are generally localized rather than epidemic. If the bacteria were sprayed in the air in an aerosol, however, the effects could be devastating. The inhalation of approximately 50,000 spores of *B. anthracis* (total weight less than a millionth of a gram) is believed to be enough to cause a 50 percent chance of contracting pulmonary anthrax. Symptoms would first appear about a day after the attack. The onset might be mistaken for a common cold, but this would be followed by severe coughing, cyanosis, respiratory failure and death. Untreated pulmonary anthrax is almost always fatal.

The WHO report gives estimates of the area-coverage capability of various biological agents. For illustrative purposes the report assumes that one light bomber delivers in a single pass ground-functioning "bomblets" containing a total of 50 kilograms of dry powdered agent along a two-kilometer line at right angles to the wind. It is assumed that the intensity of atmospheric turbulence is less than a certain level, but not so low as to be at all unusual, particularly at night. The bomblets release the agent as an aerosol, which then drifts over the target area. Such calculations take into account the dissemination efficiency of the bomblets, the decay rate of agent infectivity, the rate of vertical dilution in the atmosphere, the rate of deposition on the ground and the dose-response curve for man. For an attack with anthrax spores the WHO report predicts a high mortality rate over at least 20 square kilometers. Although there are uncertainties in the quantities that enter into the calculation, the estimate is deliberately conservative. The UN report, in a similar estimate, considers an attack by a large low-flying bomber dispensing 10,000 kilograms of agent along a 100-kilometer line by means of a spray tank. The estimated area in which a high casualty rate would occur is as large as 100,000 square kilometers, depending on the particular agent used.

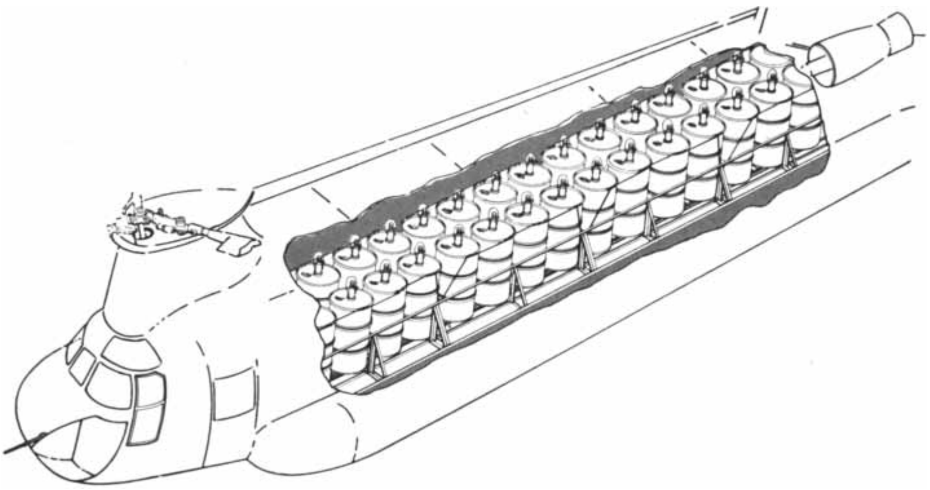
Among the lethal biological agents that might be considered for military use are the viruses of Eastern equine encephalitis and yellow fever, the rickettsia causing Rocky Mountain spotted fever, and the bacteria causing anthrax, plague, cholera, glanders and melioidosis. There are moderately effective vaccines and antibiotics against some of these diseases but none against others. Moreover, such protections might be overwhelmed by a massive attack, and for some agents antibiotics can be circumvented by the use of drug-resistant strains. Protection can be given by gas masks or air-filtered shelters if there is early warning of an attack, but no satisfactory early-warning device has yet been developed. In any case a program for supplying the civilian population with masks and shelters and maintaining discipline for their use would require a major and sustained economic and political effort—without achieving reliable protection against biological attack.

It is not to be expected that biological warfare agents would be deliberately chosen to be contagious; that would maximize the risk of spreading disease far beyond the intended target, possibly to the territory of the attacker or his allies. Nevertheless, the unnatural conditions inherent in military operations create the possibility that widespread epidemics would be unintentionally started. There is also the hazard, difficult to evaluate, that the bacteria or viruses used in an attack, or even used in a field test, could subsequently emerge from exposed populations of humans, rodents, birds or other animals with increased persistence, virulence and contagiousness for man.

From this brief account it should be clear that lethal biological weapons would present a devastating threat of killing human populations over large areas. The threat is made particularly formidable by the relative ease with which such weapons could pass into many hands if the technology becomes established and if the customs and attitudes that have generally kept nations from pursuing the development of biological weapons should change. After several years of pursuing a biological weapons program that has not had adequate review or guidance from the Executive Branch, and that has been almost entirely shielded by secrecy from public and congressional knowledge, the U.S. has decided that the best way to minimize the threat of biological weapons is to renounce them altogether. The logical case for doing so rests on the realization that the possession of such weapons would add little, if anything, to our strategic-deterrent capability, whereas their proliferation would present a major threat to the U.S. and indeed to all mankind.

The second category of weapons to be considered is incapacitating biological weapons. An example is Venezuelan equine encephalitis. It is a virus that causes severe headache, nausea and prostration but that has a case fatality rate in natural epidemics of .5 percent or lower. Methods for disseminating incapacitating biological agents and the possibilities for defending against them are essentially the same as those for lethal biological agents. The use of incapacitating biological weapons might be considered in certain unlikely and extreme situations. Perhaps the most "attractive" scenario that has been proposed imagines the entrapment of a large friendly force by enemy troops deployed over an extensive area and intermingled with civilians. In this situation the employment of incapacitating biological weapons in forward and rear areas might impede the enemy advance long enough to allow reinforcement or evacuation of the friendly troops when the alternatives might be to use nuclear weapons or to surrender.

Of course any decision to launch an incapacitating biological attack must face the fact that substantial numbers of civilians, particularly infants and the infirm, will almost inevitably be killed, even if the case fatality rate is only a few tenths of a percent. Beyond that there is the possibility that the fatality rate un-



LOADING PLAN for a CH-47 Chinook helicopter employed for air-dropping the irritating agent CS is depicted as it is shown in a U.S. Army training manual. Each bomb contains 80 pounds of CS-2. Burster tube down the middle of each bomb contains an explosive charge.

der military conditions might be much higher than the rate estimated from natural occurrences of the disease and from various kinds of experimental data. It is also important to note that this scenario assumes the *first* use of biological weapons rather than their employment in retaliation. This adds the additional risk of escalation and enlargement of the conflict that could result from the outbreak of germ warfare of any kind. A principal long-term cost to security of using incapacitating biological weapons, or even of maintaining them, would be stimulation of the proliferation of germ weapons, including lethal ones. The facilities for developing, producing and delivering incapacitating biological weapons are essentially the same as those required for lethal germs. International law and international custom do not distinguish between them.

To summarize, incapacitating biological weapons might seem logical in certain tactical situations, but such situations are most unlikely, and even then the risks would outweigh the possible gain.

Here a more general statement about germ weapons should be made. Such weapons have serious shortcomings from a military viewpoint. Their effects are not as predictable as those of other weapons. They might get out of control. Alternative and already available weapons are preferable, and the acquisition of a biological weapons capability would be an addition to, not a substitute for, preexisting military expenditures and programs.

Military officers and political leaders are strongly disinclined to use biological weapons, partly for practical reasons, partly because of unfamiliarity and partly because of the moral revulsion and apprehension that are undeniably associated with these weapons. There does not currently seem to be any serious interest in biological weapons in high military circles anywhere. Although such weapons could become a terrible menace, the likelihood of this is greatly reduced by the spectacular gesture of renunciation made by the U.S. This is the moment in history when the biological sciences, with their intimate linkage to the lifesaving ethos of medicine, may be spared from being recruited to serve military ends all over the world. Whether or not international biological disarmament can be ensured over the long run may ultimately be related to progress in chemical disarmament, for in the minds of many the two are linked.

Chemical weapons present a much more immediate problem. They were used in World War I and are stockpiled by the U.S. and the U.S.S.R. and are also possessed by several other nations. The distinction between lethal weapons and incapacitating ones has more practical importance here than it has with biological weapons. There are strong restraints against the use of lethal chemical weapons, and until recently nonlethal chemicals have been excluded from warfare as well. From an arms-control point of view there are important arguments for treating lethal and nonlethal chemicals together. Still, for the purpose of analysis it is useful to make the distinction.

Modern lethal chemical weapons employ the nerve gases first developed (but not used) by Germany during World War II. These agents are hundreds of times more poisonous than the poison gases of World War I; they kill when they are inhaled or when they are deposited as liquid droplets on the skin. The term "nerve gas" derives from the fact that these agents operate by interfering with the transmission of nerve impulses across synapses. They do so by inactivating the enzyme cholinesterase, which normally functions to terminate the transmission of a nerve impulse. In the presence of a nerve agent, nerve impulses continue without control, causing a breakdown of respiration and other functions. Death caused by nerve-gas poisoning results from asphyxiation. It is preceded by blurring of vision, intense salivation and convulsions.

The U.S. has stockpiled a variety of tactical nerve-gas weapons, and the U.S.S.R. is believed to have done so too. The weapons include mines, artillery projectiles, rockets, bombs and aircraft spray devices.

The U.S. stockpile includes two kinds of nerve agent. One is GB, a code name for isopropylmethylphosphonofluoridate. It is also known as Sarin and was produced in limited amounts by Germany during World War II. Sarin is a volatile liquid that evaporates at room temperature to a colorless and odorless gas.

Weapons containing Sarin release it as a spray, which then evaporates to create a respiratory hazard for unprotected personnel. The lethal exposure for man is estimated to be approximately 100 milligram-minutes per cubic meter. This means, for example, that a man would accumulate a lethal dose in 10 minutes if the concentration of Sarin in the air were 10 milligrams per cubic meter.

Since the hazard posed by Sarin is mainly respiratory, a gas mask provides good protection. Modern gas masks are capable of reducing the concentration of all known war gases, by a factor of about 100,000. In addition there are chemical antidotes for nerve agents that can provide protection if the dose of agent is not very great and the antidote is administered promptly.

The other kind of nerve agent in the U.S. stockpile is VX. The chemical formula of VX is still secret, although the WHO report suggests that the agent is ethyl S-dimethylaminoethyl methylphosphonothiolate. It is a member of a class of compounds first prepared in the mid-1950's in the course of a search for improved insecticides. (Sarin was also the outcome of insecticide research.) Also a liquid but several times more toxic than Sarin and much less volatile, VX is lethal either when inhaled or deposited on the skin. VX kills in a matter of minutes, and by contaminating the ground and objects on which it is deposited it can make an entire area hazardous for many days. It was VX that killed the sheep in Utah.

The lethal dose of VX applied to the skin has been estimated to be from two to 10 milligrams, depending on the site of application. Since contact with even a small droplet of VX can be fatal, adequate protection requires the wearing of a special suit as well as a gas mask. The wearing of protective suits and masks is extremely cumbersome. They are mechanically awkward, and the buildup of heat is a serious problem. Fighting efficiency would be severely reduced by the wearing of full protective equipment and also by the strict observation of various special precautions necessary for survival in a lethal chemical environment. This kind of complexity in gas warfare was clearly recognized in World War I. In the words of one officer: "The range of problems was infinite. How would the soldier eat, drink, sleep, perform bodily functions, use his weapon, give and receive commands? How would he know when his immediate area was contaminated?"

For tactical use against an enemy without protective equipment, lethal chemicals would be devastating. Against an enemy possessing suits and masks and able to impose the wearing of such gear on one's own troops by the threat of retaliation in kind, lethal chemical weapons would enormously complicate the battlefield without giving either side a major advantage. This argues for not initiating lethal chemical warfare. It also suggests, however, a reason for possessing lethal chemical weapons as a tactical deterrent if the other side is thought to have them. For example, if conventional land warfare should ever break out in Europe, with only one side in possession of lethal chemical munitions, that side might be tempted to use them in order to force opposing troops into protective gear while its own forces, taking advantage of their knowledge of the timing and location of the chemical attack, pressed the offensive. Having this knowledge, the argument goes, their operations would be considerably less complicated. It is this kind of analysis that presumably underlies the U.S. policy of maintaining lethal chemical weapons even though it is our policy never to initiate their use.

Both the plausibility and the accuracy of the foregoing scenario can be challenged. Many would maintain that a major war in Europe is extremely unlikely. It is even more unlikely that such a war could go on for many days without resort to nuclear weapons, in which case chemicals would become unimportant. Finally, it is argued, even in the event of a large nonnuclear war the use of chemicals would be strongly deterred by the risk that using such unconventional weapons to obtain any major advantage would trigger a nuclear response.

Clearly there are some risks in either approach. The second approach, however, would allow the renunciation of the possession of lethal chemical weapons.

Lethal chemical weapons could be produced by nonnuclear nations to provide a capability for strategic attack on urban populations. Under meteorological conditions favorable to the attack, a medium bomber or a converted commercial air transport can deliver enough nerve agent to kill a high proportion of unprotected people throughout the central region of a large city. For example, the WHO report estimates that an airborne attack across the wind along a two-kilometer line, releasing four tons of chemical agent over a city, would cause high casualties over an area of between two and 40 square kilometers, depending on the type of agent and munitions used. Given adequate warning a highly

AGENTS	DISEASES	INCUBATION PERIOD (DAYS)	EFFECT OF TREATMENT	CONTAGIOUSNESS
VIRUSES	EASTERN EQUINE ENCEPHALITIS	5 TO 15	NONE	BY VECTOR
	TICK-BORNE ENCEPHALITIS	7 TO 14	NONE	BY VECTOR
	YELLOW FEVER	3 TO 6	NONE	BY VECTOR
RICKETTSIAE	ROCKY MOUNTAIN SPOTTED FEVER	3 TO 10	GOOD	BY VECTOR
	EPIDEMIC TYPHUS	6 TO 15	GOOD	BY VECTOR
BACTERIA	ANTHRAX	1 TO 5	MODERATE	LOW
	CHOLERA	1 TO 5	GOOD	HIGH
	PNEUMONIC PLAGUE	2 TO 5	MODERATE	HIGH
	TULAREMIA	1 TO 10	GOOD	LOW
	TYPHOID	7 TO 21	GOOD	HIGH

AGENTS	DISEASES	INCUBATION PERIOD (DAYS)	EFFECT OF TREATMENT	CONTAGIOUSNESS
VIRUSES	CHIKUNGUNYA FEVER	2 TO 6	NONE	BY VECTOR
	DENGUE FEVER	5 TO 8	NONE	BY VECTOR
	VENEZUELAN EQUINE ENCEPHALITIS	2 TO 5	NONE	BY VECTOR
RICKETTSIAE	Q FEVER	10 TO 21	GOOD	LOW
BACTERIA	BRUCELLOSIS	7 TO 21	MODERATE	NONE
FUNGI	COCCIDIOIDOMYCOSIS	7 TO 21	POOR	NONE

BIOLOGICAL AGENTS are shown by category and effect; those that could be expected to cause death are at top and agents that might be used to cause incapacitation are at bottom. Contagion "by vector" means transmission by certain species of mosquitoes or other insects.

COMMON NAME	SARIN	VX	MUSTARD	BZ	CS AND CS-2
MILITARY CLASSIFICATION	LETHAL AGENT (NERVE GAS)	LETHAL AGENT (NERVE GAS)	LETHAL AND INCAPACITATING AGENT	INCAPACITATING AGENT (PSYCHO-CHEMICAL)	HARASSING AGENT
PHYSICAL STATE	LIQUID	LIQUID	LIQUID	SOLID	SOLID
FORM AS DISSEMINATED	VAPOR, AERO-SOL OR SPRAY	AEROSOL OR SPRAY	SPRAY	AEROSOL OR DUST	AEROSOL OR DUST
DURATION OF CONTAMINATION	HOURS OR DAYS	DAYS OR WEEKS	DAYS OR WEEKS		CS–MINUTES CS-2–WEEKS

CHEMICAL WARFARE AGENTS included in the U.S. stockpile are listed by category and some of their major characteristics. Data were assembled by the World Health Organization for its recent report on the health effects of chemical and biological weapons.

disciplined population could be defended against such an attack by a combination of gas masks, protective shelters and antidote therapy. Although strategic chemical weapons would add nothing significant to the arsenals of the nuclear powers, the proliferation of such weapons among the nonnuclear nations would obviously constitute a serious hazard. Even though it is unlikely that a small nation could deliver a chemical attack over a wide area of a country that has modern air defenses, it would be much easier to penetrate the air space over one or a few coastal cities.

It is also important to consider the possible role of lethal chemical weapons in "low level" conflicts. Today such conflicts are fought with high-explosive and flame weapons, which individually have limited area effect. Although such wars can be exceedingly destructive, they become so only when enormous quantities of weapons are used. (In Vietnam, for example, more than 6,000 tons of ammunition were expended by the U.S. daily in 1968.)

Many of the types of munitions used in limited war, however, could be filled with lethal chemicals. In such a case the "kill area" of lightweight munitions such as mortar shells and rockets could be increased by a factor of as much as 100. Even though combatants could be provided with protective equipment, such weapons would be devastating to military units caught unprepared and to civilians in urban areas. Small military units would begin to acquire strategic capabilities against cities.

It is apparent, therefore, that chemical weapons constitute a menace far beyond their possible tactical employment by the major powers. It is this menace that provides one of the chief arguments for chemical and biological disarmament. A concluding but often overriding restraint on the tactical use of lethal chemicals, particularly when the battlefield is on friendly soil, is that their large-scale employment could cause heavy casualties among undefended civilians in the combat zone and out to considerable distances downwind.

Although U.S. policy now treats toxins in the same way as biological weapons, by renouncing even their possession, the UN report classifies toxins as chemicals because they do not reproduce. Toxins are poisonous substances produced by living organisms including plants, animals and bacteria. Examples are ricin from the castor bean, tetrodotoxin from the globefish and botulin from the bacterium *Clostridium botulinum*. Some toxins, such as botulin, are highly lethal to man; others, such as the staphylococcus enterotoxin (the substance responsible for staphylococcal food poisoning), are usually only temporarily incapacitating.

Even though toxins are not capable of reproduction and therefore cannot cause epidemics, they do induce many of the same symptoms associated with infection by disease organisms. Indeed, the principal pathological symptoms of several bacteriological diseases are thought to be caused by toxins produced within the human body by the living microorganisms. Thus toxin weapons, both in terms of the means of their production and the symptoms they cause, are closely related to the biological ones.

For use as weapons toxins could be dispersed as aerosols in much the same way as biological and chemical weapons. Because toxins are not absorbed effectively through the skin, gas masks would provide protection, as would shelters fitted with special air filters. Protection can also be afforded by prior immunization with specific toxoid. Each toxoid, however, is effective only against a particular kind of toxin, and for some toxins the margin of protection is not enough to be of practical significance.

The chief military argument for having toxins is that, because of their great potency, the weight of toxin munitions needed to cover a given area would be lower than the corresponding requirement for standard chemical munitions. There are several technical reasons to question whether this is so, but even if it were, the saving would not be of very great importance for major military powers with their large logistic capability. An active U.S. toxin weapons program would have run counter to the President's decision to demilitarize and declassify U.S. biological weapons research and production facilities and would have made it impossible for the U.S. to take an unequivocal and convincing stand against the use of disease as a weapon of war.

The first chemical weapons to be employed in World War I were nonlethal. It is reported that some soldiers brought police tear-gas cartridges to the front. Soon both Germany and France began using artillery shells containing tear gas, and thousands of these shells were fired months before the famous German attack at Ypres with chlorine gas released from cylinders. Tear gas and other irritant chemicals continued to be used throughout the war—more than 12,000 tons in all. Even larger quantities of such chemicals were prepared but not employed by the belligerents on both sides in World War II.

Modern incapacitating chemical weapons are of two types, one with effects lasting considerably beyond the period of exposure and one with brief effects. President Nixon's renunciation of the first use of incapacitating chemicals has been applied only to the longer-lasting type. An example of this type is the U.S. agent BZ. This is a psychochemical, the chemical identity of which is still secret, although the WHO report speculates that it belongs to the family known as benzilates. BZ is a solid that can be dispersed as an aerosol to be inhaled by enemy personnel. It affects both physical and mental processes, causing blurred vision, disorientation and confusion. Its incapacitating effects can last for several days.

Although BZ has been standardized as a weapon by the U.S. Army and munitions have been loaded with it, it is not regarded as a very satisfactory incapacitating agent. It can elicit unpredictable and often violent behavior. Men sufficiently motivated to fight may do so more tenaciously under its influence. Furthermore, BZ has serious effects on the body's water-balance and temperature-regulation mechanisms that could lead to death, particularly under hot, dry conditions. Much effort has been devoted, without success, to finding a long-lasting incapacitant without these drawbacks or similar ones.

The principal short-term incapacitant now in military use is CS (orthochlorobenzalmalonitrile). This compound was first synthesized in the U.S. in the 1920's. After World War II it was developed by the British government as a riot-control agent and named after its American discoverers, Ben Corson and Roger Staughton of Middlebury College. When employed for military purposes, it is more accurately described as a harassing agent.

The first CS munitions operated by vaporizing the agent from a pyrotechnic mixture. The CS then condenses to form an aerosol of micron-sized particles. Pyrotechnic CS is used in grenades, rockets, artillery shells and cluster bombs. A newer form is designated CS-2. Used in both bulk-disseminating devices and bursting bombs, it is a powder consisting of micron-sized particles treated with silica gel and silicone compound to improve its flow properties and persistence in the field. CS-2 can be effective in the field for several weeks. It is reintroduced into the air by the wind and the movement of people and vehicles.

The effects of CS depend on the particle size of the aerosol. Particles larger than some 50 microns exert their predominant effect on the eyes, whereas smaller particles are more effective as lung irritants. For military use CS-2 is milled fine enough to achieve the latter effect. Exposure to either form of CS causes intense pain in the eyes and upper respiratory tract, progressing to the deep recesses of the lungs and giving rise to feelings of suffocation and acute anxiety. In humid weather moderately heavy skin exposure can cause severe blistering that requires many days for healing.

If exposure is not excessive, the symptoms usually pass within a few minutes after the exposure ends. The lethal dose for man, as estimated from animal experimentation, is very much higher than that required to cause intense irritation. Nevertheless, heavy or prolonged exposure, such as might be expected in confined spaces or in close proximity to a munition emitting the agent, could cause serious lung damage and death, particularly among infants and the infirm. No long-term aftereffects of moderate exposure to CS have been demonstrated. Although investigations of this possibility are now under way, they have not been completed.

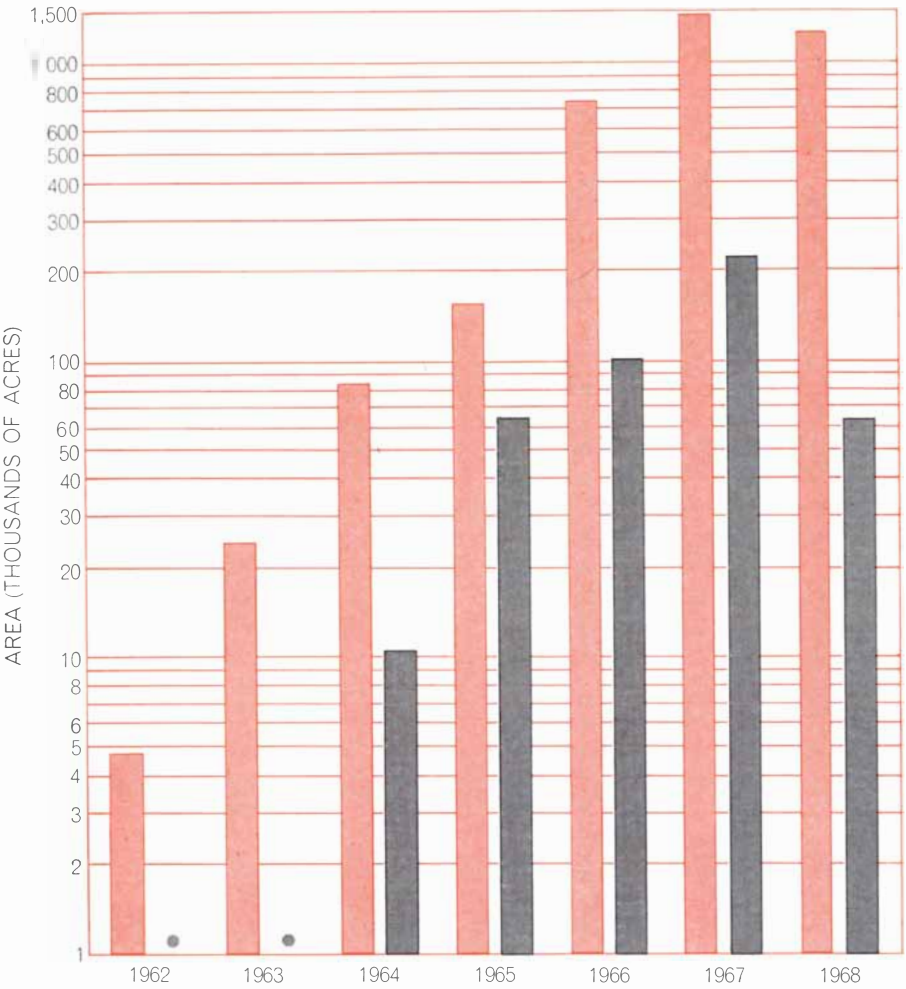
For military purposes CS has supplanted older harassing agents such as ordinary tear gas (CN, or chloracetophenone) and the emetic and respiratory agent known as adamsite or DM.

When used in war against unmasked personnel, harassing agents are effective in forcing an enemy from cover to face capture or hostile fire, to deny him terrain or to upset his fire. Against masked personnel harassing agents are very much less effective, although they reduce fighting efficiency somewhat by forcing men to put on masks. The first major application of harassing gas in combat since World War I has come in Vietnam, where more than 14 million pounds have been used by U.S. forces. At first U.S. policy was to use CS only when its employment would be more humane than the use of more lethal weapons. For example, on March 24, 1965, following the first newspaper reports of U.S. use of nonlethal gas in Vietnam, Secretary of State Dean Rusk made the following statement: "We do not expect that gas will be used in ordinary military operations.... The anticipation is, of course, that these weapons will be used only in those situations involving riot control or situations analogous to riot control."

For five months following Rusk's statement the use of harassing agents in Vietnam ceased completely. Then an event took place that put the use of CS in the most attractive possible light and

	TYPE OF WEAPON		
AGENTS	NUCLEAR	CHEMICAL	BIOLOGICAL
AREA AFFECTED	UP TO 300 SQUARE KILOMETERS	UP TO 60 SQUARE KILOMETERS	UP TO 100,000 SQUARE KILOMETERS
TIME TO EFFECTIVENESS	SECONDS	MINUTES	DAYS
DAMAGE TO STRUCTURES	WIDESPREAD DESTRUCTION	NONE	NONE
OTHER EFFECTS	PROLONGED RADIOACTIVITY IN AREA OF 2,500 SQUARE KILOMETERS	CONTAMINATION FOR DAYS OR WEEKS	POSSIBLE EPIDEMIC OR NEW FOCI OF DISEASE
NORMAL USE OF AREA	3 TO 6 MONTHS	LIMITED FOR DAYS OR WEEKS	VARIABLE
EFFECT ON MAN	90 PERCENT DEATHS	50 PERCENT DEATHS	50 PERCENT MORBIDITY

THREE WEAPONS are compared for damaging effects. The weapons are a one-megaton nuclear bomb, 15 tons of a chemical nerve agent and 10 tons of a biological agent. In each case the table assumes delivery of weapon by one bomber on an unprotected population.



USE OF HERBICIDES in South Vietnam is stated in terms of Air Force estimates for defoliation (*color*) and crop destruction (*gray*). Dots represent less than 1,000 acres. In South Vietnam some eight million acres are under cultivation and about 14 million are forested.

probably played an important role in bringing about authorization for its renewed employment. On September 5 a Marine officer came on a cave where civilians were thought to be intermingled with Vietcong soldiers. Faced with a choice between sending in an assault force, throwing in CS grenades or abandoning the mission, he decided on CS. It was reported that several enemy soldiers and 400 civilians emerged without injury to noncombatants. Following this incident soldiers and field commanders found a wide variety of uses for CS in regular combat. Soldiers encountered many situations in which it could be used to inflict casualties on the enemy and otherwise perform their mission while reducing their own losses. One of the major uses of CS in Vietnam is to flush enemy soldiers out of bunkers preceding high-explosive fire or infantry assault.

The overall utility of CS in Vietnam is not known, no systematic studies having been made. It has nonetheless been a popular weapon, and under this pressure from the battlefield its use has expanded greatly. One indicator is the yearly record of Army procurement of CS for Southeast Asia, which rose from 253,000 pounds in fiscal year 1965 to 6,063,000 pounds in 1969. Another indicator is the rapid proliferation of experimental and newly standardized CS munitions developed by the Army. As recently as July, 1966, military manuals listed only five types of CS weapons: two grenades and three bulk disseminating devices. Since then 18 new CS munitions have appeared, ranging from grenades with delayed-action fuzes for air drop up to 105-millimeter and 155-millimeter howitzer projectiles, various mortar and rocket munitions and a number of aircraft bombs with area coverage ranging up to a square kilometer.

It is sometimes argued that nonlethal chemical weapons would make war more humane. There is good reason, however, to expect the opposite. As long as lethal weapons are employed in war, if nonlethal chemicals are introduced, it must be expected that they will come to be employed not by themselves but rather in coordination with the weapons already in service, in order to increase the overall effectiveness of military operations. Certainly this has been so in the case of the agent CS.

The expansion of CS use in Vietnam has given rise to two widespread concerns. The first is that the U.S. has departed from its original humanitarian justification for the use of chemicals in war. Second, it is becoming increasingly clear that the long-term arms control cost to the U.S. may be severe. I shall return to this point.

The last category of chemical weapons to be considered here is antiplant agents. These agents were first developed for military purposes during World War II and subsequently came into wide use for weed control. Near the end of the war some consideration was given to using them to destroy rice being cultivated by Japanese soldiers in isolated island strongposts, but the plan was never authorized. Herbicides were used on a small scale to clear roadsides by the British in Malaya during their military operations there in the 1950's.

The use of herbicides in Vietnam was first authorized on an experimental basis in 1961. They next came to be employed there for increasing visibility along roads and waterways and on the perimeters of military installations; then for the destruction of crops thought to be destined for enemy consumption, and finally for the treatment of large areas suspected of harboring enemy base camps or supply routes. By mid-1969 approximately five million acres had been sprayed, 10 percent of it cropland. Following a peak in 1967, anticrop operations were substantially reduced, reflecting adverse criticism of both their propriety and their effectiveness.

Three principal antiplant agents or mixtures have been in service. They are designated Orange, White and Blue. Agent Orange is an equal mixture of the n-butyl esters of 2,4-dichlorophenoxyacetic acid (2,4-D) and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T). The agent is mainly directed against forest vegetation. It is applied undiluted at three gallons per acre, approximately 25 times the average amount for domestic application. Within a week or more after its application the leaves fall from most jungle trees. Orange has been the antiplant agent most widely used in Vietnam, but recently its employment has been suspended because of concern that 2,4,5-T may cause human birth defects.

Agent White is a 4:1 mixture of the triisopropanolamine salts of 2,4-D and 4-amino-3,4,6-trichloropicolinic acid.

The latter component is known as picloram. The agent is sprayed from a water solution at a rate of approximately 7.6 pounds of total herbicide per acre. It is generally used for the same purposes as agent Orange, although its somewhat lower volatility makes it preferable for operations where drifting would be a hazard, as in the vicinity of rubber plantations. The extreme resistance of picloram to biodegradation has been a factor in limiting its employment.

Agent Blue is a water solution of sodium dimethylarsinate, applied at the rate of nine pounds per acre. It is used mainly against rice.

Any evaluation of the military effectiveness of herbicides is made particularly difficult by the fact that they exert their effects on the enemy only indirectly and after a substantial time lag. Certainly the most dubious form of antiplant warfare from a military point of view is crop destruction. It is not generally possible to distinguish crops destined for noncombatants from those to be consumed by soldiers. Indeed, both common sense and the experience of many wars show that when the food supply is restricted, it is the civilians and not the soldiers who go on short rations, and it is the children who are most harmed by malnutrition.

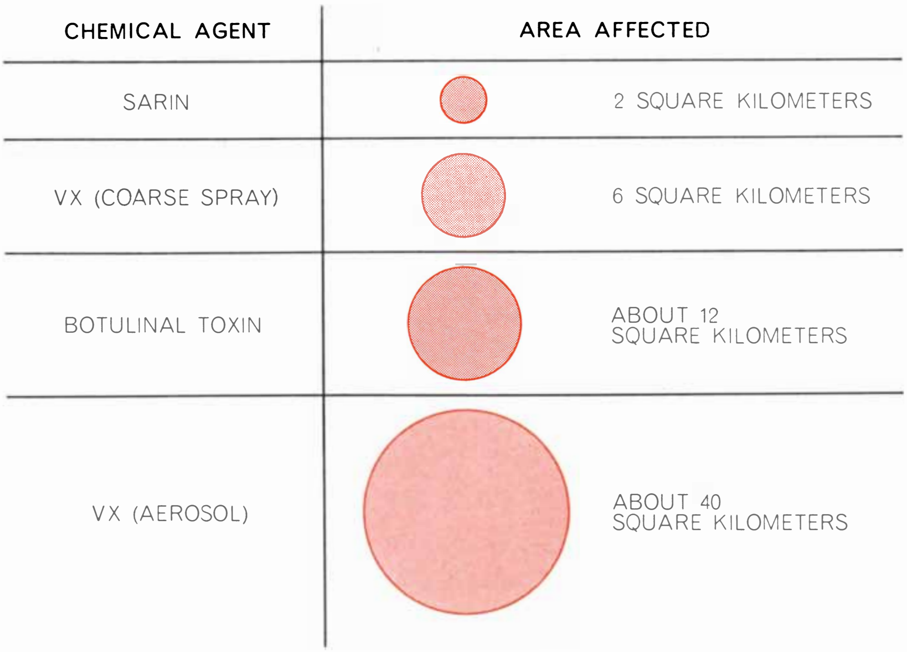
There is very little quantitative information about the overall military utility of herbicides used to improve visibility. There is no doubt that the leaves drop and visibility is thereby improved. As a result an enemy will generally choose to avoid such areas. Nonetheless, an enemy commander will not withdraw his men from action; he will deploy them elsewhere. Thus for every soldier who gains protection from improved visibility there may be another soldier or civilian receiving fire from a redeployed enemy soldier. Obviously the trade-off will not be precisely equal, but this effect will act to exaggerate the apparent military effectiveness of herbicides.

Certainly in some situations there are alternatives to chemical defoliants. In Vietnam giant plows, often working under the protection of military escorts, have been used to clear more than 500,000 acres. Where possible, this method is more effective than the aerial spraying of chemical defoliants because it removes branches and trunks as well as leaves.

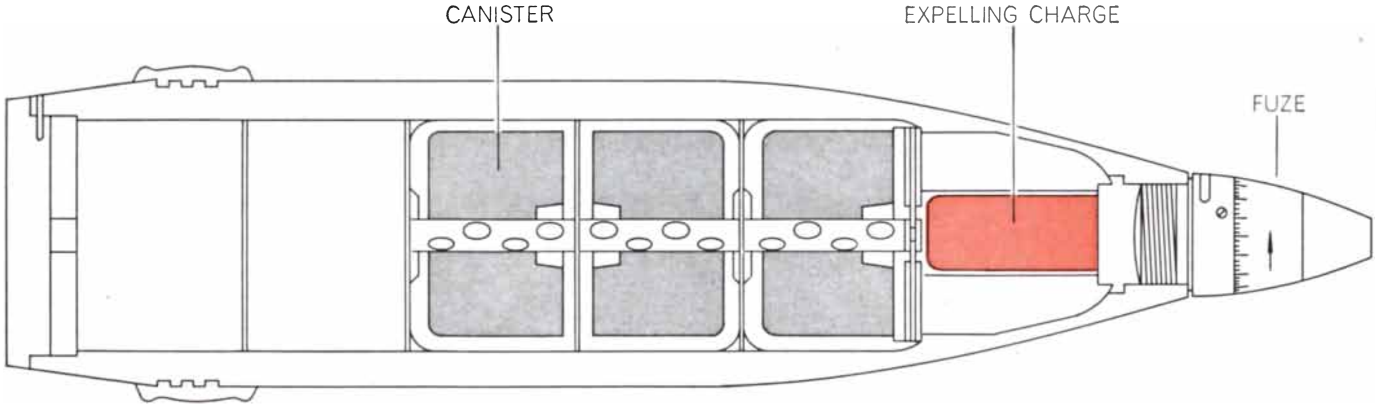
I have attempted to keep the foregoing discussion factual in order to define the issues. Emotions run high on the subject of chemical and biological weapons, however, and few persons can discuss the subject without expressing or evoking strong feelings about whether or not it is wise to use or even to possess such weapons. The strong feelings generated by these weapons have been responsible for the fact that historically they have been singled out for special efforts at arms control. The most important international effort to prohibit the use of such chemical and biological weapons is the Geneva Protocol of 1925. It prohibits (1) "the use in war of asphyxiating, poisonous, or other gases, and of all analogous liquids, materials or devices" and (2) "the use of bacteriological methods of warfare." The protocol does not prohibit research, development, testing or production of gas or germ weapons. It does not prohibit the use of such weapons in reprisal against their first use by the enemy. It does not prohibit the use of riot-control gases or other agents for domestic police purposes. It does not prohibit the use in war of nontoxic smokes used for concealment or of flamethrowers, napalm or other incendiary weapons. The language of the Geneva Protocol is derived from the peace treaties of World War I, which treated gas warfare as already prohibited and specifically forbade the manufacture and importation of war gases by Germany and her wartime allies. On the initiative of the U.S., an article based on the language of the peace treaties was incorporated in the 1922 Washington Treaty on Submarines and Noxious Gases. At the urging of President Harding, Secretary of State Charles Evans Hughes, Senator Elihu Root and a presidentially appointed advisory committee of prominent citizens, the Washington Treaty passed through the Senate with no dissenting votes. Although ratified by the U.S., Great Britain, Italy and Japan, this treaty never came into force because France, whose ratification was required, objected to its provisions on submarines.

The U.S. again pressed for a prohibition against gas warfare at the 1925 Geneva Conference on the Limitation of Arms, proposing language on gas essentially identical with that of the Washington Treaty. The prohibition was extended to cover "bacteriological methods of warfare" at the suggestion of Poland. The resulting treaty—the Geneva Protocol for the Prohibition of the Use in War of Asphyxiating, Poisonous or Other Gases, and of Bacteriological Methods of Warfare—was signed by representatives of 38 nations on June 17, 1925.

The Coolidge Administration and the various supporters of the protocol seem to have assumed that the Senate would give its consent as readily as it had to the Washington Treaty. Almost nothing was done to prepare the case for ratification or to mobilize public support. Meanwhile the Army Chemical Warfare Service, the American Legion, the American Chemical Society and segments of the chemical industry organized the opposition. The arguments



EFFECTS OF ATTACK with chemical agents are charted. The stated effects assume an attack by a single plane, along a two-kilometer crosswind line, laying down four tons of the agent. The use of VX in aerosol form would be to maximize the agent's downwind travel.



ARTILLERY SHELL designed to deliver CS irritant has the agent in canisters that are expelled when the fuze detonates the shell. The shell portrayed, which is for a 155-millimeter weapon with a range of 15 kilometers, is 60 centimeters long, weighs 44 kilograms and carries 4.4 kilograms of CS. In a normal artillery barrage several weapons are fired, delivering a number of shells to target.

made against ratification were that the protocol would be ignored in time of war and that poison gas was more humane than bombs and bullets. The protocol was debated but not acted on by the Senate—apparently because the majority leader did not have the votes. It remained on the Foreign Relations Committee docket until 1947, when President Truman withdrew it together with several other long-pending treaties.

By 1939 the Geneva Protocol had been ratified by 44 nations, including all major European powers. At the outbreak of World War II England, France and Germany exchanged assurances that they would abide by the protocol. In 1943 President Roosevelt declared that gas warfare was "outlawed by the general opinion of civilized mankind" and that "we shall under no circumstances resort to the use of such weapons unless they are first used by our enemies." Japan is believed to have used gas against China before our entry into the war but otherwise gas was not used in World War II. The threat of retaliation provided a sanction. The restraint was reinforced by widespread abhorrence of gas and germs and by military skepticism regarding their utility, but it was the protocol that placed gas and germs in a distinct category and provided a clear standard on which the belligerents could base their conduct.

Since World War II the U.S. has on numerous occasions declared its support for the no-first-use principle of the Geneva Protocol. When President Eisenhower was asked at a press conference if he planned a change in our no-first-use policy, he said: "No official suggestion has been made to me, and so far as my own instinct is concerned, it is not to start such a thing first." During President Johnson's Administration the U.S. supported resolutions passed in 1966 and 1968 by the UN General Assembly, calling for "strict observance by all states of the principles and objectives of the Protocol" and "inviting all nations that have not done so to accede to the Protocol." Some statements, however, have made the U.S. position seem ambiguous. For example, the U.S. Army manual *The Law of Land Warfare,* last issued in the 1950's, states that the Geneva Protocol is "not binding on this country."

A total of 84 nations are now parties to the Geneva Protocol; 16 of them have ratified it since the 1966 UN resolution. The parties include all North Atlantic Treaty Organization members except the U.S., all members of the Warsaw Pact including the U.S.S.R. and all nuclear powers (other than the U.S.), including the People's Republic of China. All major industrial nations except Japan and the U.S. are parties. The protocol has been signed but not ratified by the U.S., Brazil, El Salvador, Japan, Nicaragua and Uruguay.

Whether or not the protocol prohibits the use of harassing agents and antiplant chemicals is a subject of some dispute. On the first occasion when nations were canvassed for their views on the status of tear gas (at a League of Nations Commission in 1930), Canada, China, France, the U.S.S.R. and several other nations agreed with the declared British position that "the use in war of 'other' gases, including lachrymatory gases, was prohibited." None of the nations then party to the protocol made objections to this view. The U.S. delegate, however, expressed hesitation over any commitment to refrain from the use in war of agencies used in peacetime by domestic police and whose use in combat would be "more clearly humane than the use of weapons to which [nations] were formerly obliged to resort." Two years later the League Disarmament Conference unanimously recommended that the use of all gases, including tear gas, be prohibited in war. This view was accepted by the U.S. with the understanding that it did not apply to the use of tear gas for police purposes. The discussions were not directed at the Geneva Protocol but at devising a comprehensive disarmament treaty, an attempt that was disrupted by the approach of World War II. The question did not come up again until 1965, when questions were first raised about our employment of CS and herbicides in Vietnam.

Responding to these questions in 1966, the U.S. representative to the General Assembly stated that the protocol does not prohibit "the use in combat against an enemy, for humanitarian purposes, of agents that Governments around the world commonly use to control riots by their own people" or of chemicals used to control "unwanted vegetation" for agricultural and other peaceful purposes. At the time these views were contested mainly by the U.S.S.R. and its allies. As the scale of chemical operations in Vietnam has increased, however, the U.S. position has come under mounting attack. Last summer Secretary General U Thant urged the members of the UN to "make clear affirmation" that the protocol prohibits the use of all chemical agents, including tear gas, in warfare. Last winter India, Mexico, Pakistan, Sweden and 17 other nations proposed in the General Assembly a resolution holding that the Geneva Protocol prohibits the use in war of all chemical agents directed at men, animals or plants. The resolution was passed by a vote of 80 to three, with 36 abstentions. Portugal, Australia and the U.S. voted against the resolution.

Since then the British government has declared that CS is exempt from the Geneva Protocol, although Britain still considers the tear gases known in 1930 to be prohibited. The British argument was that CS is less toxic than older tear gases, but it is generally thought that the real motivation of the cabinet was to avoid risking charges that the use of CS for riot control in Ulster was illegal. If so, this reflects a confusion regarding the meaning of the Geneva Protocol, which by its terms prohibits the use of gas only in warfare. The distinction between the use of tear gas for domestic police purposes and the prohibition of its use in war has been observed without difficulty by many nations ever since World War II. Even Sweden, a nation that has led the opposition to the use of tear gas in war, uses it in riot control at home. Ironically, it may be that the massive use of CS in war and the excesses this breeds will generate serious opposition to its domestic use.

As the U.S. moves to ratify the Geneva Protocol, the Administration must decide on a policy regarding the use of harassing agents and herbicides. There is no great difficulty in identifying the pros and cons of maintaining an option to use these agents in war. The difficulty arises when one attempts to quantify the various arguments and then to place values on them in order to reach conclusions.

The principal gain to the user of these agents in war is that to some extent they enable him to increase enemy casualties and to reduce his own. These agents, however, are of significant effect almost only in counterguerilla warfare and, in the case of CS, only if opposing troops are unprotected by gas masks. Hence the arguments for keeping these weapons become important to the extent that a nation anticipates involvement in such wars. CS can be expected to lose its advantage in any case, for once the impression is created that one's forces will use gas, supplies of masks will become much more available throughout the world. North Vietnamese troops in South Vietnam are now largely equipped with fairly good Chinese Communist gas masks, and increasing numbers of the excellent Russian Shlem masks are appearing. Even for guerillas the expense of masks is not great.

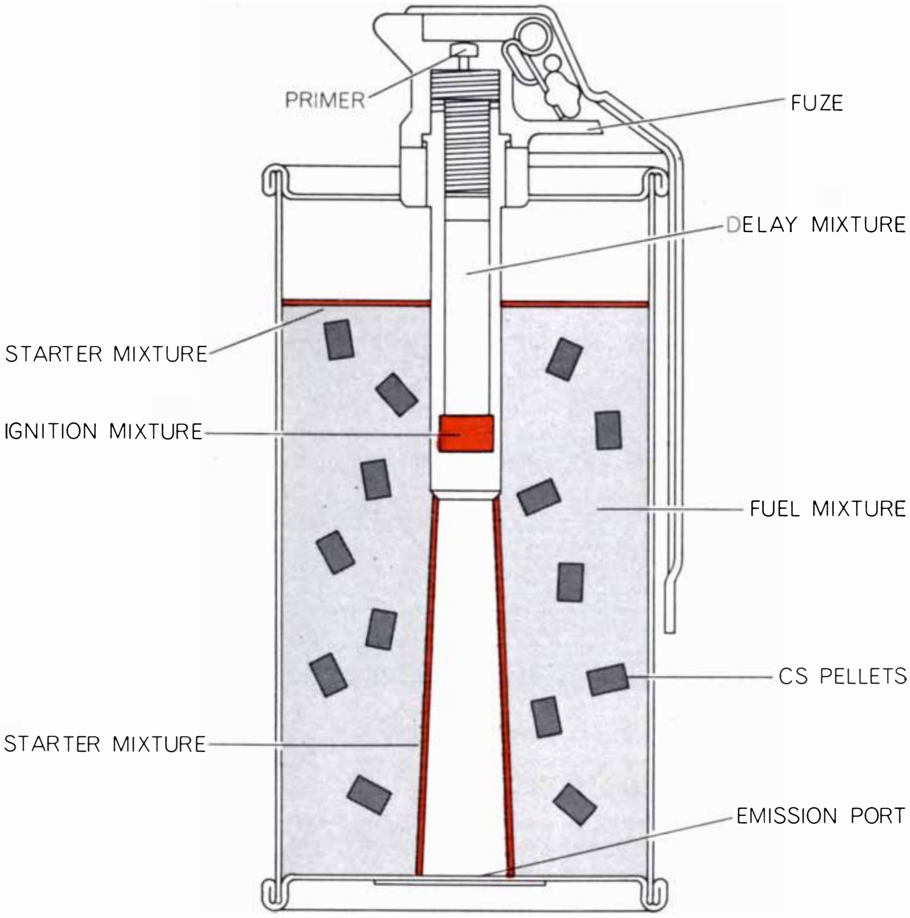
The main threat to security of continuing the use of these agents is the increased likelihood of proliferation of chemical weapons and of the breakdown of the restraints against chemical warfare. Our employment of harassing gas in war, particularly when it is done on a large scale in conjunction with ordinary military operations, stimulates military planners in other nations to secure gas masks, initiate chemical training and upgrade chemical cadres and to consider acquiring for their own nations chemical weapons of various types, including lethal ones.

The large-scale military employment of antiplant chemicals poses ecological and public health problems of which we still know little but that could be most serious in the long run. The precedent of countenancing large-scale alteration of the environment in the conduct of war has obvious perils. Moreover, in many parts of the world use might be made of chemicals as agents of starvation and economic warfare against the civil population. Because of the relative ease with which this tactic can be practiced, it would be difficult to stop once the precedent is set.

The general problem of preventing chemical and biological warfare is to a large extent a psychological one. Perhaps the central problem is to prevent the application of biochemistry and biology to the opening up of a new and highly unpredictable dimension of warfare. If we can maintain and reinforce the traditional expectation that no gas or germs will be used in war, there will not be much pressure for these weapons to proliferate.

This psychological aspect of the problem has been understood by essentially all nations, including the U.S., ever since World War I. Recently, however, a dangerous break with tradition has been allowed to occur and to escalate in Vietnam. Many who have studied the problem consider the use of chemical weapons there, even though they are not lethal chemicals, to be the major and most immediate threat to the barriers that prevent chemical warfare.

If we can accept the loss of our option to use harassing agents and antiplant chemicals as weapons of war, then, judging from the recent vote in the General Assembly, it appears likely that all important nations of the world could be brought to agree. If, on the other hand, the long-observed rule of "No chemical and biological weapons" is abandoned, there will be no unique and equally simple standard on which national practice and international agreement can be based.



CS GRENADE with a 12-second delay fuze is designed to be delivered either by a grenade launcher or by airdrop. One of these grenades weighs one pound and holds 115 grams of CS.

MARS AT A DISTANCE OF 356,000 KILOMETERS looked like this last August 4 when photographed by the long focal-length camera aboard *Mariner 7*. Some 27 hours later the spacecraft photographed portions of the same face of the planet at close range. Very nearly the same face was also turned toward *Mariner 6* when it made its near approach a few days earlier, on July 31. Thus the features visible in this far-encounter view (frame No. 67) can be compared with the details seen in the various near-encounter pictures made by the two Mariners. Notably absent in all the Mariner pictures are the networks of "canals" that some Martianologists began putting into their drawings a hundred years ago. These networks continue to appear even in recent maps of the planet (*see illustrations on pages 30 and 31*). The larger features that can be seen through earth-based telescopes, however, show up clearly in these and other far-encounter pictures taken by the two Mariners. Thus the large dark region just below the equator begins at the left with the two-pronged feature named Meridiani Sinus. The thinner dark band immediately to the right is Sabaeus Sinus, which turns down and becomes Mare Serpentis. The dark triangular region extending northward above the equator on the right side of the planet is Syrtis Major. Below it, just above the south polar cap, is the great circular "desert" Hellas, later shown to be devoid of features.

THE SURFACE OF MARS

The remarkable pictures taken by Mariners 6 and 7 reveal a planet with features unlike those seen on the moon and also unlike those on the earth, including a polar cap evidently composed of dry ice

by Robert B. Leighton

The first drawing of Mars made with the aid of a telescope shows a single round black spot in the center of a "perfect distinct sphere." The sketch was made by an Italian astronomer, Franciscus Fontana, in 1636. Thirty years later Jean Dominique Cassini observed the planet's polar caps and made sketches showing a variety of light and dark areas elsewhere on the surface. He concluded from their changing position that the planet rotates with a period of 24 hours 40 minutes, which was less than three minutes in error. In addition to the polar caps Cassini's drawings show at least two particularly bright circular features, one of which may correspond to the region now known as Nix Olympica and the other to the "desert" Elysium.

Between July 28 and August 5 of last year Nix Olympica, the desert Elysium and scores of other features of Mars, drawn and redrawn and speculated about in the three centuries since Fontana and Cassini made their observations, were recorded through the objective eye of television cameras carried past the planet by *Mariner 6* and *Mariner 7*. The two spacecraft relayed back to the earth 202 complete pictures taken at distances ranging from about a million miles (1,716,000 kilometers) to within 2,180 miles (3,500 kilometers) of the planet's surface. Another 1,177 pictures, each containing one-seventh as many picture elements as the complete pictures, were made at distances both greater and less than a million miles. Although these incomplete pictures are not beautiful to look at, they provide a rich source of data.

Each of the 202 complete pictures contains as many bits of data as the entire set of 22 pictures of Mars made in July, 1965, by *Mariner 4*, the first spacecraft to photograph another planet. *Mariner 4* was not programmed to photograph the entire disk of Mars, and its closeup pictures, remarkable as they were, shed little light on the nature of the familiar large-scale features visible from the earth. What one saw in those pictures was a heavily cratered surface that could have been the surface of the moon. This would have been quite a shock to the Martianologists of the 19th century and the early 20th, who had come to think of Mars as being rather like the earth.

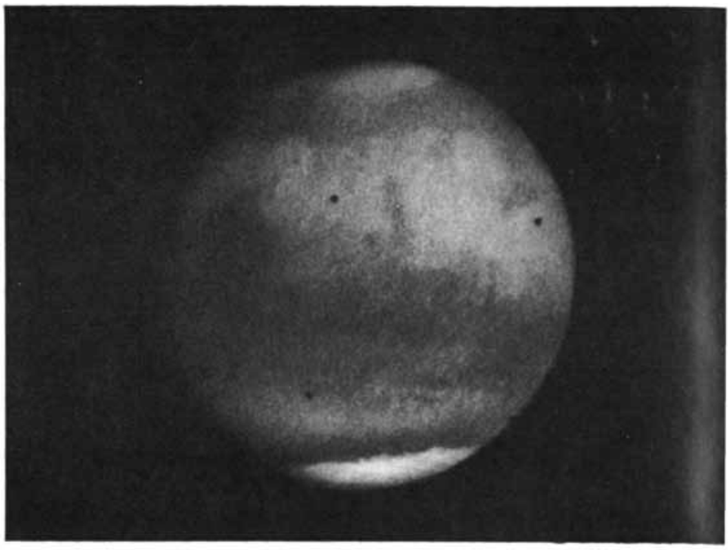
The new surprise contained in the pictures made by Mariners 6 and 7 is that Mars is not just an oversized moon but has distinctive features of its own—features unknown elsewhere in the solar system. In addition to the heavily cratered terrain first revealed by *Mariner 4* one now sees that certain large areas (notably the desert known as Hellas) are virtually devoid of craters. What could have obliterated the craters that almost surely existed at one time? We also recognize a third type of terrain that geologists term chaotic. Here too craters have been mostly erased, but something else has also happened to create a surface of jumbled ridges that is unlike anything seen on the moon, and that is not duplicated on the earth on so large a scale.

Mariners 6 and 7 also carried spectrometers for studying the atmosphere of Mars in the ultraviolet and infrared regions of the spectrum, together with an infrared radiometer for measuring the surface temperature of the planet. Additional information about the Martian atmosphere is being obtained by studying the slight changes in frequency of the radio signals from the spacecraft as each was going behind the planet and, minutes later, as each emerged. A final set of experiments involves the use of precise tracking data from the Mariners to check the dimensions of the solar system and the orbits of Mars, the earth and neighboring planets. In this article I shall discuss only the television pictures of Mars and their interpretation. My colleagues in this endeavor are Norman H. Horowitz, Bruce C. Murray and Robert P. Sharp of the California Institute of Technology, Alan G. Herriman and Andrew T. Young of the Jet Propulsion Laboratory, Bradford A. Smith of New Mexico State University, Merton E. Davies of the Rand Corporation and Conway B. Leovy of the University of Washington.

In December, 1965, five months after the successful flyby of *Mariner 4*, the Jet Propulsion Laboratory, operated for the National Aeronautics and Space Administration by Cal Tech, was authorized to design Mariners 6 and 7 and supervise their mission to Mars. The earlier craft had been launched by a two-stage Atlas-Agena vehicle, capable of sending a total mass of some 260 kilograms (575 pounds) to the vicinity of Mars. Of this mass, a single television camera made up about 15 kilograms and the remaining scientific payload another 25 kilograms.

Mariners 6 and 7 were to be launched by the more powerful Atlas-Centaur combination, in which the second stage (Centaur) uses liquid hydrogen as a fuel. The total spacecraft weight for a Mars mission could thereby be increased to about 380 kilograms and the total scientific payload could be approximately tripled, from 40 to 115 kilograms. This made possible a mission with two television cameras, one for wide-angle coverage and one for close-ups.

The single camera of *Mariner 4* had a focal length of 305 millimeters and produced a picture on the face of the Vidicon television image tube that measured 5.5 by 5.5 millimeters. The Vidicon con-



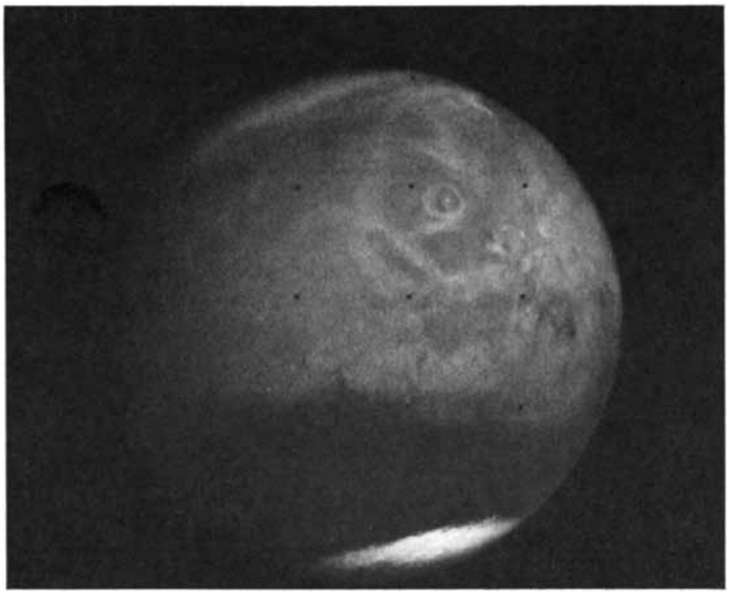
ANOTHER FACE OF MARS, centered on about 120 degrees east longitude, is shown in the earth-based telescope view at the far left, originally taken in color by the author in July, 1956, and in the three comparable views made by Mariners 6 and 7 as they approached the planet. *Mariner 7* took the first and third pictures at distances of 848,226 and 255,278 kilometers. *Mariner 6* took the

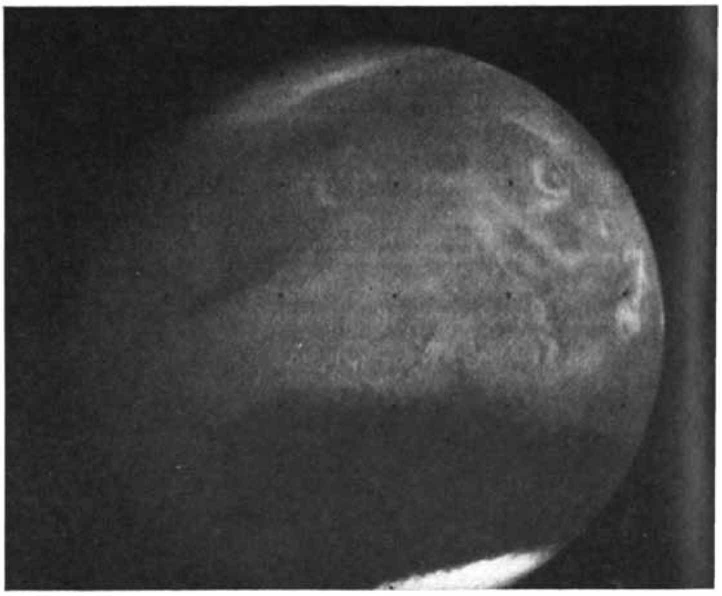
verted each picture into an image consisting of 200 lines with 200 picture elements ("pixels") per line, making a total of 40,000 pixels per picture. Each pixel was encoded into 64 brightness levels, which required six "bits" of information per pixel ($2^6 = 64$). The total number of bits per picture was therefore 40,000 times six, or 240,000. At the closest approach to Mars (9,850 kilometers) the *Mariner 4* camera covered a surface area measuring about 300 kilometers on a side and revealed craters as small as five kilometers in diameter.

For Mariners 6 and 7 the wide-angle camera (Camera *A*) had a focal length of 52 millimeters and the narrow-angle, or closeup, camera (Camera *B*) had a focal length of 508 millimeters. At close approach (3,500 kilometers) Camera *B* covered an area on the surface measuring about 72 by 84 kilometers and resolved craters as small as 300 meters across. Camera *A* covered a rectangle 10 times larger in each dimension, or an area 100 times greater.

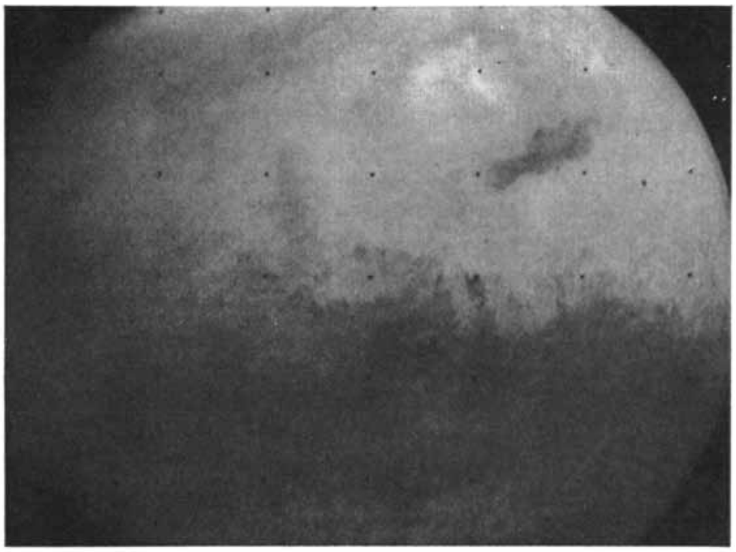
On the face of the Vidicon each camera produced a rectangular picture 9.6 by 12.3 millimeters. This was converted into a television image consisting of 704 lines with 935 pixels per line, for a total of 658,240 pixels. (Commercial television uses a 525-line picture with about 400 discernible elements per line.) Each pixel was effectively encoded into 256 brightness levels, requiring eight bits ($2^8 = 256$). Thus each picture taken by Mariners 6 and 7 was encoded into about five million bits, compared with 240,000 bits for each *Mariner 4* picture. (To encode a commercial television picture into digital form would require about a million bits per picture.)

Because of various limitations that I shall explain shortly, the pictures could not be returned to the earth in real time, like a live television show; they had to be stored on magnetic tape. The *Mari-*





AFTERNOON BRIGHTENING over certain regions of Mars is evident in several of the far-encounter sequences. Such changes in brightness had often been reported by earth-based observers. These *Mariner 7* frames (76, 78 and 79) show how brightness develops over the Tharsis-Candor region during the early afternoon. In frame No. 76, whose central longitude is 199 degrees east, no bright-



second picture at a distance of 328,075 kilometers. The central longitudes in the Mariner views are 99, 105 and 119 degrees east. The dark mass projecting upward at the extreme left in all the pictures is Syrtis Major. At the upper right the large circular desert Elysium shows up more and more clearly in succeeding frames, as does the dark feature Trivium Charontis and the "canal" Cerberus.

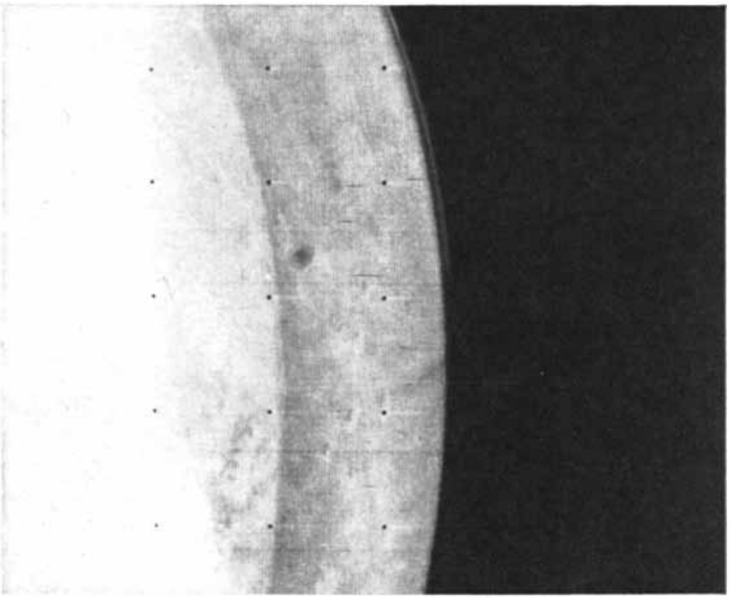
ner 4 tape had a storage capacity of about five million bits, enough for 22 pictures. These were later transmitted back to the earth at the low rate of 8⅓ bits per second, so that transmission of the complete set of pictures took more than eight hours. For Mariners 6 and 7 we chose a system involving the use of two tape recorders: one digital, with a capacity of 13 million bits, and one analogue, with an effective capacity of about 120 million bits. Both tapes were actually the same length (110 meters), had the same number of tracks (four) and ran at the same speed (30 centimeters per second).

The reason for the difference in effective bit capacity is that a digital tape is used to store only one bit (0 or 1) of information on each available magnetic "spot"; the spot is either magnetized or it is not, and the ambiguity is close to zero. In an analogue recording the same spot can be impressed with various degrees of magnetization, proportional to whatever intensity the light level happens to be. Later this analogue value can be digitized, but the result is less reliable than it would be if the information were digitally recorded in the first place.

On Mariners 6 and 7 the analogue signal from the Vidicon camera was treated in two ways. One sample was translated into an eight-bit code: a brightness level of zero was encoded as 00000000 and maximum brightness was encoded as 11111111. The first two digits were averaged over several scanning lines and were transmitted directly to the earth in real time as part of the telemetry stream of engineering data. The remaining six bits from every seventh pixel were recorded by the digital tape recorder and later played back to the earth, producing the 1,777 pictures, each one-seventh complete.

Simultaneously another sample of the Vidicon analogue signal was passed

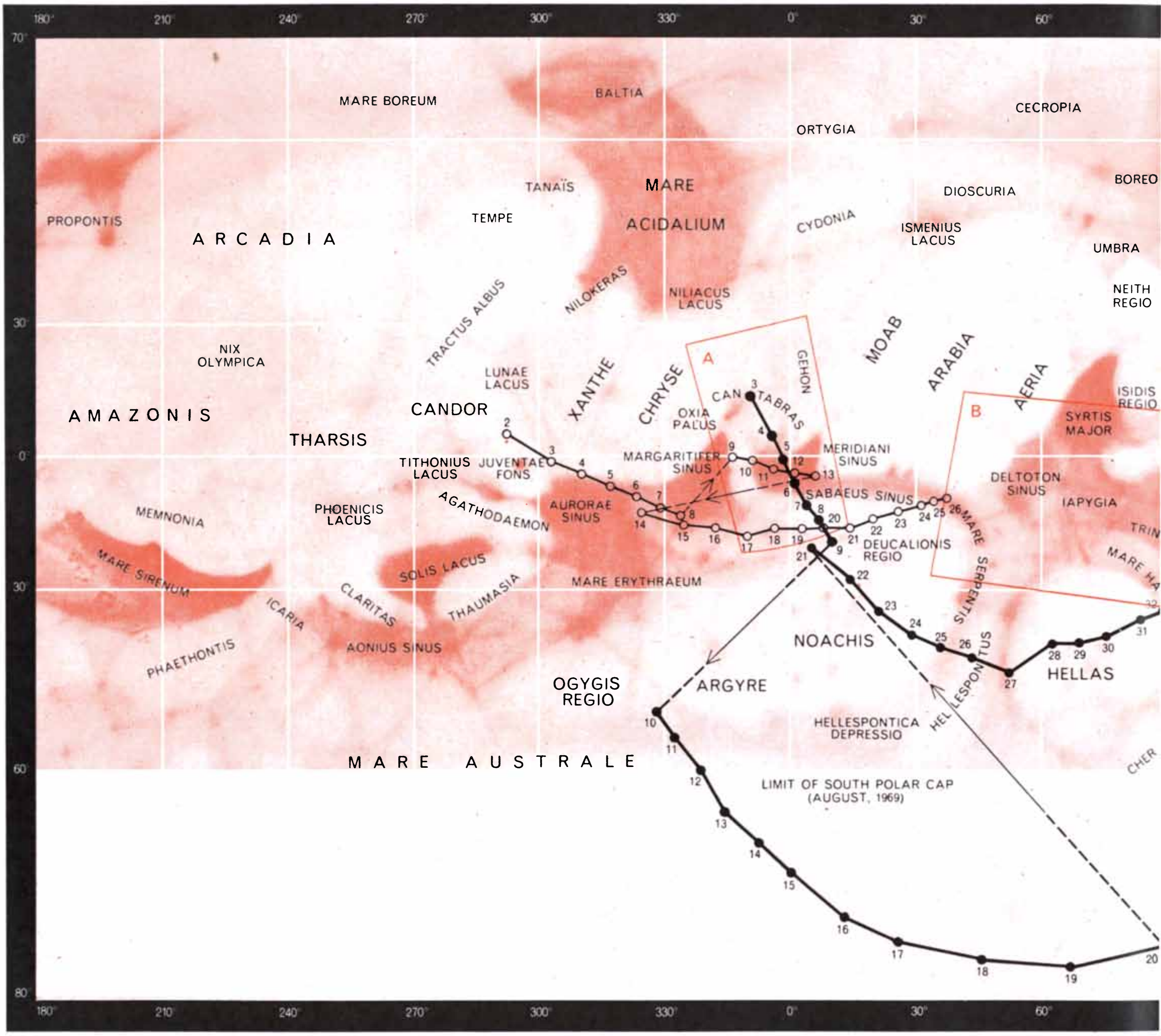
ening is visible. In the next frames, taken 95 and 141 minutes later, a distinctly bright area has appeared at the right edge of the planet. The prominent ringed crater is Nix Olympica.



THIN LAYER OF HAZE hugging the limb of Mars is clearly seen in several near-encounter frames, such as this one (No. 3), taken by *Mariner 7*. The dark band on the surface of the planet is an artifact.

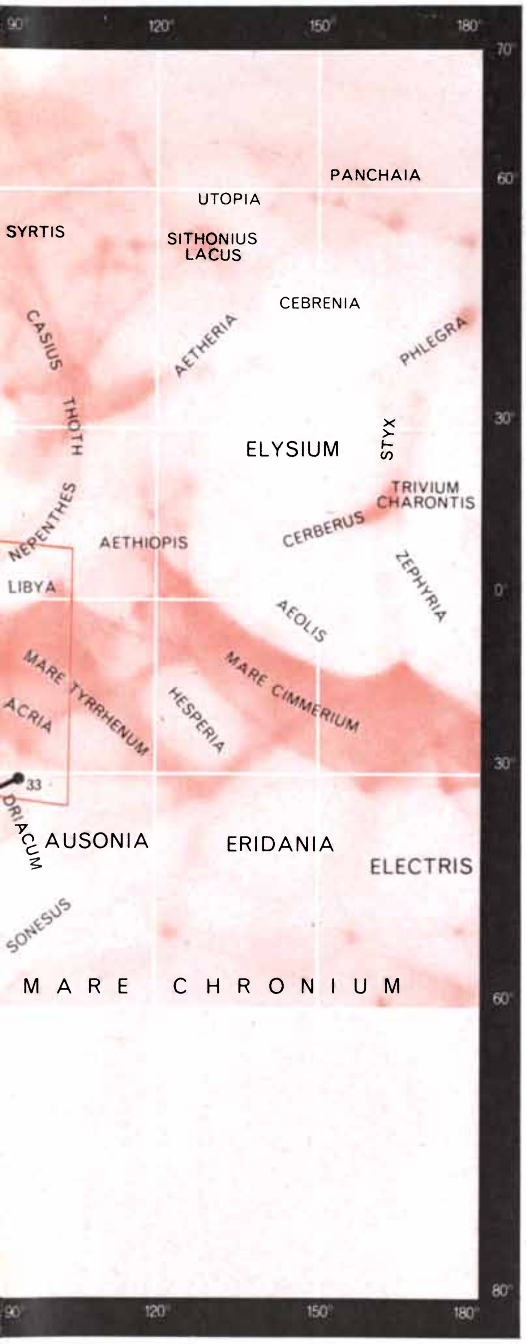
along to the analogue tape recorder, but first it was modified in two ways. In order to enhance the visibility of small-scale features the analogue signal was automatically controlled so that its average value was approximately constant (a technique called automatic gain control). In addition the signal was put through a circuit with a "cube law" response, which enhanced the local contrast by a factor of about three. The ultimate effect of this procedure was to provide a more finely graduated signal when the analogue recording was subsequently converted into a six-bit digital signal for transmission to the earth.

Later the first two bits of the digital picture signal, which had been averaged over several scan lines and returned to the earth earlier, were recovered by computer processing and merged with the analogue picture data to yield a resultant picture with a full eight-bit (256-level) encoding range. If the brightness levels of successive pixels had varied from 0 to 255 in entirely random fashion, this scheme would not have worked. We knew, however, from the *Mariner 4* results that the surface of Mars would not resemble a random-number table,

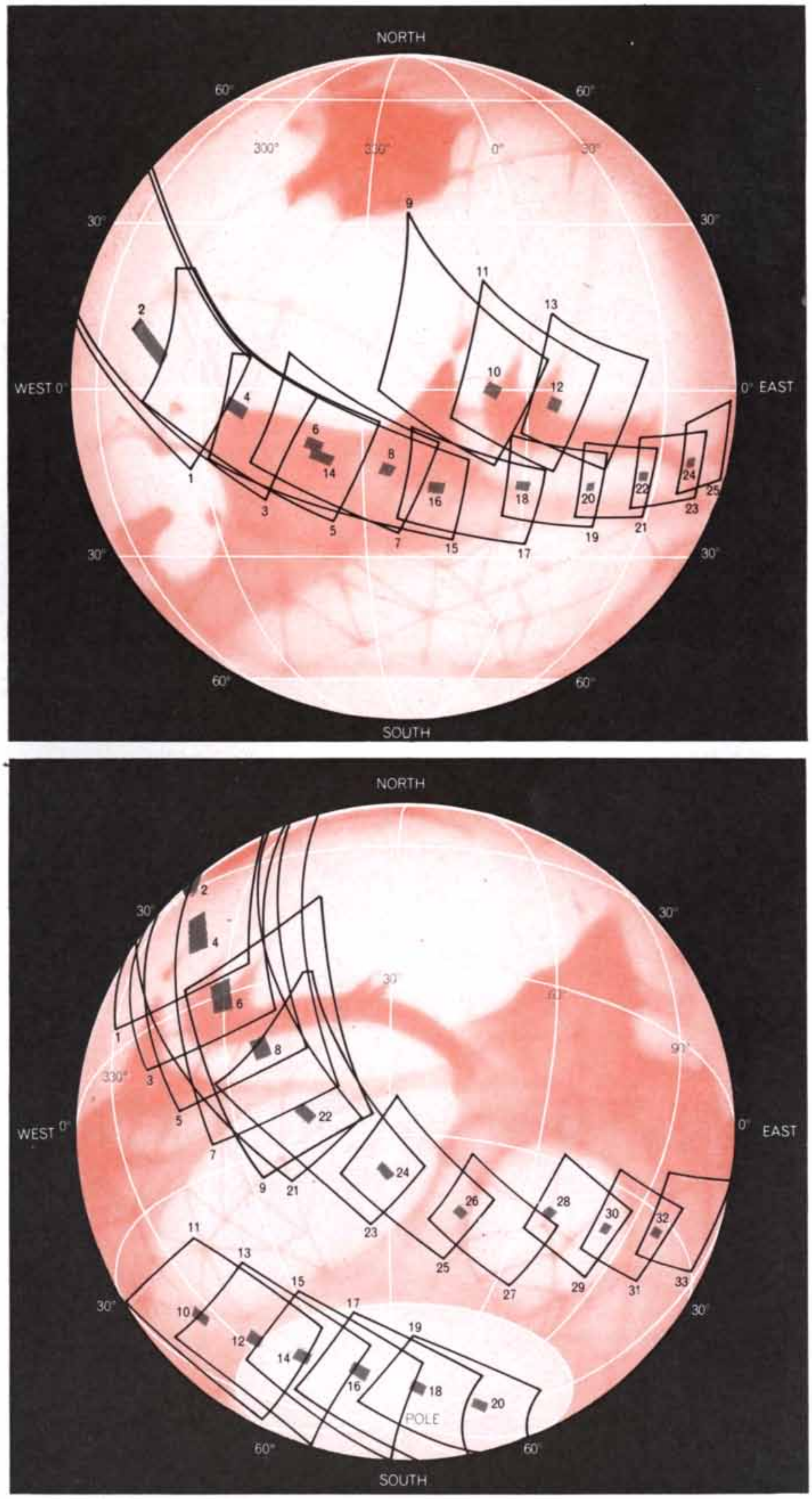


MAP OF MARS summarizes more than three centuries of telescopic observations. Yet two observers have rarely agreed on what Mars really looks like. This Mercator projection is based on a rendering prepared a few years ago by the Aeronautical Chart and Information Center of the U.S. Air Force. It perpetuates the tradition of showing Mars crisscrossed by canal-like networks. However, the map also indicates the craters photographed by *Mariner 4* in 1965; they extend from Trivium Charontis (*far right*) into Phaethontis (*far left*). It is fascinating to compare the exotically named features on the map with the complex textural details visible in the photographs returned to the earth by Mariners 6 and 7. The colored lines enclose areas depicted in one of the last far-encounter frames (*B*) and one of the first near-encounter frames (*A*). The two frames, which are reproduced at the top of page 32, show regions of special interest at intermediate scale. As *Mariner 6* swept by the planet it took 26 near-encounter pictures; *Mariner 7* took 33. Open circles, numbered from 2 to 26, identify the centers of the frames of the *Mariner 6* near-encounter sequence; the center and that it would be very low in contrast.

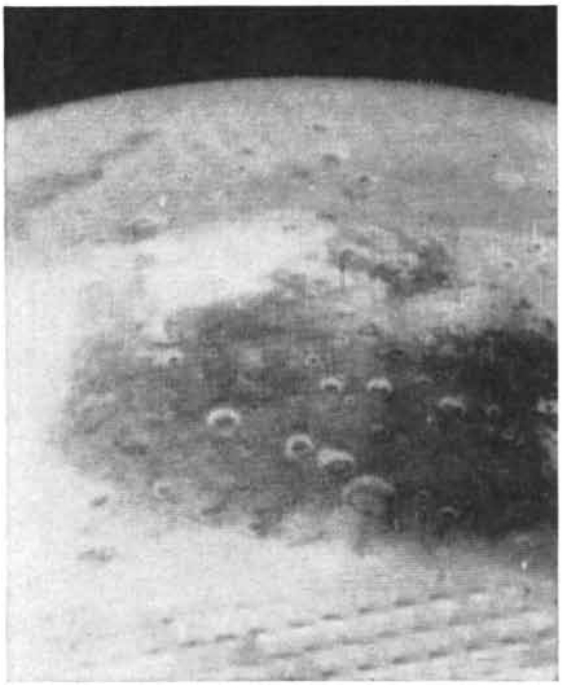
One of the most dramatic differences between *Mariner 4* and Mariners 6 and 7 was a two-thousandfold increase in the data-transmission rate: 16,200 bits per second compared with 8⅓ bits per second for the earlier flight. Many things contributed to this improvement, beginning with the fact that Mars was



of the first frame (*1*) did not fall on the surface of the planet. Solid dots, numbered from 3 to 33, identify the centers of frames taken by *Mariner 7*. During each sequence the camera platforms were slewed to take a series of photographs to one side of the main flight path. Odd-numbered frames were taken with a wide-angle lens, even-numbered frames with a narrow-angle lens.



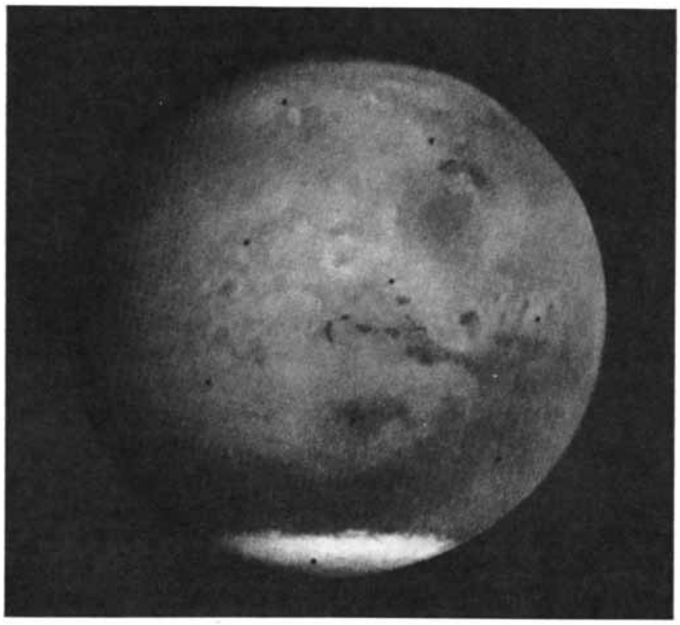
PICTURE LOCATIONS are plotted on two globes of Mars. The near-encounter frames taken by *Mariner 6* are plotted on the upper globe; those taken by *Mariner 7* appear on the lower globe. In the upper globe the central meridian is about 335 degrees east longitude. The lower globe has been rotated to the left so that the central meridian is about 30 degrees east longitude; it has also been tipped to expose the south polar cap. The wide-angle frames (*odd numbers*) were taken through filters in the sequence blue, green, red, green and so on; the narrow-angle frames (*even numbers*) were all taken through a yellow haze filter. The resolution of the wide-angle pictures is about 100 times better than can be obtained from the earth and the resolution of the narrow-angle views is about 1,000 times better.

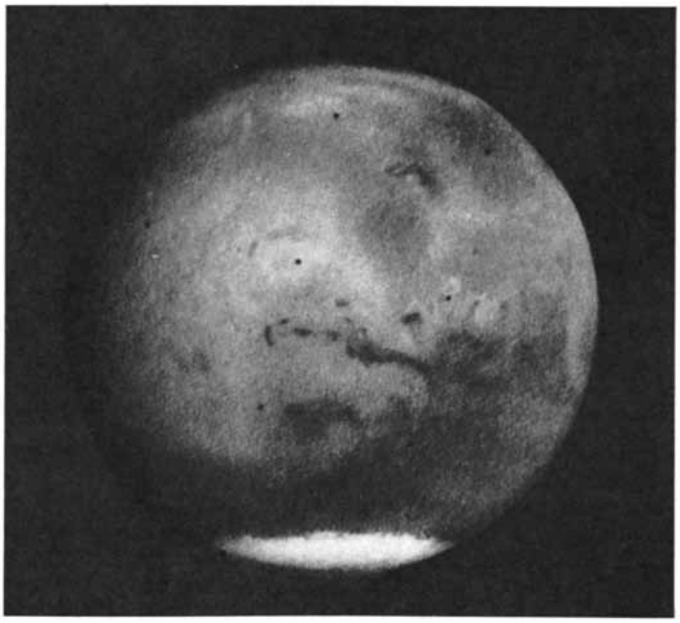


AREAS OF SPECIAL INTEREST are included within these two views taken by *Mariner 7*. The surface features depicted in the two pictures can be identified by referring to the corresponding areas (*A and B*) on the map on the preceding two pages. View *B* (*right*) is one of the last far-encounter views (No. 92). These views were transmitted without subjecting the signal from the Vidicon camera to automatic gain control; thus the actual contrast between light and dark areas was transmitted to the earth just as recorded. This was not the case in the near-encounter views. In near-encounter frame No. 5 (*A, left*) the contrast has been restored by computer processing. The dark area in the foreground of *A* is Meridiani Sinus. The several scattered craters above coincide with the position of the "canal" Cantabras. Picture *B*, centered on Iapygia, shows part of Syrtis Major and the northern rim of Hellas.

much closer to the earth in 1969 than it had been in 1965: it was only 100 million kilometers away instead of 210 million. In addition the radio transmitters aboard Mariners 6 and 7 could be operated at 20 watts, twice the power available on *Mariner 4,* and their transmission beams were narrower. The receiving antenna at the tracking center in Goldstone, Calif., was a recently completed 210-foot dish, which provided about seven times more signal-collection surface than the 80-foot dish used in 1965. Finally, there were many detailed improvements in electronic circuitry, together with a new error-checking coding system (block encoding), all of which helped to raise the transmission rate to 16,200 bits per second.

Even this rate could not keep up with the rate at which picture bits were pro-





THREE-DIMENSIONAL VIEW OF MARS can be obtained by treating these two frames as a stereoscopic pair. They are *Mariner 7* far-encounter frames No. 70 (*left*) and No. 69 (*right*). No. 69 was taken at a distance of 535,131 kilometers; No. 70 was taken 48 minutes later at 514,810 kilometers. The average central longitude of the two views is 273 degrees east. The entire region around Solis Lacus stands out sharply. Major features include Tithonius Lacus, the "canal" Agathodaemon, Juventae Fons and Aurorae Sinus.

duced by the cameras of the new Mariners: more than 100,000 bits per second. Thus the data had to be taped before retransmission to the earth. It should also be noted that the 16,200-bit rate could only be used when the large Goldstone dish could be aimed at the spacecraft, roughly six hours a day. At other times, when the receiving stations elsewhere in the world had to be used, telemetry at a slower rate (270 bits per second) had to be employed.

In mechanical design Mariners 6 and 7 were sister craft of the previous Mariners, which had flown so successfully to Venus as well as to Mars [*see illustration on this page*]. Perhaps the most important improvement was a new central computer and sequencer (CC&S): the electronic system that carries in its memory the program of specific events required during the mission. The CC&S was programmed before launching with a "standard" mission and a "conservative" backup mission. The standard mission, which could be executed only through a command from the earth, would provide the maximum picture coverage and transmit data at the high-bit rate. The conservative mission, which would be self-initiating, would provide only eight full-disk pictures of Mars from each spacecraft and would transmit the data at 270 bits per second. An important capability of the new CC&S was that it could be reprogrammed in flight to undertake any new sequence the mission controllers might choose. It was anticipated, for example, that we might wish to modify the program of *Mariner 7* on the basis of data received from *Mariner 6,* and this proved to be the case.

Different flight paths were chosen for the two spacecraft. For *Mariner 6* the experimenters and the mission planners selected an arrival date of July 31 and an aiming point that would provide near-encounter pictures in a belt between the equator and about 20 degrees south latitude. Nested within each wide-angle picture would be a closeup, narrow-angle picture. The series of pictures would provide overlapping coverage extending almost halfway around the planet. Midway through the sequence the camera platform would be slewed northward to cover the prominent dark feature known as Meridiani Sinus. The main equatorial coverage would include a number of well-studied light-dark regions, two features long known to Martian cartographers as "oases" (Juventae Fons and Oxia Palus) and a variable light region, Deucalionis Regio [*see illustrations on pages 30 and 31*].

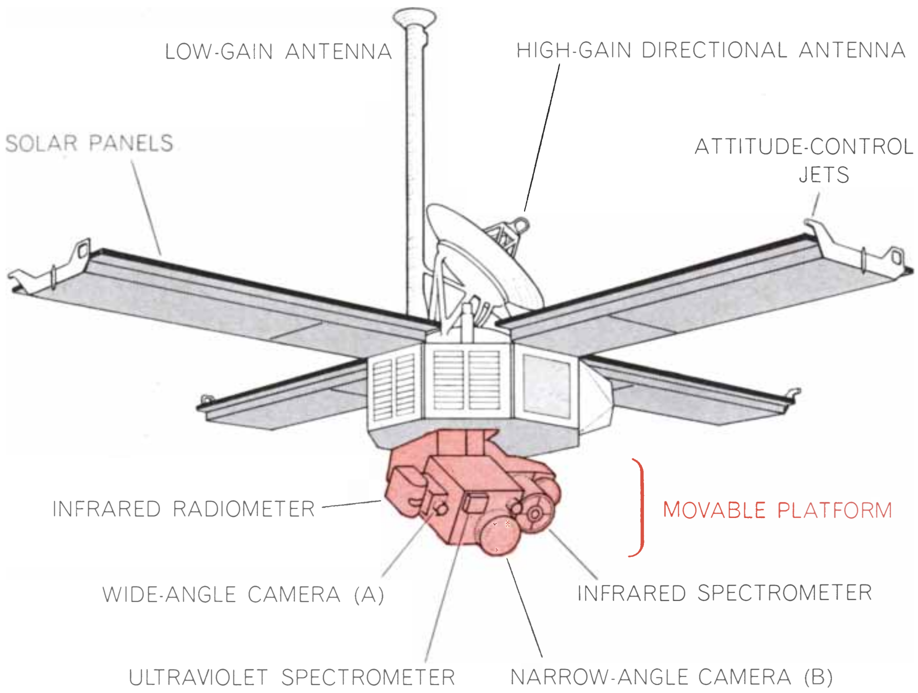
Five days later *Mariner 7* would approach the planet on a more southerly route to take a sequence of overlapping pictures that would begin just north of the equator and progress toward the southeast. This sequence would be interrupted midway to obtain a series of views showing the edge of the south polar cap and the pole itself. Included in this sequence would be Hellespontus, which appears to darken immediately after the polar cap starts to recede, and the desert Hellas. Originally we had planned to take only three wide-angle views of the south polar region. After seeing some unusual atmospheric characteristics in this area in the far-encounter pictures taken by *Mariner 6,* we asked the mission controllers to reprogram the CC&S in order to obtain five wide-angle views of the south polar cap.

In making the near-encounter pictures, the wide-angle and narrow-angle cameras operated alternately, with 42 seconds between exposures. The wide-angle camera was equipped with red, green and blue filters, which were located in the four holes of its rotary, behind-the-lens shutter. Pictures were taken in the sequence green, red, green, blue. The narrow-angle camera had a single yellow filter to eliminate any blue scattering haze that might be present in the atmosphere.

Mariner 6 was launched without incident on February 24 of last year and *Mariner 7* 31 days later. *Mariner 7* was able to reach Mars only five days behind *Mariner 6* because its flight path was nearly 20 percent shorter: 316 million kilometers compared with 390 million.

Fifty hours before closest approach the CC&S aboard *Mariner 6* swung the cameras toward Mars and activated a brightness sensor that locked the narrow-angle camera on the planet. Two hours later, and continuing for 20 hours, the camera photographed and recorded on analogue tape 33 views of the planet at intervals of 37 minutes. During this period Mars made five-sixths of a revolution and the range to the target closed from 1,241,000 to 725,000 kilometers. After the tape was played back to Goldstone it was erased and a second series of 17 far-encounter pictures was made at distances ranging from 561,000 to 175,000 kilometers. The tape was again played back and erased. The best of the second series of full-disk views showed features on the surface as small as 25 kilometers across, a factor of at least six better than any photographs taken with earth-based telescopes.

It was immediately apparent from these 50 general views—the first of their kind—that the planet more closely resembled the earth-based photographs of Mars than it did the handmade drawings of most visual observers. With a few notable exceptions the observers drew



MARINERS 6 AND 7 followed the design of previous Mariners, which flew successfully to Mars in 1965 (*Mariner 4*) and to Venus in 1962 (*Mariner 2*) and again in 1967 (*Mariner 5*). Mariners 6 and 7 each weighed about 380 kilograms, of which instruments and supporting equipment accounted for about 115 kilograms. The solar panels extend 19 feet, tip to tip.

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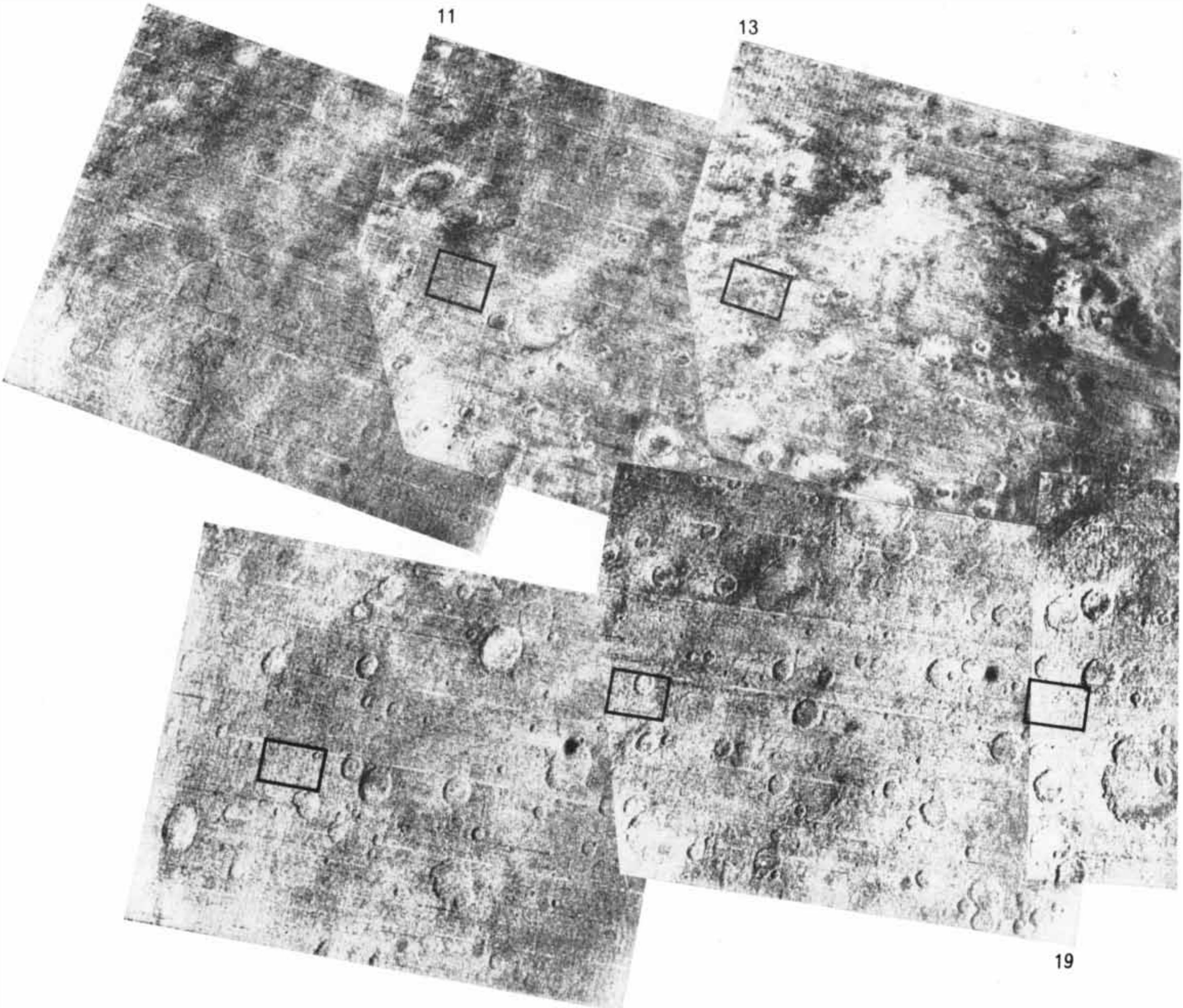

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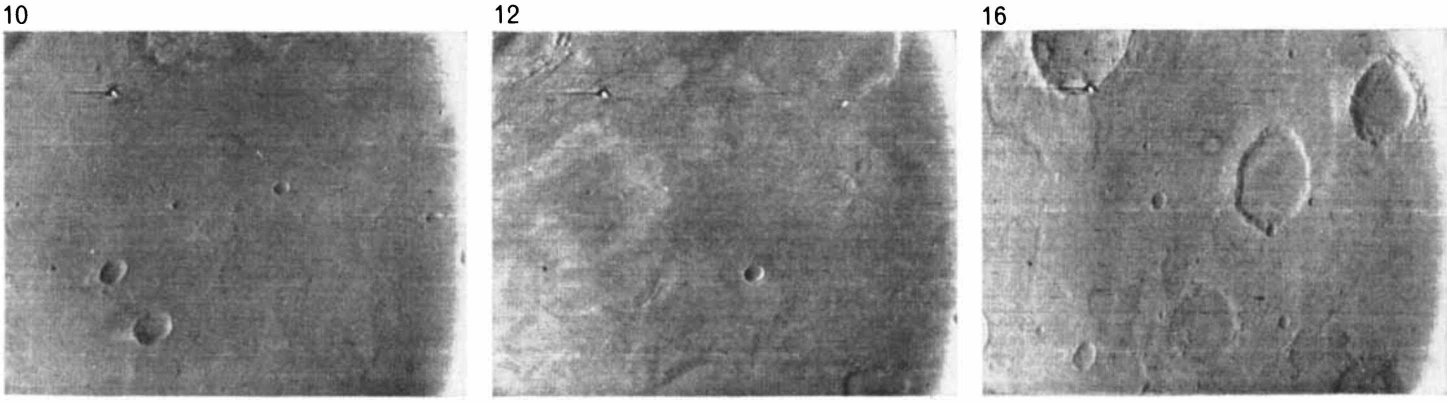
HEAVILY CRATERED TERRAIN is represented in this mosaic of seven wide-angle frames taken at near-encounter by *Mariner 6*. The slant range from the spacecraft to the target varied from 4,920 to 3,522 kilometers. As can be seen from the maps on pages 30 and 31, frames 9, 11 and 13 include Margaritifer Sinus, the "oasis" Oxia Palus and Meridiani Sinus. Frames 17, 19, 21 and 23 sweep across Sabaeus Sinus and Deucalionis Regio. In earth-based photographs, as well as in the far-encounter pictures, most of these features have

10 12 16



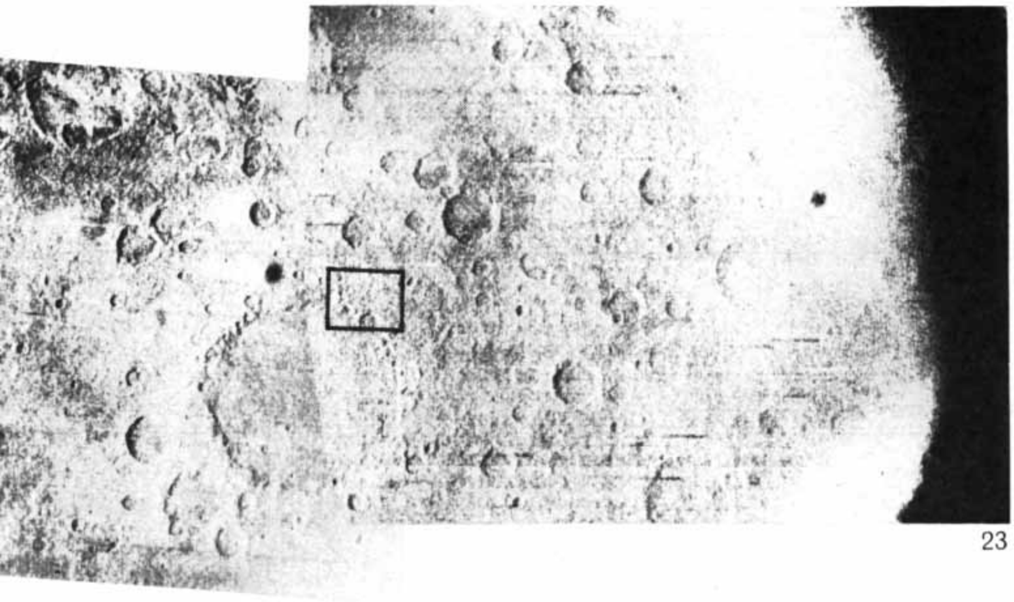
CLOSE-UPS OF CRATERED TERRAIN have a distinctly moon-like appearance. These six narrow-angle views are *Mariner 6* frames 10, 12, 16, 18, 20 and 22, which are nested within the wide-angle frames 11, 13, 17, 19, 21 and 23, shown in the mosaic at top. Narrow-angle and wide-angle pictures taken by the two Mariners contain the same number of scan lines (704), the same number of picture maps with sharp edges between light and dark regions, and in some famous renderings they included a complex network of "canals," frequently in the form of closely spaced parallel lines. These renderings were undoubtedly influenced by the tendency of the eye and brain to link closely spaced features into a continuous pattern.

The uneventful voyage of the two spacecraft was alarmingly interrupted a few hours before *Mariner 6* began its near-encounter assignments. Just at this critical moment, when all attention had to be focused on *Mariner 6, Mariner 7* intermittently went dead for seven hours. At the time it was thought that it might have been hit by a small meteoroid. When full communication was reestablished, it was found from the tracking data that the spacecraft had slowed down perceptibly and was therefore slightly off course. Worse yet, it appeared that as a result of electrical transients the camera platform had rotated by several degrees and no means had been provided for establishing its exact pointing angle except by knowing how much it had moved from its former position.

The day was saved by turning on the wide-angle television camera to locate Mars and thus reestablish the pointing direction of the camera platform. The mission was resumed with added confidence in the operational capabilities of the spacecraft because of this unplanned exercise. *Mariner 7* took three series of far-encounter pictures (93 in all) in three 20-hour periods as it closed on the planet from 1,716,000 to 127,000 kilometers. In reprogramming the CC&S to provide extended coverage of the south polar cap the spacecraft's new trajectory had to be taken into account. The "happening," as we called it, had shifted the point of closest approach 130 kilometers to the southeast of the one originally planned. It now seems that the cause of the disturbance was not the impact of a meteoroid but explosive failure of a battery, which vented enough gas to change the craft's trajectory.

The *Mariner 7* far-encounter pictures added considerably to our confidence in interpreting many large-scale surface features. The pictures show, for example, that much of the mottling seen in dark areas ("maria") as photographed from the earth is in fact associated with large numbers of craters whose diameters range up to several hundred kilometers. The borders of the maria are diffuse in some places and sharp in others. Here and there long dark fingers extend into the surrounding bright areas. Such projections appear in many drawings and earth-based photographs of Mars.

We have searched diligently for things that might correspond to the "canals": the dark, often diffuse, more or less linear features, generally of low contrast, some of which can be recognized even in earth-based photographs. Agathodaemon and Cerberus, identified in the map on pages 30 and 31, are examples. Both are easily recognized in the far-encounter pictures. Other "canals" show up as a



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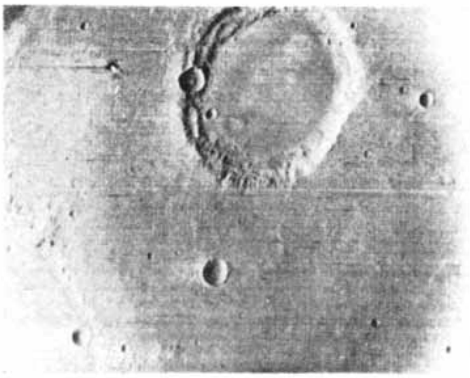
distinctive dark shapes. In all the near-encounter views, however, large-scale contrast was suppressed by the automatic gain control, whereas small-scale contrast was enhanced by roughly a factor of three. The sunset terminator shows up at the right edge of frame 23. The black rectangles identify six narrow-angle, high-resolution frames, which appear below.

18



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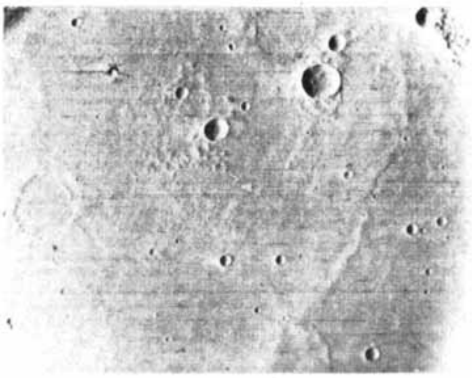

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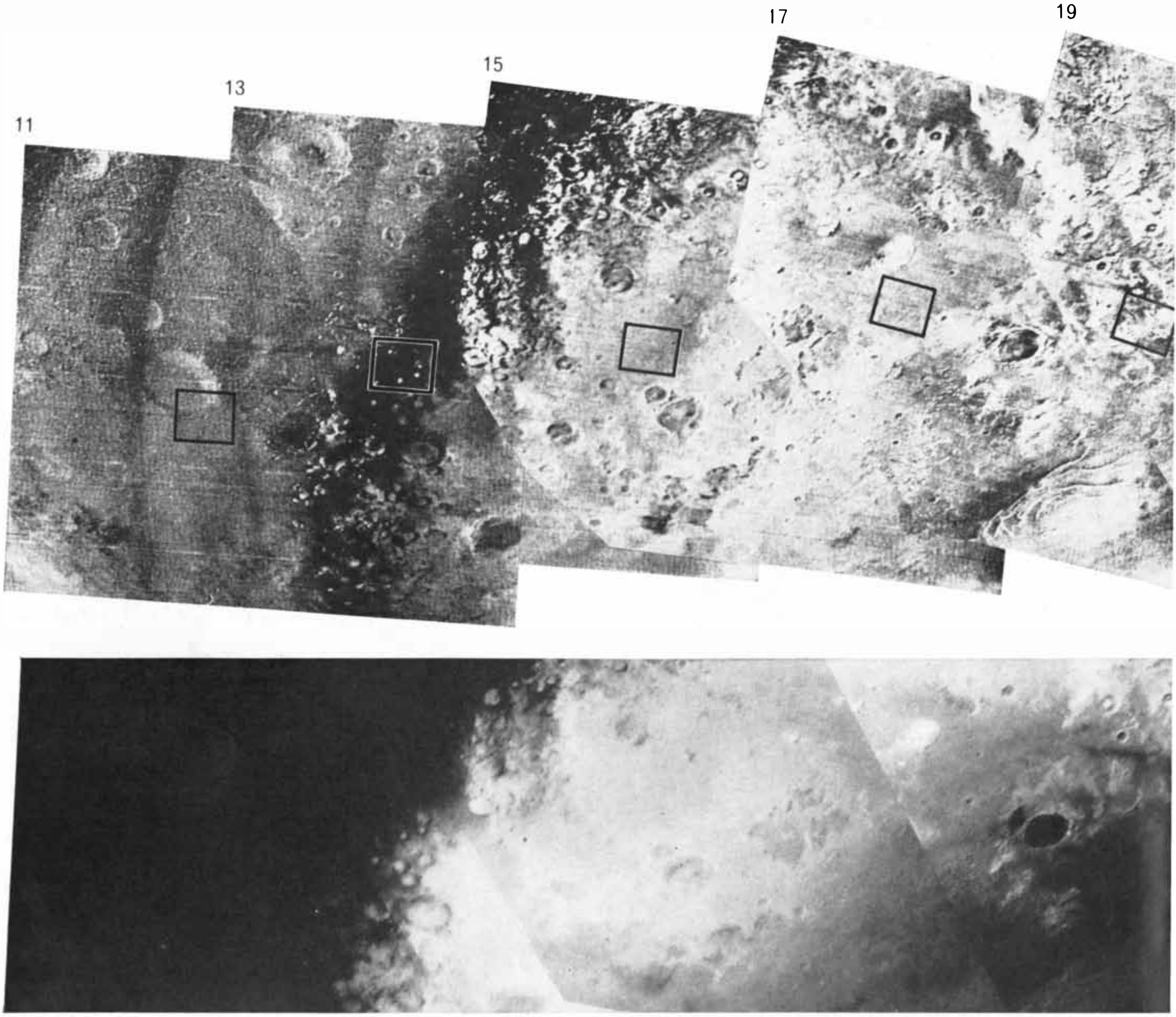
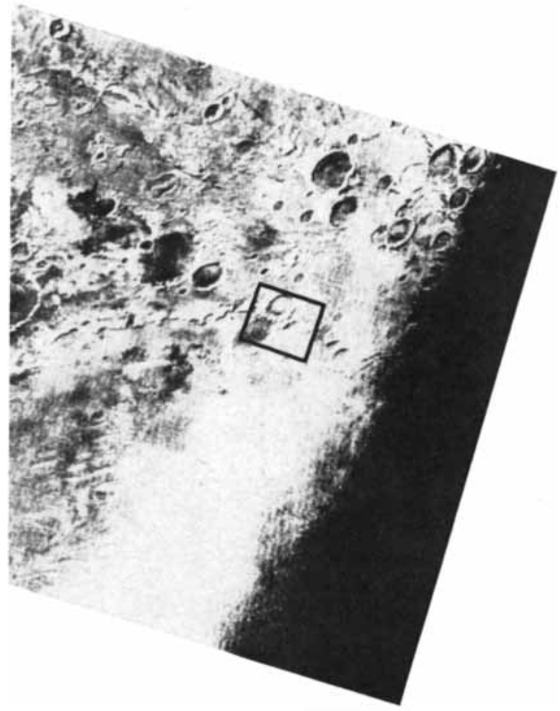
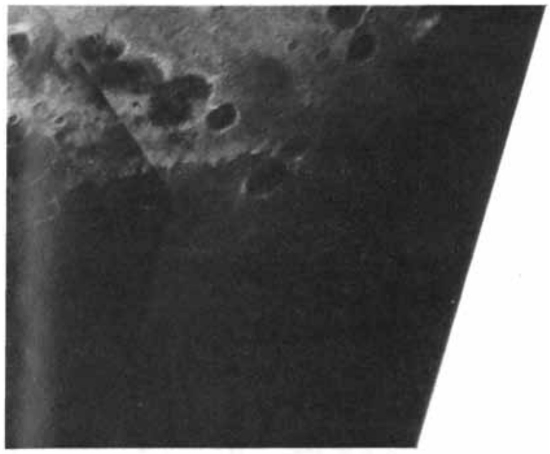
elements per line (945) and the same number of brightness levels per element (256). The narrow-angle lens has 10 times the focal length of the wide-angle lens and therefore magnifies surface features by a factor of 10; the narrow-angle camera reveals craters as small as 300 meters in diameter. The big crater in frame 18 is some 30 kilometers in diameter (*see enlarged view on page 41*).



SOUTH POLAR CAP is included in the mosaic (*top*) of wide-angle frames 11, 13, 15, 17 and 19 taken by *Mariner 7*. A central portion of the same mosaic appears directly above this caption. The mosaics are identical except that in the upper version the contrast reduction imposed by the automatic gain control has been retained; in the lower version the contrast has been restored by computer processing. Thus the lower mosaic indicates the extreme contrast in brightness between the bare Martian surface shown in the left portion of the sequence and the snow-covered polar cap itself. The location of the sunset terminator, however, shows up more clearly

CLOSE-UPS OF POLAR REGION indicate that the Martian snow (probably frozen carbon dioxide) is distributed in and around craters in a curious way. These six narrow-angle pictures are *Mariner 7* frames 10, 12, 14, 16, 18 and 20, which are nested within the wide-angle frames in the mosaics at top. Frame 10 shows a bare surface outside the polar cap. The next frame, No. 12, lies just at





in the upper mosaic (*far right*). The south pole of Mars lies near the series of ridges in the lower-right corner of frame 17. The six narrow-angle frames nested within these wide-angle frames are reproduced below.

sequence of dark patches of varying size and contrast. It seems likely that many "canals" involve the chance alignment of randomly distributed dark patches. Perhaps the most striking single feature to show up vividly in both sets of far-encounter pictures is the bright spot known as Nix Olympica, which turns out to be a crater with a diameter of about 500 kilometers—far larger than any seen on the moon [*see bottom illustration on pages 28 and 29*].

In the pictures taken by *Mariner 4* there was a hint that something in the camera or in the atmosphere of Mars had reduced their clarity. Whatever it was, it does not show up in the pictures taken by Mariners 6 and 7. The new pictures include several examples of thin atmospheric scattering layers, which appear as stratified bands adjacent to the limb of the planet [*see bottom illustration at right on page 29*]. The intensity of the scattering seems to vary with location and time of day. The principal scattering layer is about 10 kilometers thick and may lie from 15 to 25 kilometers above the surface.

A curious characteristic of earth-based photography of Mars is that most photographs taken through a blue filter show greatly reduced contrast between light and dark surface features. On rare occasions, however, the contrast is much enhanced—a phenomenon known as blue-clearing. It has been postulated that a blue scattering layer in the atmosphere is responsible. The new Mariner pictures taken through a blue filter show no evidence of being obscured by a blue haze when compared with overlapping views taken through red and green filters; the surface of the planet is clearly visible in all colors. Nevertheless, pictures of Mars taken at the same time from the earth show a typical amount of obscuration in the blue. Thus we know that Mariners 6 and 7 did not happen to fly by Mars at the time of a rare blue-clearing. The unusual effects seen when Mars is photographed from the earth through a blue filter remain unexplained.

Careful comparison of pictures taken by the two Mariners five days apart, particularly the full-disk pictures, seems to provide clear evidence of atmospheric activity. In the north polar region certain areas that were bright in *Mariner 6* pictures are much subdued in *Mariner 7* views. Inasmuch as the areas remained fixed with respect to the surface, it is possible that the change in brightness involved changes in the amount of surface frost or perhaps changes in persistent clouds associated with surface features. Farther to the south, notably in the vicinity of Tharsis, Candor, Tractus Albus and Nix Olympica, one can see localized areas that begin to brighten in the Martian forenoon and reach a maximum some hours later [*see bottom illustration on pages 28 and 29*].

A primary objective of last year's Mariner mission was to record at close range the principal kinds of Martian surface features seen from the earth. *Mariner 4* showed us that a small strip of the surface, representing about 1 percent of the planet's total area, was heavily cratered. The 58 near-encounter pictures returned by Mariners 6 and 7 cover more than 10 percent of the surface and tell a somewhat different story. In addition to cratered terrain we now see large areas entirely devoid of craters or other topographic features and still a third type of terrain that can best be described as chaotic.

Martian craters are of two general types: either large, flat-bottomed and eroded or small, bowl-shaped and fresh-

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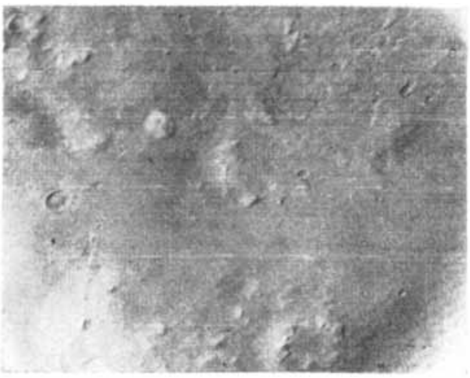

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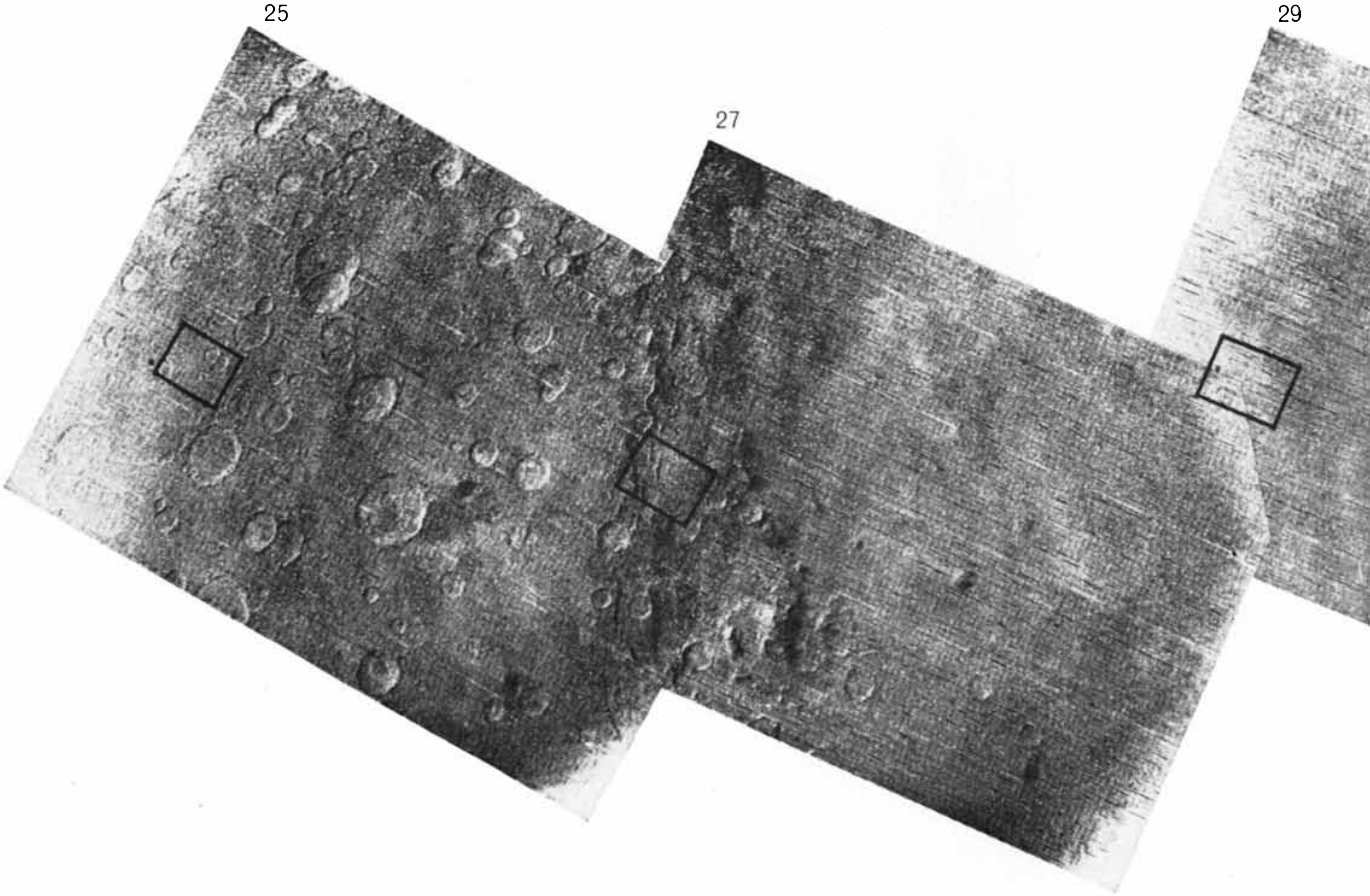
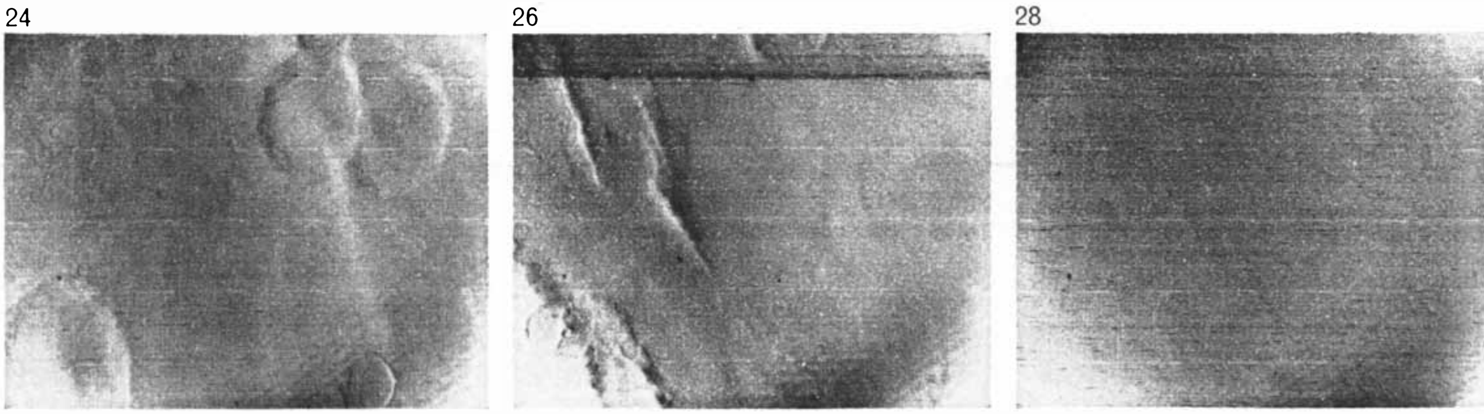
the edge of the polar cap. Although it may not seem so, the sun is shining from the left. The right sides of the craters seem to be in shadow because the snow there has been removed by the sun.

Nevertheless, snow seems to remain on the exposed central peaks within the largest of the four big craters. This suggests a tendency for snow to be carried from lower regions to higher ones.

appearing. The latter resemble the primary-impact craters one sees on the moon. We have not, however, seen anything in our pictures resembling the larger and older craters on the moon that appear to have been flooded with molten rock that subsequently hardened (the crater Plato, for example). Nor have we observed on Mars the rays and swarms of secondary craters that are associated with large impact craters on the moon. Although one can discern aprons of ejecta around some of the Martian craters, they are less extensive than those surrounding lunar craters. The missing features are precisely the kind most easily hidden by erosion or blanketing, which is consistent with the observation that Martian craters are generally shallower and smoother than lunar ones. The planet's thin atmosphere undoubtedly

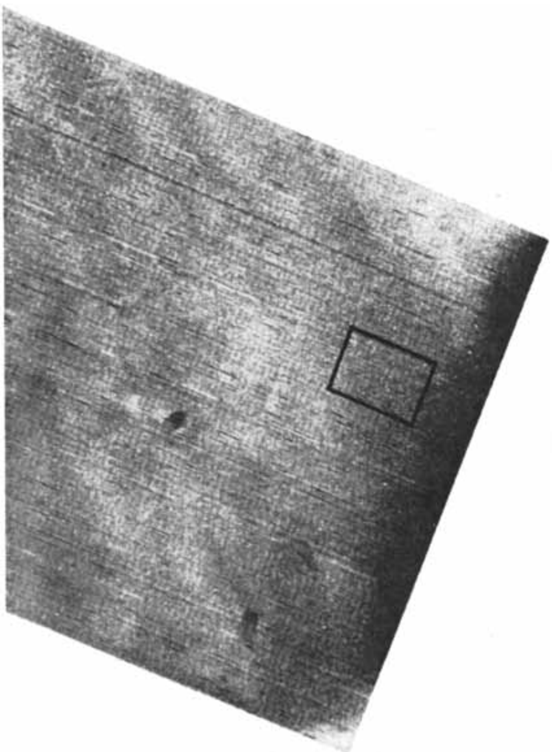


FEATURELESS TERRAIN was revealed in a sequence of three wide-angle views taken by *Mariner 7:* frames 25, 27 and 29. The pictures sweep across Noachis, Hellespontus and into the "desert" Hellas, which sometimes appears more brilliant than the south polar cap in earth-based telescopes. The craters abruptly end at the left of frame 27, and for the next 1,600 kilometers, spanning nearly the entire width of Hellas, scarcely a crater is to be seen. Their absence is a profound mystery. That such a large area could



REMARKABLE SMOOTHNESS OF HELLAS can be seen in the two narrow-angle frames at the right in this set of four, which provide close-ups of the areas within the small rectangles in the mosaic at top. Whatever erosion process accounts for Hellas also seems to have been at work in the areas shown in the first two frames. These four pictures were taken while *Mariner 7* was making its closest apcontributes to these marked differences.

In a few pictures one can see low, irregular ridges similar to those on the lunar maria, and also some faint, shallow linear features. We have not been able to identify with confidence, however, anything resembling the flat-bottomed, graben-like rills (either straight or sinuous) that are seen on the moon. Moreover, to our surprise the latest Mariner pictures do not seem to include a single example of the kind of straight cracklike line that cuts cleanly across one of the craters photographed by *Mariner 4*. In photographing an area 10 times larger than the area covered by *Mariner 4* we expected several such lines to turn up. Finally, we can say that we do not see a sign anywhere of earthlike tectonic forms that might be associated with mountain-building, the formation of island arcs or deformations caused by compression.



have remained uncratered for aeons is altogether improbable. The amazing smoothness of Hellas is shown in two of the high-resolution pictures (frames 28 and 30) below.

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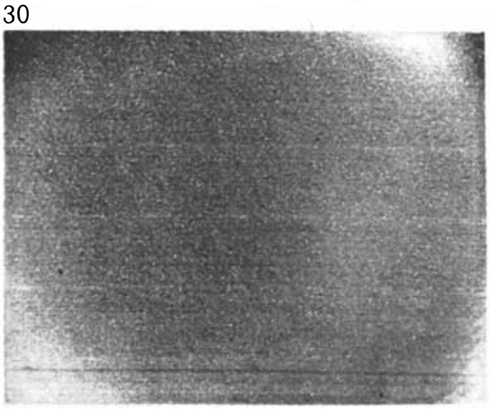


proach to the planet (3,620 kilometers), hence they exhibit the highest resolution of which its narrow-angle camera was capable.

In a sense the early Martianologists who called Hellas a desert were right. The entire circular area, roughly 1,600 kilometers across, seems to be completely free of craters or any other topographic form down to the resolution limit of our cameras (300 meters). No area of comparable size and smoothness is found on the moon. Its nearest terrestrial counterpart would be either one of the great deserts or one of the great plains.

Wide-angle frames 25, 27, 29 and 31 taken by *Mariner 7*, and the even-numbered narrow-angle frames in the same sequence, begin in the dark area known as Hellespontus and cross Hellas [*see illustrations on these two pages*]. Hellespontus is heavily cratered. There is then a ridged transitional zone ranging in width from about 130 to 350 kilometers that is also well cratered and seems to slope gently down to Hellas. There, within the first 200 kilometers, the craters fade out.

One must assume that craters once existed over this entire area and that they were obliterated by some kind of erosion or blanketing process that is still operating—or that was operating almost up to the present. But what kind of process was it? The effect must involve either the nature of the local material or the response to local stress patterns. One can hardly imagine winds so localized that they would produce a dust cover over Hellas (and perhaps a few similar places not included in our pictures) but would leave craters elsewhere comparatively untouched.

A very tentative suggestion, which we call the pink-popcorn hypothesis, may meet the requirement. Perhaps the huge asteroidal impact that presumably created Hellas generated enough heat to melt the rock and release volatile constituents as gas, thereby creating large amounts of light pumice or ash in the form of particles of popcorn size, light enough to be driven by the Martian winds but too heavy to be carried outside the area. These hypothetical particles might also be pink to agree with the fact that Hellas often has a strong pinkish cast.

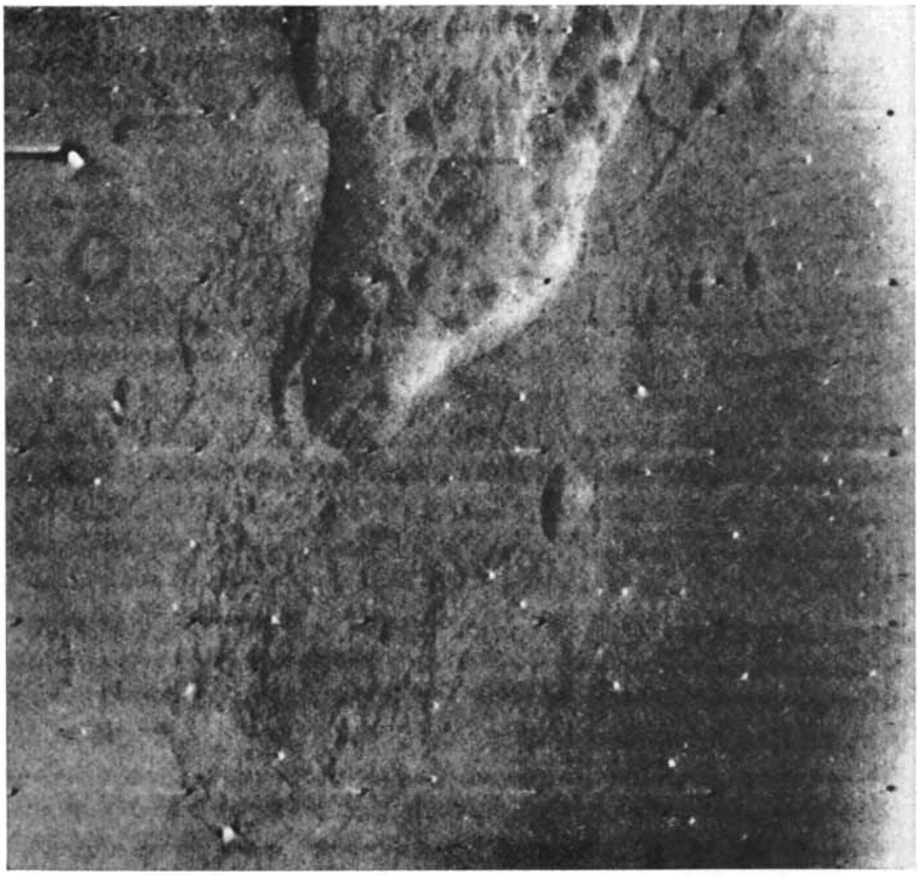
The third type of terrain, which we have termed chaotic, turned up near the middle of the sequence of pictures made by *Mariner 6* [*see illustrations on next page*]. Geologists use "chaotic" to describe a surface consisting of short, jumbled ridges and valleys. We infer from the narrow-angle pictures that such terrain may cover as much as a million square kilometers, or approximately half of the area included in a sequence of wide-angle views running essentially parallel to and south of the Martian equator. Not only is this terrain crisscrossed by short ridges but also it is practically free of craters.

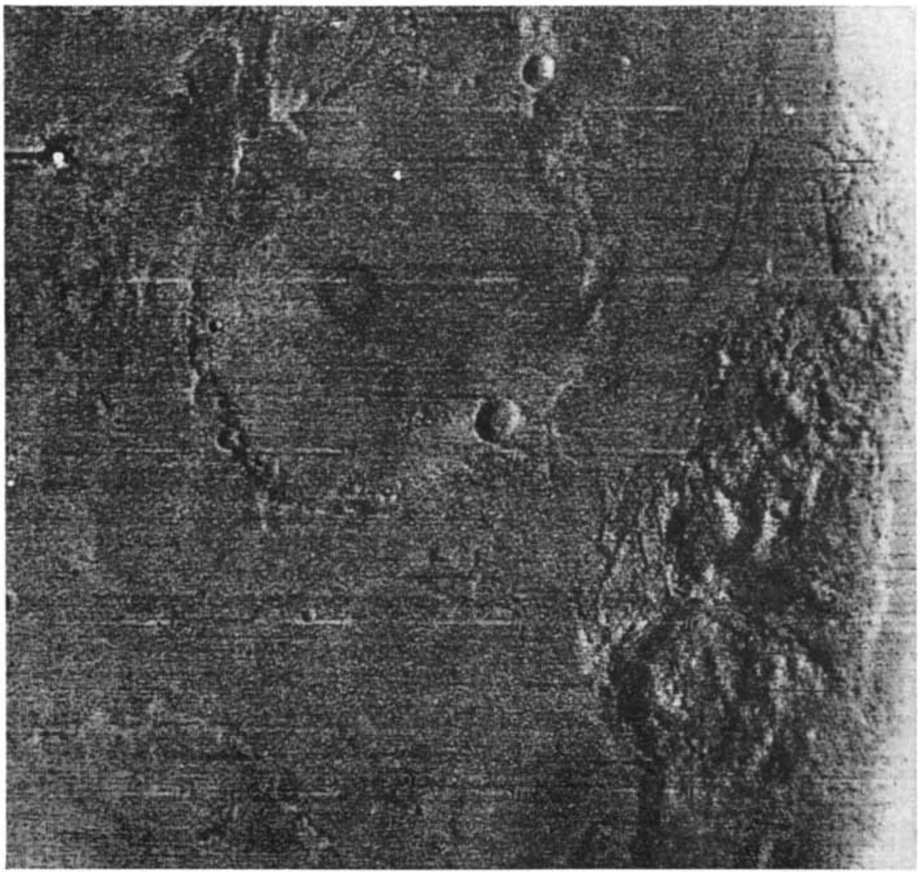
Chaotic terrain is different in its setting and pattern from those lunar regions where crater ejecta provide a somewhat similar appearance. One has the impression that much of the area has collapsed as a result of the withdrawal of some underlying substance, conceivably a thick layer of permafrost. Another possibility is the withdrawal of magma or some other disturbance close to the surface associated with volcanism. The apparent absence, however, of other characteristic volcanic structures on the surface would seem to rule out this possibility.

The photographs of the south polar cap were not expected to settle the debate between those who believe the caps consist of ordinary snow or ice and those who believe they are composed primarily of frozen carbon dioxide (dry ice). Those of us involved in the picture-taking experiment believe that most of the plausible inferences one can draw from the photographs favor the frozen carbon dioxide hypothesis.

The observed brightness of the polar cap could be produced by a thin coating of any white, powdery material. On the other hand, certain kinds of topographic relief present in the narrow-angle polar-cap pictures—but not seen in narrow-angle frames outside the polar cap—suggest that the snow (whatever it is) has been piled into drifts several meters deep. At the same time the structure of the edge of the polar cap suggests that evaporation caused by solar heating is more influential than local winds.

Assuming that the evaporation rate is principally governed by midday heating, one can estimate that the net daily loss is about a gram per square centimeter





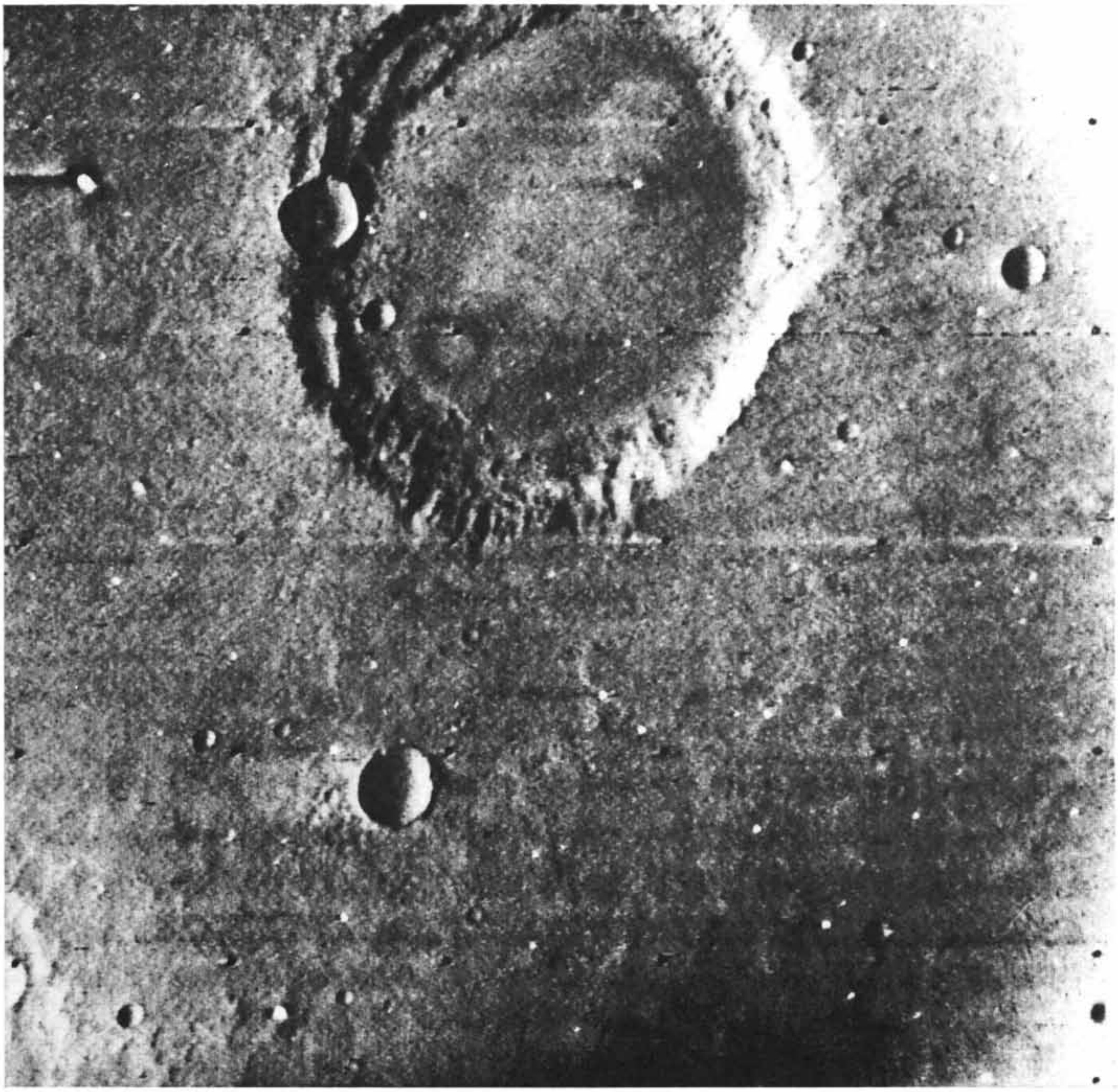
CHAOTIC TERRAIN, as remarkable and unexpected as the featureless terrain of Hellas, was found in *Mariner 6* pictures covering a strip some 2,000 kilometers long just south of the Martian equator, in the region of Aurorae Sinus. Details of chaotic terrain can be examined in these two narrow-angle views, frame 14 (*top*) and frame 8 (*bottom*). The area shown in frame 14 is approximately 235 kilometers long and 100 kilometers wide. The area in frame 8 is 126 by 97 kilometers. The chaotically jumbled ridges in these pictures have no counterpart on the moon and there seems to be nothing quite like them on the earth.

for solid carbon dioxide compared with only a tenth that amount for water ice. Since the complete evaporation of the cap at a given latitude requires many days, one can multiply these rates by the number of available spring and summer days (at least 100, say) and obtain an estimate for the minimum total thickness of the cap. The result is tens of grams per square centimeter for frozen carbon dioxide compared with several grams for water ice.

One can now ask if the Martian atmosphere, which is composed chiefly of carbon dioxide with only a tiny amount of water, could plausibly transport one or the other of these two materials from one pole to the other between summer and winter. One must conclude that even the apparently small amount of water indicated by the evaporation calculations would vastly overtax the ability of the atmosphere to hold it, much less to transport it from pole to pole. For carbon dioxide, however, pole-to-pole transportation is not necessary because the atmosphere is already full of that gas; the atmosphere simply shifts over a little. Thus we conclude that the snows of Mars consist largely, if not entirely, of frozen carbon dioxide.

One puzzle presented by the polar-cap pictures is that many of the craters have dark floors and bright rims. This is what one would expect on the earth, where snow is more likely to fall and remain at higher elevations. On Mars, however, precipitation should occur mostly at lower elevations, where the atmospheric pressure is greater. Hence we are prompted to look for mechanisms capable of transporting snow from lower areas to higher ones. Although winds are a conceivable transporting mechanism for solid carbon dioxide, it is more likely that carbon dioxide may evaporate from the crater floors and reprecipitate at higher elevations, where it is colder. Another possibility is that some of the crater floors look dark because they are covered with smooth, frozen sheets of carbon dioxide, which, like a freshly frozen lake on the earth, can look distinctly black.

To no one's surprise, the pictures taken by Mariners 6 and 7 provide no direct evidence for the existence of life on Mars. If life existed at all, it would most likely be unicellular and therefore quite invisible. One may still ask: Does the existence of life seem possible? We must conclude from the Mariner pictures that the evident scarcity of water is the most serious limiting factor for the existence of life as we know it. The



MOONLIKE ASPECT OF MARS is represented in this close-up (frame 18) taken by *Mariner 6*. To appreciate the detail captured by the narrow-angle cameras this picture should be compared with the smaller version of the same frame at the bottom of page 35. The large, flat-bottomed crater is typical of craters thought to be old. Craters thought to be younger have rounded bottoms. These narrow-angle frames show craters a third the size of the smallest that can be seen on the moon with earth-based telescopes.

abundance of craters and the absence of earthlike tectonic structures argue further that Mars has not had oceans of terrestrial size for a very long time, and that possibly it never had any. Still, no one can say how big an ocean is required for life to start or how long the ocean must last. If Mars is to be a testing ground for our notions about the origin of life, we must avoid using these same notions to conclude in advance that Mars is lifeless.

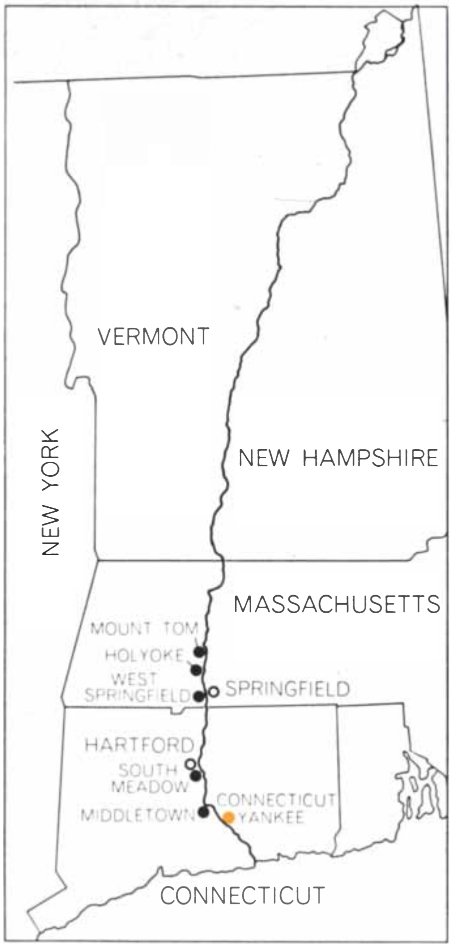
I have not discussed some of the most important results that are expected to come out of the Mariner pictures: those that flow from *quantitative* measures of the brightness and geometric relationships of the physiographic features in the pictures. The picture-reconstruction process that will eventually provide such data is still under way, and most of the applications will require considerable time and great care for their successful completion. The eventual results will be a much improved knowledge of the size and shape of the planet; a planet-wide map referred to a network of fixed topographic control points; a more precisely defined direction of the rotation axis; quantitative measures of topographic slopes and deviation differences; more accurately known colors and reflectivities of surface materials, and better knowledge of the scattering and absorption effects of the Martian atmosphere. The Mariner 6 and 7 pictures will long stand as a landmark in our understanding of the past history and present condition of our tantalizing neighbor in space.

The Calefaction of a River

Calefaction means warming, and the industrial warming of rivers and other waters is a cause of concern. A study of the warming of the lower Connecticut River, however, reveals no drastic effects

by Daniel Merriman

In recent years there has been much concern that the waste heat being discharged into rivers, lakes and seas by industrial activities is having a catastrophic effect on the populations of fishes and other organisms that live in these waters. This concern is eminently justified; clearly there is an upper limit to the amount of heat that can be introduced into such waters without harmful results. It is now possible, however, to view the biological effects of heating with some degree of perspective. A long-term study in which I am participating, for example, has shown that industrial heating in a major river of the northeastern U.S. has so far had no drastic biological consequences. The levels of heating we are encountering may even turn out to have beneficial long-range results. In such circumstances the term "thermal pollution," which is currently in wide use, is misleading because it suggests that any amount of heating is harmful. A better word is "calefaction," which is simply defined as the state of being warmed.



CONNECTICUT RIVER divides Vermont from New Hampshire, crosses Massachusetts and Connecticut and then empties into Long Island Sound. The Connecticut Yankee Atomic Power Company's generating plant (*color*) is one of six power plants on the Connecticut that use its water for cooling.

The river being investigated in our study is the Connecticut, which flows generally southward some 400 miles from its source in northeastern New Hampshire, collecting the runoff from a good part of central New England before emptying into the eastern end of Long Island Sound. The study is focused on a five-mile stretch of the river above and below Haddam Neck, a site 15 miles from the mouth of the river where the Connecticut Yankee Atomic Power Company has built a nuclear power plant. The steam condensers of this plant (not the nuclear reactor) are cooled by water from the river.

The study has been under way since 1965, and it will continue at least until the end of 1972. It was undertaken at the expense of the power company as one of the conditions set by Connecticut state authorities for approval of the Haddam Neck plant's construction. Our investigations started about 30 months before the plant began to return to the river water that was 20 degrees Fahrenheit warmer than when it was withdrawn. As a result we can now begin to compare conditions then with conditions today, at the end of a roughly equal span of plant operation.

The effluent from the Haddam Neck plant is now discharged at an average rate of 828 cubic feet per second (almost 372,000 gallons per minute). At this point the Connecticut is a tidal river with a maximum depth of 30 feet at low tide and a maximum width of more than 2,000 feet. Flood tides in Long Island Sound push water of diminishing salinity upstream as far as East Haddam, a few miles south of the plant, and raise the level of the river as far north as Hartford, 45 miles inland. The difference between high and low tide in the vicinity of the plant is about 2½ feet.

Seasonal variations in river temperature range from the winter low of freezing to a summer high that seldom exceeds 86 degrees F. The flow of water in the river is at its peak from March through May, as the river is fed the runoff from melted winter snow. In summer the river dwindles, even though the average monthly precipitation is about the same throughout the year. (Monthly precipitation at Hartford, for example, averaged between three and four inches from 1900 through 1939.) The summer shrinkage of the river is the result of evaporation and of the uptake of rainfall by plants during the growing season. Over the past five decades the average daily rate of flow of the Connecticut, as recorded by the U.S. Geological Survey, has been about 16,000 cubic feet per second. During this period the maximum flow was 282,000 cubic feet per second (recorded on March 20, 1936); the minimum was 968 cubic feet per second (recorded on October 20, 1963), a scant 140 cubic feet more than is now diverted to the Haddam Neck plant. These measurements were made well above the zone of tidal influence. In the vicinity of the

NUCLEAR POWER PLANT occupies the light-colored area near the center of this aerial photograph, at the head of a canal that was dug at Haddam Neck to carry warmed river water back to the Connecticut after it has been used to cool the plant's condensers.

power plant the daily average tidal flow has a minimum rate of 15,000 cubic feet per second.

The calefaction of U.S. rivers, lakes and coasts is certain to increase as the power industry meets the rising national demand for electricity. The generating capacity of power plants in the continental U.S. (Alaska excluded) is estimated by the Edison Electric Institute to have been 315,000 megawatts at the end of 1969 and is expected to reach 576,000 megawatts by 1980. Nearly 1.5 billion megawatt-hours of electric power was produced in 1969; the Edison Institute forecasts an output close to three billion megawatt-hours in 1980 and between six and 10 billion megawatt-hours by the year 2000.

The average daily natural runoff of water in the continental U.S. (again excluding Alaska) is about 1.2 trillion gallons. We use perhaps 10 percent of this amount, or 120 billion gallons, for cooling the condensers of steam-turbine power plants. These plants, whether fired with fossil fuels or nuclear fuels, are rapidly growing in number. It is possible to forecast a daily requirement of more than 200 billion gallons of cooling water by 1980 and of 600 billion gallons, or 50 percent of all the available water, by the year 2000. If calefaction is ecologically harmful, quite a lot of harm lies just over the horizon.

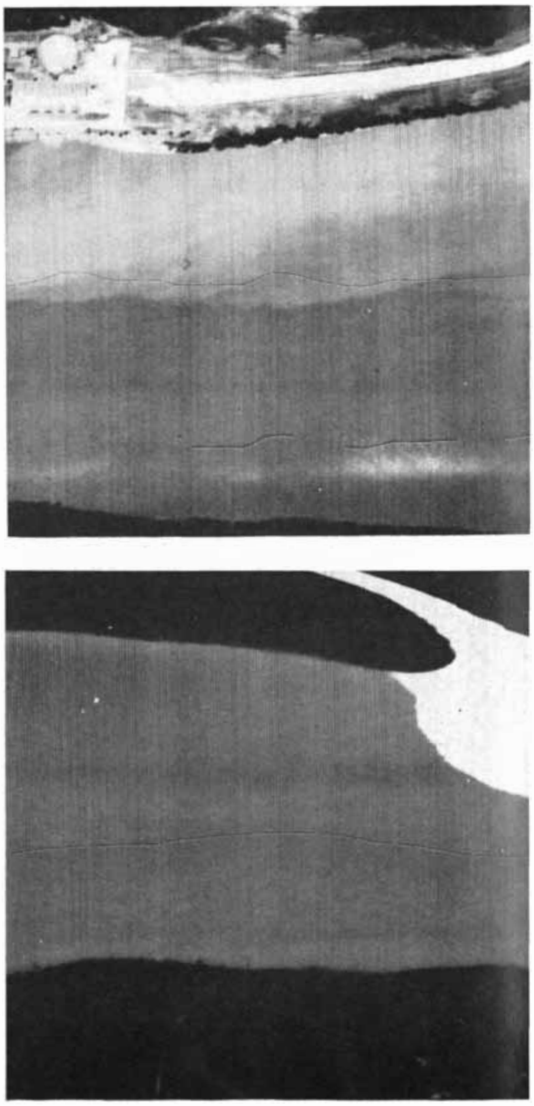
Haddam Neck is a low-lying tongue of land on the east bank of the river just above the point where a tributary, the Salmon River, joins the Connecticut [*see illustration on preceding page*]. The Connecticut Yankee Atomic Power Company completed acquisition of a 500-acre tract at Haddam Neck in August, 1963. Hearings on the issuance of a final construction permit were held before the Connecticut Water Resources Commission in the summer and fall of 1964. Earlier the U.S. Atomic Energy Commission had granted the various approvals that lie within its jurisdiction, and the U.S. Army Corps of Engineers, which oversees the navigability of the river, authorized the dredging necessary to allow construction of a water-intake area upstream of the plant and an effluent-discharge area downstream.

The Water Resources Commission hearings afforded an illuminating example of the extent to which public concern about environmental degradation can be quite innocently misdirected. After the first hearing, in July, 1964, I received a number of telephone calls from people who were genuinely alarmed by the prospect of a fission-powered generating plant being built in their vicinity. No amount of reassurance I could offer them on the improbability of radioactive pollution of the environment lessened their concern about a neighboring atomic plant. Not until the second hearing, in September, did attention become focused more appropriately on the effect on the ecology of the river of the heated effluent from the plant. Thereafter the fear of radioactive pollution began to abate. I suppose, however, there will always be those who will point an accusing finger at the plant when any unusual natural phenomenon occurs on the lower Connecticut, in spite of the fact that radiological monitoring of the river's water, its sediments and its plant and animal life has revealed nothing but the normal background radioactivity in the 30-odd months since the plant began operation.

On October 21, 1964, the Water Resources Commission approved the planned intake of river water for cooling purposes and the return of the warmed water to the stream on the condition (among others) that the power company finance a thorough study of the river environment throughout the start-up and early operating stages of the plant and for a period of five years after the level of full operation was reached. A further condition of approval was that, should the study reveal adverse effects on the river attributable to calefaction or other aspects of plant operation, it would be the company's responsibility to take remedial action.

The Connecticut River Study was set up in January, 1965, with myself as director and Lyle M. Thorpe, recently retired as director of the State Board of Fisheries and Game, as associate director. We established our base at the Essex Marine Laboratory, a nonprofit private institution, and began a series of ecological observations that extended from the mouth of the Connecticut to the dam across the river at Enfield, some 60 miles upstream near the Massachusetts border. Our staff has varied seasonally from 10 to 15, including technical and part-time help. From its inception the study has had the benefit of counsel from a five-man advisory committee representing several scientific disciplines; this committee has met with us at least twice a year. We have made progress reports to the Water Resources Commission at six-month intervals, beginning in July, 1965. The cost of our study to the power company for the five years through 1969 has been approximately $750,000. Other contributions of company personnel to the study have been substantial. We have also had support from the U.S. Bureau of Commercial Fisheries and the Connecticut State Board of Fisheries and Game, and we have had the help of faculty members of the University of Connecticut, both at the Storrs campus and at the university's marine research laboratory in Noank. In addition specialists at the British Museum (Natural History), the Smithsonian Institution and the Museum of Comparative Zoology at Harvard University have identified various invertebrate specimens for us. Other specimens were identified by H. B. Herrington of Westbrook, Ont., a student of freshwater mollusks.

The river water that is used to cool the steam condenser at the Haddam Neck plant leaves the plant at a temperature 22.4 degrees F. above the temperature of the river water. It then flows through a mile-long canal on the east bank, where heat exchange with the atmosphere serves to reduce its tempera-



DISCHARGE OF WARM WATER from the Haddam Neck canal is shown at different tidal stages in these two aerial ther-

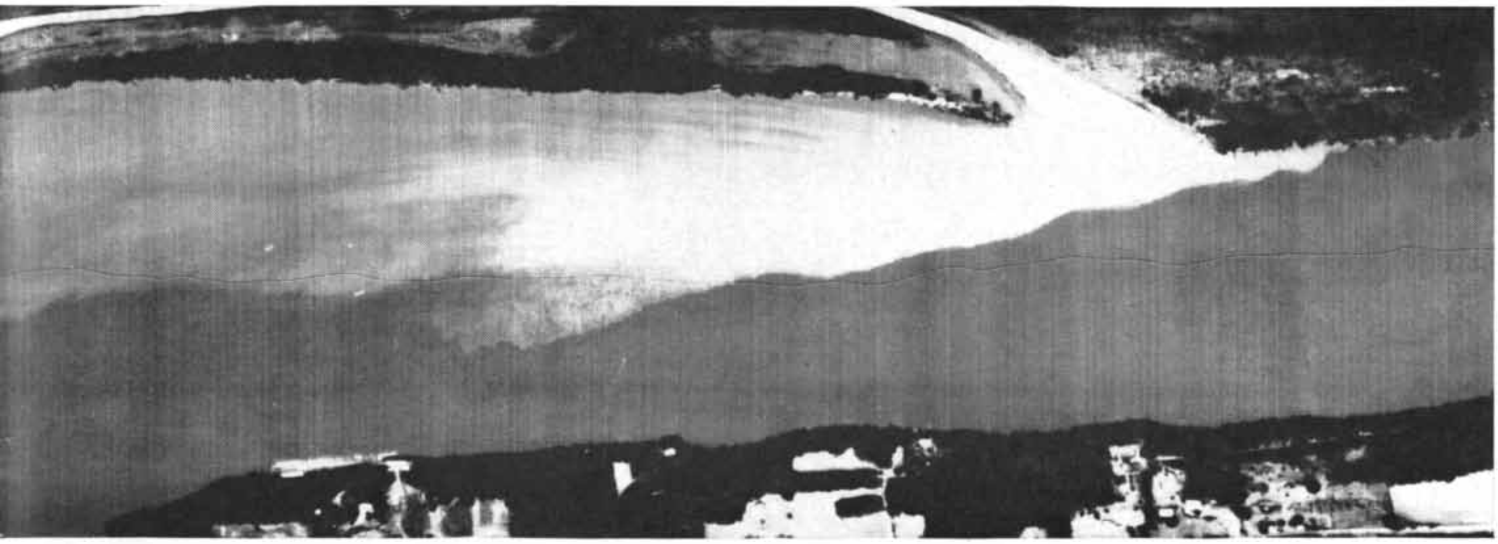
ture to an extent dependent on the seasonal temperature of the air. The canal has a fan-shaped mouth that lowers the velocity of discharge into the river and also tends to keep the effluent near the surface of the river water. Depending on the tide, the plume of warm water moves either upstream or down. On the ebb tide the plume is indistinguishable from other river water with respect to the temperature of the first three feet of water below the surface by the time it reaches the East Haddam bridge, some three miles downstream. On the flood tide the plume becomes indistinguishable a little above Haddam Island, or two miles upstream from the plant [*see illustration on next two pages*].

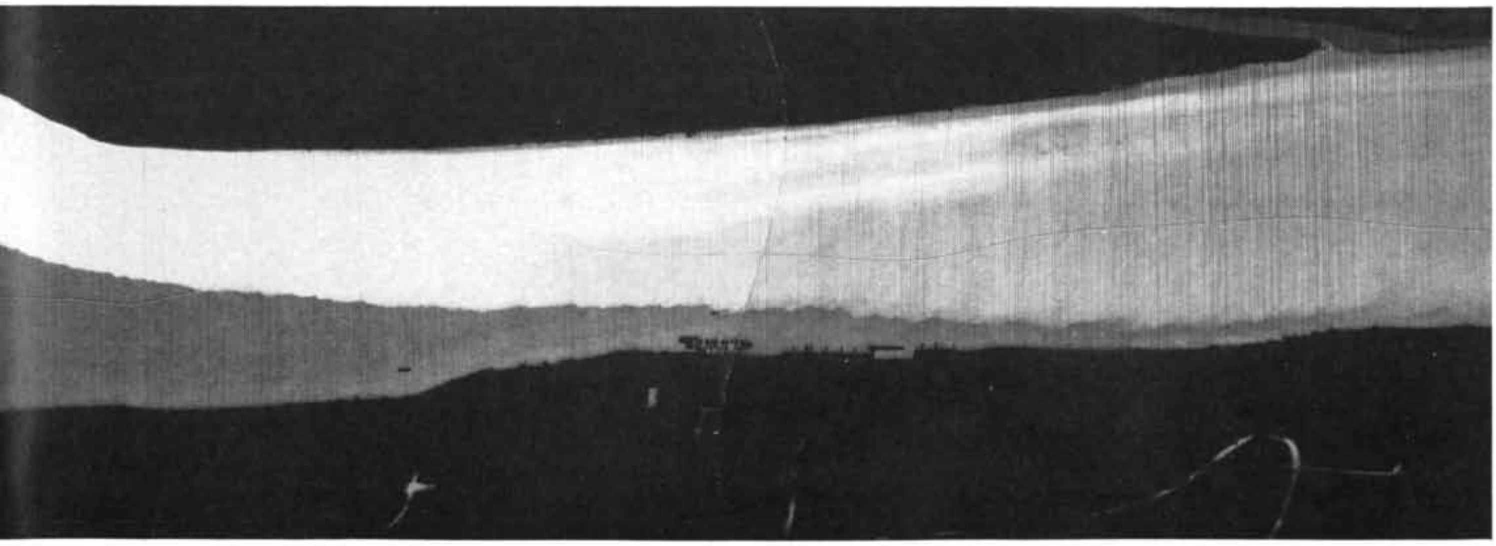
The shape of the warm plume, both at the surface and at certain subsurface levels, varies widely in response to variations in river flow between one high-water stage and the next, and also in response to differing weather conditions and seasonal circumstances. The warm water not uncommonly occupies the entire surface of the river in the vicinity of the canal mouth, so that the effluent reaches the west bank of the river. This does not, however, produce a "thermal block" in the river, because the warm effluent does not extend to the bottom of the river, which here lies some 15 to 30 feet below the surface.

Early in our study we decided to establish five monitoring stations along the river to record continuously such data as rate of flow, temperature of surface and subsurface water, variation in electrical conductivity (which reflects the relative salinity of the water), oxygen content of the water and so forth. Two of the stations were located well outside the area that was to be influenced by the effluent when the plant began to operate; these served as controls. A third station was set up on the west bank of the river opposite the plant and the other two were situated somewhat upstream and downstream respectively from the plant. The stations were designed and their construction was supervised by William A. Boyd, director of the Essex Marine Laboratory; all five were in full operation by the end of June, 1966.

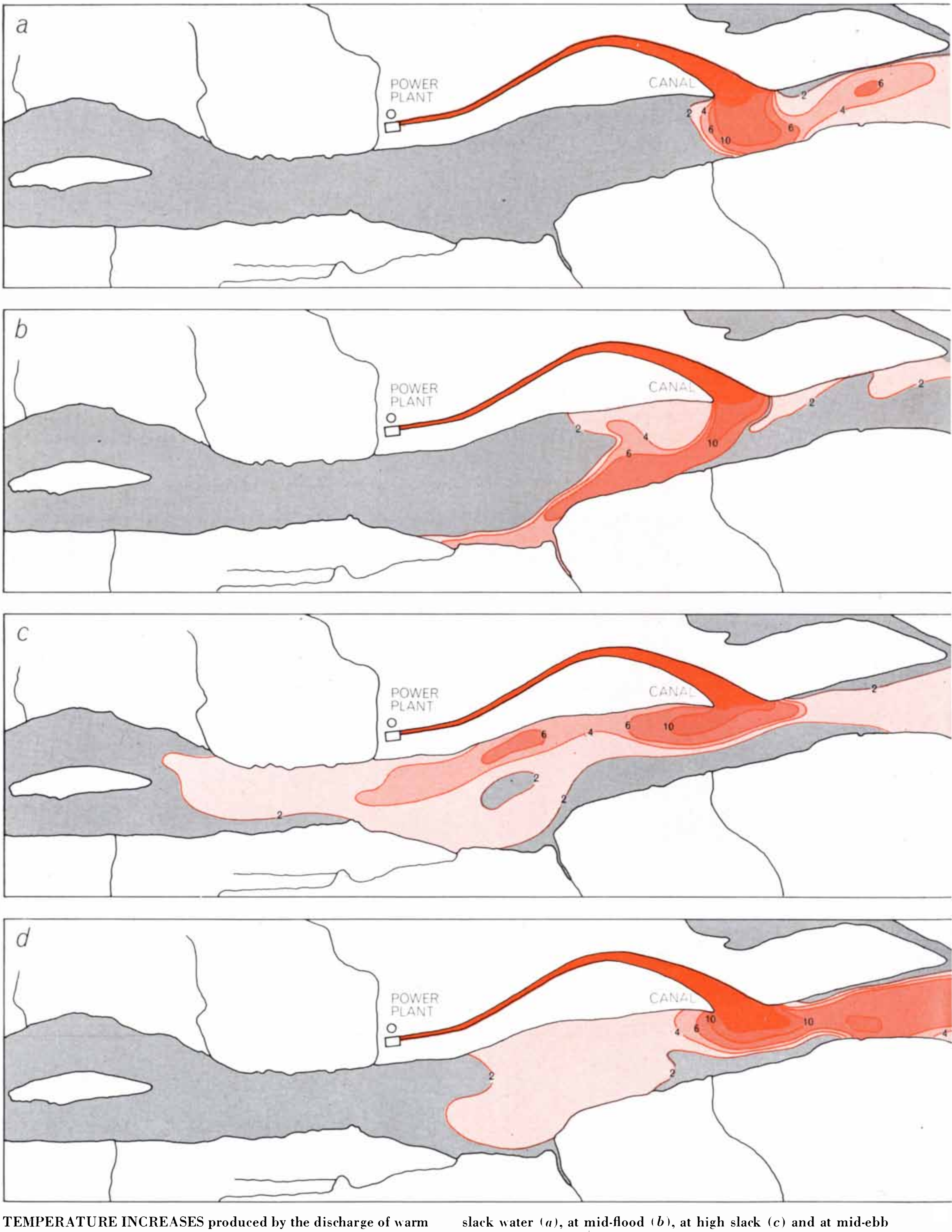
In the period before plant operations began we established a number of facts about this section of the Connecticut. Variations in water conductivity, for example, showed that water from Long Island Sound made its way above the East Haddam bridge only at times when high tides coincided with a low level of river flow.

In October, 1967, the Haddam Neck plant completed start-up procedures and began to generate power at less than full capacity. The instruments at our monitoring stations promptly recorded

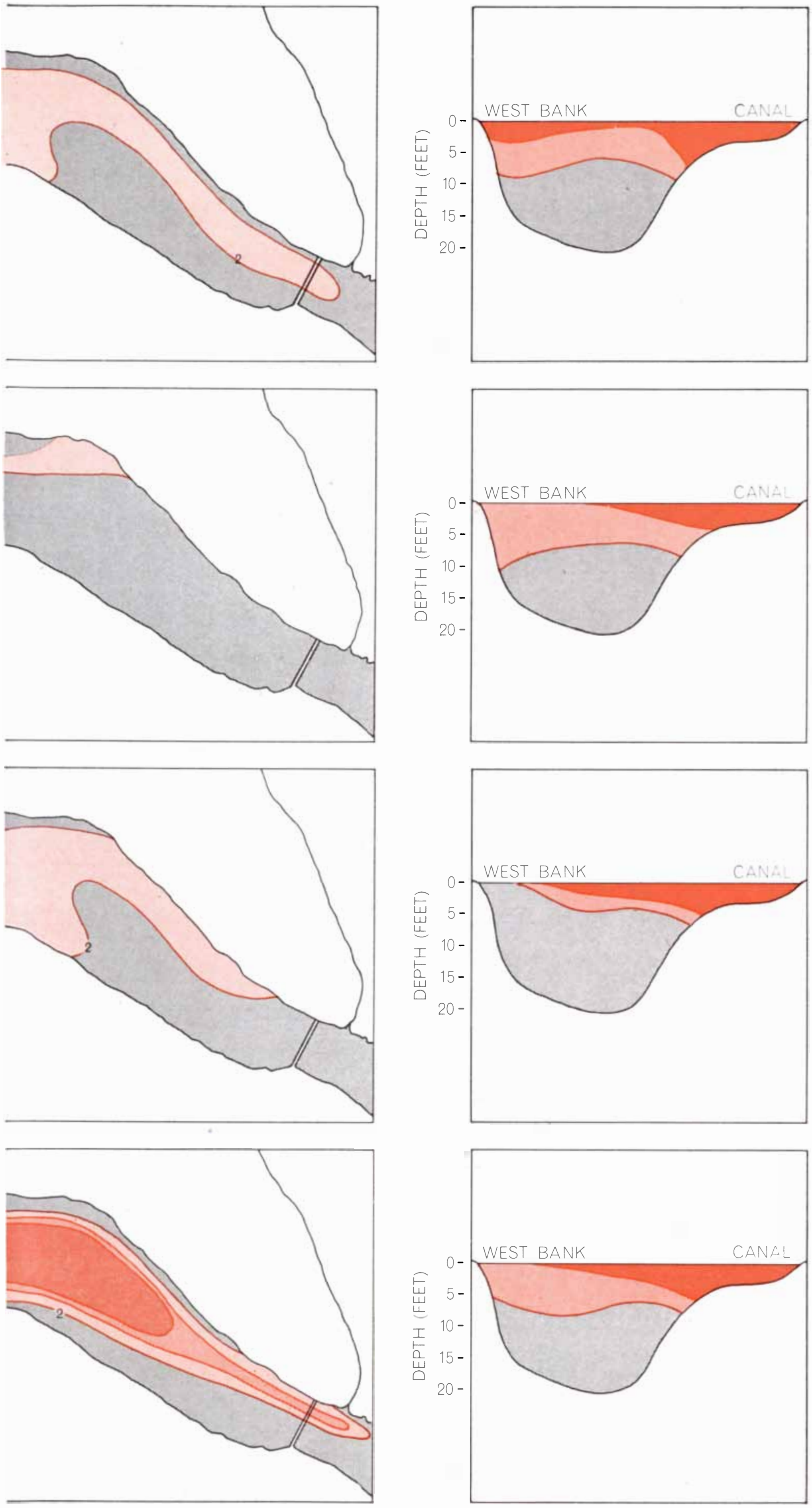




mal-scanning images, which record the infrared radiation from surface areas as various shades of gray. As the tide rises (*top*) the warm water is carried upstream; as it ebbs (*bottom*) the movement is reversed. The warming effect of the plant effluent cannot be detected beyond two miles upstream and 2.2 miles downstream. The scans were made for the U.S. Geological Survey by HRB-Singer, Inc.



TEMPERATURE INCREASES produced by the discharge of warm water from the Haddam Neck canal were measured in September, 1968, when the Connecticut was near its seasonal low and the water temperature was near its seasonal high. Readings were made at low slack water (*a*), at mid-flood (*b*), at high slack (*c*) and at mid-ebb (*d*). Surface temperatures are shown in the diagrams above, subsurface temperatures at far right. Shades of color indicate water warmer than normal river water; numbers indicate temperature



above normal in degrees Fahrenheit. In the subsurface diagrams light color indicates water up to five degrees F. warmer than normal, dark color more than five degrees. No "thermal block" was formed at Haddam Neck, although warm water often covered the surface of the river. The channel is more than 20 feet deep; the water below 12 feet was not heated.

the addition of the warm effluent to the river. The station opposite the plant, for example, logged increases in temperature that persisted from an hour to an hour and a half before the plume was carried away from the west bank by the effect of rising or falling tide. On several occasions the temperature of the surface water near the west bank was raised by 10 degrees F. above the ambient temperature of the river, and at a depth of four feet the temperature rose four degrees. Similar (although smaller) effects, together with a reduction in oxygen content, were recorded at the stations two miles upstream and 1.8 miles downstream from the discharge canal. It was apparent by October, 1968, 15 months after start-up, that the plume of warm water was quite sharply defined in terms of temperature: it streamed downriver during ebb tide, spread across the river during the reversal from ebb to flood, streamed upriver during flood tide and then spread across the river once more at the reversal from flood to ebb.

At this stage the power company ordered an independent survey of variations in river temperature to determine how calefaction under actual operating conditions compared with the predictions made by the engineering firm of Stone & Webster before construction. Temperatures were taken at mid-ebb, at low slack water, at mid-flood and at high slack water; while the survey was in progress the flow in the Connecticut was near its seasonal low and the water temperature was near its seasonal high.

The survey confirmed the readings made at our own stations and provided additional information. When the warm plume reached the west bank, for example, the heating of the subsurface water did not exceed two degrees F. at a depth of 12 feet. The survey set the upstream limit of the plume at two miles above the canal (which agreed with our study) and the downstream limit at 2.2 miles (several hundred yards below our monitoring station in that area). Last summer we conducted plume studies of a rather more complex design than the company's 1968 study, and we hope to conduct as many as 10 more such studies this year.

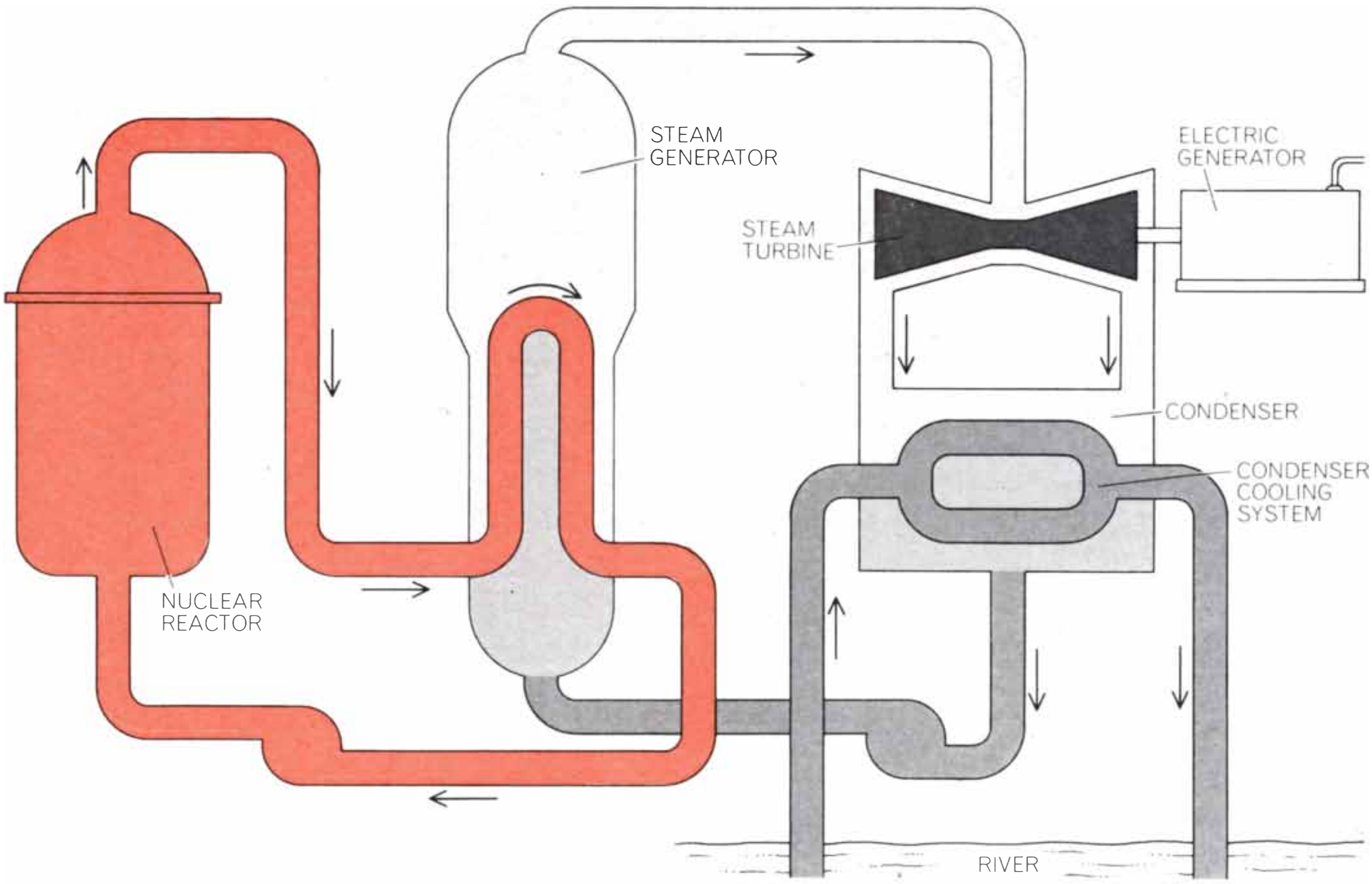
From 1966 through 1968, in addition to hydrological work in the immediate vicinity of the discharge canal, we conducted more than 24 surveys that extended from the mouth of the river to a point well upstream from the plume. Eighteen stations were established, and at each station we recorded the temperature, salinity and oxygen content of the river water near the surface, near the bottom and at an intermediate level under varying tidal circumstances and rates of river flow. Over this three-year period, which started before the plant went into operation and ended nine months after operation at the commercial level had begun, the surveys have shown essentially identical results.

Having generally established the nature and extent of the thermal disturbance in this area of the Connecticut, we now faced the question of its biological effect. In the realm of microbiology we soon learned that a series of studies was already in progress under the direction of John D. Buck and his associates at the marine research laboratory of the University of Connecticut with the support of the Federal Water Pollution Control Administration. Sampling the river water in the vicinity of the power plant every three weeks or so, Buck's group observed seasonal fluctuations in river bacteria. They found no alterations that appeared to be attributable to calefaction except in the immediate vicinity of the canal mouth. There the diatoms that normally dominate the river phytoplankton, the species *Melosira ambigua,* yielded that role to blue-green algae. This change in flora does not seem to portend obnoxious conditions either in the discharge area or farther downstream, although it is important to emphasize that we are dealing here with short-term observations.

Because Buck's extensive microbiological studies covered that area of research, we turned to investigating the river's bottom-dwelling fauna and its populations of fishes, some of them resident and some transient. In order to study the bottom community we established 17 stations spaced along a zone extending from four miles below the point of effluent discharge to four miles above it. At fortnightly intervals we sampled the river bottom in as many as 10 places at each station over a period of more than two years before the power plant began operations. In 1969 we added 12 new stations to this bottom-study network, all of them within the canal that carries the effluent to the river.

It had been our original plan that, once the tedious task of identifying the members of the bottom community was complete, we would undertake to determine the presence or absence of the more than 100 bottom-dwelling animal species with respect to a range of water temperatures from two degrees Celsius (35.6 degrees F.) to 38 degrees C. (100.4 degrees F.), or roughly seven degrees F. above the water temperature usually considered fatal to fishes of the Temperate Zone. It soon became clear that considerations other than temperature, among them the amount and velocity of river flow and changes in the composition of bottom sediments, were of equal concern with respect to the well-being of these mainly sedentary animals.

The dominant animal species of the Connecticut bottom sediments are an aquatic worm of the genus *Limnodrilus* and, where the bottom is sandy, a freshwater clam of the genus *Pisidium.* The larvae of two insects—the midges *Procladius* and *Cryptochironomus*—are the next most abundant animals under normal river conditions. During the first 11 months that the power plant was in operation it became increasingly evident that the areas adjacent to the effluent discharge harbored a greater variety of organisms than they had before. The newcomers included the larvae of beetles, dragonflies, damselflies and other insects. This diversity has remained high in the area where the canal water enters the river. Both the degree of diversity and the total numbers in the populations of this area, however, have declined sharply on several occasions. These changes were apparently related to a



TEMPERATURE of river water is raised 20 degrees Fahrenheit as it flows through a condenser (*right*) where the steam that drives the power-plant turbine is cooled. At the seasonal peak of river temperature, effluent temperature can exceed 108 degrees F.

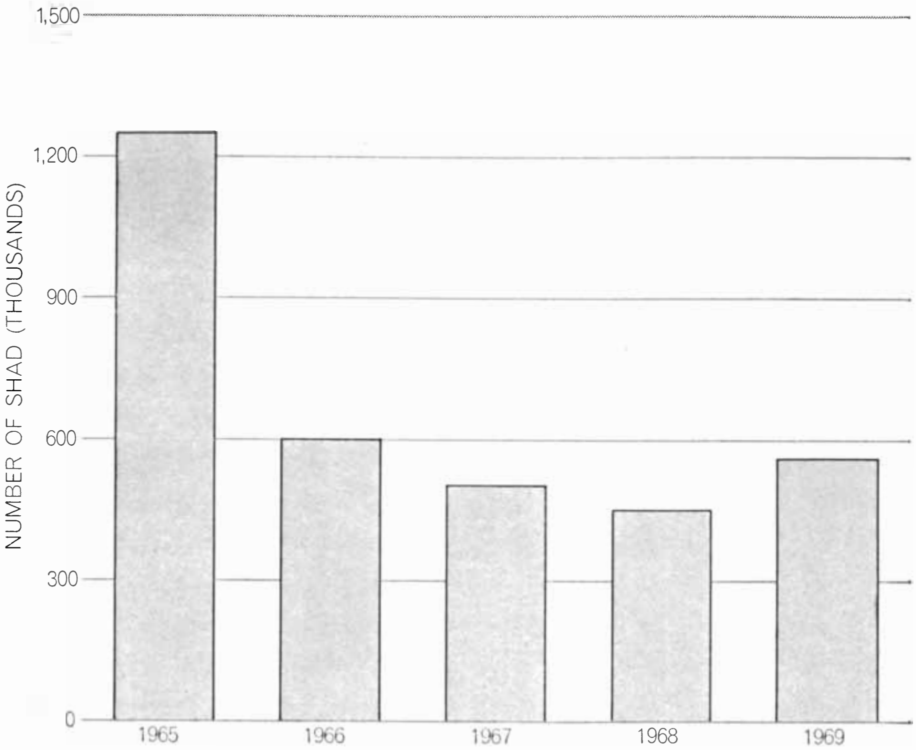
shutdown of the plant in March, 1968, which halted the flow of effluent, and to the spring freshets in May of the same year.

Near the water intake of the plant conditions are the opposite. Here both diversity and numbers show a substantial decrease. Evidently the velocity of the water as it is pumped from the river is high enough to wash away the silt and sand of the river bottom, together with the organisms dwelling in them. The bottom in this area is now gravel and cobblestone, wholly unsuitable for the worms and clams that formerly inhabited it.

The river bottom near the discharge canal, which was formerly sand covered by a thin layer of silt, has been changed to loosely consolidated silts that in places are several inches deep. This is a highly suitable habitat for the worms and also for insect larvae; hence the abundance and diversity of the newcomers. At the same time it is not a good habitat for the clams, because the silt tends to cover their siphons; as a result the population of clams in the area has substantially decreased.

Our interest in these bottom-dwelling animals arises from their role as an integral link in the river's food chain. Most of them are eaten by the fishes that live in the river the year round (as opposed to migratory fish populations): catfishes, perches, pickerels and other species. In any particular part of the river the density of the bottom-fauna populations influences the abundance of fish, not only at certain seasons but also throughout the year. The striped bass, for example, is a seasonal inhabitant of these waters, but it is known to spend the winter in a number of northern localities where warm effluents have made the winter environment tolerable both for the bass and for the bottom organisms they eat. Since 1968 increasing numbers of striped bass have been taken in waters near the mouth of the Haddam Neck effluent canal.

We are now investigating which bottom organisms are important as food for which fishes. We are also assessing what happens to organisms that are drawn into the power plant with the cooling water and involuntarily travel through the condenser system. We know from observations made early in 1969 that invertebrate organisms such as worms and clams survive the 6,000-foot trip in spite of a rise of more than 20 degrees F. in water temperature. Live invertebrates have also been found in the canal during the summer when the water temperature



NUMBERS OF SHAD that have entered the Connecticut to spawn in each of the past four years have not changed significantly since the Haddam Neck power plant began start-up procedures in July, 1967. The abundance of shad in 1965 is attributable to above-average spawning success in 1960. Shad are the river's economically most important natural resource.

was above 100 degrees F., which is some 14 degrees above the maximum summer temperature of river water. Further analysis of the bottom populations in the canal should help to clarify the picture.

In analyzing the fish populations of the Connecticut we have worked our way from the mouth of the river to as far north as Northampton, Mass., 90 miles upstream. In the first three years of our study, before the Haddam Neck plant had gone into operation, we made collections with bag seines and trawls in three depth zones: from the surface to five feet, from three feet to 10 feet and from 20 feet to as much as 40 feet in places where the depth of the river allowed it. A total of 364 separate collections proved to contain representatives of 36 species of fish.

The most common resident fishes in the Connecticut are the white and brown bullhead catfishes (*Ictalurus catus* and *I. nebulosus*), the white perch (*Roccus americanus*), the yellow perch (*Perca flavescens*), various sunfishes (*Lepomis*), the spottail shiner (*Notropis hudsonius*), the darter (*Etheostoma olmstedi*), the white sucker (*Catostomus commersoni*) and the killifish (*Fundulus diaphanus*). The common eel (*Anguilla rostrata*) is also an inhabitant of the river, but it spawns in the ocean and is therefore not strictly a resident fish. Since it spends most of its young and adult life in fresh water, however, we include it among the river residents. Censuses of the fish caught by fishermen during 10 months of the year from 1965 through 1969 show that 85 percent of the catch in the Haddam Neck area consists of catfishes, perches, eels and sunfishes.

The operations of the Haddam Neck power plant do not seem to have significantly affected the small but relatively stable catch of resident fishes. At the mouth of the Salmon River, about a mile below the mouth of the plant's discharge canal, however, the catch rate showed an increase in 1969; this may be correlated with the presence of the warm-water plume nearby. Indeed, a number of fishermen now prefer to fish near the mouth of the canal.

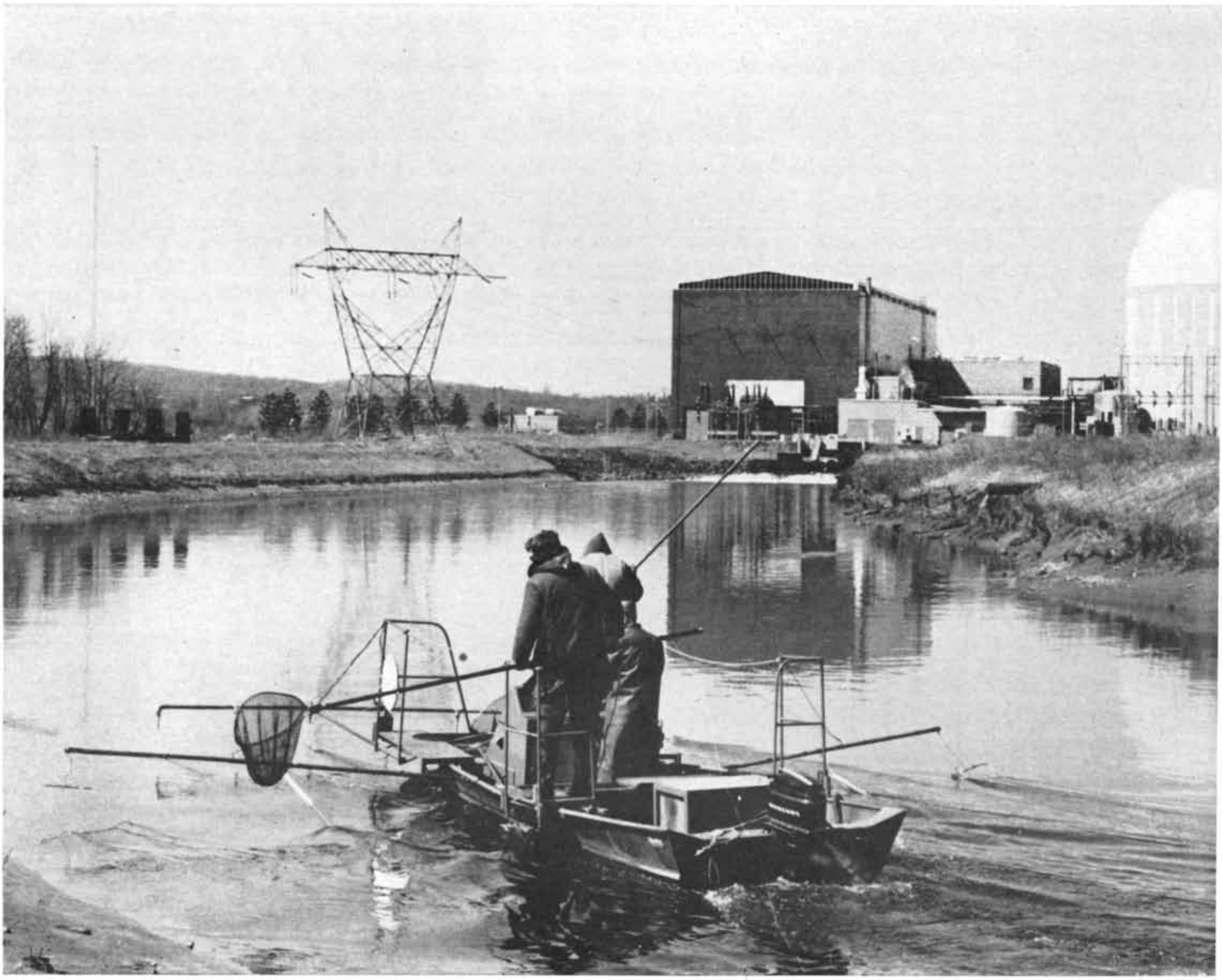
In studying the catfishes and perches we tagged more than 1,000 of these fishes in 1968 and some 5,000 of them in 1969. The object of the study is twofold: to provide information on the fishes' rate of growth and to trace the movements of the fishes upstream, downstream and in and out of the discharge canal. Tag returns in 1969 ran above 10 percent, and significant information from this work is already emerging. For example, representatives of both catfish species and of the yellow perch have been recaptured from 35 to 40 miles upstream of the power plant and from six to 15 miles downstream.

The fishes that have moved from the river into the discharge canal are now being studied intensively. A preliminary estimate of their numbers indicates that in winter between 12,000 and 21,000 brown catfish and between 3,000 and 7,000 white catfish are present in the canal. In spite of the greater availability of food in the canal area the condition of the canal catfishes is considerably poorer than the condition of river catfishes living beyond the influence of the plume. The factors responsible for this appear to include the fishes' higher rate of metabolism in the warmer water, the increased expenditure of energy required to cope with the relatively high rate of flow in the canal and the effects of crowding.

Young schooling fishes, such as shiners and killifish, have been taken in the canal when the water temperature was 98.6 degrees F.; their condition appeared to be good. The upper limit of water temperature tolerable for the adult fish, on the other hand, is only slightly above 93 degrees, a temperature that is frequently surpassed in the canal during the summer months. It is of interest in this connection that observations made in 1968 and 1969 showed that adult fish will move from the cooler river back into the canal when the temperature of the effluent has fallen less than two degrees F. below the upper limit. It may well be that the knowledge gained in these studies will be useful in fish farming.

The migratory fishes that are dominant in the Connecticut are three members of the genus *Alosa:* the glut herring (*A. aestivalis*), a summer spawner; the alewife (*A. pseudoharengus*), basically a spring spawner, and the American shad (*A. sapidissima*), also a spring spawner and one of the most delectable of all fishes to eat. The three species are not easy to tell apart when they are adults, and it is even more difficult to do so when they are juveniles. When they are larvae, it is only possible to distinguish them by counting muscle segments under the microscope.

Of the three migrant species the shad is the most important economically. The commercial shad fishery on the Connecticut has an annual capitalized value of some $7.5 million and the sport fishery an additional value of $14 million. The fish spawn in fresh water and the



CENSUS OF FISHES found in the mile-long effluent canal at Haddam Neck utilizes a launch that belongs to the State Board of Fisheries and Game and is equipped to stun fish with an electric shock. Netmen on the launch and on following craft retrieve the stunned

juveniles go to sea some five months later. They remain at sea for four to five years, and little is known of their movements and habits during this interval. When they have reached maturity, they return to spawn in fresh water. They come back to the stream in which they developed, apparently with the same high degree of precision exhibited by the salmon of the Pacific. Some shad are single-time spawners; others are repeaters. The fish that find their way back to the sea again, known as "runners," are emaciated and debilitated.

One of the several shad studies we undertook was to locate the areas in the Connecticut River where the shad spawn. This involved day and night visual observations from the shore and from boats, and the collecting of eggs in towed and stationary plankton nets. Because shad swim in a characteristic circular pattern when they are spawning, with their fins and backs out of the water, visual observations are not difficult. In June, 1967, for example, we observed shad swimming over a period of nearly a week in a circular pattern 150 feet from the west bank of the Connecticut 1½ miles south of the Windsor Locks bridge above Hartford. The spawning area was a gravel bottom at a depth of from three to four feet. When we towed plankton nets in this area, we collected numerous shad eggs in a relatively early stage of development.

fish for examination and tagging. Census is conducted by the Connecticut River Survey.

We rigged stationary bottom nets, attached to buoys to allow for tidal changes, at 31 points from Essex upstream to Thompsonville, 18 miles above Hartford. On the basis of the number and the age of the eggs collected in these nets we were able to conclude that the shad spawning areas were far more numerous above Hartford than below. We obtained eggs both in May and in June, when the temperature of river water ranged from a low of 50 degrees F. to a high of 73.4 degrees; the majority of the eggs were collected when the water temperature was at the upper end of this range. Eggs were found in both fresh and tidal water. We discovered that, compared with the major shad spawning areas north of Hartford, spawning in the vicinity of the Haddam Neck power plant was minimal.

One of the critical periods in the early life of the shad is when the juvenile fish move downstream en route to the sea. This procession starts in the latter half of August and continues into November; the fish are from three to five inches long. We wanted to learn something about their rate of movement downstream and whether or not their passage would be impeded by the plume of warm effluent from the Haddam Neck plant. As a first step we marked 18,000 juvenile shad by clipping their fins and 7,000 more by spraying them with a fluorescent dye. Since we were unable to recapture any of these fish, we rigged gill nets that extended to a depth of 16 feet in the vicinity of the plume and then checked the catch at intervals that enabled us to compare the depths at which the fish traveled by day and by night. We found that the fish swim in deep water by day and nearer the surface at night. Even at night, however, they apparently pass under the plume at depths below four feet, the level where a five-degree temperature rise is encountered. There is no evidence that the juvenile shad suffer any detrimental effects in traversing the river region affected by the effluent.

In an attempt to learn more about how juvenile shad react to rapid changes in water temperature we conducted a series of experiments in 1966 and 1967 at the Essex Marine Laboratory. The preliminary tests showed that an instantaneous rise in temperature to 91 degrees F. (more precisely, a rise over a range of from 16 degrees above an ambient water temperature of 75 degrees to nine degrees above an ambient 82 degrees) was lethal to the young shad within five minutes. Later experiments showed that the juvenile fish actively avoided water characterized by such severe temperature gradients. In this connection, larval fishes appear to have a greater immunity to the effects of calefaction than juveniles. A plankton-net tow made in the discharge canal in July, 1968, when the water temperature was 93.2 degrees F., yielded more than 650 *Alosa* larvae; they were mostly at the late yolk-sac stage, which suggests that they were the product of upstream spawning. They had apparently entered the plant intake and passed through the condenser unscathed.

Midsummer fish kills are not uncommon in the lower reaches of the Connecticut. We have observed three since the beginning of our investigations, all before the Haddam Neck plant went into operation: on July 2 and July 13 in 1965 and on July 4 in 1966. The size of the second kill in 1965 was estimated at 100,000 fish and the 1966 kill at 50,000 fish. In all three instances the principal fatalities were glut herring (99.9 percent of the kill in 1966) and alewives. Shad, catfishes, white suckers, eels and white perch were killed in far smaller numbers. The kills were apparently the result neither of toxic effluents nor of a parasitic infestation. Their most probable cause appears to be the combination of low river flow, water temperatures in excess of 80 degrees F., a depleted supply of dissolved oxygen and, in the case of the summer-spawning glut herring, the stress associated with spawning activity. In many areas that we sampled the water contained less than five parts of oxygen per million, a level that is generally considered unfavorable for fish life. Our samples were taken in daylight; since the photosynthetic activity of aquatic plants is reduced at night, the oxygen content must have been even lower in the predawn hours when spawning activity is greatest.

We needed to establish other facts about the shad. What is the rate of the upstream migration in the spring? How many fish return each year to spawn? Might the plume of warm water from the plant keep the mature fishes from traveling upstream to their usual spawning grounds? To answer these questions we instituted another intensive shad-tagging program. So far more than 18,000 migrating shad have been marked by setting a "spaghetti dart"—a short barbed rod with a long bright-colored streamer—in the back muscles of the fish. Another 200 fish have been "force-fed" small sound transmitters so that the details of their upstream movements can be monitored by hydrophone. We found that the speed of upstream migration ranged from less than a mile per day to five miles or more once the shad had moved upstream from brackish water to fresh. There seems to be no "normal" speed of migration; instead the rate of the fish's progress appears to depend on the temperature and salinity of the water.

It appears that the effluent from the plant has no significant retarding effect on the shad's upstream progress. The fish follow the river channel, which is close to the west bank in the area affected by the plume, and sonic tracking shows that within the channel they tend to move along its west side. They either pass through or under the plume without apparent difficulty or significant hesitation. Under the environmental conditions existing during the shad runs of 1968 and 1969, two years when the power plant operated at nearly full scale, there has been no thermal blockage of the Connecticut. At the present level of plant operation, assuming that environmental conditions remain the same, no blockage is anticipated.

The return of spaghetti tags, in combination with other data, has provided the basis for good estimates of how many shad return to the Connecticut each year. We estimate that in 1965 the number was more than a million; this appears to reflect an unusually successful spawning season five years earlier. From 1966 through 1969, we estimate, the number of returning shad has fluctuated around the half-million mark [*see illustration on page 49*]. The population trend in future years remains to be seen.

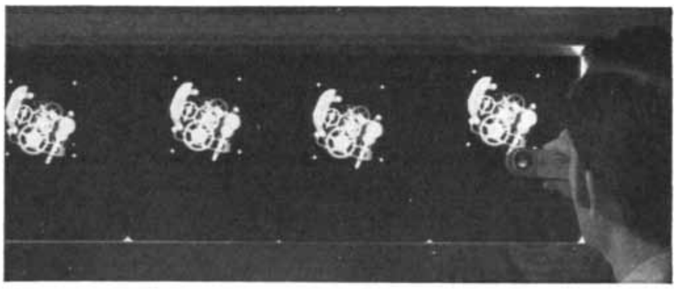
The shad fishery is the Connecticut River's only major economic resource at present. The alewife and the glut herring, however, are a resource that, although it has suffered from mismanagement in the past, could well be rehabilitated given the proper incentives. Under prudent control the stock of these river herrings could withstand heavy harvesting (as in fact it did in the earlier part of the century, when the overall catch along the East Coast of the U.S. ranged from 30 to 60 million pounds per season). When the problems besetting the production and marketing of fish-protein concentrate are surmounted, these fishes should be exploitable in the Connecticut and in other Eastern rivers.

How can our studies of the Connecticut up to the present be summarized? First of all, it is necessary to avoid anticipating the final conclusions of the comprehensive study; the collecting of data for that report will not be finished before the end of 1972. Anything we can say at this stage must be accepted as a short-term evaluation. Not only will several more years of intensive research be needed to lay a firm foundation for future decisions about heating the river but also continued testing and observation are necessary if we are to detect subtle long-term ecological effects that are not now even predictable. It is nevertheless possible to report that the operation of the Haddam Neck power plant and the consequent calefaction of the Connecticut River in the vicinity of the plant has had no significant deleterious effect on the biology of the river. There have been changes in the flora near the plant, in the bottom fauna at the point of effluent discharge and in the condition of the bottom habitat near the plant intake. Of the river's fishes, the catfish that enter the discharge canal do not fare as well as those that do not enter. These effects can hardly be regarded as being calamitous, and in the long run the calefaction may even prove to be beneficial in one way or another.

It is currently recalled that two centuries ago Edmund Burke declared that "the public interest requires doing today those things that men of intelligence and good will would wish, five or ten years hence, had been done." Where the calefaction of streams, rivers and lakes is concerned, what must be done is not only to squarely face the ecological problems that the rising demand for power are creating but also to accompany programs of construction with programs of environmental research so that the most favorable possible conditions are achieved. Such a course requires rational give-and-take and a willingness of strong-minded people on both sides of such problems to bend enough to arrive at the optimum balance of interests.

CATFISH FROM CANAL is examined by Barton C. Marcy, Jr., of the Connecticut River Survey staff. Because the higher temperature of the effluent increases the fishes' rate of metabolism while the rate of effluent flow forces them to swim more vigorously than when in the river, the condition of the canal catfish is relatively poor in spite of more plentiful food.

We want to be useful ...and even interesting



X-rays of mass-produced goods?

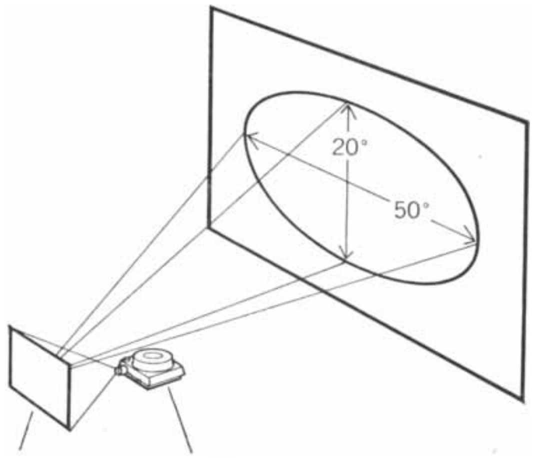
Nonsense. But what if no people were needed to look at the film?

Take an item a bit more advanced than a windup alarm clock, like a bill-changing machine. Even that kind of merchandise can't carry too heavy a cost load for inspection—radiographic or whatever is technically required—and survive in the marketplace. The public has to accept the facts of life: scientists discover new principles, engineers apply the principles with great ingenuity, but the resulting gadget will not necessarily work literally *every* time someone fumbles around with it on a dark night. Accept it, even if you don't like it.

This bothers certain idealists, some of whom work in the Kodak Research Laboratories on automatic pattern recognition. They are so hypnotized by the subject that the Medical Department doesn't always like the hours they insist on keeping.

While the human nervous system is hard to beat at pattern recognition, it falls prey to boredom and ambition. Machines have been taught to inspect millions of bubble pattern photographs for indications of interesting nuclear physics. Discovering poorly seated screws may be no harder. That inanimate inspectors would still be using film may surprise you. Though concocted from silver, bones, and a little chemical magic, it is still far from fully exploited for information-packing density, which correlates strongly with economy. If every alarm clock or every nozzle for a steam-driven automobile is to require a bit of film, it will have to be a rather *small* bit of film.

It's a little in the future. Don't write yet.



Light delivery

The big screen in the above demonstration is a conventional one. It is simply showing you the light distribution pattern from an unconventional 40″ x 40″ screen facing it. Call the unconventional one KODAK EKTALITE Projection Screen, Model 2, when ordering it from a dealer listed in the Yellow Pages under "Audio Visual Equipment." As compared with a non-directional screen, it delivers 6 to 8 times as much light into the viewing space, at the expense of light sent outside the space, where there are no eyes to receive the picture being shown. Classrooms that use it need never be darkened to keep the sunlight from diluting slides and films. Other uses are conceivable.

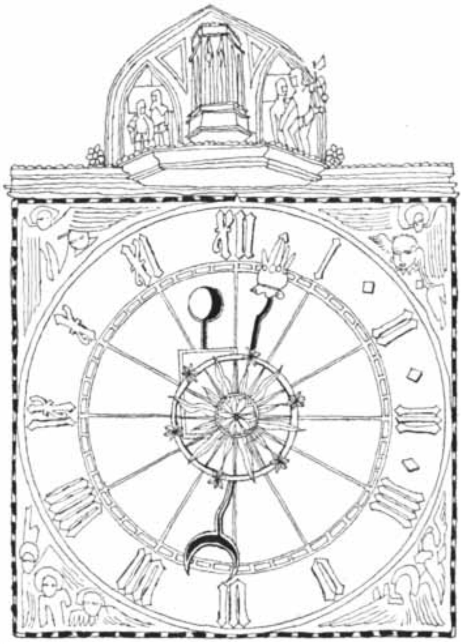
Looking at the pool

Happy splashes are about to rise from America's full complement of 10^6 swimming pools. That water, as warned on p. 608 of the May, 1967 issue of the *Journal of the American Water Works Association,* had better contain at least 0.4 ppm of free chlorine. You are further warned therein against deceiving yourself by including weakly disinfectant chloramine, as you do with the old o-tolidine test unless difficult corrections are applied.

Lest all these details spoil the fun, several firms have built a business in kits for testing pools and other bodies of water. This year—which ought to be the best they have ever had—they also offer a kit based on the work of Black and Whittle, authors of the warning here cited. Associate Prof. George P. Whittle, a civil engineer-chemist at the University of Alabama, has even been moved to write us in commendation of the consistent high purity of EASTMAN Organic Chemical No. 3651, the leuco form of crystal violet. Its usefulness for assaying Cl_2 and I_2 in water was discovered by him and Professor-Emeritus A. P. Black of the University of Florida.

Those who know better than to expect us to ship EASTMAN *Organic Chemicals to a residential address with pool or without, and who do not find the kit approach to difficult questions always best, may wish to send for U. S. Public Health Service Publication No. 1988 to Analytical Reference Service, Environmental Health Service, 5555 Ridge Avenue, Cincinnati, Ohio 45213.*

SCIENCE AND



Space in the 1970's

A special panel of the President's Science Advisory Committee has recommended that manned space flight be deemphasized in the 1970's in favor of using instruments and automatic devices to gather scientific information. The panel concluded that "the presence of man could not be shown unequivocally to be essential for any of the probable scientific objectives of space programs in the next decade." In a separate statement President Nixon endorsed the panel's recommendations in general but predicted that the U.S. "will eventually send men to explore the planet Mars." The earliest "realistic" date for such a voyage is 1986.

The Space Science and Technology Panel said that in the coming decade the nation's space effort should emphasize "reaping rewards in terms of basic new scientific knowledge and applications of value to man's life on earth." The panel observed that if the space program were evaluated solely on the basis of its scientific and technical content and on direct benefits from applications, it would now have to be judged to be too large by a factor of two. On the other hand, the panel said it recognized that there are values in the space effort "that go beyond science and technology," and that these values may justify a larger expenditure. The President's statement said the part of the U.S. space budget administered by the National Aeronautics and Space Administration would remain at about $3.5 billion per year. According to the panel's report, the Department of Defense spends about $2 billion per year on space activities.

The panel urged the expansion of earth-oriented studies to gain a better understanding of the dynamics of the atmosphere, to improve weather forecasts, to extend space communications and to catalogue resources. The panel also concluded that a space-satellite system offers the best hope for controlling air traffic, which has been doubling every five years. Such a system would be "capable of following the locations of individual aircraft to a few hundred feet accuracy in three dimensions." A system for the North Atlantic corridor could be developed and functioning "in the next three or four years."

The Space Panel recommends that the remaining Apollo flights to the moon be limited to a maximum of two a year to provide adequate time for analysis of results. The cost of two flights is $1 billion. The panel recommends that, when these flights are completed in the mid-1970's, NASA undertake a much more thorough biomedical program than it has had so far. This will involve development of the nation's first space station, in which men will be able to spend up to eight weeks in orbit.

The late 1970's will provide a rare opportunity to send spacecraft on a "grand tour" of all the outer planets except Pluto with a minimum expenditure of energy. Jupiter, Saturn and Uranus will be aligned in such a way that a well-aimed vehicle will be accelerated as it passes each of them, and will eventually be sped on its journey to Neptune. The entire trip will take 11 years. The panel urged that this opportunity not be missed; the President said he would support the effort. The panel recommends that outlays for astronomy in space be increased throughout the 1970's and beyond them, with emphasis on observations that cannot be made from the ground. The panel estimates that $500 million per year, about three times the current expenditure, could usefully be spent on space astronomy.

The panel also recommends the development of reusable launch vehicles as the single most effective way to reduce the cost of putting men and machines in orbit. To place an unmanned craft in an orbit a few hundred miles above the earth now costs about $1,000 per pound; to do so in a synchronous orbit (one 22,-300 miles high) costs 10 times as much. With shuttle systems that could be used as many as 100 times the cost of reaching a low earth orbit might be reduced to $100 per pound; the cost of a round-trip ticket for a human passenger would then be a mere $20,000 or so.

The Monkey War Resumes

The classic controversy about evolution has resumed once again in California. The State Board of Education has held that Darwin's theory of evolution through natural selection is just one of a number of possible theories on the origin of life and of man and must be presented as such in the public schools. Several school boards and other groups in the state are threatening lawsuits to block the board's action, which took the form of new guidelines for science teaching that were approved last fall and are now being promulgated. The board inserted into the guidelines, which had been prepared by a committee of science teachers, a statement that "scientific evidence concerning the origin of life implies at least a dualism or the necessity to use several theories." This will presumably require that such competing theories as the story given in Genesis and Aristotle's theory of spontaneous generation be taught along with Darwinism. Textbooks that do not do so will not be bought by the state for the elementary schools or put on the approved list for local purchase by secondary schools. The decision could affect the teaching of biology throughout the country, since California accounts for some 10 percent of all textbook sales and publishers are not likely to give up the California market or to publish special versions tailored to one state's requirements.

The board's decision was reached, according to the *San Francisco Chronicle*, after a seven-year campaign by Fundamentalists who argued that evolution contradicts the Bible and that its teaching therefore undermines religious training. They first sought to have Darwinism eliminated from the curriculum, but they were unsuccessful and settled for the competing-theories approach. Opponents of the board's action maintain that to present fundamentalist Biblical doctrine on the same basis as the findings of scientific investigation is to teach a religious belief in public schools and is therefore unconstitutional. Moreover, they urge that a doctrine of "equal validity" for various theories would lead to chaos in science teaching.

The Arms Spiral (Cont.)

The world's expenditures for weapons and armed forces reached a record of $200 billion last year and has risen 44 percent since 1964, according to the U.S. Arms Control and Disarmament Agency. During the six-year period the outlays for these purposes have amounted to more than $1 trillion, which is, the agency said, "as much public money as was spent by all governments on all forms of public education and health care." The figures appear in the agency's fourth annual report on military spending, titled *World Military Expenditures 1969*. In the introduction the director of the agency, Gerard C. Smith, says: "The report shows the rise in military spending continuing, although it is less sharp. The world remains the poorer for it."

As in previous years the agency found that "the advanced industrial nations continue to dominate world outlays" but that the highest spenders with respect to gross national product are all poor countries (see "The Cost of World Armaments," by Archibald S. Alexander; SCIENTIFIC AMERICAN, October, 1969). A recent trend, which became evident in 1968 and continued in 1969, is that the proportion of military spending by nations outside the two major blocs (the North Atlantic Treaty Organization and the Warsaw Pact group) is increasing. If this trend continues, the agency said, "the developing countries may increase their share of world military power but risk shrinking even further their modest share of world economic power."

Catch Two

The samples of surface material collected last November at the *Apollo 12* lunar landing site south-southwest of Copernicus in the Ocean of Storms have now been subjected to preliminary examination and have been compared with the *Apollo 11* samples. The single most striking difference, according to a report in *Science,* is that the *Apollo 12* rocks are about a billion years younger than the *Apollo 11* rocks. The *Apollo 12* samples evidently crystallized some 2.3 billion years ago. This indicates that the lunar maria were formed over a period of at least a billion years.

Superficially the two landing sites were very similar. The pads of the landing craft penetrated about the same distance, and the footprints of the astronauts were of roughly equal depth: less than a centimeter in the harder areas and up to several centimeters in softer areas. The color, grain size, adhesion and cohesion of most of the soil samples were also similar. At the *Apollo 12* site, however, the astronauts were able to drive their core tubes to the full depth of 70 centimeters, whereas the *Apollo 11* explorers were able to drive the tubes only to about 15 centimeters. Improvement in bit design had something to do with the difference in depth.

There were a number of other differences between the two sites. The regolith, or mantle rock, is only about half as thick at the *Apollo 12* site as it is at the *Apollo 11* site. The amount of solar-wind material (chiefly gases of low atomic weight) is much lower in the *Apollo 12* fines than in the *Apollo 11* fines (indicating a shorter time of exposure to the solar wind). The *Apollo 12* rocks contain less titanium, zirconium, potassium and rubidium than the *Apollo 11* samples, and more iron, magnesium and nickel. Samples from both sites are rich in glass, much of it in the form of tiny spherules. The larger rocks from the two sites are also similar: they tend to be rounded on one surface and to have pits lined with glass. Irregular patches of glass have also been spattered on the rock surfaces. In short, there is abundant evidence that both sites were heavily bombarded by meteorites of all sizes. The recent failure of *Apollo 13* means that investigators will have to wait a little longer for samples from a highland region, which should be distinctively different from the maria samples.

Super Superconducting Magnets?

One of the most serious limitations on the use of extremely powerful superconducting magnets for certain research projects has been the fact that beyond a critical point a magnetic field tends to penetrate the superconducting material and destroy its superconductivity (its complete lack of resistance to an electric current at temperatures near absolute zero). It was therefore with particular interest that workers engaged in such projects received the announcement at the recent meeting of the American Physical Society in Dallas that critical magnetic fields substantially higher than any previously reported had been measured in two superconducting alloys. The announcement of the new measurements, which were performed in a specially constructed pulsed magnet at the Francis Bitter National Magnet Laboratory of the Massachusetts Institute of Technology, was made by a joint research team consisting of Simon Foner and Edward J. McNiff, Jr., of the laboratory staff, Bernd T. Matthias of the University of California at San Diego and the Bell Telephone Laboratories, Theodore H. Geballe of Stanford University and Bell Laboratories, and Ronald H. Willens and Ernest Corenzwit of Bell Laboratories.

One of the two superconducting alloys tested was a three-metal system consisting of niobium, aluminum and germanium. At the boiling point of liquid helium (4.2 degrees Kelvin, or degrees Celsius above absolute zero) this material remained superconducting in the presence of a magnetic field of up to about 420,000 gauss in strength. The transition temperature at which the alloy enters the superconducting state is approximately 21 degrees K.

The other superconducting material tested was a two-metal alloy of niobium and aluminum. At 4.2 degrees K. it maintained its superconductivity in a magnetic field as high as 290,000 gauss. Its transition temperature is about 18 degrees K.

The new findings appear to have a special relevance to the problem of investigating the prospects of controlled thermonuclear power, since some of the newer designs for experimental fusion machines call for very strong magnetic fields to confine the hot plasma, or gas of charged particles, in which energy-releasing fusion reactions are expected to take place. It had earlier been thought that materials considerations imposed a practical upper limit of about 100,000 gauss on the strength of the superconducting magnets available for this purpose. The new alloys have not yet been tested for such important physical properties as ease of fabrication and mechanical strength under the stress of very strong magnetic fields.

Reconstituted Amoebas

A nucleus removed from one amoeba, the cytoplasm removed from a second and the outer membrane of a third can be reassembled into a living amoeba, report James F. Danielli, Kwang W. Jeon and Joan Lorch of the State University of New York at Buffalo. Moreover, nuclei, cytoplasms and membranes from different strains of amoebas can be so assembled.

Writing in *Science*, the Buffalo workers describe how they have reconstituted more than 692 amoebas by a three-step procedure. First the nucleus was removed by means of a microprobe. Next most of the cytoplasm was extracted through a pipette with a bore of from one micron to five microns in diameter. (An alternative method was to remove the cytoplasm by centrifuge.) Then the membrane was refilled with cytoplasm from another cell and a new nucleus was inserted.

If all the components came from amoebas of the same strain, as many as 85 percent of the new amoebas behaved and reproduced normally. When one or more components came from different strains, some agent (probably factors produced by one strain that is lethal to others) allowed fewer than 1 percent of the new cells to form viable lines.

The technique may help to clarify many aspects of cellular activity. The interaction of organelles in cells could be examined by observing what happens when they are assembled to form a composite cell. Another problem involves cell division. Normally amoebas are immortal in that they divide indefinitely. Starvation, however, gives rise to changes that limit the number of times the descendants of a cell can divide. By transplanting the nucleus of an amoeba that has been inhibited by starvation into a cell assembled from the parts of other amoebas that have divided normally, the nature of these changes might be identified. The technique might also be applied to creating new strains of bacteria that are highly efficient at performing industrial tasks such as breaking down wastes.

Superhenge

Stonehenge, the Bronze Age circle of stones near Salisbury, England, is such a striking work of man that the many similar arrays throughout the British Isles are now called "henge monuments." Some of the other henges, such as the one at Avebury in Wiltshire, are also built of stone. The majority, however, which survive only as traces of extensive earthworks and holes that originally held wooden posts, were "woodhenges." All these works that can be dated (including the earthworks at Stonehenge itself) appear to have been built originally in later Neolithic times, roughly from the middle of the third millennium B.C. to early in the second millennium.

The four largest henge monuments in England, each surrounded by earthworks measuring more than 1,000 feet in diameter, are Avebury and three woodhenges: Mount Pleasant (near Dorchester), Durrington Walls and Marden (both on the River Avon). Recent salvage archaeology in advance of highway construction at Durrington revealed traces of two circular timber structures that presumably had been ceremonial roofed buildings; a survey of the enclosure suggested that several other such ceremonial structures had once stood within it. Last year archaeologists of the Ancient Monuments Department in the Ministry of Public Buildings and Works undertook limited excavations at the largest henge in England: Marden, which embraces 35 acres. Two 10-meter squares, dug just inside the northwest entrance to the enclosure, revealed that a roofed circular timber structure some 30 feet in diameter had stood there early in the second millennium B.C. As at Durrington, this was evidently only one of several structures the henge had contained.

Commenting on the ritual significance of this and other British superhenges, the editors of *Current Archaeology* note that a new picture of religion in late Neolithic Britain is emerging: "Four 'cathedral' henges—Avebury, Durrington, Marden and Mount Pleasant—take pride of place, and Stonehenge is demoted to being . . . a 'parish church' as it were—even if [its] sophistication . . . means that it must be accounted as a very 'royal' parish church."

Bicycle Built for None

A bicycle traveling at a good clip feels quite stable to the rider. Even without a rider a bicycle can proceed for as long as 20 seconds before falling over. What elements in the structure of a bicycle account for this remarkable stability? Several answers have been proposed but little experimental work has been done, according to David E. H. Jones, writing in *Physics Today*. Jones, a chemist who became interested in the problem, decided to supply the missing data by building an unridable bicycle. He reasoned that if he designed a bicycle lacking those features that a particular explanation names as the source of stability, then the machine would be unridable and the theory would be confirmed.

Do gyroscopic forces generated by the front wheel stabilize a bicycle? In order to test this proposition Jones built Unridable Bicycle Mark I. It was a normal bicycle equipped with an extra front wheel mounted free of the ground so that it could counterrotate and generate gyroscopic forces that would cancel those produced by the normal front wheel. No matter which way the extra wheel was spun, however, the machine proved frustratingly ridable.

Unridable Bicycle Mark II was designed to test the notion that steering geometry creates stability. According to this idea, the location of the point at which the front wheel touches the ground with respect to the steering axis is the critical factor. The steering axis is a line running down the steering post to the ground. If stability is a function of whether the contact point is in front of the steering axis or behind it, a wheel mounted directly under the steering axis should be highly unstable. Mark II was therefore fitted with such a wheel, an adapted furniture caster. The results were inconclusive. The machine was unstable, but this could be attributed to the fact that the caster could not ride over a bump higher than half an inch. The caster also became extremely hot when the bicycle was pedaled at any speed.

Unridable Bicycle Mark III approached the steering-geometry problem in a new way. Its front fork bent backward toward the rider, instead of forward as it usually does. Jones expected Mark III to be at least slightly unstable, but to his surprise it could run for many yards without a rider. It was hard to ride only because its stability interfered with the rider's normal riding reflexes.

With the aid of a program called BICYC Jones undertook to analyze the source of Mark III's stability by computer. He found that the farther the contact point is moved behind the steering axis, the stronger is the torque, or twisting force, exerted on the axis when the bicycle leans over. The torque stabilizes the bicycle by turning the wheel in the direction of the lean. Another force, the castering force, prevents oversteering by causing the rest of the bicycle to swing into line behind the turning front wheel.

In order to confirm the importance of these forces Jones built Unridable Bicycle Mark IV. Whereas the front-wheel contact point of Mark III was behind the steering axis, the front wheel of Mark IV was mounted four inches ahead of its normal position, so that its contact point was well forward of the steering axis. This arrangement reversed the effect of the lean-induced torque. Mark IV was gratifyingly unstable. It was "very dodgy" and crashed instantly when released while moving without a rider.

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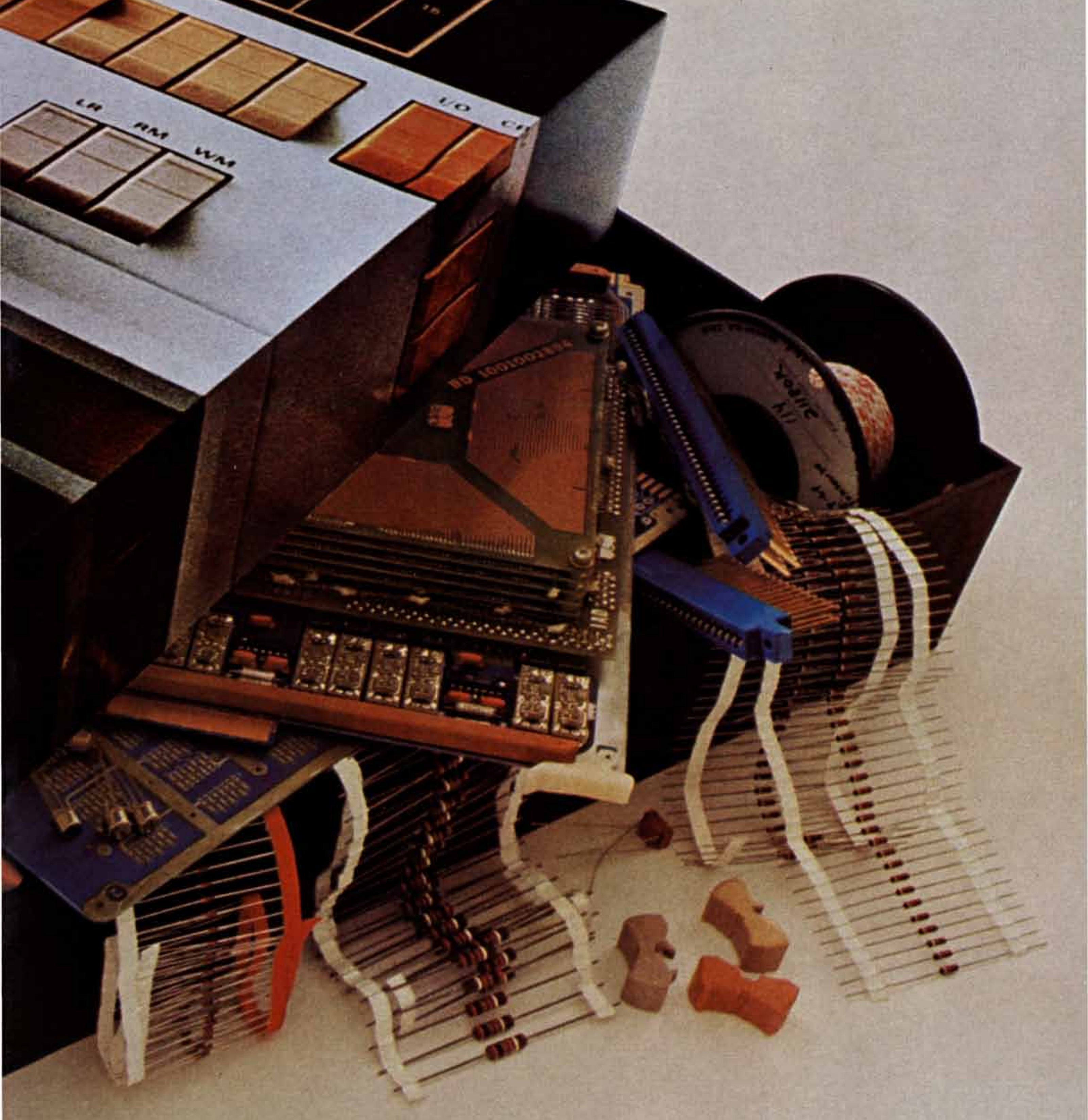

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The demands of modern agriculture and industry have increased consumption of the element fortyfold since 1900. It comes from many sources, and some 87 percent of it goes to sulfuric acid

by Christopher J. Pratt

The U.S. economy uses sulfur at a rate of more than 100 pounds per year for every inhabitant of the country, and yet the average inhabitant seldom if ever sees any. It permeates his environment in largely invisible ways: as the sulfuric acid used extensively in the manufacture of fertilizer, textiles, plaster, paint and many other products; as an essential nutrient of food crops; as an ingredient of medicine, and as a pollutant of the air in the form of sulfur dioxide. Indeed, one's chances of seeing sulfur would have been better in an earlier time, when sulfur was commonly burned (it gets its old name, brimstone, from variously spelled Anglo-Saxon words for burn-stone) to drive away evil spirits, repel insects, bleach fabrics and fumigate houses after illness. The 15th-century traveler Leo Africanus once referred to sulfur-burners (alchemists in particular) as "stupid fellows who mummify themselves with sulfur and other horrid stinks."

Sulfur is a nonmetallic element with a strong propensity for combining with other elements. In its elemental form it is found chiefly in sedimentary and volcanic deposits. Nonelemental sulfur—sulfur in combination with one or more other elements—occurs mainly in sulfides and sulfates. Contrary to the opinion of anyone who has been exposed to the pungent odor of burning sulfur or the rotten-egg smell of hydrogen sulfide, sulfur by itself is odorless. It is also tasteless. Among other things, it is an extremely poor conductor of heat and electricity and is insoluble in water and most acids but soluble in carbon disulfide and many other organic liquids.

A measure of the economic importance of sulfur is its annual production in various forms in the U.S. and Canada, amounting to the equivalent of 13 million long tons. About 87 percent of all production goes to sulfuric acid, which traditionally has been called the workhorse of chemistry because more of it is used in chemical processing than any other intermediate. Appreciable amounts of sulfur are burned to form sulfur dioxide for use in a number of processes, including the manufacture of sulfuric acid. Indeed, because of the amount of sulfur consumed and the wide variety of its uses, it is often considered—together with salt, limestone, coal and oil—as one of the five basic raw materials of the chemical industry.

Distinctive Properties

In its elemental form sulfur can assume an unusual variety of complex molecular configurations and crystal states. A basic molecular structure is a twisted ring of eight atoms; 16 rings make up the stable crystal form termed rhombic and six rings the unstable form known as monoclinic. Some 36 crystalline forms of sulfur have been identified.

The cooling and heating of sulfur give rise to unusual properties. Sudden chilling of molten sulfur produces a rubbery material in which clusters of eight-atom chains can be detected. After chilling, the chains slowly revert to stable rhombic crystals. If sulfur is heated, the rhombic form changes reversibly at a temperature of 95.4 degrees Celsius into the monoclinic form, which melts at 115.2 degrees and becomes a straw-colored liquid with an eight-atom structure. Further heating increases the fluidity of the liquid, as one would expect, and darkens the color.

At about 160 degrees C., however, the melt suddenly becomes extremely viscous, like setting glue. This phenomenon is apparently attributable to the formation of long-chain polymers. If small amounts of organic matter or elements such as chlorine and iodine are present in the sulfur, the changes in viscosity are reduced, probably because the other materials block the formation of long polymer chains.

The viscosity persists until the temperature reaches 230 degrees C. At higher temperatures the viscosity decreases, but the dark color remains until the boiling point of 444.6 degrees is reached. Further heating of the vapor induces a two-atom and finally a one-atom structure. Slow cooling produces these phenomena in the reverse order.

Sulfur's high reactivity makes possible a great number of natural and synthetic compounds in which the element is bonded covalently with one or more other elements. (Covalency refers to the number of electrons shared between atoms and is a measure of chemical reactivity; whereas most oxygen compounds show a covalency of 2, sulfur exhibits covalencies of 2, 3, 4 and 6.) Sulfur combines with all but a few elements; the exceptions include gold, platinum and the inert gases. Among the most familiar and useful compounds are

SULFUR VAT is built up at the plant of the Texas Gulf Sulphur Company in Newgulf, Tex. The purplish material in the upper part of the photograph on the opposite page is molten sulfur that has recently been sprayed on the vat. The yellow material in the lower part of the photograph is sulfur that has solidified. Both parts of the photograph show the top of the vat, although the solidified sulfur is a few feet higher than the molten sulfur. At upper left in the distant background is the vat that appears in the photograph on the cover.

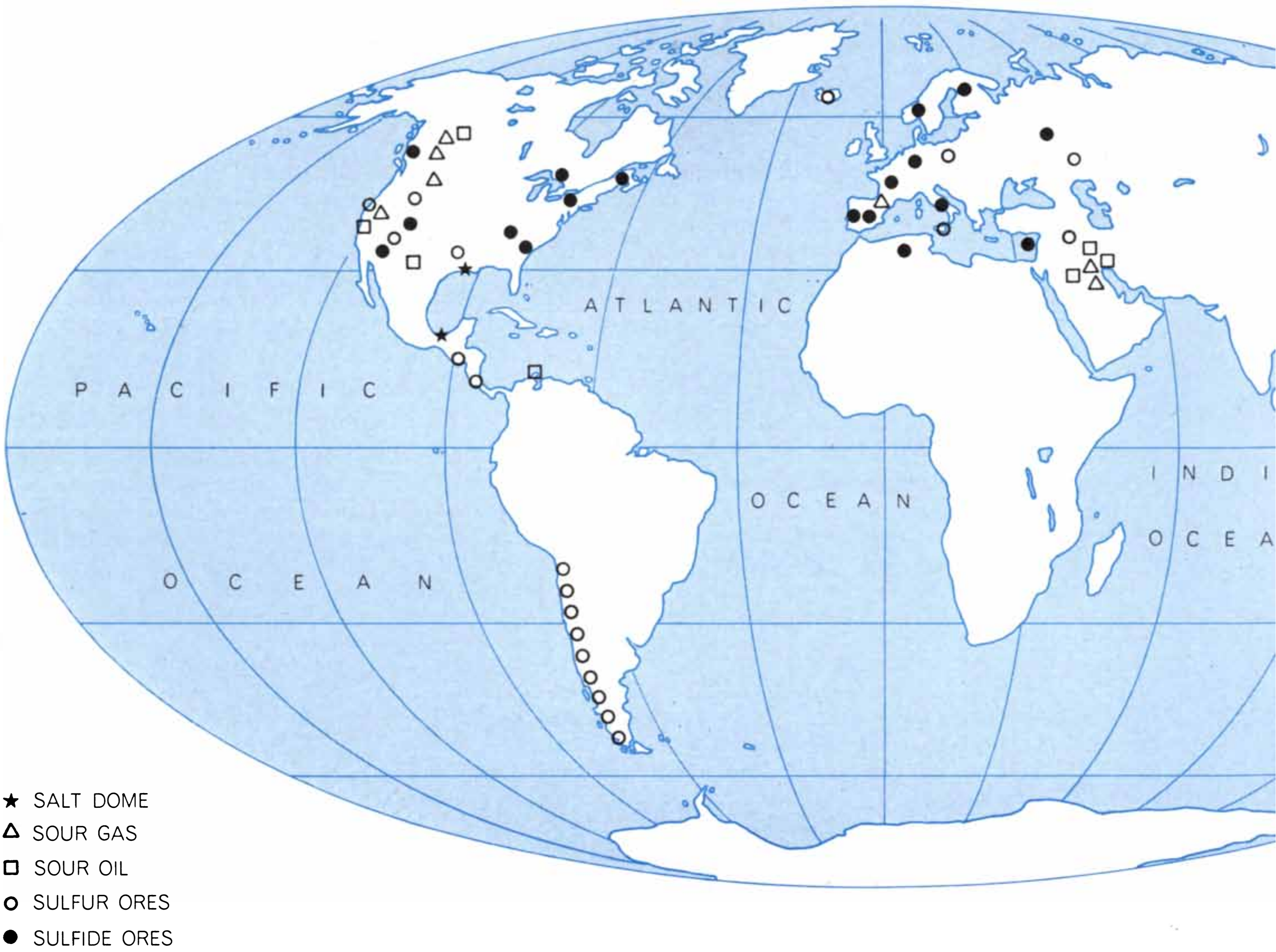
hydrogen sulfide (H_2S), sulfur dioxide (SO_2), sulfuric acid (H_2SO_4) and such familiar materials as Glauber's salt (sodium sulfate) and gypsum plaster (calcium sulfate).

Attempts to classify the derivatives of sulfur are in fact rather difficult because of the element's many forms and broad reactivity. Most of the derivatives, however, can be divided on a structural basis into molecular, or finite, derivatives and nonmolecular derivatives. An example of a molecular derivative is sulfur dioxide, which is produced by burning sulfur in air. Polysulfides, polymeric forms of sulfur and many organic compounds are also in this category. Nonmolecular compounds include water-soluble ionic salts such as the sulfates and water-insoluble metal sulfides such as those of lead and silver. Compounds of the water-insoluble type are crystalline and therefore have the theoretically infinite structure of the crystal lattice. Some of the most insoluble compounds known result from this type of atomic array, and for this reason many sulfide ores have resisted natural leaching over long periods of time.

Sources of Sulfur

Sulfur is distributed widely on the earth in a considerable variety of elemental and nonelemental forms. It is possible that both types originated early in the earth's history from volcanic emissions of lava and gases containing sulfur. The phenomenon can still be observed: in certain places in Japan and Chile, for example, hydrogen sulfide gas issuing from volcanic vents is oxidized and continues to form local deposits of sulfur that may be of commercial value. Native sulfur is also found in the vicinity of a number of hot springs.

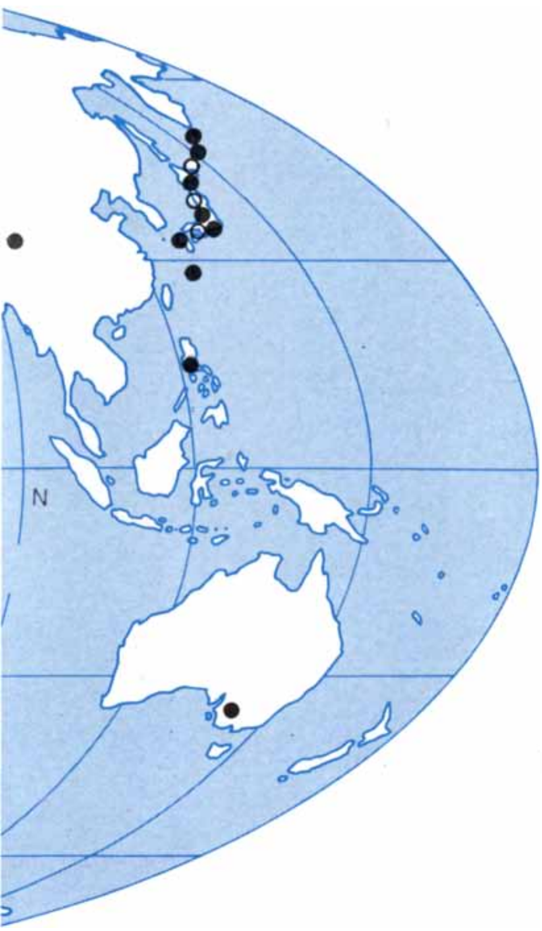
The largest-known reserves of sulfur are in sedimentary deposits. In many of these deposits the sulfur is associated with gypsum (calcium sulfate dihydrate, $CaSO_4 \cdot 2H_2O$), anhydrite (anhydrous calcium sulfate, $CaSO_4$) or limestone (calcium carbonate, $CaCO_3$). The sedimentary sources include the deposits of elemental sulfur found in Sicily, Poland, Iraq, western Texas and the region of the Gulf of Mexico. The combined sulfur in the sour-natural-gas fields of southern France, western Canada and several countries of the Middle East is probably also sedimentary, as are the sour petroleum crudes of the Caribbean and the Middle East, the many sulfurous-coal deposits of the world and much of the vast amount of sulfur present in the ocean as dissolved salts. In the earth's crust sulfur is not one of the more abundant elements: it occurs at an average abundance of .06 percent, compared with 8 percent for aluminum, 4 percent for iron, 3.4 percent for calcium, .005 percent for copper and .001 percent for



SOURCES OF SULFUR are identified. A salt dome is the kind of geological structure where elemental sulfur is sometimes found in the rock overlying the dome; such is the case with the sulfur-mining operation in Newgulf, Tex. In the other sources depicted sulboron. (Sulfur has also been found in rocks brought back from the moon by the Apollo astronauts; analysis by the Institute of Geophysics and Planetary Physics of the University of California at Los Angeles showed the concentration of sulfur in six samples to range from 230 to 650 parts per million.)

One reason for the close association of sulfur with sedimentary rocks may have been the reduction of calcium sulfate materials such as anhydrite and gypsum by organic material with the aid of bacteria. There is evidence that sedimentary sulfates, which perhaps originated from reactions between sulfurous volcanic emissions and calcium oxide in molten rocks, were reduced by methane and anaerobic bacteria such as *Desulfovibrio desulfuricans* to hydrogen sulfide and calcium carbonate. This hypothesis assumes that the necessary organic matter and other sustaining factors were available from decaying cellular material originating in primeval swamps and forests. Presumably the subsequent oxidation of hydrogen sulfide (by natural chemical means and also with the assistance of such bacteria as *Thiobacillus thioparus*) led to the deposition of elemental sulfur. The simultaneous occurrence of sulfur and mineral hydrocarbons such as bitumen, petroleum and natural gas has been known since ancient times; because the anaerobic oxidation of organic matter in conjunction with methane is apparently a key step in each case, the association is not surprising. Indeed, the detection of sulfur or hydrogen sulfide having certain specific isotopic ratios is often a clue to the presence of oil. It is generally believed that most sedimentary sulfur was formed epigenetically, or after consolidation, and not syngenetically, or during deposition.

In addition to the vast sedimentary deposits of elemental and combined sulfur, substantial deposits of nonelemental sulfur exist in many places as sulfide ores of iron, copper, lead and other metals. The fact that these ores are highly insoluble in water, so that they would not dissolve in water and be carried off to become sedimentary deposits, suggests that their origin is volcanic. Sulfides, particularly the hydrogen sulfide in sour natural gas, provide substantial amounts of the sulfur now consumed.



fur is found in combination with another element such as carbon, hydrogen or iron.

Methods of Production

Until the end of the 19th century much of the world's supply of sulfur came as native brimstone from Sicilian deposits, where it was obtained by shaft-mining methods much like those employed in mining iron and coal. The ore was refined by heating it in furnaces or open piles; on heating the sulfur melted and flowed away from the other substances in the ore. These processes are still in limited use, as are more modern methods of obtaining sulfur from ores: extraction by an organic solvent such as carbon tetrachloride or toluene; froth flotation that employs selective wetting agents to separate sulfur from other material, and melting by means of steam or superheated water.

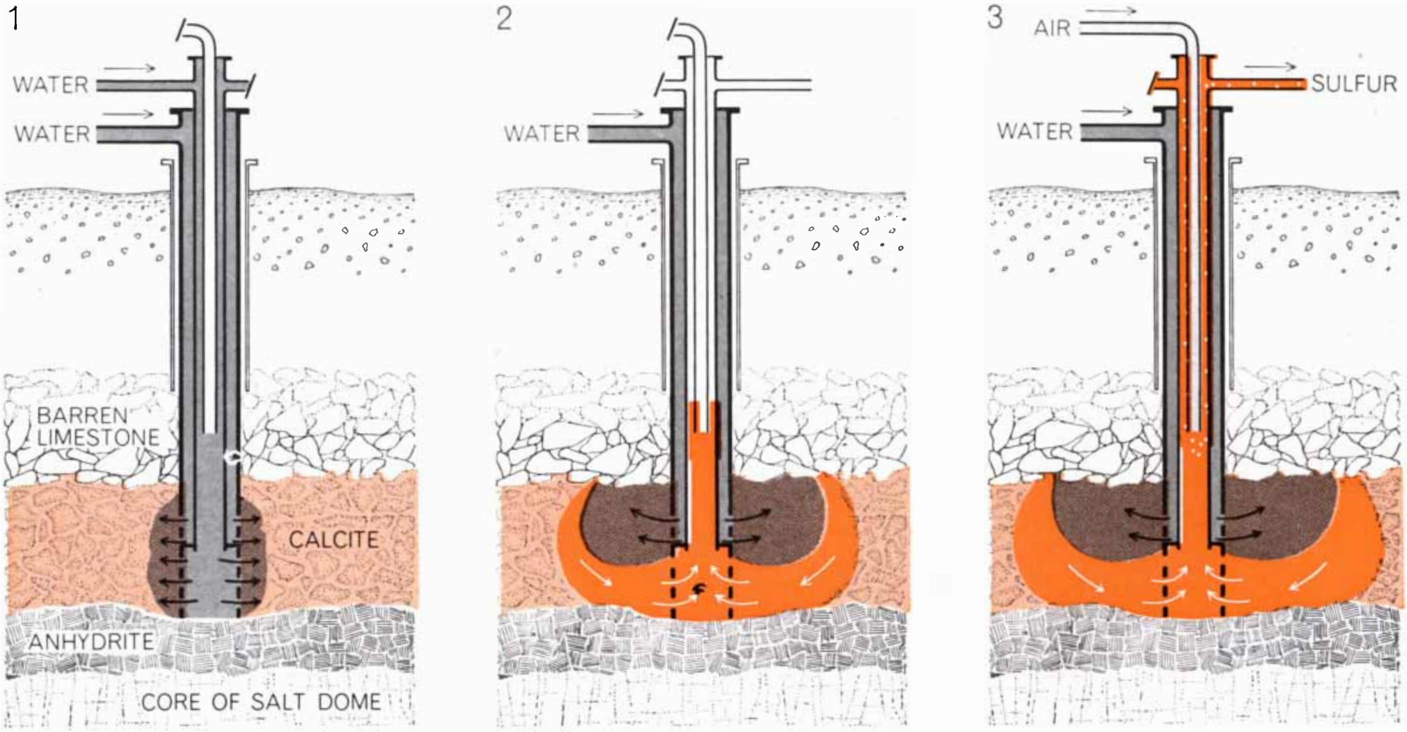
A potential major source of sulfur became known in the early days of the oil boom, but its exploitation had to wait until production difficulties could be overcome. Drillers in Louisiana had discovered a salt dome with a vein of sulfur 100 feet thick running through the cap rock. Test drilling revealed 400 feet of clay and gravel, then quicksand and a heavy flow of sulfurous water, followed at 600 feet by a thick layer of sulfur-filled limestone and, finally, a layer of gypsum. Repeated efforts to tap the sulfur by shaft mining were thwarted by the quicksand, heavy flows of sulfurous water and pockets of noxious hydrogen sulfide gas.

The solution to these problems was provided in 1890 by Herman Frasch, a petroleum chemist. He proposed that, since rhombic sulfur melts at a fairly low temperature, one could get it out of the ground by melting it in the cap rock and then pumping it up through wells as though it were oil or brine. His scheme for melting the sulfur was to put superheated water into the cap rock.

The Frasch method, first attempted in 1894, was successful and now accounts for the major portion of elemental sulfur production in North America, largely from salt domes around the Gulf of Mexico. A Frasch well [*see top illustration on next page*] is installed by sinking a protective casing as far as the upper part of the anhydrite or gypsum bed underlying the sulfur-bearing stratum. Three concentric pipes are put down into the casing. First an eight-inch pipe is sunk through the cap rock to the bottom of the sulfur deposit. The lower end of the pipe is perforated with small holes. Inside this pipe a four-inch pipe is lowered to within a short distance of the bottom. Last and innermost is a one-inch pipe that reaches more than halfway to the bottom of the well.

Water heated under pressure to a temperature well above its boiling point is pumped down the space between the eight-inch pipe and the four-inch pipe and also, at first, down the four-inch pipe. The superheated water flows through the holes of the eight-inch pipe and into the sulfur-bearing deposit. The sulfur melts and, being heavier than water, forms a pool in the bottom of the well. The pumping of water down the four-inch pipe is then discontinued. The static pressure of the hot water that has been forced into the rock formation then forces liquid sulfur several hundred feet up the four-inch pipe. Compressed air forced down the one-inch pipe foams and lightens the sulfur so that it rises the rest of the way to the surface.

At the surface molten sulfur is either pumped to huge vats for solidification or put into steam-heated tanks for delivery later to heated ships, railroad cars or trucks that carry it to market in molten form. A sulfur vat, such as the one on page 62, is a spectacular sight. A typical vat, which is actually a huge yel-



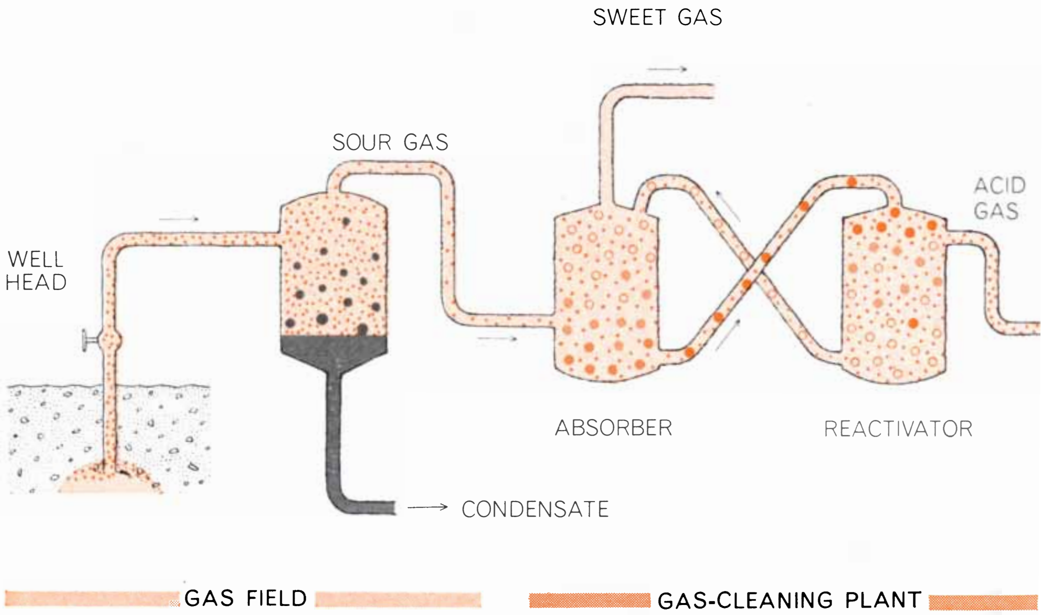
FRASCH PROCESS is employed to extract sulfur from rock overlying a salt dome. The process entails placing three concentric pipes inside a casing that lines a shaft drilled to the base of the sulfur deposit. Typical diameters for the pipes are eight inches, four inches and one inch. Water heated to a temperature well above the boiling point is pumped (*1*) down the space between the four-inch pipe and the eight-inch pipe and also, in the initial stage, down the four-inch pipe. It flows through holes in the casing and into the rock, where it melts the sulfur (*2*), which forms a pool at the bottom of the well and, under the pressure of the water, rises partway up the four-inch pipe. Compressed air forced down the one-inch pipe (*3*) lightens the sulfur so that it rises to the surface.

low block of solidified sulfur, may be 50 feet high, 1,200 feet long and 180 feet wide and hold some 400,000 tons of sulfur. A vat is built up by spraying molten sulfur thinly over the surface. Interlocking aluminum forms around the top edge of the vat contain the sulfur until it solidifies; they are then lifted up for the next layer. Sulfur is broken out of the vat as needed for shipment by railroad cars, barges or ships.

Other Processes

Large quantities of nonelemental sulfur are also processed in various ways. These types of sulfur include iron sulfides (pyrites), the sulfides of heavy nonferrous metals and, to a lesser extent, the sulfates of calcium. Such minerals are particularly important in Europe, Japan and other regions that do not have substantial supplies of elemental sulfur. Only in a few cases is the production of elemental sulfur from these ores attempted; usually the cost is prohibitive. Most of the ore is roasted in special furnaces or fluidized beds and thereby converted to sulfur dioxide, which is in turn converted to sulfuric acid. When pyrite ores are used, the remaining iron oxide, or "cinder," is often discarded unless it contains other elements such as copper in amounts sufficient to justify recovery. It is also used sometimes as a feed for blast furnaces. Nonferrous ores are roasted primarily for their metal content. In these cases the sulfur dioxide is the byproduct, and often there is no market nearby for sulfuric acid, so that the sulfur dioxide is vented to the air and becomes a pollutant.

It can be expected that increasing demands for a cleaner environment will reduce the release of sulfurous fumes not only from smelters but also from factories and power plants burning high-



RECOVERY OF SULFUR from sour natural gas, which is called sour because of its high content of hydrogen sulfide, is an increasingly important source of sulfur. In the first step the liquid hydrocarbons in the gas are separated in a condensate separator. The hydrocarbons go to a refinery and the gas, still sour, goes to a cleaning plant where the hydrogen

sulfur coal and oil. The result should be to encourage the recovery of by-product sulfur. Other secondary sources include the numerous plants now being built for the removal and recovery of sulfur in elemental form from heavy petroleum fractions.

The related process of removing sulfur from sour natural gas, which is called sour because of its high content of hydrogen sulfide, is becoming a major source of elemental sulfur in Canada, Iran, France, Germany and elsewhere as the demand for sweetened natural gas and its products rises. Usually the first step in the process is the removal from the gas of liquid hydrocarbons, which are sent to refineries. The gas is dried and transferred to a cleaning plant where the hydrogen sulfide is removed by an absorbent solution. This step produces sweetened natural gas, which is piped to the market. The absorbent moves to a reactivator where the hydrogen sulfide is stripped from it by steam and then burned with air to produce liquid sulfur and several sulfurous gases. Further processing extracts more liquid sulfur from the gases.

Canadian production of sulfur from sour natural gas is approaching four million tons per year. It could reach eight million tons by 1980 because of rising demands for sweetened natural gas in Canada and the northern U.S.

Several companies in Europe produce sulfuric acid by roasting calcium sulfate minerals with coal and sand. The process yields an almost equal amount of cement clinker, which is used in the manufacture of portland cement. A plant in Texas has begun to make elemental sulfur by a process said to be based on reducing gypsum with hydrogen obtained from natural gas. Processes still to be developed may extract sulfur from the sulfide minerals associated with coal and from seawater (by way of the scale from the boilers of large desalination plants). Another possibility that would also require new technology is accelerating the action of microorganisms on sulfate and sulfide minerals, which under normal conditions might take several million years to turn into deposits of commercial significance.

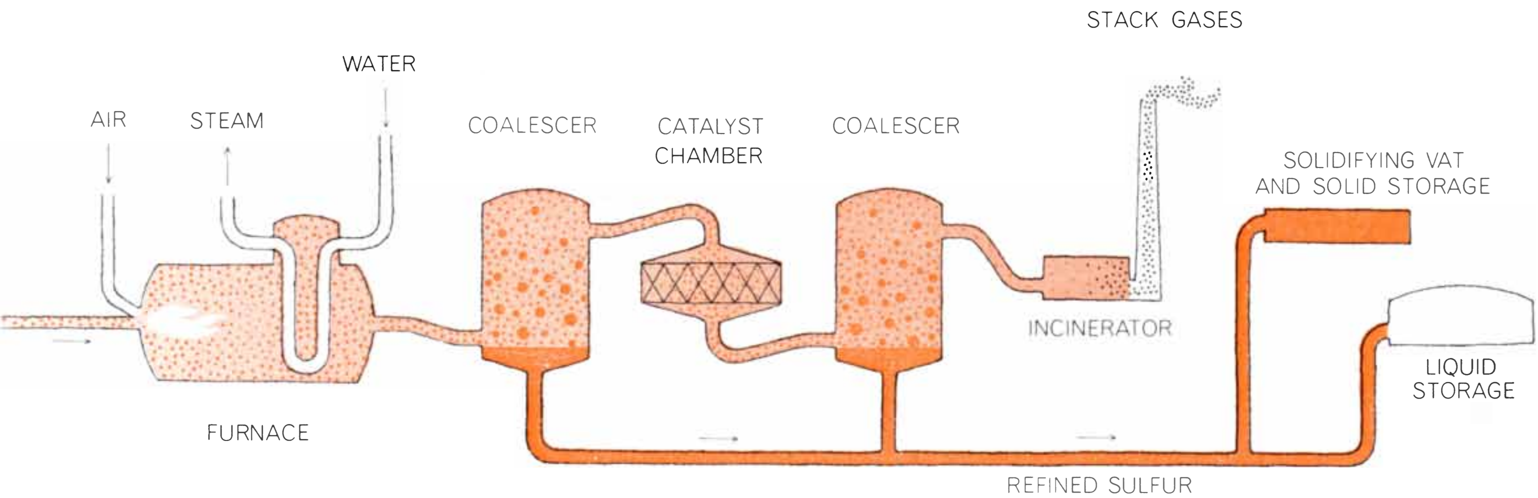
The Uses of Sulfur

With most of the sulfur from all sources being converted into sulfuric acid, and with about 60 percent of the sulfuric acid being used by the manufacturers of fertilizer, roughly half of the sulfur produced goes into agriculture. Much of the sulfuric acid thus consumed is used to dissolve phosphate rock for the production of water-soluble fertilizers such as the superphosphates and the ammonium phosphates. Substantial quantities of ammonium sulfate are also used in agriculture, since the product contains both nitrogen and sulfur.

Additional uses for sulfuric acid are so numerous that I can mention only a few of the major ones. In the refining of petroleum it is employed to remove undesirable components from feedstocks and products. In the metallurgical industry it is used to dissolve such minerals as bauxite for the manufacture of alumina and aluminum, fluorspar for making hydrogen fluoride, and ilmenite for making titanium dioxide pigment. The steel industry takes large quantities of sulfuric acid for pickling (removing mill scale from plate and strip steel).

The almost innumerable other sulfur compounds are best divided into inorganic and organic derivatives. Closely allied to sulfuric acid in the inorganic category are sulfurous acid and oleum. Sulfurous acid is made by absorbing sulfur dioxide in water, and oleum is made by absorbing sulfur trioxide in concentrated sulfuric acid. Both products are used in the manufacture of chemicals, as are other inorganic compounds of sulfur based on chlorine, carbon, phosphorus and hydrogen. They can be made by heating sulfur with the other element, often with a catalyst. The monochloride is a rubber vulcanizer; the disulfide is a solvent with a disagreeable smell, and the pentasulfide of phosphorus is an important intermediate for certain pesticides. Among the organic sulfur compounds are sulfa drugs, sulfa dyes and the sulfonated organic compounds used in detergents.

Considering only the U.S. economy, about 85 percent of the sulfur produced is used as sulfuric acid. By industry the approximate breakdown is 50 percent for fertilizer, 20 percent for chemicals, 4 percent for pigments and paints, 4 percent for petroleum refining, 3 percent for



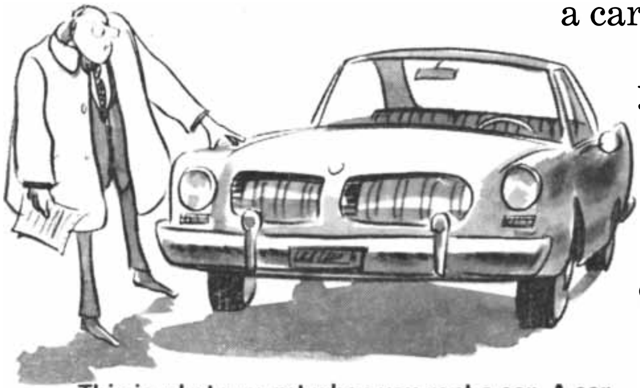
SULFUR PLANT

sulfide is absorbed in an amine solution. The sweetened gas is carried off and sold; the absorbent goes to a reactivator where the hydrogen sulfide, or "acid gas," is removed and carried into the sulfur plant. There air is added and the hydrogen sulfide is burned to form a mixture of vapor and sulfurous gases. Most of the sulfur is condensed; the remaining gases go to a catalyzer where more hydrogen sulfide is converted to sulfur vapor. In the coalescer the sulfur is condensed to liquid form. Waste gas is burned.

Renting a car vs.

When you walk up to the counter of any of the major rent a car companies, you have a right to expect certain basic things from them.

If you've made a reservation in advance, you have a right to expect that the car will be waiting and ready to go when you are.



This is what you get when you rent a car. A car.

You should expect the car to be clean. And you should also expect that it received more attention since the last guy rented it than just running it through a car wash.

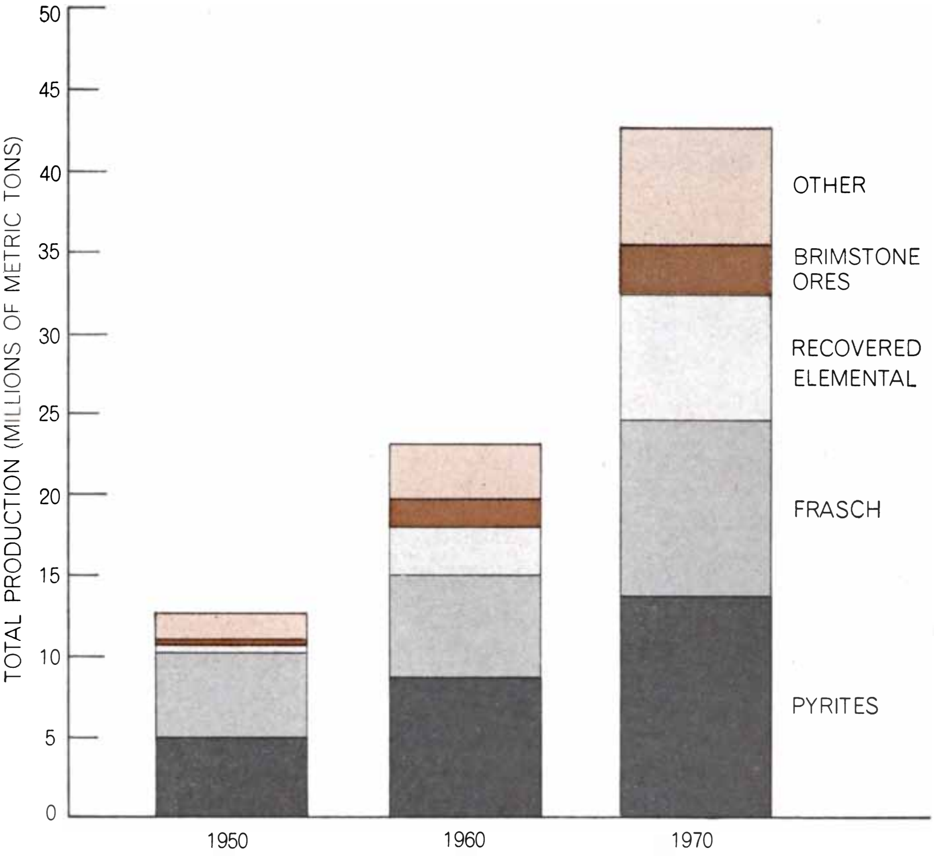
When you get out on the road, you have a right to expect that the car will do more than start and stop.

That it will run at least as well as the car you have in your garage.

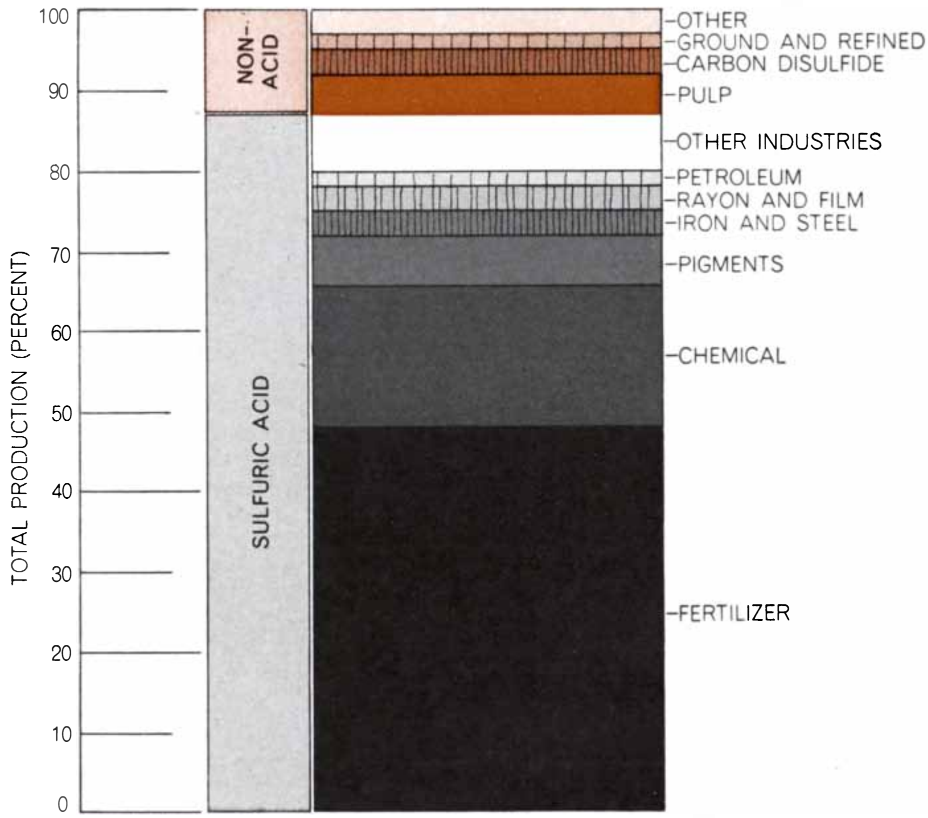
All of this together is what's commonly known as renting a car.

When you rent a car and a company, you also have a right to expect certain things, like your reservation should be kept, your car should be clean and it should run well.

But you also get things you don't expect.



PRODUCTION OF SULFUR has nearly tripled since 1950 and the proportion of the various sources has altered. Pyrites are minerals containing iron and sulfur in combination. Much of the increase in the category labeled "Other" is attributable to the recovery of sulfur from sour natural gas, which in turn reflects the increasing demand for sweetened gas.



USES OF SULFUR are mainly in the form of sulfuric acid. Its role in the manufacture of fertilizer is largely in dissolving phosphate rock to yield phosphate fertilizers. Much non-acid sulfur is used in the paper industry to dissolve impurities in pulp and to bleach pulp. Ground sulfur is used for vulcanizing rubber; refined sulfur, in medicine.

rayon and films, 1 percent for iron and steel and 3 percent for other industries. The 15 percent of sulfur that is used in elemental form is roughly apportioned as follows: 6 percent to pulp and paper; 3 percent to carbon disulfide (used for the manufacture of rayon, cellophane and carbon tetrachloride, among other things, and as a solvent for rubber); 3 percent that is ground, mainly for rubber compounding and crop-dusting, or refined for use in medicine, and 3 percent for other purposes.

Transcending sulfur's industrial importance is its vital role in life processes. If sulfate ions are deficient in the soil, the growth of plants is stunted even though other necessary nutrients are abundant. The condition is found increasingly as a result of heavy cropping and failure to apply enough sulfur-containing fertilizer. This condition upsets the formation of certain complex organic sulfur compounds such as the amino acids methionine and cystine, which are constituents of plant protein. A deficiency of such compounds in nutrition can cause serious problems, inasmuch as the metabolic processes whereby enzymes, hormones, skin and hair are formed cannot continue.

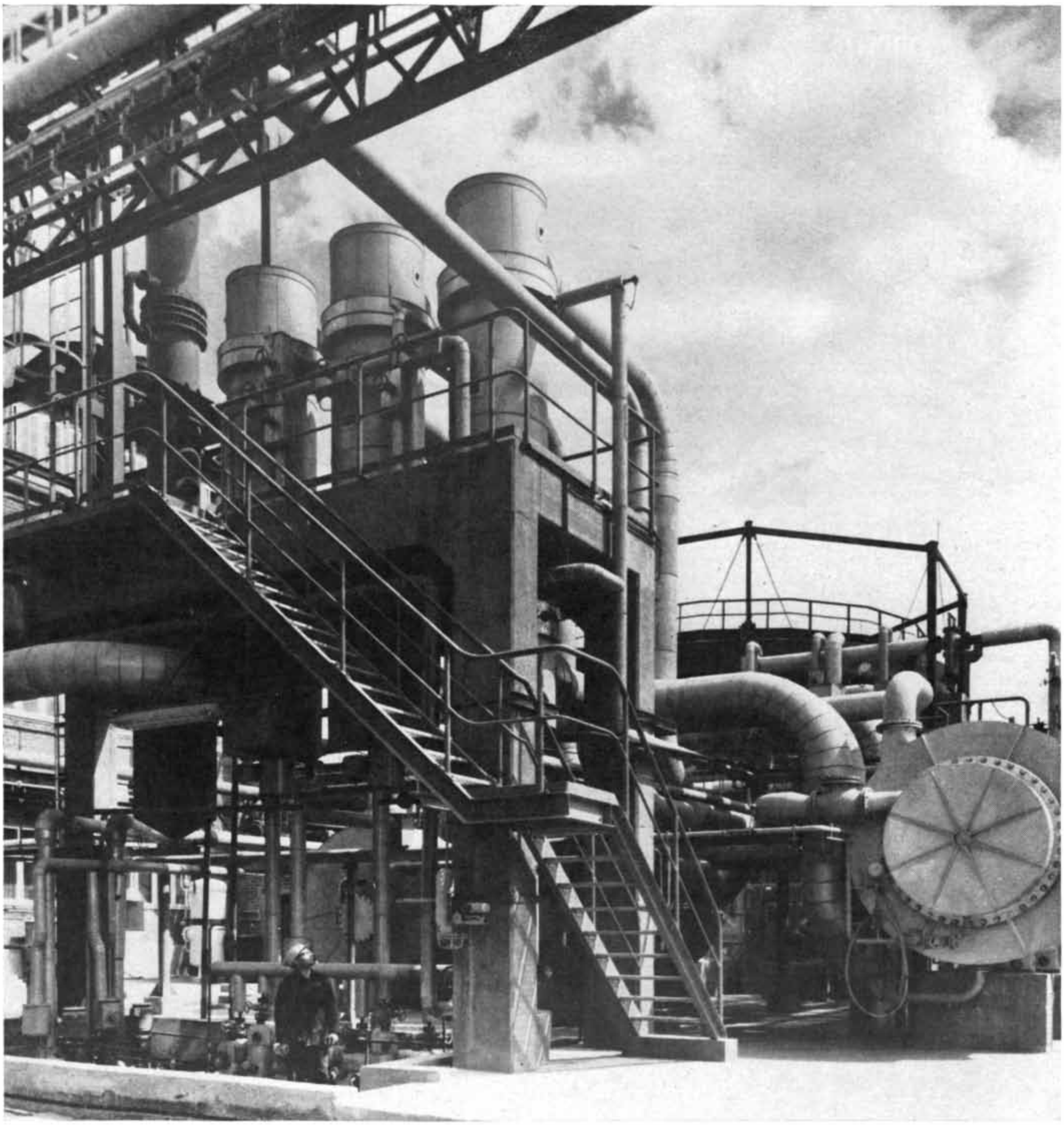
Supply and Demand

The combination of population growth and rising standards of living has caused the demand for sulfur to rise by an average of some 4 to 5 percent per year over many years. Put another way, world consumption of sulfur has risen from about one million tons in 1900 to an estimated 40 million tons in 1969. Correspondingly, the principal sources of sulfur have been expanded from the brimstone deposits of Sicily to include pyrites, Frasch deposits, sour natural gas and several others.

Even with large increases in production, demand outran supply in the early 1950's and again in the mid-1960's. On each occasion the shortages and the resulting high prices generated worldwide searches for additional supplies and led also to much new technology, not only on the part of producers but also on the part of various classes of consumers who sought ways of reducing their dependence on sulfur as a raw material. For example, European manufacturers of phosphate fertilizer began to turn to nitric acid in place of sulfuric acid, and steel producers in several countries switched to hydrochloric acid for descaling.

The combination of new sources, new technology and the resort to alternative substances brought the most recent shortage of sulfur to an end by about the middle of 1968. The increased supplies now available should be adequate for at least the next decade. Moreover, additional supplies are in prospect, notably from efforts to reduce air pollution. The petroleum industry is now facing a limit of 1 percent or less on the amount of sulfur in fuel oil burned in many localities. Removal of sulfur from such fuels may in time generate one of the biggest sources of elemental sulfur, particularly if oil from shale and tar sand comes to be more extensively exploited.

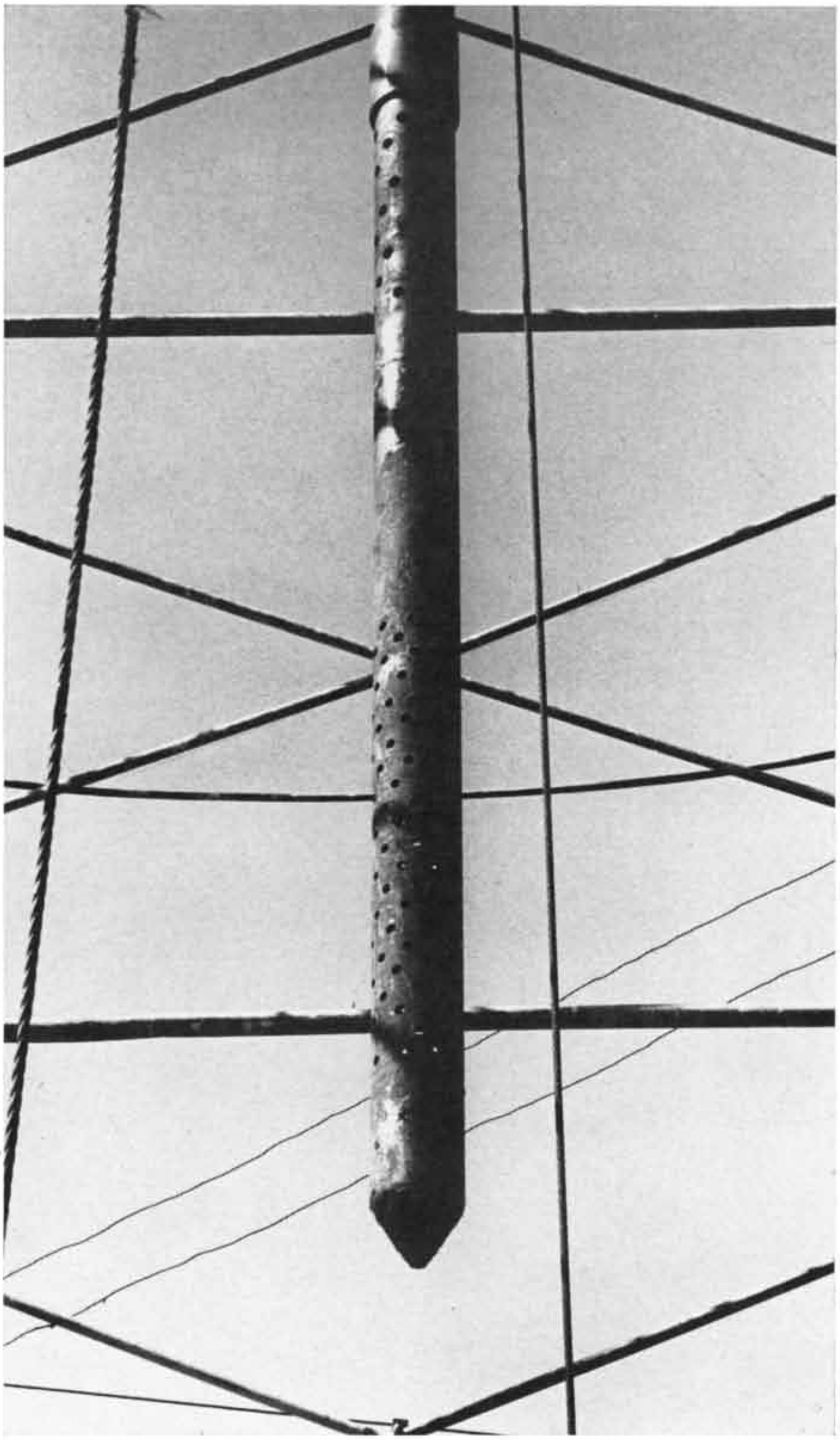
At present coal with a high sulfur content cannot be treated before combustion with the same effectiveness as oil and gas, because much of the sulfur is present in combined organic form or as closely associated pyrites and suitable removal techniques have not been developed. A good deal of work is being devoted to removal of sulfur compounds from stack gases after coal has been burned and also to the recovery of sulfur in a salable form such as sulfuric acid, ammonium sulfate or elemental sulfur. In the U.S. alone the amount of sulfur released to the atmosphere by plants burning solid fuel is estimated at some six million tons annually. Although it is likely that the treatment of stack gas



SOUR-GAS PLANT in West Germany processes hydrogen sulfide that has been removed from various sour gases. The hydrogen sulfide is partly burned to sulfur dioxide in the horizontal vessel at right. The two gases react and are cooled to form molten sulfur, which collects in the pit in the left foreground. This process accounts for about 70 percent of the sulfur that was in the feed gas. The remaining sulfur is reheated, passed through an aluminum oxide catalyst and recovered in the vertical condensers at left.

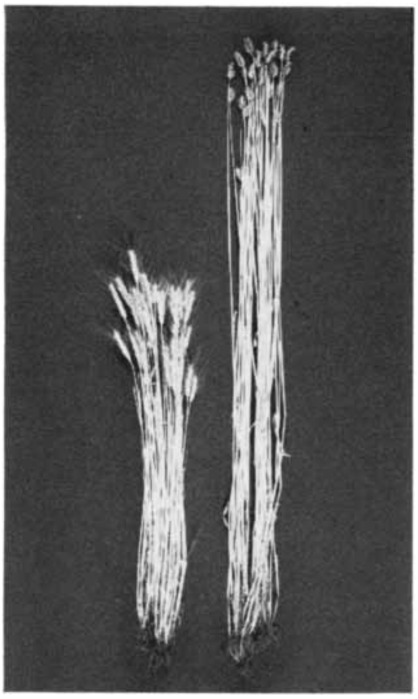
will be undertaken on a large scale, probably only a fraction of the sulfur will be recovered in a useful form because of the costs involved. A cheaper alternative may be to treat the stack gases with limestone and discard the resulting product.

In any case, the potential supplies of sulfur seem substantial. Already an excess of sulfur produced in Canada from sour natural gas is in prospect because of the steadily rising demand for sweetened natural gas. In the long run there need be no shortage of sulfur, particularly if the technology is developed to extract economically the billions of tons that exist in calcium sulfate minerals, in many coals and in seawater.



STEEL PIPE employed in the Frasch process is rigged for lowering into a well. When it is in place, hot water flows through the upper perforations and into the sulfur-bearing rock, and melted sulfur flows from the rock into the pipe by way of the lower perforations.

The "super" wheat is on the right, right? Wrong.



Some 40 years ago, Washington State University and the USDA began joint efforts to improve the production capability of wheat. After years of steady advances and significantly increased yields from new Washington strains, an unusual barrier to further progress arose: as the new varieties produced the desired bigger and heavier spikes, the stems of the wheat often failed to support them. Result? The straw collapsed, thus causing wasted wheat. Here's how the Washington scientists cut the problem down to size.

Because of the vital role of wheat in man's food supply, it was essential that efforts be made to further its yielding capability. Thus, when the superior producing strains of Washington wheat became so large that the plants began to "lodge" or fall over, the scientists at Washington State University undertook experiments with Japanese semi-dwarf strains, especially Norin 10, a type noted for its very short, wiry stems.

Before the new strain of lodge-resistant winter wheat—named Gaines—was able to raise its distinctive bearded head and white chaff in the wheat fields of eastern Washington State, numerous crosses from some five different wheat strains were made and tests were carried out not only in Washington but in Oregon and Idaho as well.

One of the most intriguing aspects in the development of Gaines was the reliance by the scientists on one of nature's oldest laws: survival of the fittest. With initial test plantings of some 1,000 new strains, massive doses of soil nutrients were applied. Since Gaines used fertilizers and moisture more efficiently than other wheats, large, mature heads soon began to appear. Harvesting was simple. Only the plants that stood up were picked. Any that didn't were left behind. This "random harvest" technique ensured the kind of vigor and lodge resistance that was needed for improved production in the winter rainfall climate of the Pacific Northwest states. Once the research techniques were completed, sufficient quantities of seed were then available for certification and release.

If you stack Gaines against such varieties as Omar (as shown in the photo above) you'll see it doesn't measure up. In high rainfall areas, the Gaines plants may be as much as 18 inches shorter than those of other wheat. In low rainfall areas, they are about four inches shorter. But what is more important is that in the medium to high rainfall areas of the Pacific states, Gaines produces from 10 to 100 percent more grain than other wheats.

Gaines can also be seeded from one to three weeks earlier in the fall than other varieties and will produce the best returns with higher than usual levels of nitrogen. It is also moderately to highly resistant to most of the common wheat diseases, and although highly shatter resistant, Gaines is remarkably easy to combine and thresh. Not the least of its good qualities is its ability to make mouth-watering pastries and cookies.

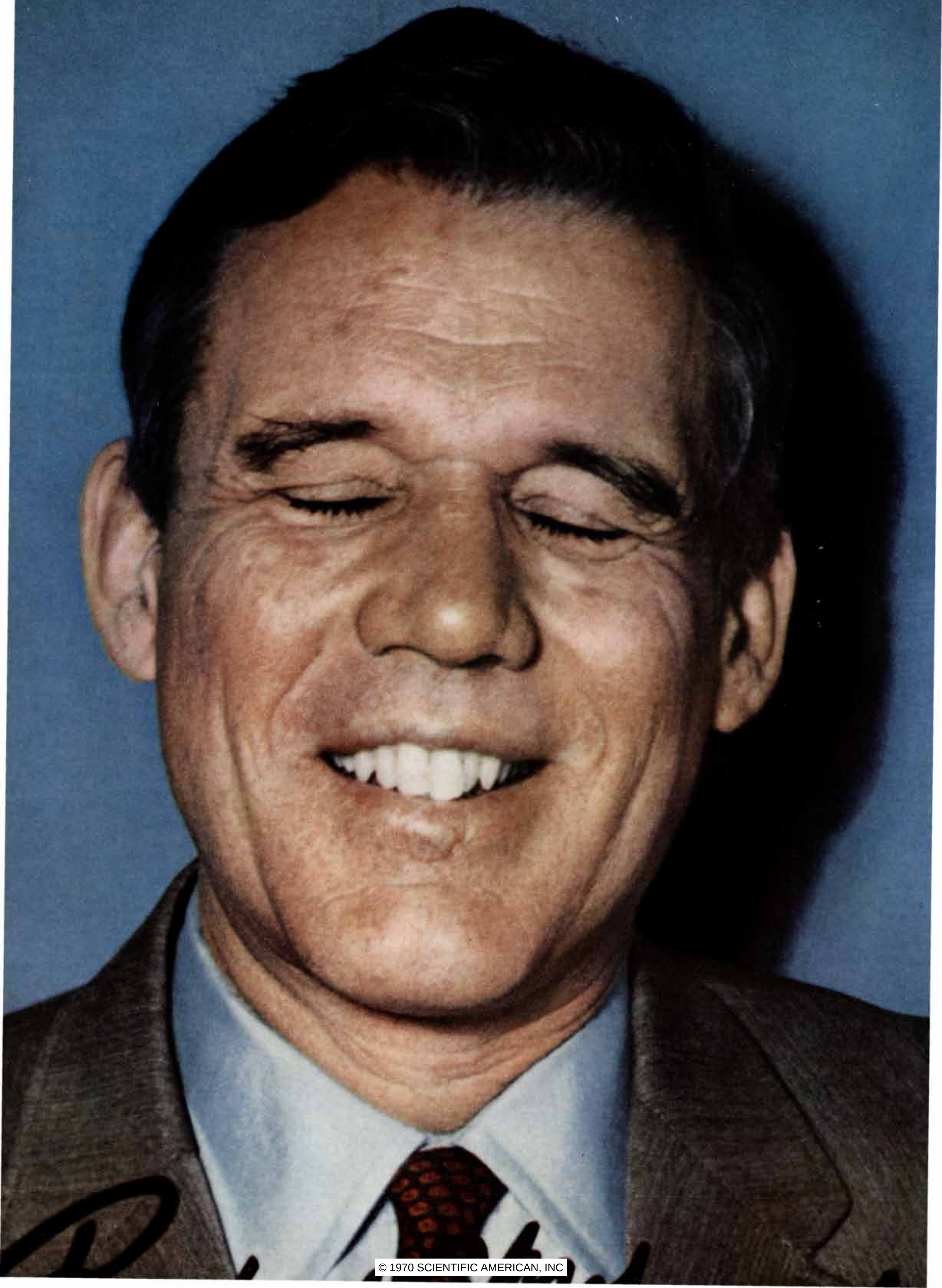
Washington State holds the world's record yield in bushels of wheat per acre—209 bushels per acre. Now that a difficult hurdle in growing improved wheat has been cleared, the chances for more consistent high production have been greatly improved. In the light of current predictions about man's diminishing food resources, that makes it a pretty important step.

The State of Washington is a fertile field for exciting breakthroughs in industry. In agriculture, forestry, aerospace, oceanography, bio-engineering, nuclear energy and many other areas, the smart money is betting on the State of Washington.

Daniel J. Evans
Governor

STATE OF WASHINGTON

For business location information, write: Daniel B. Ward, Director, Department of Commerce and Economic Development, Olympia, Washington 98501



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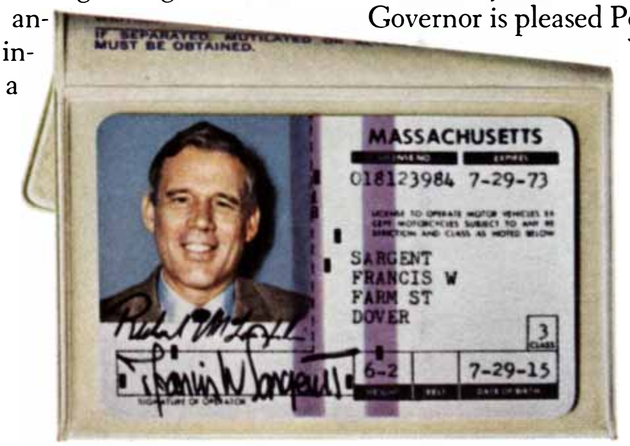

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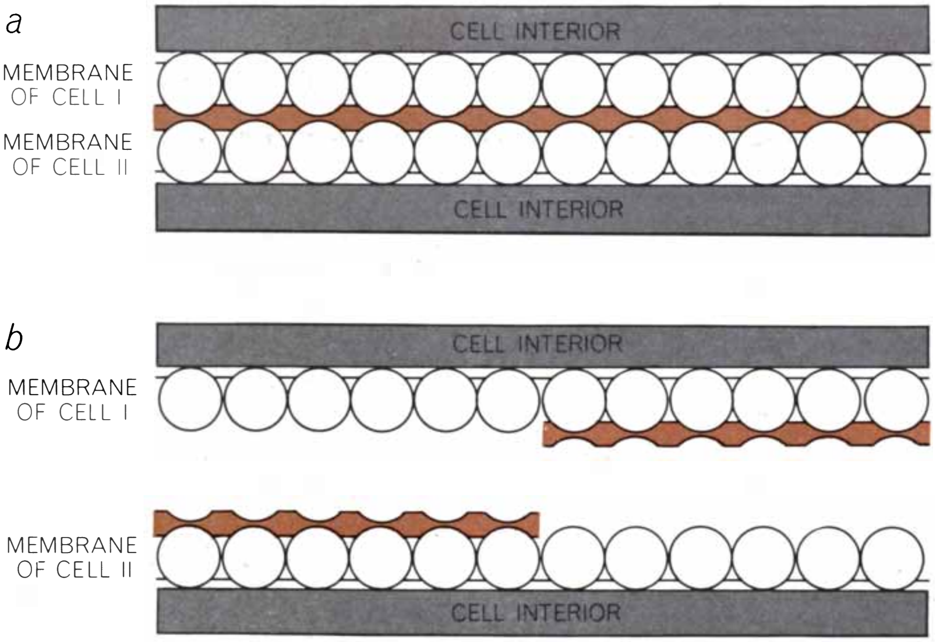
INTERCELLULAR COMMUNICATION

The cells of living tissue act in concert in various ways. A newly observed pathway may allow signal molecules to travel from one cell interior to the next through special junctions in the cell membrane

by Werner R. Loewenstein

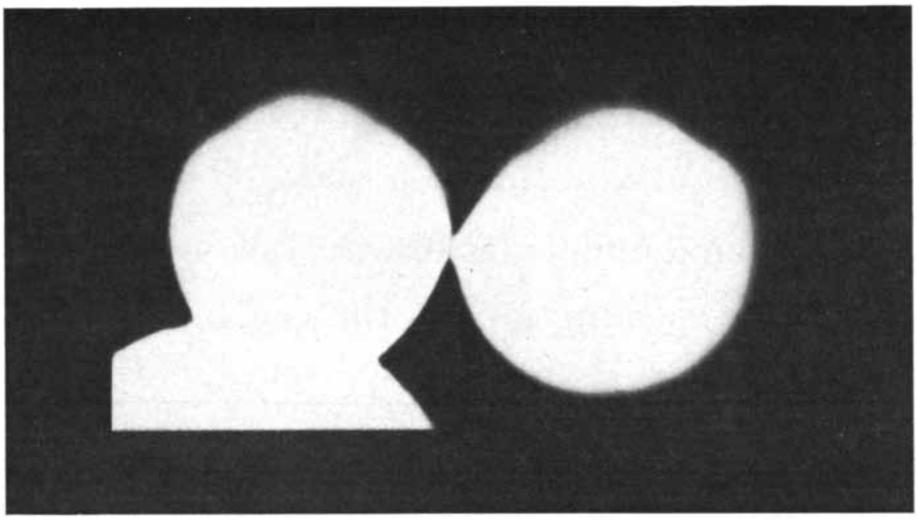
A multicellular organism is a community of cells that act in a co-ordinated way and are ordered according to a pattern. To say this is to state an obvious truth, but when we ask how the order comes about, we are immediately plunged into one of the mysteries of life. Order requires communication. Certain forms of communication are fairly well known; for example, a hormone carries a message to a cell that is specifically sensitive to it, and an antibody recognizes a cell surface antigen by its molecular shape. Recently a form of communication has come to light wherein the interiors of cells are directly connected through special molecular arrangements in the cells' surface membranes. This kind of communication seems ideally suited for controlling the patterning of cells in a developing organism.



AREAS OF CONTACT between the membranes of two liver cells are shown enlarged 140,000 times in the electron micrograph on the opposite page. Stanley Bullivant of the University of Auckland prepared the specimen by the "freeze-fracturing" process; the specimen was broken at extremely low temperature and shadowed with platinum to reveal three-dimensional detail. The diagrams (*above*) show the specimen schematically in transverse section, before fracturing along the plane of contact (*a*) and afterward (*b*). The colored area represents intercellular space. Only the lower fragment is seen in the micrograph; all the upper membrane has been broken away except for a part lying in the fracture plane (*left*). The break appears in the micrograph as a bright vertical "escarpment." To the left of it is an inside aspect of Cell I membrane as seen from that cell's interior; the closely spaced "pockmarks" indicate a zone in intimate contact with the membrane of Cell II. To the right is an inside aspect of Cell II membrane as seen from intercellular space. The small oval cluster of particles (*far right*) is a zone formerly in intimate contact with the membrane of Cell I above it. Contact zones may provide the junctions for intercellular communication.

My story starts with a chance observation. In 1962 Yoshinobu Kanno and I were studying the permeability of the membrane around the cell nucleus. For this work we used the large cells of the salivary gland of the fruit fly larva. We injected an electric current into the nucleus of one cell with a micropipette and discovered to our great surprise that the resulting electrical potential in the adjacent cell was nearly as high as the potential in the injected cell. Evidently a large fraction of the current had passed from one cell to another through regions in the cell membrane where the cells were in contact. At about the same time Stephen W. Kuffler and David D. Potter at the Harvard Medical School made a similar observation on nerve satellite cells of the leech. Half a year later Kanno and I injected relatively large molecules into a salivary-gland cell and found that they also passed across regions where cells were in contact.

These results were startling. The prevailing belief was that cells are separate units. This tenet was at the center of cell theory, which has had a strong hold on biologists, and for good reason. Cell theory originated in the first half of the 19th century, when cells were everywhere found to be self-replicating anatomical units. If any doubts remained about the anatomical independence of cells, they were dispelled during the past two decades, when the electron microscope detected a continuous membrane bounding all cells, even where the membrane had not shown up in the light microscope. It was assumed that this membrane is a continuous barrier; similar electron-microscope membrane images were seen in skeletal muscle cells, nerve cells and red blood cells, and the boundary of such cells had been shown conclusively, by osmotic and electrical



MOMENT OF CELL JUNCTION is captured in this micrograph, which shows two giant cells, isolated from a newt embryo, being manipulated into contact. The cells are .3 millimeter in diameter; measurements show that they communicate fully in a few seconds.

SALIVARY GLAND of a living midge is prepared for a study of intercellular communication by inserting micropipettes into individual cells; two of the pipettes are seen entering the cell second from left. An experiment using the technique is shown on the opposite page.

techniques, to be a continuous barrier. The membrane of these cells thus became the prototype of the cell surface membrane. The only misfits were heart cells and certain nerve fibers, which Silvio Weidman (working in 1952 at the University of Cambridge) and Edwin J. Furshpan and Potter (working in 1957 at University College London) had shown to be electrically coupled. Since these cells specialize in communication by electrical impulses, however, such phenomena were properly considered to be specializations adapted to this mode of communication.

What was thought to be the cell-membrane prototype turned out to be an exception instead. Work over the past few years in our laboratory at the Columbia University College of Physicians and Surgeons has shown that cells in a wide variety of animal tissues that are not engaged in electrical signaling communicate through permeable membrane junctions. We found this to be true of all epithelial cells we examined: cells of salivary gland, liver, kidney, thyroid, skin, urinary bladder, stomach, gut and sensory epithelia.

Electrical measurements in these cell systems showed that the small inorganic ions that carried our probing currents can move rather freely from one cell interior to another but not to the exterior. Where the cells are in contact the membrane regions (junctional membranes) are 1,000 to 10,000 times more permeable to these ions than the membrane regions facing the exterior (nonjunctional membranes). Moreover, the system's interior is effectively isolated from the exterior at the level of the cell junction. The electrical measurements thus told us that the membrane junctions must be organized to form passageways between cells. We still know very little about the structure of the passageways, but we can guess at their general location on the cell membranes. With the high resolution of the electron microscope several investigators have obtained pictures showing organized connecting regions in the areas of membrane contact. Known as "tight junctions," "gap junctions" and "septate junctions," these regions (particularly the last two) are likely sites for communication because they show some structured continuity between the cells and because they are commonly present in communicating cell systems. In order to resolve the structural organization, however, we shall need more refined techniques that do not alter the membrane structure as preparation for electron microscopy currently does.

Since epithelial cells normally are not engaged in communication with electrical signals, the question naturally came up of whether or not particles larger than potassium or chloride ions, the carriers of our probing electric currents, pass through the junction too. To explore this question we turned to molecules tagged with fluorescence or color so that they could be traced inside the cells. We injected these molecules with micropipettes under hydraulic or electric pressure. Our first tracer particle was fluorescein, a negative ion with a molecular weight of 330 that fluoresces intensely when it is excited by ultraviolet radiation or blue light. When fluorescein was injected into a cell of a salivary gland while the cell system was observed in the microscope under the exciting illumination, we found that the molecules passed from one cell interior to another without significant leakage out of the cells or their junctions. Moreover, the passage of fluorescein was blocked by treatments that block the passage of the small ions, which leads us to believe the relatively large fluorescein particle takes the same route through the cell junction that the smaller ions take.

More recently the passage of fluorescein was also shown in experiments on fibroblast cells by Furshpan, Potter and Edwin S. Lennox at Harvard University and the Salk Institute for Biological

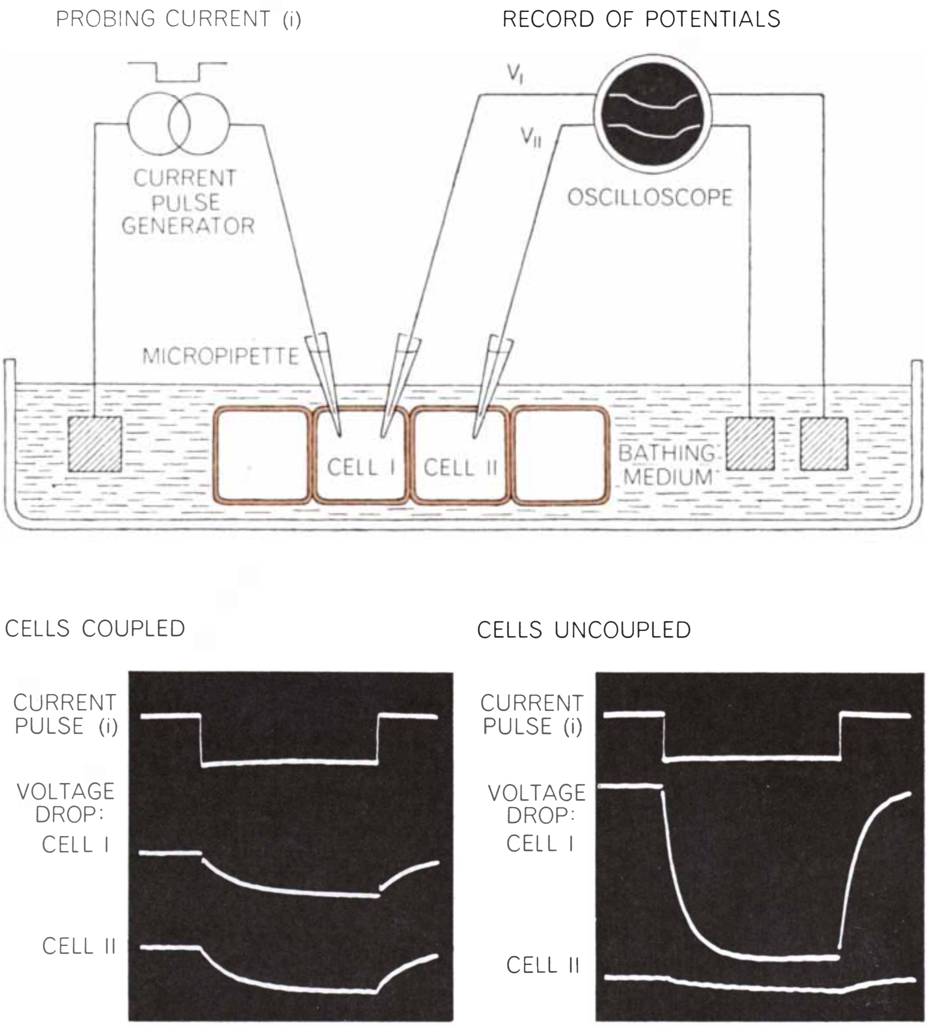
Studies, and on an electrically transmitting nerve-cell junction by Michael Van der Laan Bennett at the College of Physicians and Surgeons. In further work in our own laboratory we have found that molecules with a molecular weight of the order of 1,000 and in some instances of the order of 10,000 (but not higher) go through the cell junctions in salivary-gland cells. This leaves ample room for the cell-to-cell passage of a wide variety of cellular substances.

How does a communicating cell junction form? Here the first clue came from experiments Shizuo Ito and I did with individual cells that we manipulated into contact while monitoring the electrical resistance of their surface membranes. Cells paired up in this way produced a communicating junction in a surprisingly short time: within minutes in the case of sponge cells, and within seconds in the case of cells from early newt embryos. When the cells were separated again by manipulation or chemical treatment, the formerly permeable junctional membranes sealed rapidly and became as impermeable as the membrane of a normal free-floating cell. A new communicating junction could then be made by pushing the cells into contact again. Since the contact occurred at random at different places on the membranes, a large part of the total cell surface membrane must have the potential for forming a communicative junction.

A second clue came from experiments done in collaboration with Muhamed Nakas and Sidney J. Socolar showing that junctional-membrane permeability somehow depended on the calcium ion. Ordinarily the concentration of calcium ions in a cell's cytoplasm is several orders of magnitude lower than the concentration outside the cell. We injected calcium ions into the salivary-gland cells of midges and found that the permeability of the junctional membranes fell rapidly. Several other procedures that raised the level of calcium ions in the cytoplasm produced the same result. Under conditions where the level of calcium inside must have approached the level outside, the junctional membranes were no longer distinguishable in their permeability from the nonjunctional membranes; communication was effectively interrupted.

Another clue was provided by experiments showing that junctional-membrane permeability depended on the insulation around the junction. In these experiments I assembled pairs of sponge cells and played with the concentrations of three factors known to promote the process by which cells stick to one another: a glycoprotein-containing material at the cell surface (discovered by Tom D. Humphreys and Aron A. Moscona at the University of Chicago) and calcium and magnesium in the medium. When the concentrations of these factors in the medium were above certain values, good insulation developed around the junction, and the membranes in the junction became permeable. When the medium was deficient in these factors, no insulation formed and the junctional-membrane regions stayed as impermeable as they were when the cells were fully separated. Furthermore, when I spoiled the insulation at an established junction by removing some, but not all, of the calcium and magnesium from the medium, the formerly permeable junctional membranes sealed themselves off. This change from high to low permeability was also shown in several more organized and cohesive cells of higher animals, including mammals, by treating the tissues with certain enzymes that spoil the insulation.

On the basis of these results we have put forward the simple hypothesis that communication comes about by a conversion in permeability in the membranes owing to change in the concentration of calcium ions. We assume first that the experimental decrease in membrane permeability with an increase in calcium is one side of a two-way process, the other being an increase of permeability with a decrease in calcium. Stated differently, the assumption is that certain binding sites on the surface membrane, occupied by calcium in the impermeable state, are unoccupied in the permeable state. This is a familiar supposition to investigators in the field of biological membranes; perhaps the only unusual



INTERCELLULAR COMMUNICATION is demonstrated by passing small inorganic ions from one cell to the next (*top*). Two micropipettes containing a salt solution that conducts electricity are placed in Cell I (*left*) and a similar pipette is placed in Cell II. An electrical pulse is applied to the first cell and the resulting changes in voltage across the surface membranes of both cells are recorded by the deflection of two oscilloscope beams (*bottom*). When the cells are communicating fully and the ions move quite freely from cell to cell, the pulse produces nearly identical voltage changes in both (*left*). When the cells are uncoupled (*right*), the pulse that produces a large drop in Cell I is barely detectable in Cell II.

feature here is the wide span of the membrane permeability. From our three experimental clues the hypothesis follows: On formation of the insulating seals around the portions of the cell membranes in contact these portions are incorporated into the intracellular compartment, where they face a calcium-ion concentration several orders of magnitude lower than they did when they faced the outside medium. The chemical gradients now favor the detachment of calcium from these portions of the membrane, and their conversion from low permeability to high permeability ensues [*see top illustration on page 84*].

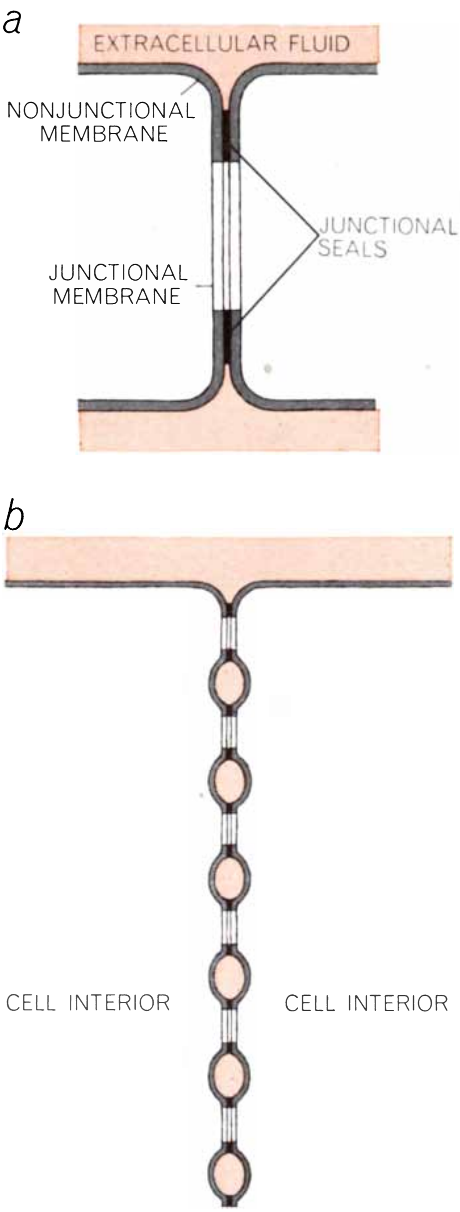
This has been our working hypothesis for two years. The hypothesis is attractive because it requires no special properties of the membrane regions that are to become junctional and no special switching mechanism for turning communication on. The essential element for triggering the permeability transformation and restricting it to the junctional-membrane region is the insulating seal, and the driving forces behind the transformation are the same forces that keep the calcium level low inside the cells. The fate of the membrane calcium inside the cell system is the same as that of all cytoplasmic calcium ions. The calcium goes to cellular depots—the mitochondria and other organelles—or to the outside through the nonjunctional membranes. As for the fate of the calcium ion on the outside of the membranes, this needs no special consideration. If the electron microscope gives anything like the true picture, there is no room to trap a significant amount of calcium ions between the intimately joined portions of membrane.

Several important points in the calcium hypothesis still lack proof. We have no direct evidence that the calcium-induced decrease of permeability in the junctional membrane is reversible or that the calcium ion reacts directly with the membrane. Even so, the hypothesis has led to new experiments telling us more about the mechanisms that promote communication between cells.

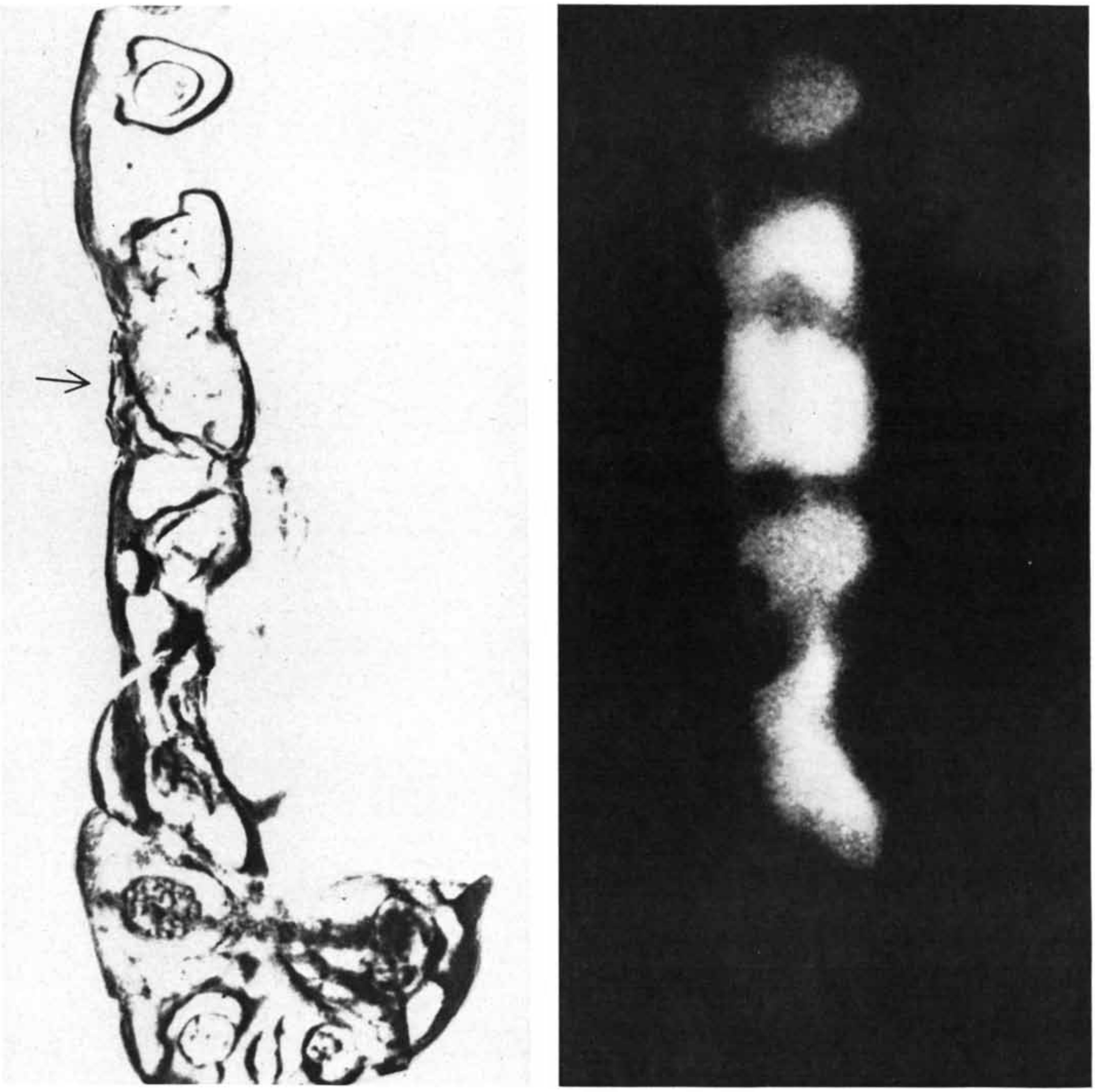
Central to the hypothesis is the idea that the low level of calcium ions within the cells is responsible for the state of high permeability in the junctional membranes. The maintenance of the low calcium level is known, in several types of cell, to require continuous transport of the ion to the calcium-rich outside by energy ultimately coming from the metabolism of the cell. One would therefore expect inhibition of metabolism to reduce the permeability of the junctional membranes. This consideration prompted Alberto Politoff, Socolar and me to investigate the effects of metabolic inhibitors of junctional communication in midge salivary-gland cells. In one set of experiments we inhibited the cell's metabolism by cooling the tissue or by adding to the bathing medium small amounts of a poison (such as cyanide, dinitrophenol or oligomycin) that blocks the synthesis of adenosine triphosphate (ATP) and other sources of energy in the cell. This treatment produced a decrease in junctional-membrane permeability, effectively uncoupling communication between the cells. The onset of uncoupling took some time: from 15 minutes to two hours. The uncoupling by some of the treatments was reversible; repetition of the treatment then produced uncoupling with practically no delay. Presumably on repetition of the treatment the cells no longer had a reserve of ATP such as they had before the initial experiment. In another set of experiments we combined the metabolism-inhibiting treatment (dinitrophenol) with the injection of ATP into the cells. This prevented or reversed uncoupling in a fair proportion of the trials [*see bottom illustration on page 84*].

A further upshot of the calcium hypothesis was the finding that substitution of lithium for sodium in the extracellular medium causes uncoupling. Such substitution was known to produce an increase in cytoplasmic calcium in various tissues. Peter Baker, Mordecai Blaustein, Alan L. Hodgkin and Robert Steinhardt at the University of Cambridge had just shown that in squid nerve fibers this increase was due to a slowing of outflow and a speeding up of inflow of calcium ions. Birgit Rose in our laboratory now undertook to study the effects of lithium substitution on cell communication. She found that within three hours of replacing all the sodium with lithium in the medium bathing the salivary glands of the midge, the cells became uncoupled. That this was not simply due to the lack of sodium ions was shown by experiments in which choline instead of lithium was the sodium substitute; then communication was maintained just as well as when sodium was present.

We come now to the question of what kind of information may be conveyed through the cell junctions. The most interesting finding in this connection was that fairly large molecules can pass by this route from cell to cell. The range in the size of particles permeating the junction is wide enough to include most molecules involved in metabolism (metabolites) and many other molecules that regulate cellular activities. Thus the exciting possibility presented itself that the size range also included substances that regulate gene activity, or, to put it more bluntly, that the junction is instrumental in conveying substances that control the growth and differentiation of cells. This possibility was appealing because the preceding 10 years of microbial genetics had shown that metabolites



PASSAGEWAY UNITS in a portion of a cell junction are represented schematically. The elements of each unit, as identified by means of intracellular probing, are shown at top (*a*), and an array of units between two cell membranes in close contact is shown at bottom (*b*). The three passageway elements are nonjunctional membrane (which is relatively impermeable), junctional membrane (which is permeable) and junctional "seals" where the nonjunctional membranes of two cells meet. Seals may simply be formed by the close contact between two membranes or they may be some kind of separate structure.

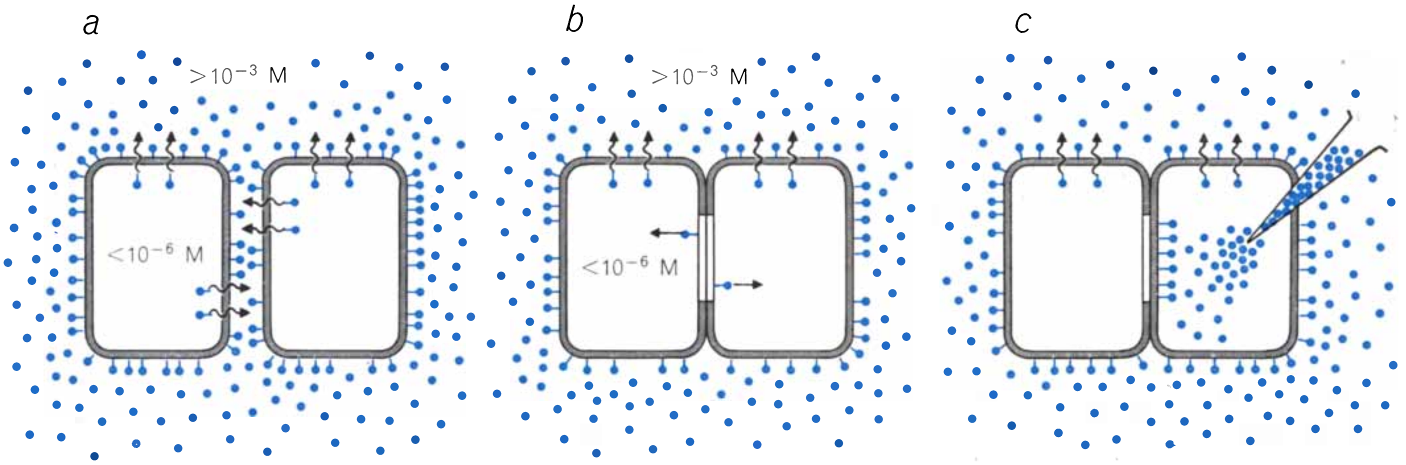


CELL-TO-CELL FLOW of relatively large molecules is demonstrated in the salivary gland of a midge. A fluorescent tracer is injected into one cell (*left, arrow*). When the tracer is excited by blue light 10 minutes later, it has spread into the cells on both sides.

and other molecules of comparable size can regulate genes in bacteria, and because the past 40 years of experimental embryology had firmly left the lesson that differentiation in the embryo involves some form of close-range interaction between cells with diffusible molecules. In junctional communication we had an obvious candidate for close-range interaction: a closed system in which molecules can diffuse from cytoplasm to cytoplasm with little loss. There are, of course, other possible close-range forms of intercellular communication; for instance, molecules can be passed between cells through the extracellular liquid, and this form of communication is undoubtedly important in embryonic development. Junctional communication has an unusual potential, however, in developmental processes where information about the number and position of cells in a cell community must be conveyed. The cell community has a finite volume and a sharp peripheral diffusion boundary (the nonjunctional membranes and the junctional seals), and it thus has the potential for obtaining such information on the basis of simple clues in the concentration of diffusing signal molecules.

When we found that a particle as large as fluorescein could pass through a cell junction, we were immediately drawn to the exploration of the possibility that the communication system disseminates signal molecules for the regulation of cellular growth and differentiation. We would have liked to play with the communication signals, but in no instance of close-range embryonic development had a signal molecule been identified. We therefore had to resort to the indirect tactic of examining the communication situation in aberrant cells where the control of growth had obviously gone wrong.

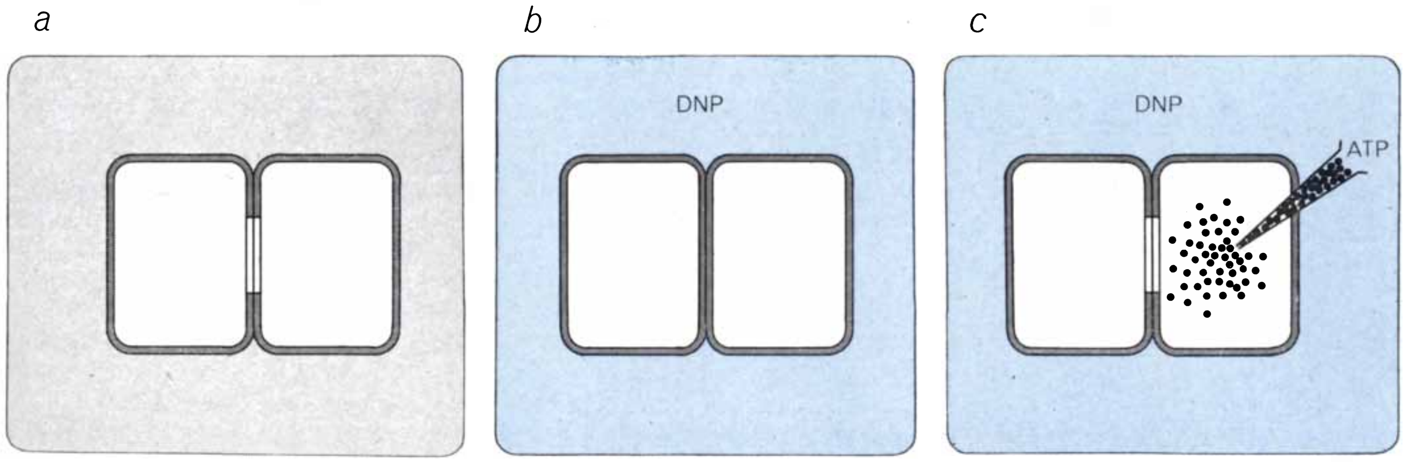
We began with experiments intended



CONVERSION HYPOTHESIS assumes that the permeability of cell membrane is determined by the concentration of calcium ions (*"a," colored dots*) in the medium on both sides of the membrane. On a membrane surface exposed to normal extracellular medium, with a calcium concentration greater than a thousandth of a mole per liter, calcium binding sites are largely occupied. Inside the cell calcium ions are comparatively rare; they are constantly being expelled (*wavy arrows*) by energy derived from cell metabolism and the calcium binding sites on the membrane interior are sparsely occupied. When two cells come together (*b*), junctional seals enclose regions of the membrane surface that were formerly exposed to the extracellular medium. The regions lose their former quota of ions (*straight arrows*) and become permeable (*white area*). The reverse process may be demonstrated experimentally (*c*). Junctional membranes between communicating cells become impermeable when one cell interior is artificially loaded with calcium ions.

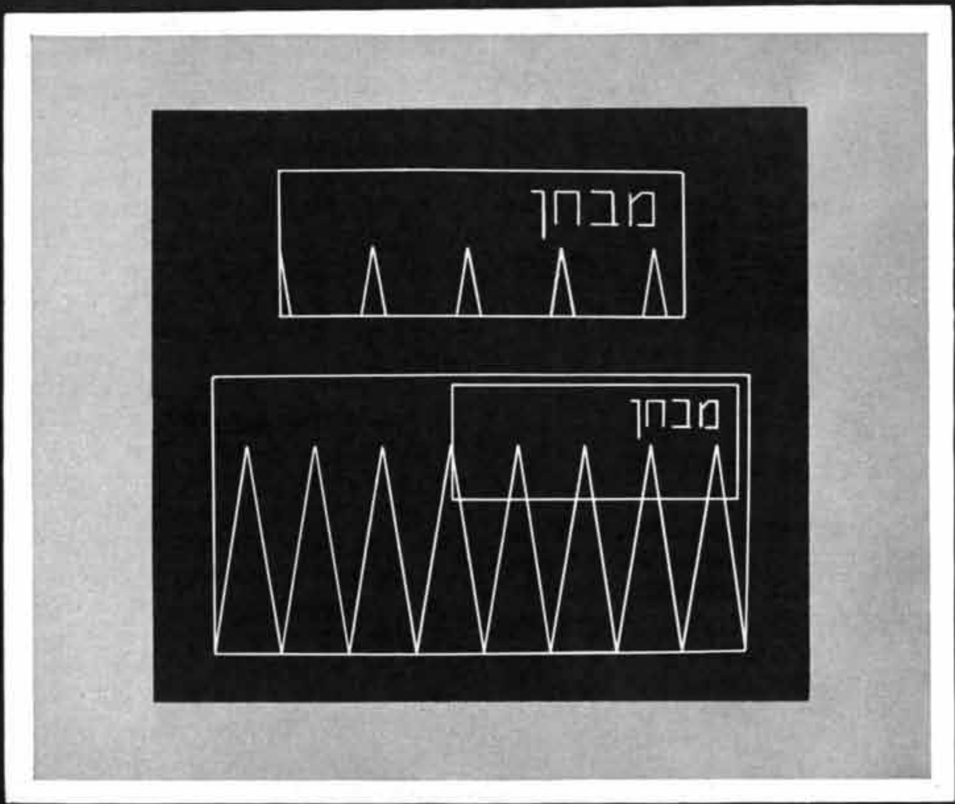
to determine if cells in a developing organism actually do communicate by means of junctions. Our first attempts in this direction were discouraging. Robert Ashman, Kanno and I spent the summer of 1964 at the Marine Biological Laboratory in Woods Hole studying the communication between the earliest cells of a starfish embryo: the first daughters of the egg cell. In these large and transparent cells we could monitor communication electrically throughout the division of the egg cell, from the time the cell begins to cleave until the first cell pair in the organism is formed. We found good communication early in cleavage, when there was presumably still protoplasmic continuity between the cells. When cleavage was completed, however, the cell pair ceased to communicate. This was the opposite of what we had expected. An attempt the following summer by Ito and myself on the first cell pair of another marine organism, the sand dollar, gave the same disappointing result.

A year later my colleague Ito and also Furshpan, Potter and Lennox at Harvard had more exciting results with older embryos. Ito, using newts, had evidence that most, and perhaps all, cells of the embryo are communicating by the time the embryo has become the globular cluster of cells called the morula. The Harvard group, working with the squid embryo and later, when joined by Judson Sheridan, with the chick embryo, found extensive junctional communication at even later stages, when the cells had visibly differentiated. The results of the Harvard group were particularly interesting; they showed that there was communication between various kinds of embryonic tissue whose fully differentiated cellular descendants are clearly unconnected in the adult animal, and that certain cells lose their connections in the course of development. Recently Bennett and J. P. Trinkhaus also found communication in the early embryos of the fish *Fundulus*, as did Christina Slack and J. F. Palmer at the Middlesex Hospital in London in the toad *Xenopus*. The demonstrations in



ROLE OF METABOLIC ENERGY in maintaining the permeability of junctional membrane is demonstrated in the case of two communicating cells (*a*). Dinitrophenol, a poison that blocks synthesis of the energetic substance adenosine triphosphate (ATP), is added to the extracellular medium. Fifteen minutes later junctional membrane permeability has fallen markedly (*b*); the cells are no longer communicating. Uncoupling presumably occurs because ATP is no longer available to power the expulsion of calcium ions from the cell interior. As the number of these ions within the cytoplasm rises the membrane becomes impermeable (*see illustration at top of page*). Next (*c*) one cell is artificially loaded with ATP. Calcium expulsion and communication resume in spite of poisoned medium.

Two views of a zig-zag test pattern and Hebrew text are shown. The overall view is preserved in the lower part of the scope. A magnified view of the picture is shown above. The part being magnified is in the rectangle inset. Note that the lines in the zig-zag pattern are clipped off in the magnified view.



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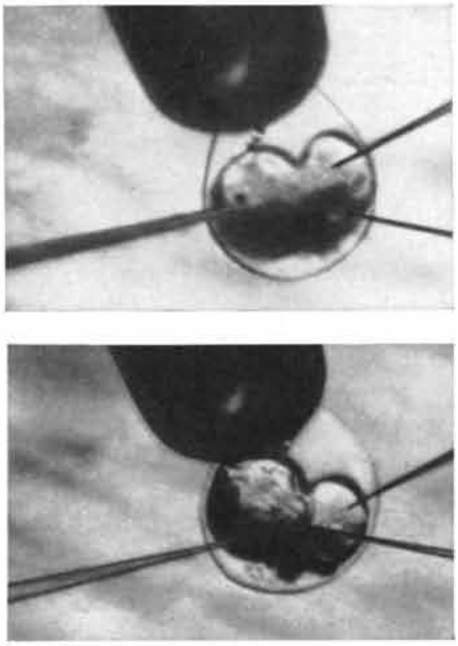
these five animals, belonging to widely different groups, established that junctional communication is present during the period of active growth and differentiation.

Our work with aberrant cells was prompted by the consideration that if the junction was indeed a gateway for growth-controlling substances, one could expect that unregulated cell growth such as cancer might in some cases be due to poor junctional communication. We hoped that our electrical techniques for probing the junctional passage of small inorganic ions would be useful for detecting any such alterations in communication.

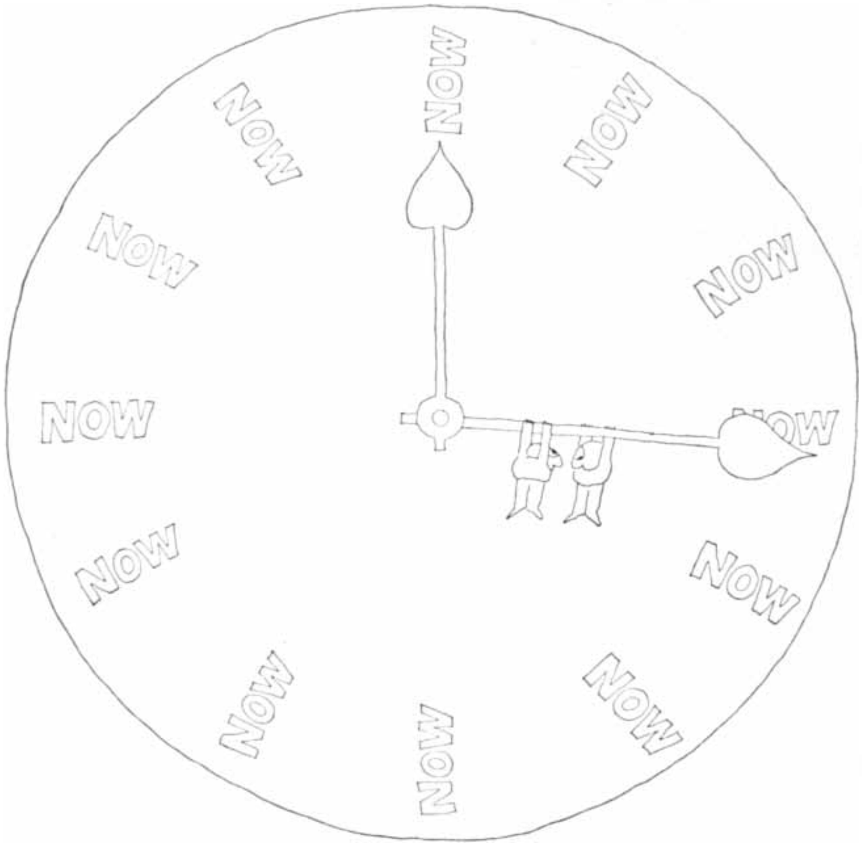
A suitable cell material for this work was the mammalian liver. My colleague Richard D. Penn had already found that cells of normal liver have good junctional communication, and various kinds of mammalian liver tumors, produced experimentally, were available from several laboratories. Kanno and I examined four types of such tumors, representative of a broad spectrum of growth rates and differentiation; in none could we detect communication. In later experiments the same proved to be true of tumors of thyroid in the rat and of human stomach epithelium. My colleagues Carmia Borek and Shoji Higashino performed experiments along similar lines with liver cells in culture. In these experiments cells from normal and cancerous liver were grown in glass dishes where electrical measurements of communication could be made under conditions closely matched for all the cell types. Here again only the junction between normal cells turned out to be communicating; there was no communication detectable between one cancerous cell and another, or between a cancerous cell and a normal one. Apparently the membrane of these cancerous cells, unlike their normal counterparts, is rather impermeable even where the cells are in contact. The contact regions also appear different in the electron microscope; several investigators have found that cancerous liver and certain other cancerous tissues lack some of the structures that join normal cells.



COMMUNICATION between embryonic cells is monitored electrically by measuring the resistance to ion movement across the plane of cleavage. Electrodes are inserted (*top*) into a fertilized starfish egg. When cell division is complete (*bottom*), communication between the two cells has virtually halted. It begins again at a later stage.

The lack of junctional communication appears to be a manifestation of cancerous growth but not of growth in general. Penn and I showed this in a study of regenerating liver. The liver of an adult rat—like the liver of the legendary Prometheus—is capable of regenerating itself rapidly. If a part of the liver, say two-thirds, is cut off, the stump grows at the rate of a billion cells per day (a rate more rapid than that of the fastest tumor we have examined) during the first four days. The growth then slows down. By the seventh day, when the liver has regenerated to nearly its original size, growth is down to less than 8 percent of the maximum rate. This pattern of regenerative growth mirrors the picture of normal growth in an organ of the embryo. It is the picture of a cell population that knows when and where to stop growing. We found that such a regenerating cell population in fact possesses junctional communication.

Not all cancerous cell types lack junctional communication. Over the past four years the Harvard group and our own have encountered a variety of cancerous cells that show no defects in the passage of small inorganic ions or (in one case) the passage of fluorescein. This was not surprising. Defects in junctional communication are of course not the only possible cause of uncontrolled growth. Cancerous growth may arise from defects in the production or in the reception of growth-controlling substances, quite apart from defects in their intercellular passage. The finding that some forms of cancer are associated with failure in intercellular communication, however, is an encouraging development. It opens up a new approach in the story of cell growth, and research in this direction is now going forward.



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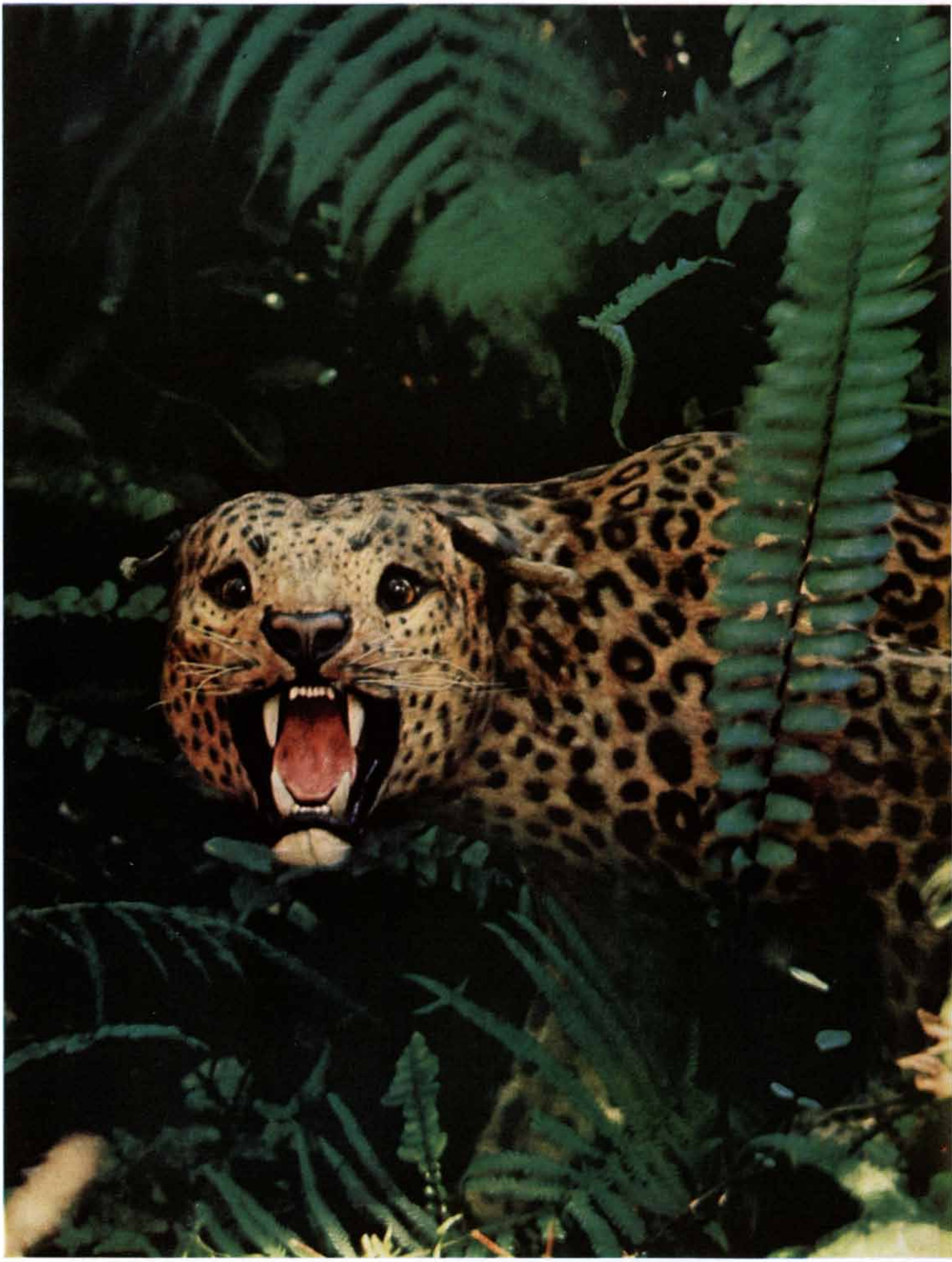

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"Second Sound" in Solid Helium

Until recently thermal waves analogous to "first sound," or ordinary acoustic waves, were thought to exist only in liquid helium. They have now been detected in solid helium and may occur in other substances

by Bernard Bertman and David J. Sandiford

Since the early 19th century physicists and engineers have regarded the flow of heat in materials as a diffusion-like process that is proportional to the temperature difference per unit length of material between the heat source and the heat sink; the constant of proportionality for a given material is called its thermal conductivity. Recent experiments have shown, however, that heat can sometimes flow in a completely different manner. Investigators at Duke University and the Los Alamos National Laboratory have reported that under certain conditions heat can flow in solid helium as a wave. (The solid helium is obtained by compressing helium that has been liquefied by cryogenic methods.) The only other known exception to the rule of heat flow by diffusion was observed some years earlier in "superfluid" liquid helium, where the wavelike thermal behavior was described as "second sound." It now seems likely that the phenomenon of second sound is much more general than had been supposed, and that under the right conditions second sound should be detectable in many materials other than liquid and solid helium.

How can one tell the difference between heat flowing as a wave and heat flowing by diffusion? It is helpful to consider the following hypothetical experiment. A long rod with one end in a bucket of ice water is at a uniform temperature of zero degrees Celsius [*see bottom illustration on page 94*]. A source of heat (such as a butane lamp) is brought near the top end of the rod and the flame is allowed to heat that end for a fraction of a second. What happens to the temperature of the rod?

At the moment the end is heated that part of the rod shows a considerable increase in temperature; elsewhere the temperature is still at zero degrees C. [*see top illustration on page 95*]. One second later some of the added thermal energy of the rod will have flowed away from the heated end toward the end in the ice water, and the temperature profile will begin to flatten out. At subsequent one-second intervals the temperature profile will continue to flatten as some of the heat flows from the hot end of the rod to the cold end. This process is rapid at first because the temperature gradient is large, but it gradually slows down as the temperature gradient becomes smaller. Eventually all the added heat leaves the sample material and the rod returns to a uniform temperature of zero degrees C.

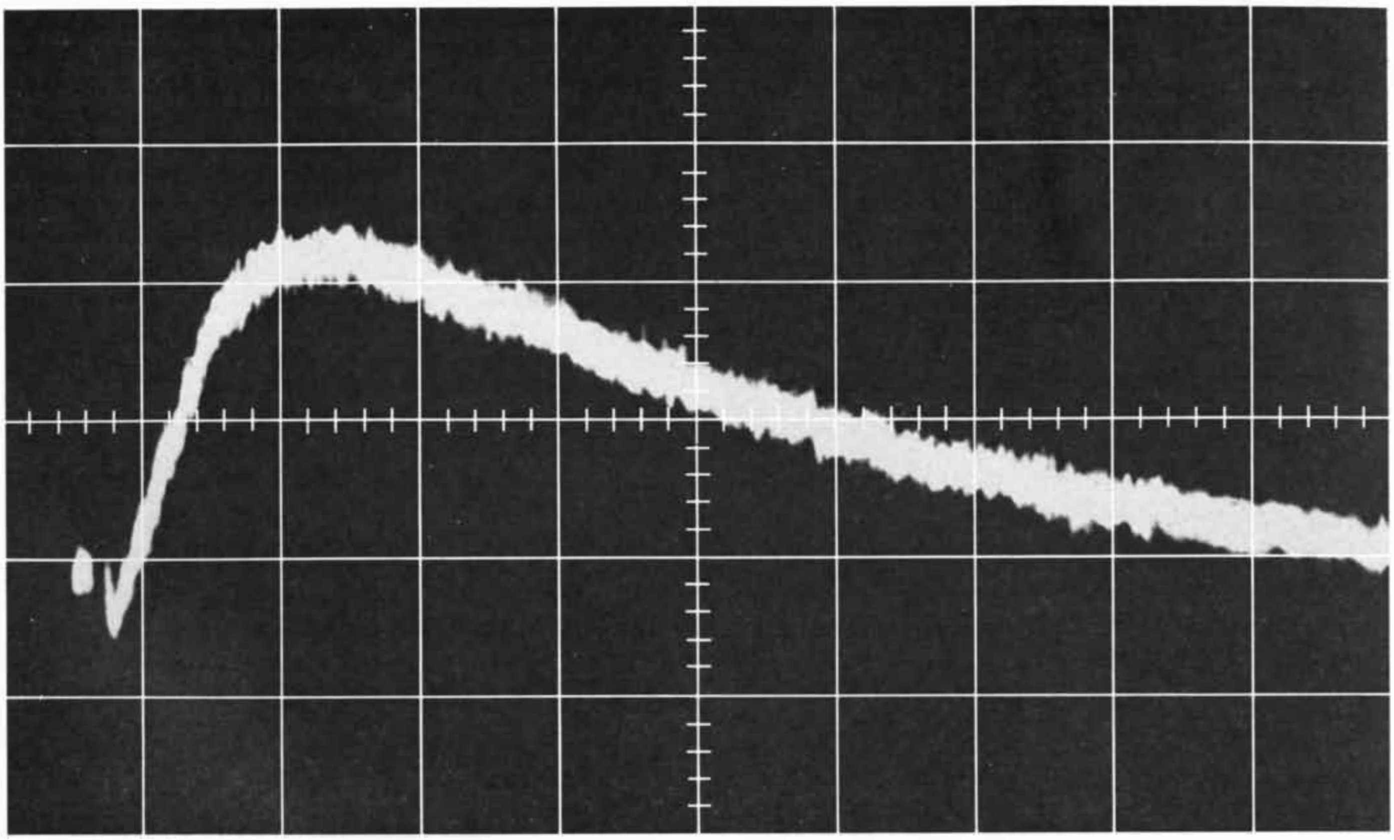
If one places a thermometer at some position on the rod, what temperatures will be recorded after the heat is applied to the end? Obviously one can obtain this information from the temperature profiles already described. The size and shape of the temperature pulse depend on where the thermometer is placed; close to the heated end the pulse will be high in temperature and not as extended in time as it would be if the thermometer were farther away where the temperature rise is lower. These results are characteristic of heat flow by diffusion.

Now, suppose temperature could move through a material as a wave. Then the corresponding temperature profiles would look completely different [*see bottom illustration on page 95*]. The temperature increase would move with a constant speed through the material, and all the heat would immediately be taken from the hot end of the rod. The heat would be contained within a small region of space that changed its position in a very simple way. The temperature recorded at a fixed point on the rod would rapidly rise and fall again. Moreover, the temperature pulse would not vary in height or width with changes in the position of the thermometer. Only the time of arrival of the heat pulse would change. Until recent years the only known example of a temperature pulse moving in this way was observed in superfluid liquid helium at a temperature near absolute zero.

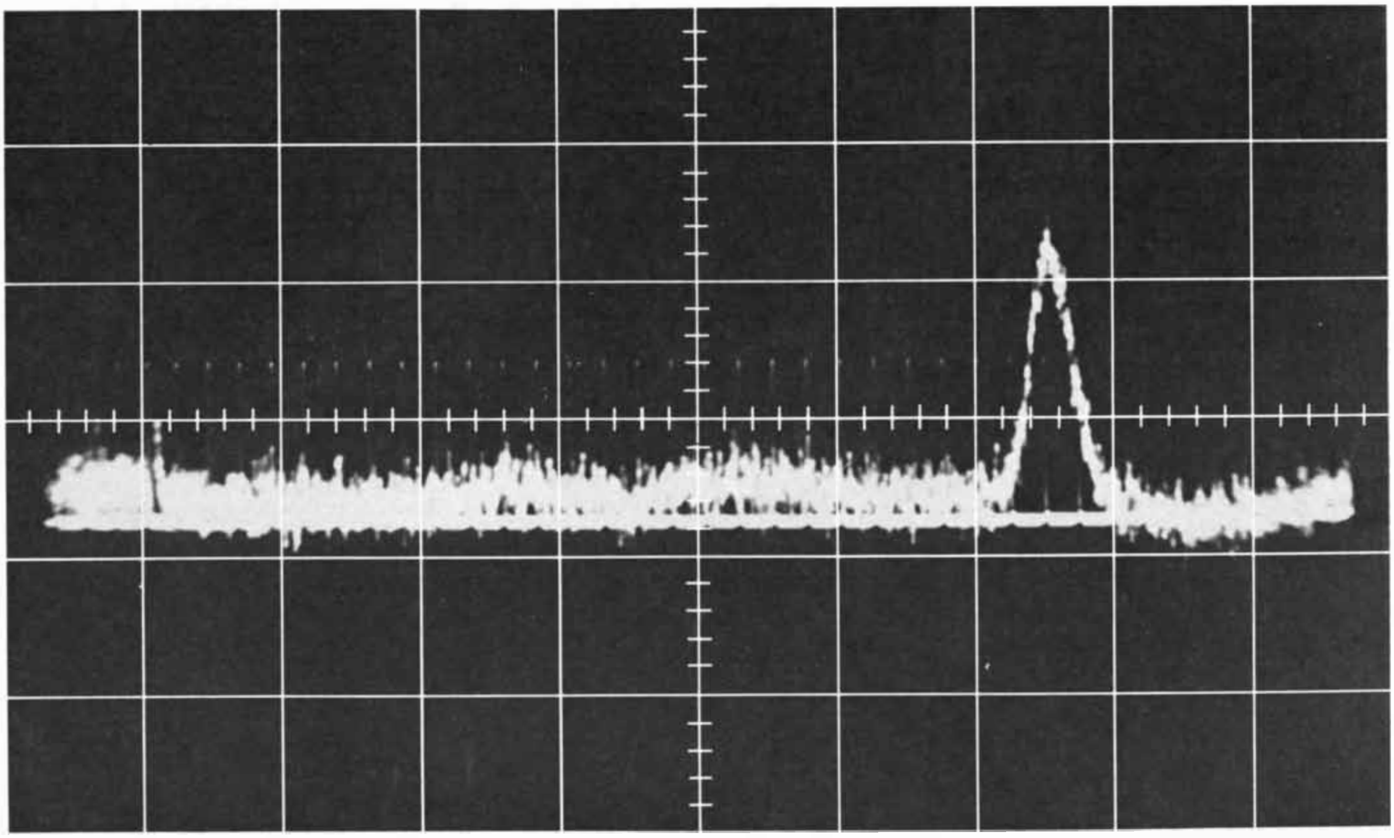
Expressions such as "heat flow" and "temperature" have a loose meaning in everyday life. In order to go further in this discussion, however, it will be useful to have a more precise idea of what these expressions mean to a physicist. For an understanding of how these terms are defined on a microscopic or molecular scale, consider first of all a gas. In a gas such as the air around us there are some 3×10^{19} nitrogen and oxygen molecules per cubic centimeter, all moving in many different directions and frequently colliding with one another. The average distance between molecules in air is about 30 angstroms (hundred-millionths of a centimeter). Between collisions the average molecule in air at normal room conditions moves at a speed of about 300 meters per second in a fairly straight trajectory until it collides with another molecule. Such collisions restrict the average molecule's trajectory to a distance of about 1,000 angstroms. This distance is called the mean free path of the molecules in the gas.

After a collision the two molecules that participated in it will have new speeds and new directions of travel. The new velocities are related to the former velocities by the conservation laws of mechanics: the combined energy before is the same as the combined energy afterward, and the combined momentum before is the same as the combined momentum afterward. The movement of the molecules is at all times governed by these laws.

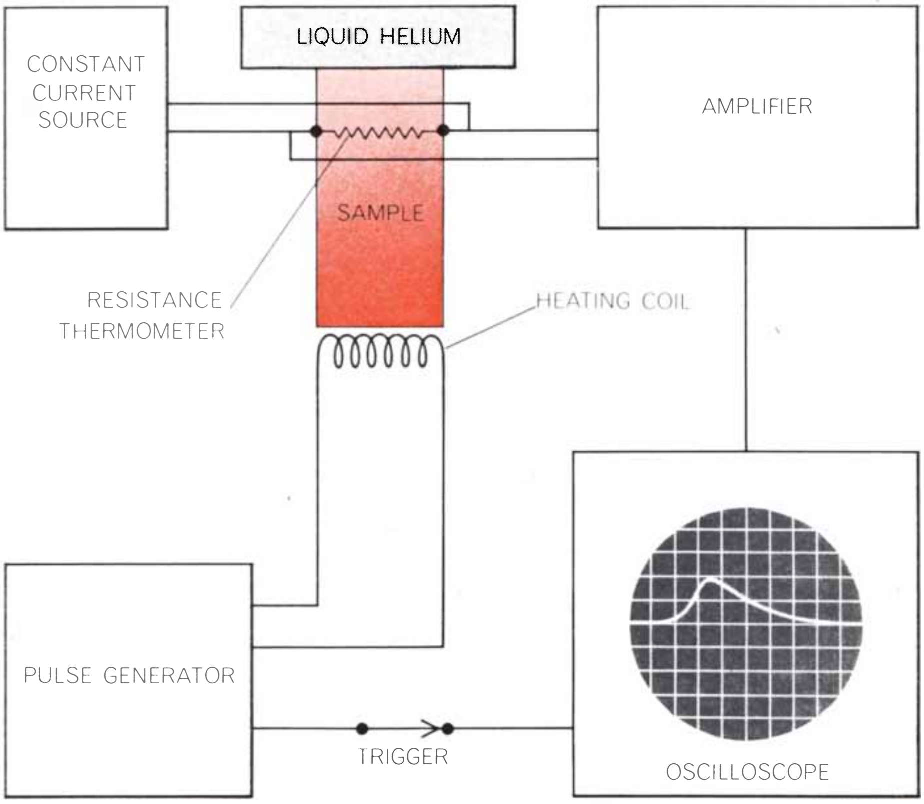
In a gas most of the energy of the



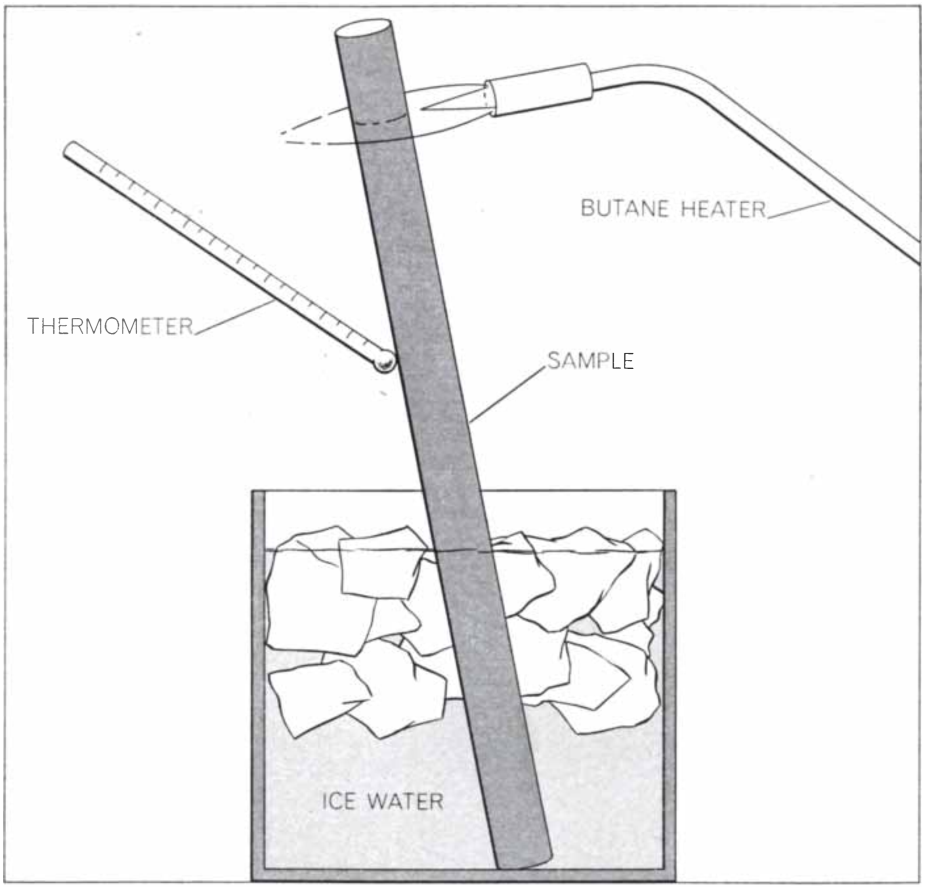
HEAT FLOW BY DIFFUSION is represented by this oscilloscope trace, which plots the temperature of a sample material as a function of time at a given distance from the heated end of the sample. The oscilloscope is triggered at the moment the heat pulse is applied to the sample. The gradual rise and fall in temperature at the measuring point is characteristic of a diffusion-like process.



HEAT FLOW BY WAVE PROPAGATION is represented by this oscilloscope trace; the sample material was superfluid liquid helium at about one degree Kelvin. The temperature recorded at the fixed measuring point rises and falls sharply at a certain time after the heat pulse is applied to the end of the sample. The temperature pulse moves with a constant speed through the sample and does not vary in height with changes in the position of the thermometer; only the time of arrival of the heat pulse changes. This behavior is characteristic of thermal waves, which were originally called second-sound waves in analogy to first-sound, or acoustic, waves.



EXPERIMENTAL SETUP was used to make the oscilloscope traces on the preceding page. An electrical pulse from a generator applies a pulse of heat to the sample and simultaneously triggers the oscilloscope. Temperature is recorded by a resistance thermometer.



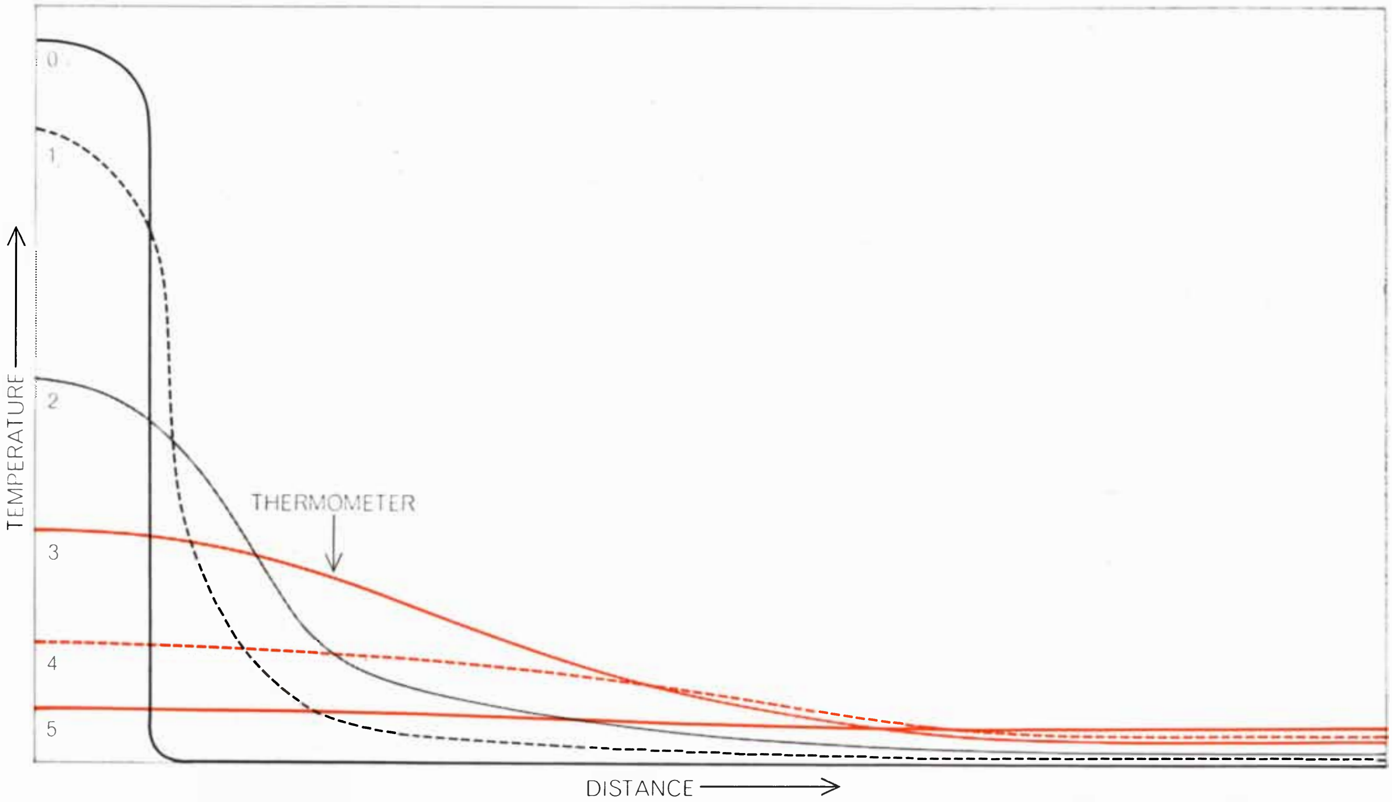
HYPOTHETICAL EXPERIMENT is helpful in understanding the difference between heat flowing as a wave and heat flowing by diffusion. A long solid rod with one end in a bucket of ice water is at a uniform temperature of zero degrees Celsius. The other end is heated briefly with a butane lamp. The temperature of the sample material can be measured in two ways: either all along the rod at a fixed time or at a fixed point for successive time intervals.

molecules is kinetic energy, both the kinetic energy of straight-line motion and the kinetic energy of rotation (if the molecule is not spherically symmetrical). The kinetics of the collection of molecules is special in that the collection contains molecules moving randomly, that is, in all possible directions. This motion is called microscopic thermal motion, and it must be distinguished from ordered motion. An example of ordered motion would be if all the molecules were given a velocity of, say, 10 meters per second in a northerly direction. This would be a wind (a bulk movement of all the air) at 10 meters per second northward and would not affect the collisions between atoms, since their relative velocities would be unaltered. The total internal energy of the gas is given by the addition of all the random kinetic energies of the molecules.

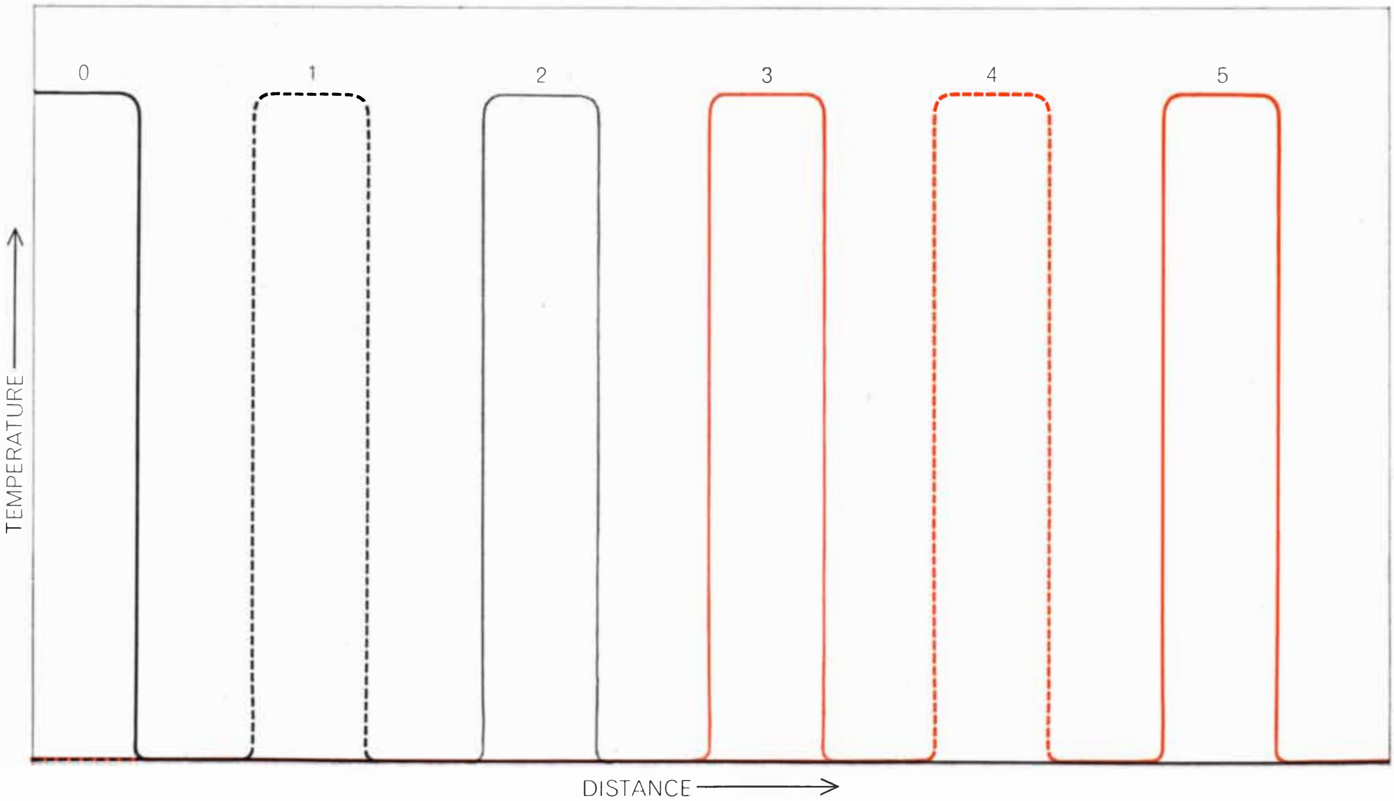
It is an important result of classical physics that the internal energy of a gas is proportional to the absolute temperature in degrees Kelvin (degrees Celsius above absolute zero). Thus if the air temperature rises from 300 degrees K. to 330 degrees, the kinetic energy of random motion of the molecules increases by 10 percent.

Thermal conductivity is a measure of the ease with which thermal energy flows by diffusion. The thermal conductivity of air, for example, can be measured by a simple experiment. Consider two plates separated by an air gap; the top plate is at a temperature of 330 degrees K. and the bottom plate is at 300 degrees [*see top illustration on page 96*]. Molecules colliding with the top plate have, after collision, an average kinetic energy that is proportional to the temperature of this plate. The same is true for molecules colliding with the bottom plate. In other words, the molecules at the top have on the average more kinetic energy (10 percent more) than those at the bottom. In a steady state the net flow of molecules upward is exactly equal to the net flow downward (because the total number of molecules between the plates is a fixed number); this condition is equivalent to saying that the total upward momentum of molecules is the same as the total downward momentum.

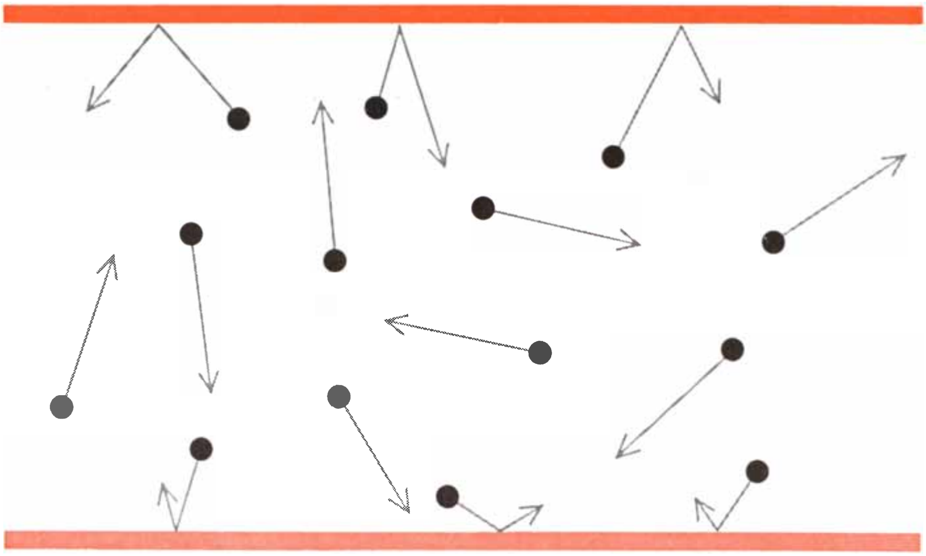
Although there are as many molecules arriving at the top plate as there are molecules leaving it, those that move down take with them more kinetic energy than those that move up. It follows that there is a net flow of random kinetic energy downward, in short, a heat flow. The theory of this phenome-



TYPICAL TEMPERATURE PROFILES for the experiment shown at the bottom of the opposite page are shown here for successive seconds of time after the heat is applied; the numbers next to the curves denote time in seconds. At the moment the end is heated that part of the rod shows a considerable increase in temperature; elsewhere the temperature is still at zero degrees C. One second later the thermal energy has begun to diffuse through the rod and the temperature profile begins to flatten out. At subsequent one-second intervals the temperature profile continues its decline, eventually returning to a uniform temperature of zero degrees C.



PULSELIKE TEMPERATURE PROFILES would result if thermal energy could move through the rod as a wave. The heat would be contained within a small region of space that travels through the material at a constant speed. Temperature pulses of this type were observed recently in samples of solid helium by experimenters at Duke University and the Los Alamos National Laboratory.



IN A GAS thermal energy is conducted by diffusion of the randomly moving gas molecules. In this simple apparatus, designed to demonstrate the thermal conductivity of air, heat is conducted from the hotter plate (*top*) to the cooler plate (*bottom*), because most of the molecules that strike the hotter plate leave with increased kinetic energy. At the cooler plate the reverse process occurs and a net amount of energy is given up by the molecules.

non was worked out early in the development of the kinetic theory of gases; the thermal conductivity was correctly related to the mean free path, the average speed of the molecules and the specific heat of the gas. Thermal conductivity in a gas, then, is a fairly well-understood phenomenon. What about thermal conductivity in a solid?

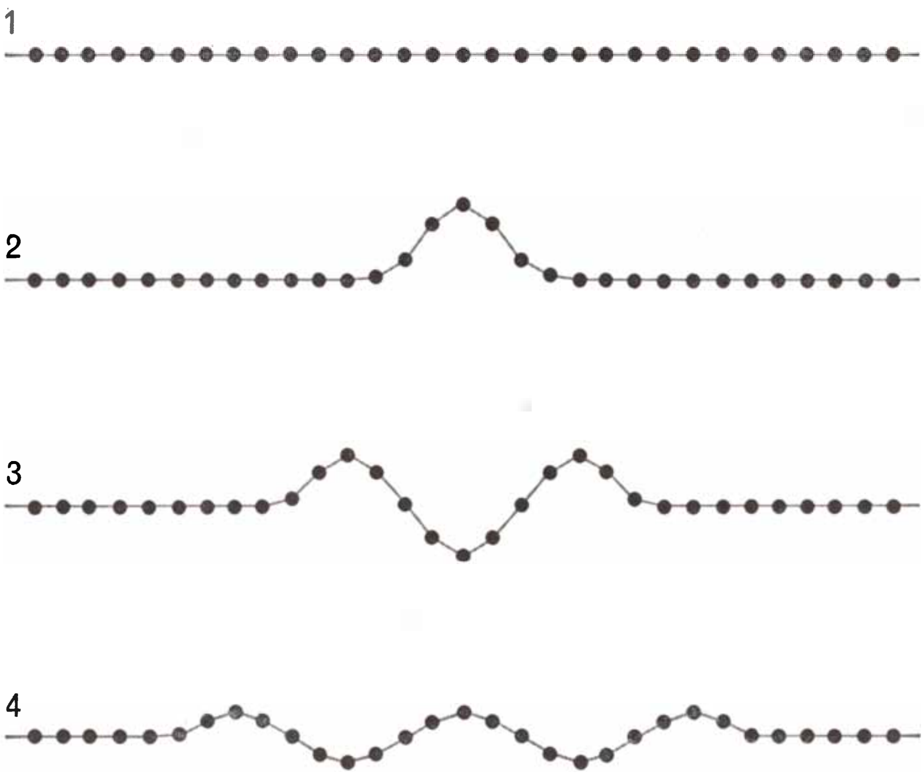
In this discussion we shall be concerned only with electrically nonconducting solids. In metals and semiconductors electrons can also conduct heat, and this makes the analysis of heat flow in these materials much too complex to consider here. In any event, second sound has not been observed in these materials.

In order to understand the flow of heat in solids one must examine the details of how thermal energy manifests itself in crystalline solids, such as diamond or solid helium. The most characteristic feature of these solids is their regularity. When a theoretical physicist sets out to calculate some property of a crystalline solid, his first approximation is that the solid is a completely regular array of atoms held together with forces that act much like springs. The atoms are not at rest but are vibrating slightly around their fixed sites in the crystal lattice.

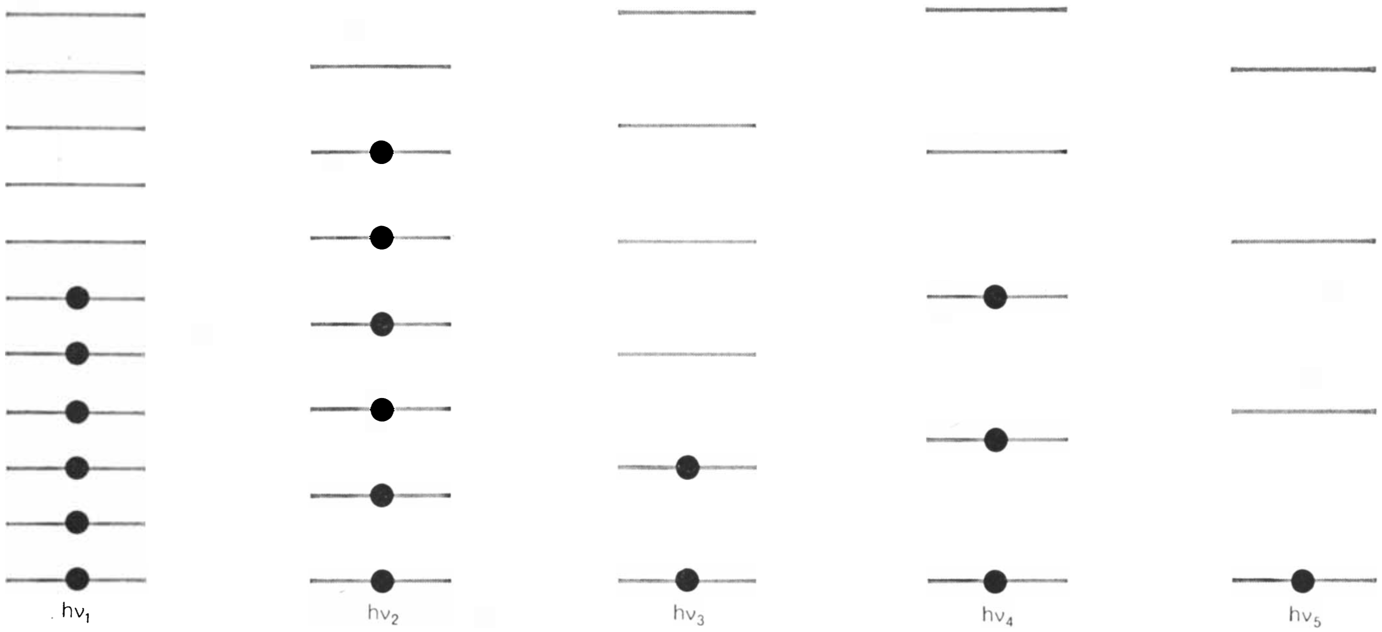
Suppose one has a crystal at absolute zero. What happens inside the crystal when one increases the thermal energy by adding heat? At absolute zero all the atoms are vibrating in their lowest possible energy states, that is, with the smallest allowable amplitude. Now, suppose one puts a heater in contact with one end of the sample. The heater of course is at a higher temperature; in other words, its atoms are vibrating much more violently. As the atoms of the heater collide with those at the end of the sample, the sample atoms will be excited in their vibrations. The springlike forces will then transmit the excitation to the atoms in the interior of the sample, so that all the sample atoms will be in higher energy states of vibration. Thus the entire sample will eventually be at a higher temperature.

One microscopic manifestation of an increase in thermal energy is evident in the increased vibrational kinetic energy of the individual atoms. The increases in vibrational energy, however, do not appear randomly among all the atoms. They are constrained by the periodic and elastic nature of the interatomic forces to take the form of waves traveling through the sample. This can best be understood by analogy with an array of balls equally spaced along a stretched rubber band [*see bottom illustration at left*]. If one of the masses is displaced slightly and then released, it not only will vibrate but also will transmit its displacements to its closest neighbors, which will as a result also begin to vibrate. Their vibrations in turn will be transmitted to their neighbors, and so on as the disturbance spreads along the rubber band. If one makes a photograph at any instant of time, the masses will be seen to have the form of a wave spreading outward from the original displacement.

The actual solid behaves in much the



IN A CRYSTALLINE SOLID an increase in thermal energy is manifested in the increased vibrational energy of the atoms around their fixed lattice sites. These increases are constrained by the springlike interatomic forces to take the form of waves traveling through the sample. The situation is analogous to an array of balls equally spaced along a stretched rubber band (*shown here*). When one ball is displaced slightly and then released, a wave spreads out from the initial displacement because of the periodic elastic coupling of the balls.



PHONONS, the hypothetical particle representations of thermal waves required by quantum theory, can exist in a solid only at certain discrete frequencies. The energy of each phonon is given by the equation $E = h\nu$, where E is the energy, h is Planck's constant and ν is the phonon frequency. The total thermal energy in a crystal is the sum of the energy of each frequency times the number of phonons with that frequency. Thus in the example represented by this diagram the total energy is $6h\nu_1 + 6h\nu_2 + 2h\nu_3 + 3h\nu_4 + h\nu_5$.

same way. The increase in vibrational amplitude at one end is transmitted to the nearest atoms and in turn to all atoms in the crystal in the form of traveling waves. Thus thermal energy is manifest as traveling waves in the solid.

It is well known that classical physics is not adequate to describe phenomena on the atomic or the molecular level, so that it is appropriate to seek a quantum-mechanical description of these "thermal waves." One of the important results of quantum theory is that wave phenomena also have particle properties and can be described as particles. The particle representations of thermal waves are called phonons, in analogy to the photons of light. Hence a solid can be described as a box containing a gas of phonons.

According to quantum mechanics, some physical quantities cannot have just any value. They can have only certain distinct values. The energy of a thermal wave, one of its most important properties, is quantized in this way. The energy difference between any two allowed values is related to the frequency of the wave by the quantum condition $\Delta E = \pm h\nu$, where ΔE is the energy difference, h is Planck's constant and ν is the frequency of the wave. The plus sign corresponds to an increase in energy; in quantum-mechanical language one would say that a phonon has been created. Similarly, when $\Delta E = -h\nu$, one would say that a phonon of energy $h\nu$, moving in the direction of the thermal wave, has been destroyed. When one adds thermal energy to a solid by placing it in contact with a heater, one actually excites thermal waves and therefore creates phonons. These considerations illustrate an important way phonons differ from the molecules of a real gas. They can be created or destroyed; their number need not remain constant. In fact, the number of phonons present depends on the temperature; the higher the temperature of a solid sample, the more phonons are present.

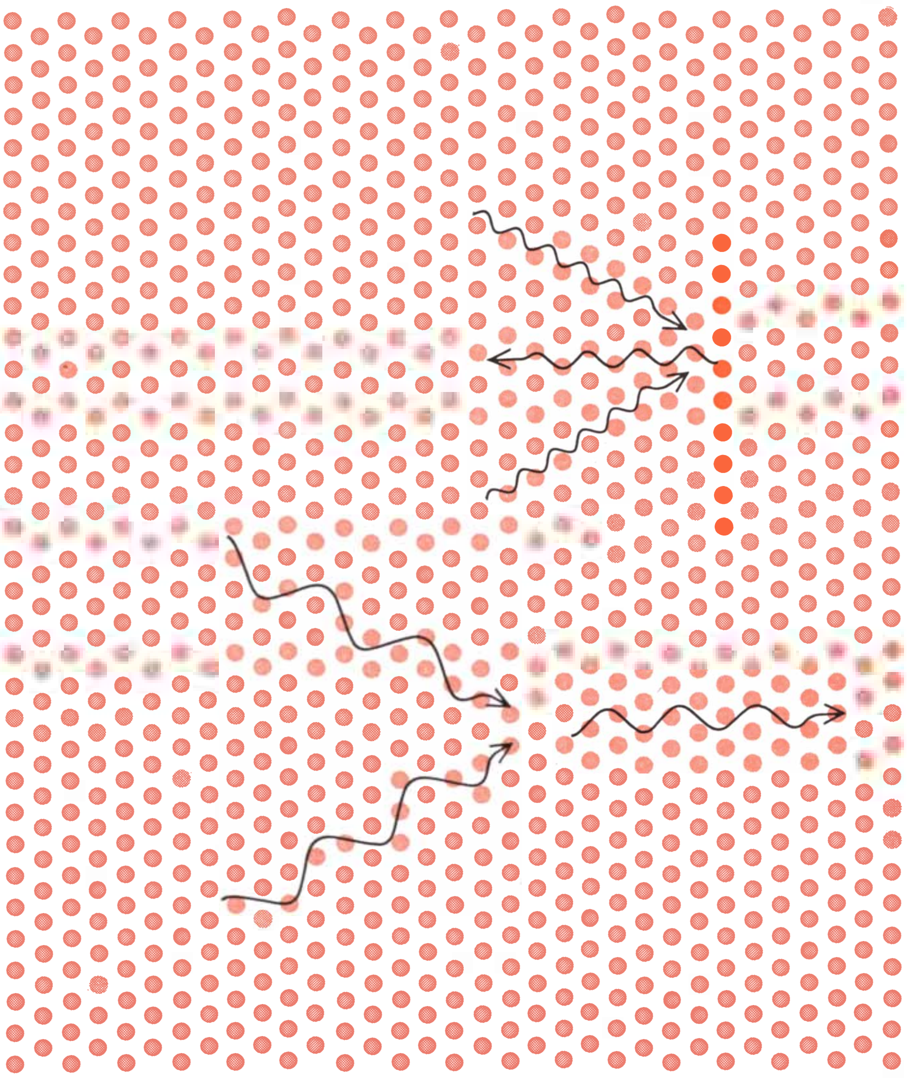
When a phonon is destroyed, what happens to its energy? Can new phonons be created to take up that energy? It turns out that this kind of "phonon interaction" can and does occur. One phonon can break up to form two new ones and two can come together to form one. These interactions occur in the presence of planes of atoms in the crystal [*see top illustration on next page*].

An analogous situation is the reflection of light from a mirror. In this case the incident photons "bump" into the mirror and are reflected back. In solids two phonons bump into the crystal planes and form another phonon whose energy is equal to the sum of the incident-phonon energies. The crystal planes deflect the direction of the resulting phonon, and in the most extreme case the energy flow can be completely reversed.

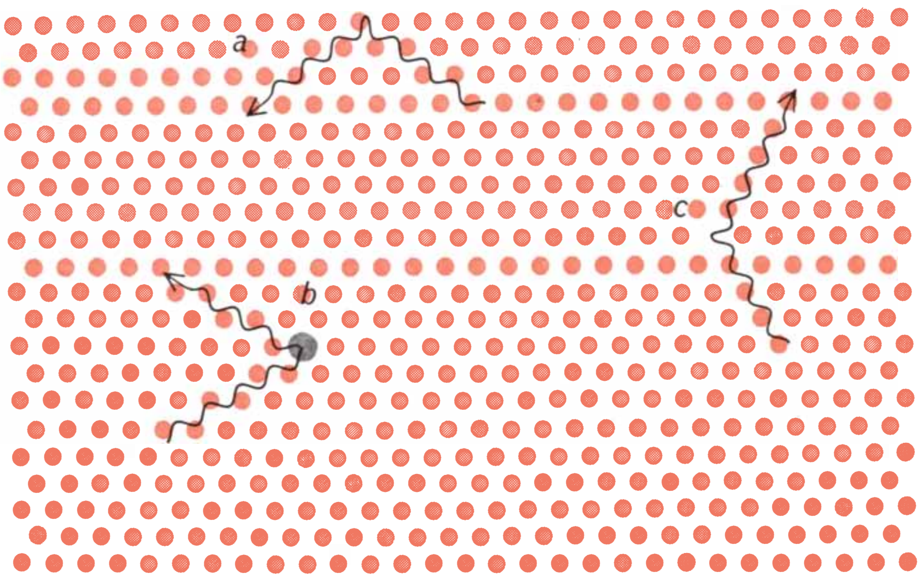
The three-phonon interaction in which the direction of energy flow is altered is called an "umklapp," or U, process (from the German word meaning "flopover"). Another type of three-phonon process is also possible, one in which reflection from the crystal planes is not involved. In this normal, or N, process the resulting energy flow is in the same direction as it was before.

For a U process to be possible at least one of the two incident phonons must have a wavelength comparable to the spacing between the crystal planes. Such a phonon has an energy $h\nu$ close to the maximum one can ever find in a solid. The number of U processes taking place increases as the solid is heated, because at high temperatures there are correspondingly more phonons of large energy (and small wavelength) available. The number of N processes taking place also increases with temperature, since more phonons (of all wavelengths) are available. The average distance traveled by a phonon before it is scattered is called its mean free path, by analogy with the molecules of a gas. The dependence of the phonon mean free path on temperature for solid helium, shown in the illustration on page 100, is typical of solids in general.

As in all other physical phenomena, energy must be conserved in all three-phonon processes: the total energy of the resulting phonons must equal the total energy of the incident phonons. In addition the wave front of the emerging thermal wave will be given by adding together the displacements of the incoming waves. As a result the direction of the resulting phonons is not arbitrary but is subject to this interference condition. Directions of physical quantities are specified by using vectors to describe



PHONON INTERACTIONS take place in the presence of planes of atoms in a crystal. In the normal, or *N*, process (*bottom*) two phonons come together to form a third phonon traveling in the same direction (alternatively one phonon can break up to form two new ones traveling in the same direction). In the "umklapp," or *U*, process (*top*) the direction of energy flow is reversed by reflection in the vertical plane of atoms (*solid color*).



PHONONS ARE SCATTERED by any deviations from perfect periodicity in the atomic structure of a crystalline solid. For example, as this illustration shows, crystal boundaries (*a*), atomic-scale "point defects" (*b*) and lattice vacancies (*c*) all scatter phonons strongly.

them, and the phonon wavelengths and direction can be related to a vector quantity called quasi-momentum, a quantity whose magnitude is inversely proportional to the wavelength. Quasi-momentum is conserved in a normal three-phonon process in much the same way that real momentum is conserved in collisions of gas molecules.

So far we have regarded phonons as being the particle representations of traveling waves in a perfectly periodic crystal. One might expect any departure from perfect periodicity to perturb the wave or scatter phonons. This is the case. We shall now describe some important phonon-scattering processes.

Perhaps the simplest and most abrupt change in periodicity occurs at the crystal boundary. One therefore expects phonons to be strongly scattered at the boundaries, as indeed they are. All crystal imperfections such as vacancies and dislocations also scatter phonons [*see bottom illustration at left*].

"Point defects" are deviations from periodicity that have atomic dimensions. A chemical impurity (an atom of a chemical species different from that of the host lattice) strongly scatters phonons. An atom of the same chemical species but of a mass different from that of the atoms of the host lattice is called an isotopic impurity. Since phonons are made up of mechanical vibrations of atoms, mass differences are departures from periodicity.

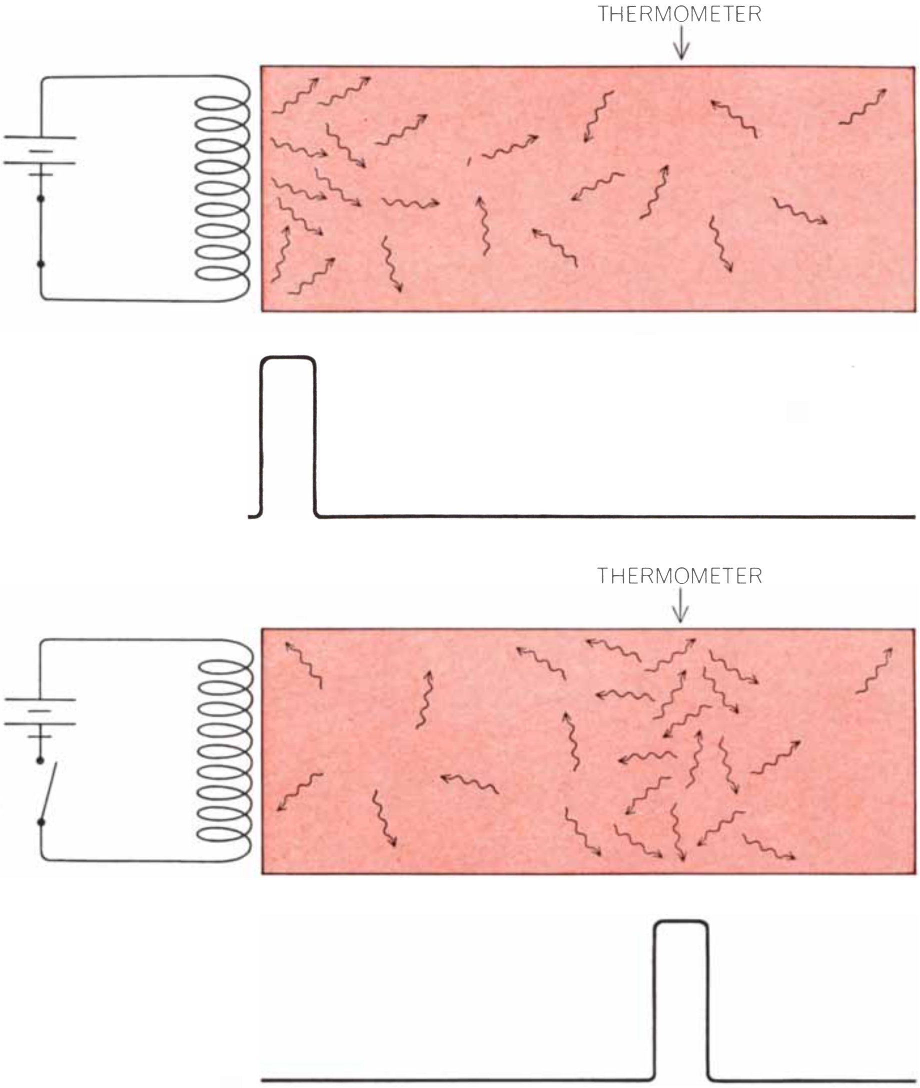
Phonon-scattering processes and umklapp processes alter the direction of energy flow; they are called resistive processes because they cause resistance to thermal conduction. The thermal conductivity of a solid depends on the mean free path for the various resistive processes. Normal processes do not directly cause thermal resistance. They serve to enable the phonons to redistribute energy among themselves.

The discussion so far has brought us to an interesting insight: The quantum-mechanical description of what happens inside a crystalline solid when it is heated is strikingly similar to the classical description of what happens inside a gas when it is heated. In a gas molecules move about with different kinetic energies and momenta; in a solid phonons move about with different energies and quasi-momenta.

Everyone knows that sound can propagate through a gas such as air. Sound is of course a wave phenomenon. For historical reasons we shall call this wave first sound. Suppose a loudspeaker is producing music from a record player. The cone of the loudspeaker is caused to vibrate backward and forward synchronously with the vibrations needed in the air to reproduce the music that arrives at our ears as sound waves. Music frequencies range from about 20 to 20,000 cycles per second and sound waves travel at a speed of about 350 meters per second in air, so that a typical wavelength (at a frequency of 1,000 cycles per second) is 35 centimeters. This wavelength is very large compared with the mean free path of an air molecule. This is a significant point. It means that the pressure variations of the air (and a sound wave is a movement through air of pressure variations) do not propagate by individual molecules but by the effect of many molecules. The molecules of air collide so frequently that for distances on the order of centimeters one can ignore the microscopic graininess of the gas. The sound waves travel in an almost continuous elastic medium.

Of course sound, and indeed music, is not a continuous wave of unlimited duration. For example, a violinist can pluck a string and a pulse of sound energy is caused to move through the air. As the loudspeaker cone pushes on the molecules that strike it, the momentum of the molecules (and therefore their average kinetic energy) is on the average increased. These molecules then collide with other molecules within a distance of several mean free paths from the loudspeaker, and the increased momenta and kinetic energy are transferred to other molecules. The density of the molecules (the number per cubic centimeter) is also increased in the immediate vicinity of the loudspeaker cone, and this together with the increased kinetic energy means that the pressure has increased. The increased average molecular kinetic energy corresponds to a slightly higher temperature of the gas. In other words, not only is ordinary sound, or first sound, a wave that transports pressure variations but also it can give rise to small temperature variations.

Let us repeat the important parts of this line of reasoning, because we shall later argue by analogy with this transport of first sound. The facts are these: One knows that first sound can be propagated in a gas when the molecules of the gas collide so frequently with one another that the wavelength of first sound is much greater than the mean free path. The interactions among molecules in such a gas obey the mechanical laws of physics, that is, the conservation of energy and of momentum. First sound is a wave and simultaneously propagates



DISTRIBUTION OF PHONONS inside a heated sample is shown for two stages during the propagation of a pulse of second sound. First the heater is turned on briefly (typically for about a millionth of a second) and many phonons are created (*top*). At some time after the heater has been switched off the phonon pulse has traveled a distance to the right (*bottom*).

pressure and temperature variations with very little loss of energy from the wave. This is quite different from temperature diffusion, which proceeds in the absence of pressure variations.

The argument extending these ideas to other systems goes as follows. Suppose one has a system of particles that interact with one another in such a way that both energy and momentum (or quasi-momentum) are conserved. Then one might hope that such a system would allow waves to be propagated as long as their wavelength is greater than the mean free path.

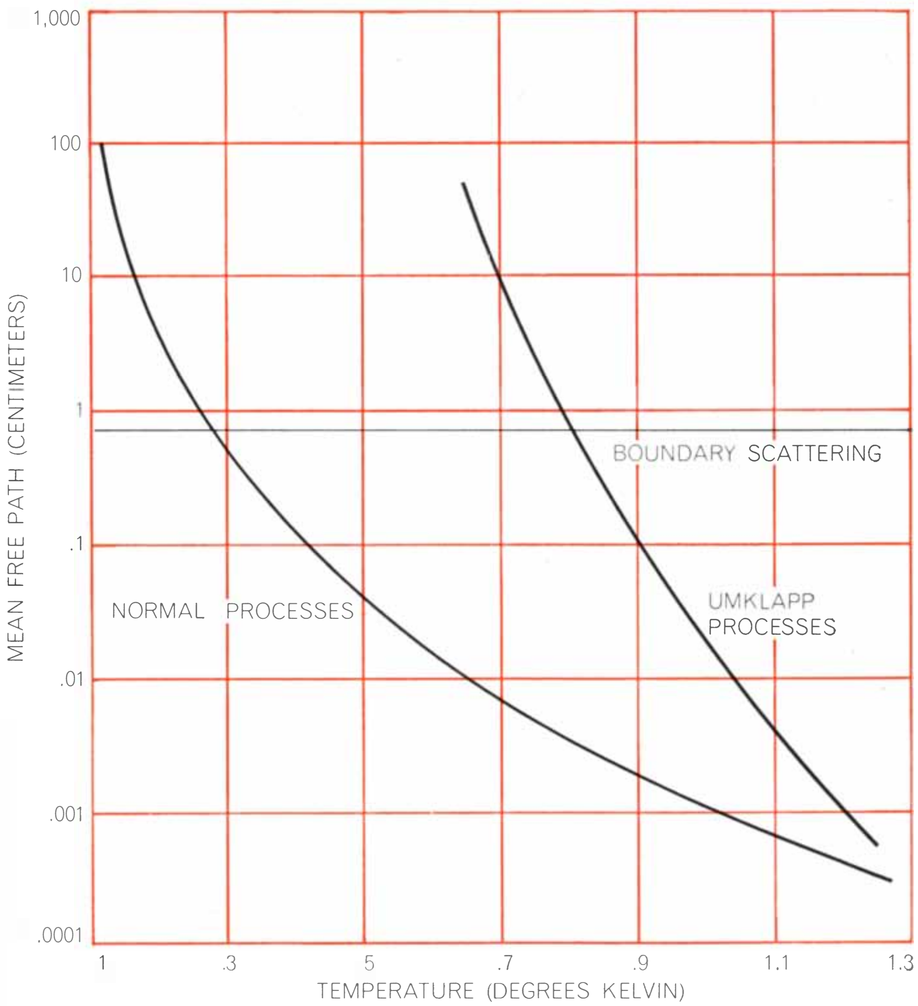
This possibility was independently suggested in 1938 by Laszlo Tisza and in 1941 by Lev D. Landau in the case of superfluid liquid helium for temperatures below 2.2 degrees K. [see "Superfluidity," by Eugene M. Lifshitz; SCIENTIFIC AMERICAN, June, 1958]. Landau suggested that the behavior of superfluid helium is exactly described by a gas of what he termed "elementary excitations" of the liquid. There are two types of excitation in superfluid liquid helium: phonons and rotons. The number of each type present depends only on the temperature. These particles can be readily created and destroyed. In fact, as long as they are in equilibrium among themselves the density of excitations tells one immediately what the temperature is. The phonons and rotons interact with one another and have a mean free path that is dependent on temperature and is much smaller than a millimeter at temperatures above one degree K.

This collection of elementary excitations, or particles, satisfies the conditions necessary for the propagation of waves. That is, collisions between excitations above one degree K. are very frequent (as in the collisions between molecules in air with a short mean free path), and in such collisions momentum and energy are conserved (again as in a molecular collision in air). Landau predicted that there would be a wave in the elementary excitations (just as first sound is a wave in air molecules). Landau called this wave second sound; it is a temperature wave because a variation in the density of elementary excitations is the same as a variation in the temperature.

Solids differ from superfluid helium in that the elementary excitations—phonons—suffer resistive interactions that alter the direction of heat flow, that is, they do not conserve quasi-momentum. Most solids have many point defects, such as chemical and isotopic impurities, and they may also have many crystal imperfections, such as dislocations in the crystal lattice. All these defects scatter phonons strongly and resistively, so that resistive interactions take place much more frequently than normal processes.

Let us now consider the flow of heat in the light of our model of a solid as a box containing a gas of phonons. A pulse of heat is applied to one end of the box, creating extra phonons at that end. As the phonons interact with their neighbors they are subjected to many interactions that deflect their direction of flow. The gas of phonons then transports thermal energy by diffusion.

Suppose we have a very pure sample with a perfect crystal structure, and suppose momentum-destroying *U* processes and other resistive processes occur very infrequently and that *N* processes occur very frequently. In other words, compared with the length of the solid, the mean free path for momentum-conserving collisions is short, whereas the mean free path for resistive interactions is long. This condition can be achieved in solid helium between about .4 and .9



CONDITIONS FOR SECOND SOUND in solid helium at a density of .205 gram per cubic centimeter can be obtained from this plot of the phonon mean free path versus the temperature for various types of phonon-scattering processes. At this density solid helium has a hexagonally close-packed crystal structure; the curves shown in the graph refer to a single crystal approximately five millimeters in diameter. Boundary scattering and umklapp scattering are called thermally resistive processes; normal scattering is a nonresistive process. The conditions for second sound (normal mean free path much greater than resistive mean free path) are satisfied for this particular sample between about .4 and .9 degree K.

degree K. [*see illustration on opposite page*]. The phonon gas is now much like the air that is excited with a loudspeaker cone. A pulse of thermal energy applied at one end creates some phonons. This number fluctuation in the phonon gas travels as a wave. Since the number of phonons depends in a strict way on temperature and vice versa, there is also a temperature wave. Second sound is being propagated in the phonon gas.

Why, then, is it a matter of common experience that thermal diffusion is nearly always observed? The answer is that it is very difficult to obtain most substances in pure enough form so that the condition of resistive mean free path being much greater than the normal mean free path is satisfied. Impurities scatter phonons so strongly that their presence even in minute amounts leads to thermal diffusion. The key to the observation of second sound in solid helium is that this substance can be obtained in extremely pure form. All chemical impurities are frozen out at the temperature of liquid helium, so that a solid made from this liquid is very pure. Of the two stable isotopes of helium, helium 3 is extremely rare in nature, so that isotopic impurities are not important in natural samples of helium 4. On the other hand, helium 3 can now be made artificially as a product of the radioactive decay of tritium, and because of the large relative mass difference between it and helium 4 the helium-4 impurities can be removed. The art of making good defect-free single crystals of helium is reasonably well developed [see "Solid Helium," by Bernard Bertman and Robert Guyer; SCIENTIFIC AMERICAN, August, 1967].

So far helium is the only solid in which second sound has been observed. Can we hope to observe second sound in other solids? At present it is very difficult to obtain substances that are both chemically and isotopically pure enough. John Rogers and Robert O. Pohl of Cornell University have observed an indication of second sound in a carefully prepared crystal of sodium fluoride, but the task was extremely difficult. As the technology of purifying materials develops we can expect to observe thermal waves in other substances. The necessary low temperatures are available in many laboratories.

Second sound is at least as fundamental as diffusion. Its general absence is due only to the accident that most solids are basically dirty and the fact that most experiments are not performed at a sufficiently low temperature.

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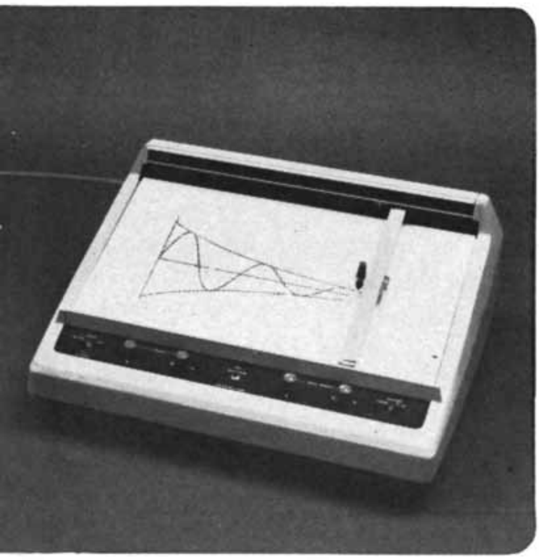

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How We Remember What We See

It depends on whether what we see is pictorial (scenes, photographs and so forth) or linguistic (words, numbers and so on). Experiments indicate that the linguistic memory is different from the pictorial

by Ralph Norman Haber

Visual perception is as much concerned with remembering what we have seen as with the act of seeing itself. When I look at a picture, I am aware that I am seeing it, and I can describe the experience of seeing. I can also remember what I saw after the picture is no longer there. How does this kind of perceptual memory work? Is it perhaps a process involving several steps in sequence, or one involving only one step during which many processes occur in parallel? Are scenes, faces and pictures remembered differently from linguistic material such as words and numbers?

In seeking to answer such questions my colleagues and I at the University of Rochester and workers in other laboratories have been studying the process of visual memory in human subjects. Our tools include tachistoscopes (devices that can display a series of images in rapid succession), slide projectors and screens, instruments for following eye movements, instruments for measuring the time needed to respond to stimuli, and various kinds of pictorial and linguistic material. These experiments are beginning to reveal several important characteristics of the visual memory process. Among the most significant of these findings is the suggestion that there is one kind of memory for pictorial material and another for linguistic.

The capacity of memory for pictures may be unlimited. Common experience suggests that this is so. For example, almost everyone has had the experience of recognizing a face he saw only briefly years before. (It is significant, as we shall see, that the name is usually harder to recall.) The reality of such experiences is supported by experiment. In one such experiment subjects were able to recognize as many as 600 pictures they had seen for only a short period of time. More recently Lionel G. Standing and I have conducted an experiment showing that at least four times this amount of material can be recognized.

In our test of visual memory capacity subjects were shown 2,560 photographic slides at the rate of one every 10 seconds during viewing sessions held on consecutive days. Suspecting that fatigue might have some effect on performance, we had some of our volunteers follow a rigorous viewing schedule that consisted in looking at 1,280 pictures a day during four-hour sessions on two consecutive days. The rest of the subjects viewed only 640 pictures a day during two-hour sessions on four consecutive days.

One hour after a subject had seen the last of the slides he was shown 280 pairs of pictures. One member of each pair was a picture from the series the subject had already seen. The other was from a similar set, but it had never been shown to the subject. When the subjects were asked to say which of the two pictures they had seen before, 85 to 95 percent of their choices were correct. Surprisingly, subjects whose endurance had been pressed did as well as subjects who had followed a more leisurely viewing schedule. In another version of the experiment the high scores were maintained even when the pictures were shown as their mirror image during the identification sessions, so that the right-hand side became the left-hand side. The scores diminished only slightly when the subjects were asked if the pictures had been reversed [*see illustration on page 106*].

Although a person may remember almost any picture he has ever seen, he frequently is unable to recall details from a specific image when asked to do so. In another experiment Matthew H. Erdelyi and I attempted to find out what happens to these omitted details. Are they never seen in the first place? Are they seen but then forgotten, or are they seen and remembered but in such a way that they are not retrievable under normal circumstances? In order to find out each subject was briefly shown a very detailed picture and then was asked to recall both in words and in a drawing all of the picture he could remember seeing. When he said he could remember no more, we asked him nondirective questions until his ability to recall all further details seemed exhausted. (For example: "You drew a man standing here; can you describe his clothing?" "You left the lower right-hand corner of the drawing blank; can you remember anything in the picture down there?")

After this initial questioning half of the subjects were individually engaged in a 30-minute game of darts, described as an unrelated experiment. Each of the remaining subjects was asked to lean back in his chair, stare at a projection screen, relax and report whatever words came to his mind. The first 10 words spoken by the subject were written down on separate cards. Each card was then handed one at a time to the subject, who was asked first to associate more words to it, and then to express any thoughts that came to his mind in relation to the word. The entire association exercise usually lasted about 30 minutes.

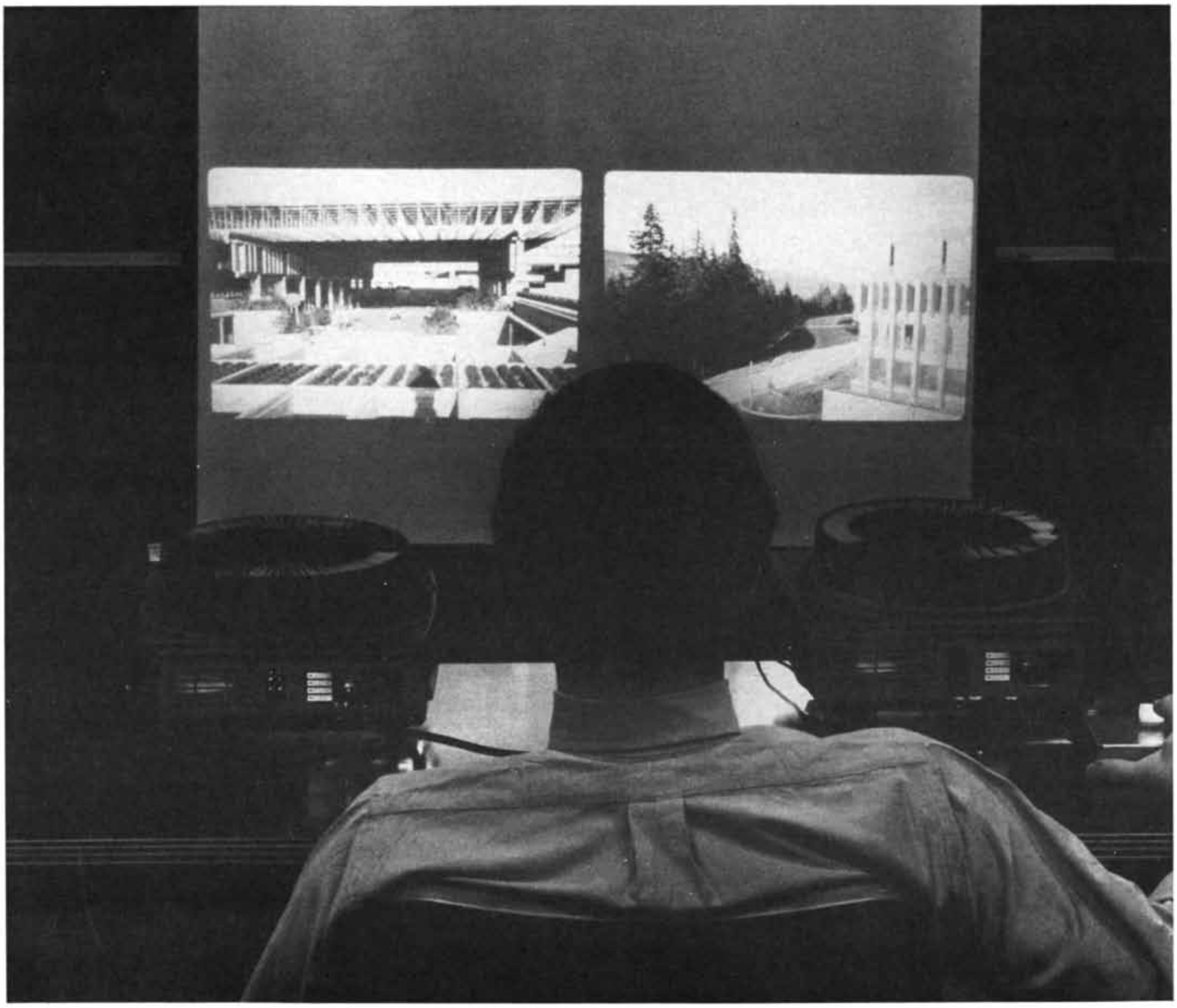
Following either the dart game or the word-association task, each subject was asked again to try to recall the picture by talking about it and redrawing it. The same kinds of probing questions were asked. All the subjects were given a rationale for the interpolated task. The dart-throwers were told that we expected their memory to improve because they had spent 30 minutes thinking about something unrelated, and the word-associators were told that we expected their memory to improve because they had just spent 30 minutes intensively exercising it.

We found that the dart-throwers' ability to recall more pictorial detail neither improved nor deteriorated. Each word-associator, however, recovered a number of details he had left out of his earlier recall. We also analyzed the content of the associations themselves, and we found that if a previously unrecalled detail was prominent in the associations, it was more likely to be recovered on the subsequent recall. These results, in addition to those from other parts of the experiment, indicate that some information about fine details is maintained in memory even though it may not normally be available for report. If this were not so, even the most intense memory-jogging and free association would have failed to yield more detail than was originally reported.

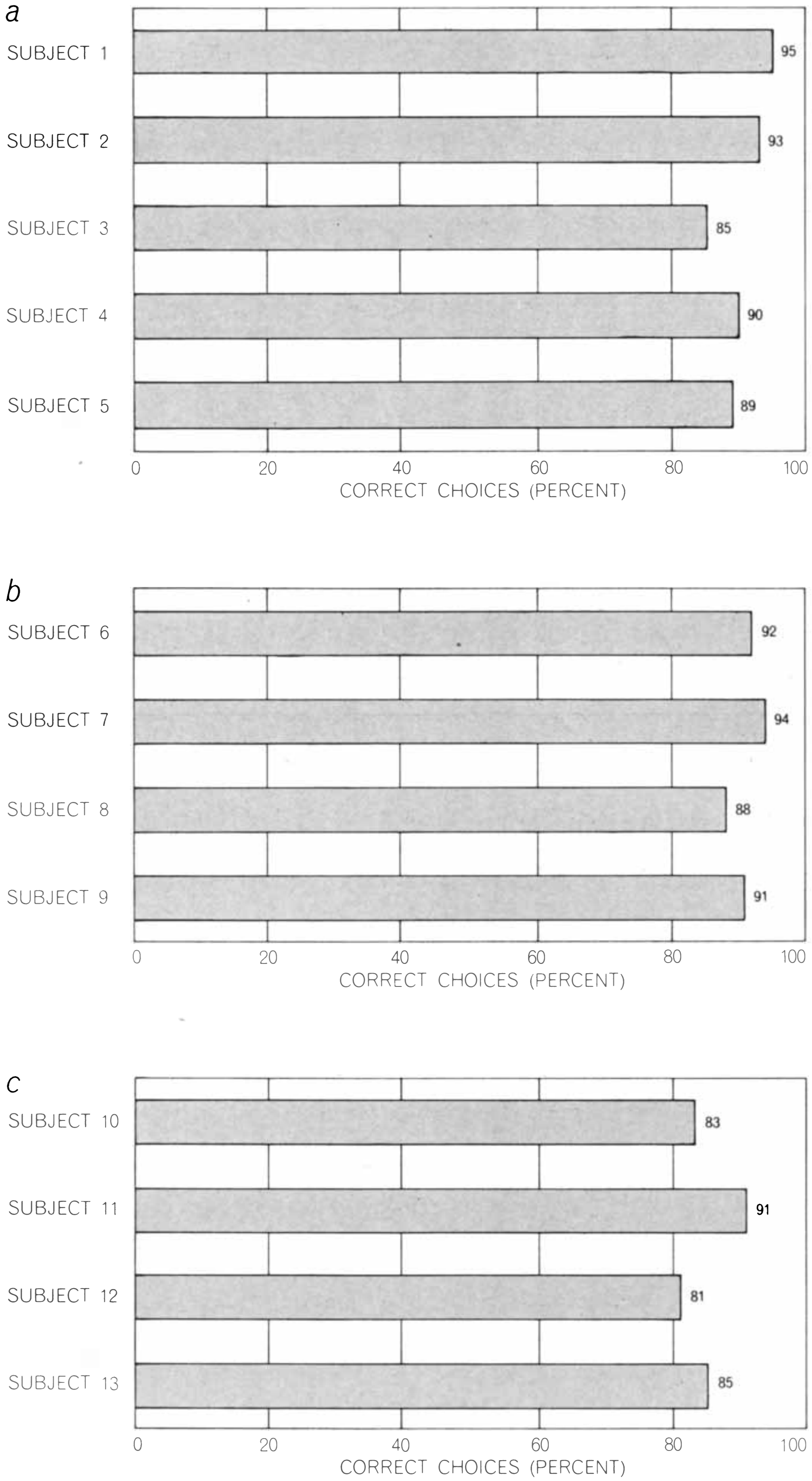
Another conclusion can be drawn from this experiment. It would appear that the pictures were not originally stored in the form of words. If they had been, the details would have been recalled during the first questioning. Instead a period of intense associative activity was required during which the subject was able to attach words to the pictorial images so that the individual details of the picture could be recalled.

The first of these experiments with pictorial stimuli suggests that recognition of pictures is essentially perfect. The results would probably have been the same if we had used 25,000 pictures instead of 2,500. The second experiment indicates that such recognition is based on some type of representation in memory that is maintained without labels, words, names or the need for rehearsal. If the representation were linguistic, subjects asked to recall the details of a picture in words or other symbols should remember much more than they actually do. The test results also suggest that since the pictures are not stored in words they cannot be recalled in words either, at least not in much detail, unless the memory is stirred by an activity such as the free-association exercise.

One implication of these findings is that if techniques could be found to facilitate an attaching of words to visual images, recall might dramatically improve. Some people believe they have this ability, for example politicians who seem to be able to associate a name with every face they ever saw. Freud argued



VISUAL MEMORY EXPERIMENT required a test subject to look at 280 pairs of photographic slides. Each pair consisted of one slide that had been shown to subject before in a series of 2,560 viewed at the rate of one every 10 seconds. Subject presses button that signals that he thinks slide on left was one he had seen. Subjects remembered nearly all the slides they had been shown.



RESULTS OF VISUAL MEMORY EXPERIMENT indicate that the capacity for remembering pictures may be unlimited. Subjects in *a* recognized between 85 and 95 percent of the 2,560 slides they had previously viewed. In order to determine whether fatigue would reduce memory capacity, subjects No. 4 and No. 5 viewed 1,280 slides a day on each of two days, whereas subjects No. 1, No. 2 and No. 3 viewed only 640 slides a day on each of four days. Surprisingly, there was no significant difference between the scores of the two groups. Subjects in *b* looked at slides shown in mirror-image orientation, so that left became right, yet they were still able to identify slides as accurately as the subjects in *a* did. Subjects in *c* were also shown slides that had been reversed. When they were asked if the orientation of each photograph had been changed, the subjects responded correctly in most instances.

strongly that free association was an ideal way to recover irretrievable memories. Although Freud was concerned with repressed memories rather than with merely irretrievable ones, a more general statement is possible: The recall of previous stimulation may fail because we do not use words to remember pictures or feelings, and therefore we have difficulty using words to describe the memory later.

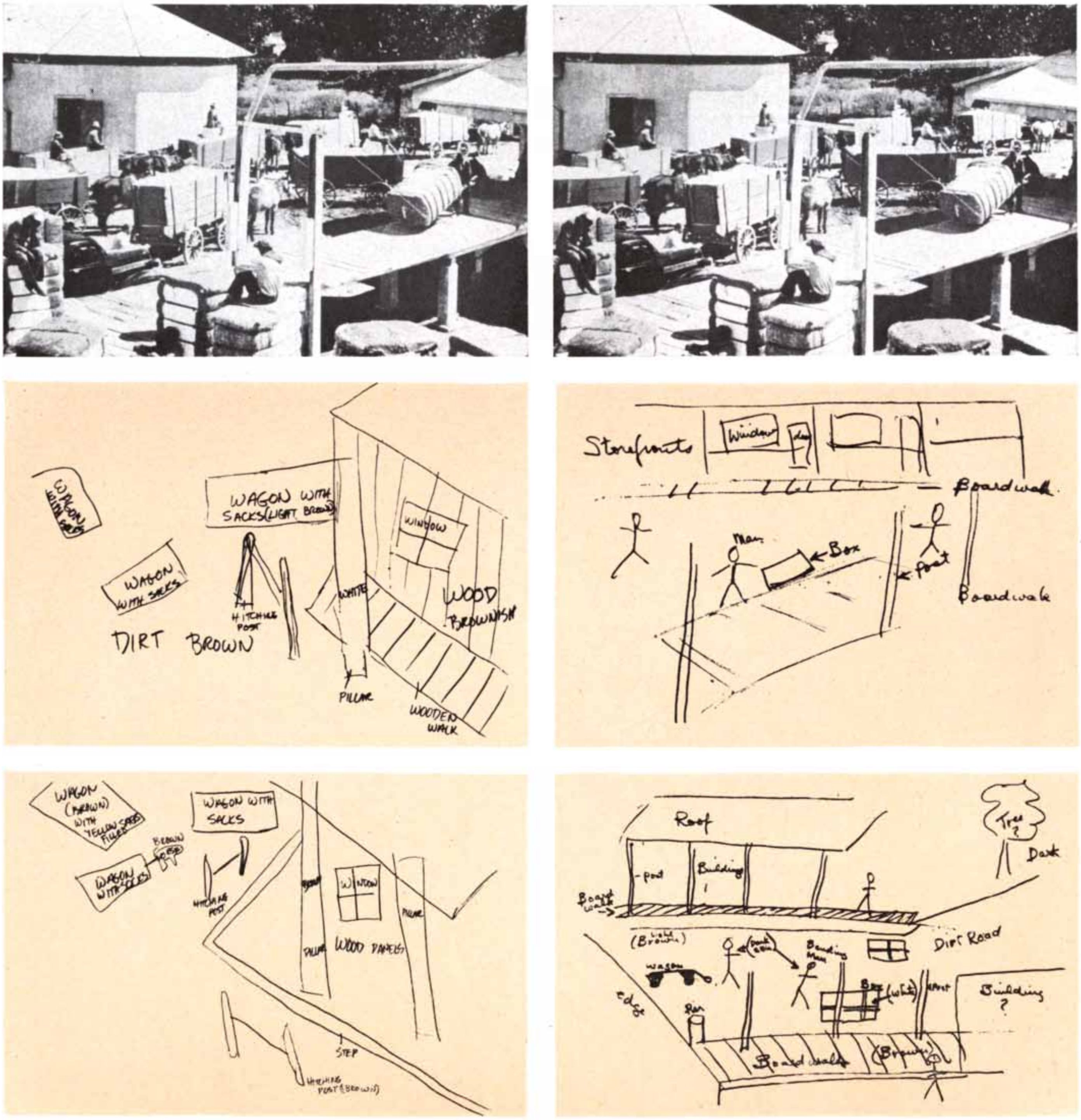
When the pictorial memory process is compared with the process by which words, numbers and other symbols are remembered, it becomes clear that the two systems are probably very different. Each kind of memory handles material that is perceived when light stimulates the retina, generating impulses that are then coded, organized and sent to the brain. In the case of pictures the image is received and stored permanently in pictorial form. Where words or other symbols are concerned the first step of memory is to take the stimulus out of its visual, pictorial form, code the items and extract their meaning. The collection of letters making up a printed word is not remembered as an image of distinct letters on a page; they are stored and recalled as the word itself. And words are remembered as ideas, not as a literal collection of words. A road sign is not remembered as a brightly colored panel with an arrow or a warning on it but as a message to stop, slow down or turn.

This particular memory process accounts for the ease with which a reader may overlook spelling errors in printed text. Instead of visualizing the word as it actually appears in physical reality, the reader tends almost immediately to extract the word itself from the printed characters and thus does not see the error. By the same token an unskilled proofreader may overlook the fact that a single letter in a word is printed in a typeface different from the face of the rest of the letters because he sees not the physical character but the spelling of the word.

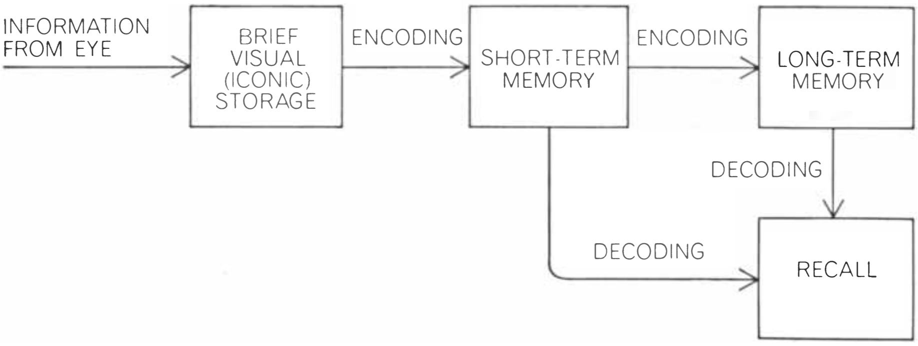
The process of extracting linguistic material from its representational form and storing it conceptually appears to consist of several steps [*see top illustration on page 108*]. The first step is a brief moment of "iconic," or visual, storage. As we shall see, this storage lasts less than a second after perception. During this time the image may be scanned and coded. (For instance, a word may be taken out of the form of a collection of letters and translated into spoken form.) This item is then stored in the short-term memory. From the short-term memory the item is passed on to the long-term memory.

The short-term memory can probably hold from four to six unrelated items without decay, but beyond that number some kind of rehearsal is needed to prevent loss. A common example of rehearsal is our need to repeat a telephone number we have just looked up or heard as we hurry to the telephone to dial it. The seven digits cannot survive in the memory for more than a few seconds without some repetition. Another strategy for increasing the capacity of the short-term memory consists in recoding the item to be remembered. A long series of letters can be more easily held in the short-term memory, for instance, if they are made into an acronym or a word. In this case the word rather than the individual letters is remembered.

How does the material move from the short-term memory to the long-term one? Recoding from the names of the items to their meanings, a semantic coding, probably underlies this transition. No further maintenance is needed to hold



RECALL OF DETAIL indicates that pictures, faces and other pictorial material are stored in the memory as images. In this experiment two subjects were shown the same photograph of a rural scene (*pictures at top*) and each was asked to recall as much of the picture as he could by describing and drawing it (*middle picture*). At this point both subjects displayed similar levels of recall. One subject then threw darts for half an hour while the other tried to recall more details by thinking about the picture and speaking whatever words came to mind. Afterward both subjects were asked to redraw the picture. Drawing at lower left by dart-thrower indicates that his memory was relatively unchanged by his activity. Drawing at right by other subject contains much detail not present in his earlier drawing, indicating that the memory exercise helped him to attach words to the pictorial detail in his memory. If such details had been stored in the form of words rather than pictures, both subjects should have remembered all of them at first recall.



MEMORY PROCESS for words, numbers and other linguistic material has several stages. At left information such as a printed word seen by the eye is briefly stored as it actually looks. While this visual image lasts the word can be scanned, even if the original stimulus has disappeared. At center, during scanning, the word is encoded into its name (the letters *c*, *a* and *t* may become the word "cat") and is then entered in the short-term memory. At right the word enters the long-term memory, perhaps by being encoded again, this time from its name into its meaning. At lower right word is recalled by being decoded into its name.

the information in recallable form at this point, although the information may have to be coded back into names if it is to be recalled. The evidence does not yet indicate whether awareness of seeing the stimulus is synonymous with the iconic storage or short-term memory, or is something that happens with or after semantic coding.

This model of the linguistic memory process is a rather generalized one. Many specific models have been proposed, and the experimental evidence is not yet complete enough to choose between them. Nevertheless, several recent experiments have clarified what happens in the early stages. One problem that was investigated was the source of the errors that are made when an individual is asked to recall several items in a large display. Do such omissions indicate a limited memory capacity or are they due to a failure to perceive some of the items?

It is known that only four to six items can be remembered without the aid of rehearsal or recoding. Thus it seems possible that whereas all the objects might have been perceived at first, some were simply lost because there was no room for them in the short-term memory. Items might also be lost at later stages in the memory process.

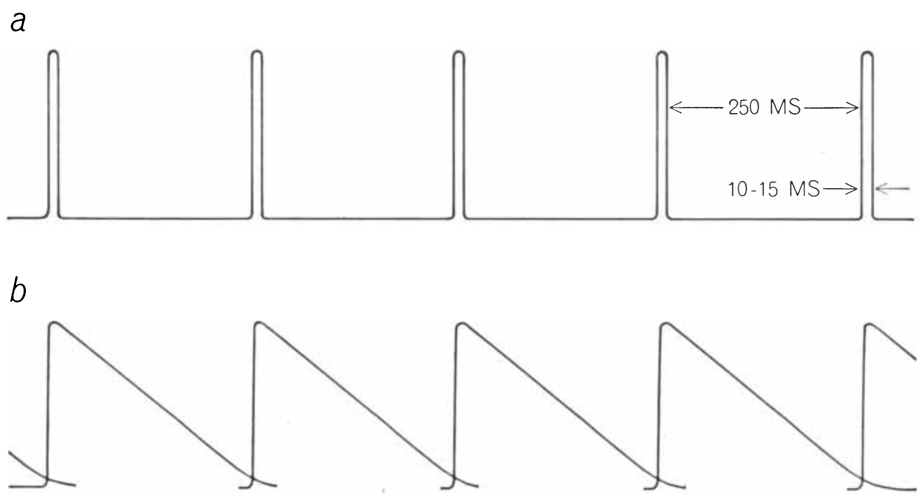
How could these hypotheses be tested? How, in other words, could failure to perceive be experimentally distinguished from some limitation of memory capacity? One cannot solve the problem merely by asking the subject if he saw every item in the display when it was first perceived. If a subject's memory capacity is too limited to contain all the items in a display, he will not be able to recall whether or not he perceived each of them initially.

An experimental approach to this problem, developed a century ago by N. Baxt, was rediscovered by George Sperling of the Bell Telephone Laboratories. In one of Sperling's experiments based on Baxt's method the subject was presented with an array of letters in a tachistoscope. The array remained visible for about 50 milliseconds. Once the display ended, the subject was asked to remember all the letters until a marker appeared that indicated the position of from one to four of the letters that he was to report. If there was no delay, that is, if the indicator came on immediately after the termination of the display, the subject made virtually no errors. This period of error-free reporting lasted for approximately 250 milliseconds (a quarter of a second). As the delay between the end of the display and the appearance of the indicator increased, however, so did the frequency of the subject's errors.

Some important conclusions about the memory process and the source of the errors can be drawn from these results. If recall is perfect at the instant after the tachistoscopic flash of the array ends, it follows that nearly all the information in the display has probably been stored in the memory. If the storage were not virtually complete, the subject would be unable to recall some items because those indicated for report are selected randomly. There is accordingly no way for the subject to remember only those items to be selected for recall.

It can also be concluded from the highly accurate recall that the initial perception, that is, the image conveyed by the visual system to the memory system, must itself be accurate. If perception were not detailed and inclusive, the iconic image in the memory would contain errors and so would the recall. The initial perception, then, cannot be the source of the errors.

Since the subject is never asked to report more than four items, a quantity within the capacity of the short-term memory, the errors and omissions subjects make when they try to recall items from a large display must apparently originate in the later processing stages of the memory, not in the initial iconic-



VISUAL IMAGE in an observer's memory makes a flash of light appear to persist after it has actually faded. In one experiment demonstrating such persistence a subject watched a train of flashes, each lasting between 10 and 15 milliseconds and spaced 250 milliseconds apart. In *a* flashes are represented by peaks. In *b* the images excited by the flashes are represented by curves indicating how the flashes looked to subject. The curves show that a visual image is excited by each flash (*sharply rising phase*). This image persists in the memory, fading gradually over 250 milliseconds so that it outlasts the flash itself. Because one image is still perceptible when the next image begins (*intersections of falling and rising curves*) flashes appear to subject to blend into each other, forming a flickering train.

storage stage or in a limitation on reporting by the subject.

These experiments suggested, but did not directly confirm, that the iconic image persists in the memory for about a quarter of a second. Standing and I devised two further experiments that provided this confirmation. Our results also confirm that the iconic image is visual. We argued that if a visual representation actually persisted for 250 milliseconds or so after the termination of the flash, it should be possible to have a subject estimate this persistence directly. We knew that it is not possible, however, to ask him to provide a judgment of absolute duration. With suitable adjustment in intensity, flashes lasting from one nanosecond (10^{-9} second) to 10 milliseconds (10^{-2} second) seem equal. We have tried two other procedures, both considerably more direct than Sperling's estimates.

Our first experiment tested the assumption that a brief flash of light creates an iconic image that persists in the memory for perhaps 250 milliseconds after the stimulus has ended. If this were so, it could be predicted that when the interval between flashes is equal to or slightly shorter than the duration of the iconic image, the subject should report that no flash completely faded away before the next one began. The train of flashes might appear to be flickering, but there should be no completely dark intervals between the flashes. We tested this prediction by recycling a briefly presented small black-on-white circle in one channel of a two-channel tachistoscope. The other channel was set at the same luminance as the one with the circle, in order to keep the subject's eyes adapted to light. The flash presenting the circle lasted from 10 to 15 milliseconds. A number of trains of flashes were presented, each with a different interval between flashes. After the subject had viewed a particular train of flashes he was asked to indicate if the circle completely faded away each time before it reappeared. As long as the interval between flashes did not exceed about 250 milliseconds all the subjects reported that the form never completely faded away. Intervals longer than 250 milliseconds produced reports of complete fading.

What effect, if any, did the length of the flash itself have on the duration of the iconic image? We found that for relatively short presentation times ranging between four and 200 milliseconds (well above threshold) the iconic image still persisted for about 250 milliseconds. In other words, the duration of the iconic image seemed to be independent of the duration of the original stimulus, at least for very brief stimuli.

TACHISTOSCOPE (*tall box at right*) is a viewing chamber in which an experimental subject watches rapidly changing stimuli such as images or light flashes. Apparatus at left controls timing and presentation of the stimuli. The subject also wears earphones through which he hears clicking sounds. He controls the tone generator that produces the clicks so that one coincides with the onset of an image and the other with the termination. Such experiments reveal how the memory processes letters, numbers and similar material.

Our evidence for the existence of an iconic image seemed to be falling very neatly into place. None of the tests we had conducted so far, however, excluded the possibility that we were measuring the properties of a retinal image rather than an image formed during the first stages of the memory process. In order to eliminate this possibility—or to substantiate it—we devised another procedure. In this variation of the experiment the first flash of a train was presented to the right eye while the left eye's vision was blocked; then the right eye's vision would be blocked while the next flash was delivered to the left eye, and so forth. Under these conditions subjects still needed about 250 milliseconds between flashes. This result clearly indicates that although there may be some persistence at the retinal level, the iconic image exists centrally, after the information from the two eyes has been combined. If this were not so, the flashes would have had to be only 125 milliseconds apart (250 milliseconds to each eye separately).

In our next experiment we attempted to refine and extend our earlier results. Following a plan suggested by Sperling, we used a three-channel tachistoscope. One channel was a blank illuminated field, the second displayed the target whose duration was to be estimated by the subject and the third presented random designs (the visual equivalent of "noise"). The subject wore earphones through which he heard a brief click at about the time the target was presented in the tachistoscope. His task was to turn a knob so that he judged the click and the beginning of the flash to come at exactly the same time. There was a click-flash presentation every few seconds. When the subject was satisfied with the match between the click and the beginning of the display, he had to repeat the procedure, but this time he had to match the click to the end of the display. The difference in the timing of the clicks thus represented the subject's estimate of the duration of the display.

As we expected, the second click followed the actual termination of the very brief display by about 200 milliseconds, indicating that the iconic image is of that duration. It will be recalled that in the preceding experiment the duration of the iconic image was independent of the duration of a flash less than 200 milliseconds long. In this experiment the persistence of the image decreased, however, as the stimulus's duration increased. When the display lasted for 500 milliseconds, the image persisted for less than 50 milliseconds. The iconic image associated with a one-second flash is less than 30 milliseconds. An iconic image lasts longer than about 250 milliseconds—for 400 milliseconds, in fact—only when the subject is dark-adapted.

Both of these studies are in close agreement with the more cumbersome estimates in the literature. They confirm the fact that the memory process seems to increase the effective length of all brief flashes to at least 200 milliseconds. If the flashes are already that long, further increases are minimized. The studies also clearly demonstrate that the brief storage Sperling postulated is in fact visual, since subjects describe the iconically stored image as if they were talking about the flash itself.

What other factors determine the length of this visual storage? Can it be lengthened or shortened under normal as well as experimental circumstances? What role does it play in the extraction of information from visual stimuli? It should be obvious that a brief period of visual storage, effectively extending a stimulus for less than a second, will be useful only when that extension provides some critical advantage. Are perceivers only asked to describe the effects of brief flashes when experimental psychologists present such flashes? Have we perhaps invented a concept of visual storage that serves no function in nature (except perhaps to read in the dark during a lightning storm)? I believe quite the contrary. There are many rapidly presented visual stimuli encountered in the environment. For literate adults the most important and continuing visual experience is reading, and reading if nothing else is a task of viewing a rapid succession of brief visual exposures containing large amounts of information.

Evidence that the persistent iconic image aids in reading and therefore in similar visual tasks has been suggested by many workers. These investigators have found that a slow reader or someone reading slowly fixes his eyes on each word for about a quarter of a second. A faster reader also fixes his eyes for about the same amount of time. Such a fast reader attains his higher speed by reducing the number of fixations, that is, he looks at and processes several words instead of one word during each fixation. Both kinds of reader need from 30 to 50 milliseconds to shift their eyes from one fixation point to the next.

It would seem, then, that both fast and slow readers need about a quarter of a second to perceive and extract the information contained in any word. Since the length of this interval is under the reader's control, the conclusion can be drawn that the interval constitutes the adequate minimum processing time for encoding linguistic material into the memory. If this is true, it follows that a visual storage medium might serve the purpose of prolonging a stimulus that does not last long enough to be recognized otherwise. It should not be regarded as mere coincidence that the duration of iconic storage and the minimum fixation time in reading are both about a quarter of a second.

Evidence supporting this line of reasoning is beginning to accumulate, but it is still by no means adequate. Part of the evidence concerns how an iconic image is erased and what effect erasure has on information processing. If a persistent iconic image helps the viewer to process information, there should also be a way to erase the iconic image when it has served its purpose. If there were no erasing process, a reader or someone rapidly scanning the faces in a crowd might be hampered by the persistence of an iconic image from the last stimulus as he tried to assimilate a new one.

A large number of experiments show that superimposing a new visual pattern or a visual noise field over the old one will in fact wipe out the iconic image, thereby interfering with or actually stopping the processing of information contained in the pattern. This will normally

ADAPTATION CHANNEL

IMAGE CHANNEL

SOUND

DURATION OF VISUAL IMAGE is measured. In an experiment shown schematically the subject was asked to match a clicking sound (*bottom*) to the onset of a repeated stimulus consisting of a black circle on a

ADAPTATION CHANNEL

IMAGE CHANNEL

SOUND

LONG-LASTING STIMULUS in the tachistoscope produces a brief visual image in the memory. In *a* subject has already adjusted

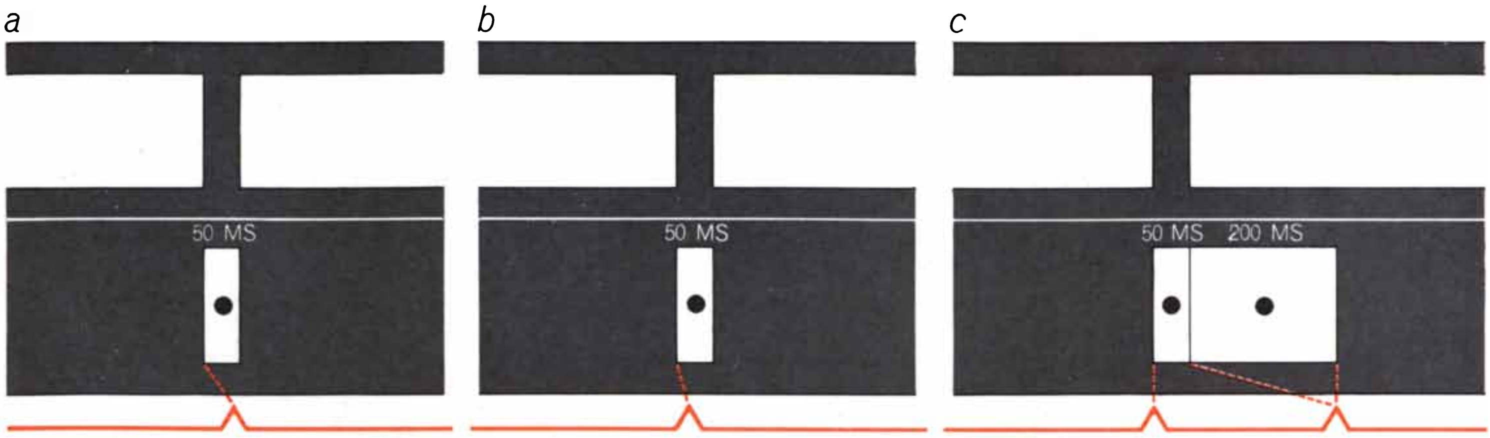
ADAPTATION CHANNEL

VISUAL NOISE CHANNEL

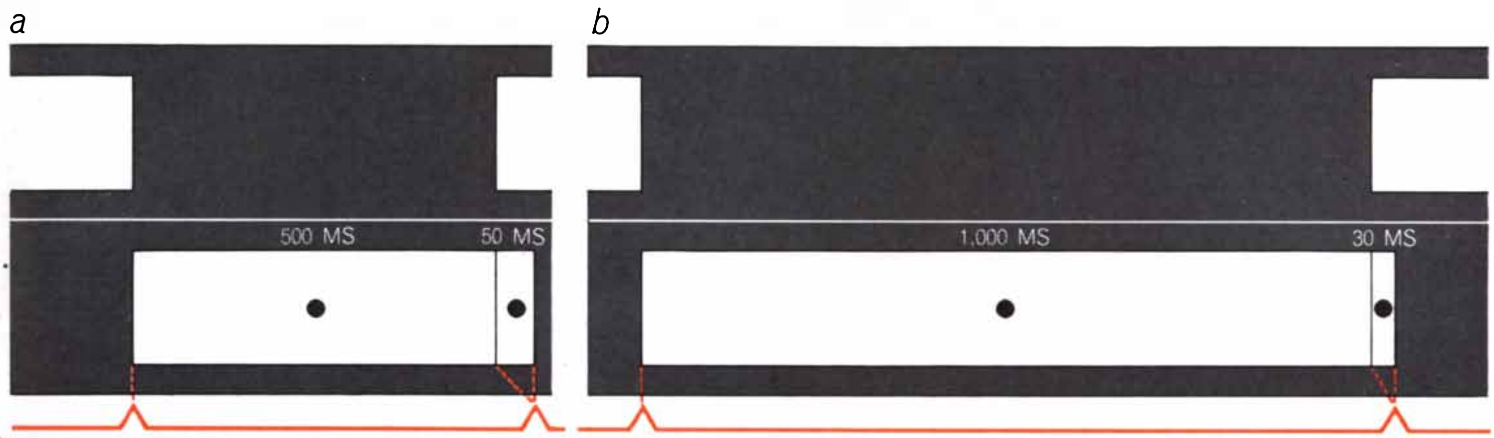
IMAGE CHANNEL

SOUND

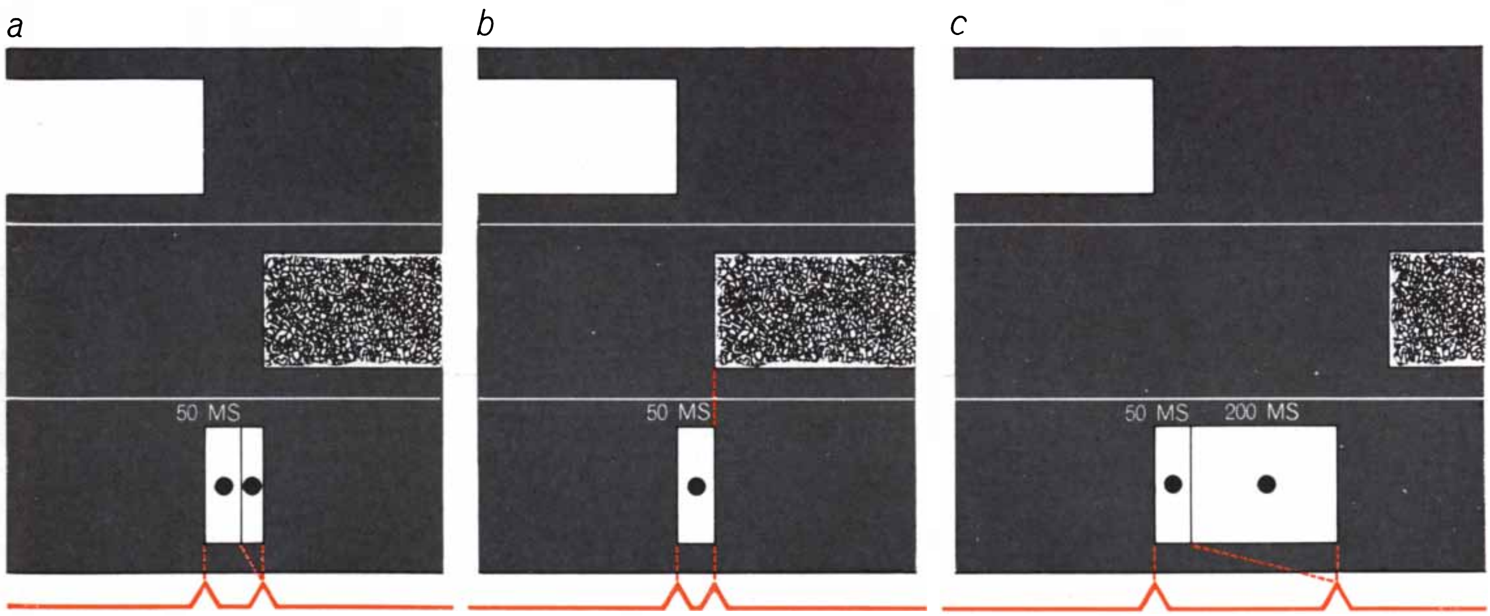
VISUAL IMAGE IS ERASED by the appearance of a new stimulus. In *a* black circle is presented for 50 milliseconds, an interval normally long enough to produce a



white field displayed in the tachistoscope. Adaptation field in the tachistoscope (*top*) keeps the subject's eyes adjusted to a given light level. In *a* the subject hears a click after he sees the stimulus. In *b* subject has begun to make the click coincide with the onset of the next image. In *c* adjustment has been made and subject has also matched a second click with what he perceives as the end of the stimulus. Actually the click marks the end of the visual image in the subject's memory rather than the end of the stimulus itself, which has faded out 200 milliseconds earlier. This interval from fade-out to click therefore represents duration of the visual image.



one click so that it coincides with the beginning of the stimulus and another so that it coincides with the perceived end. The stimulus actually lasts for 500 milliseconds. The interval between clicks, however, is about 550 milliseconds, an indication that the visual image lasts 50 milliseconds. In *b*, when stimulus lasts twice as long as in *a*, visual image it excites is still shorter, about 30 milliseconds.



200-millisecond visual image. In this instance, however, visual noise (a random pattern of letters) appears. This new stimulus ends the visual image of the black circle after only a few milliseconds. Therefore interval between clicks is only slightly longer than the duration of the stimulus. In *b* noise begins as circle vanishes, so that interval between clicks equals the duration of stimulus, indicating that there is no visual image at all. In *c* the noise has no effect on image because it begins after the image has faded.

happen in reading when the eyes focus on a new portion of print. The new stimulus wipes out the iconic image of the old, so that the way is cleared for the processing of new material.

The experiment of the click-flash pairings is relevant to this issue. The third channel of the tachistoscope in another condition of that study presented visual noise in the form of random patterns. At various times after the flash this visual noise channel was turned on. If the new stimulus (visual noise) erased the image of the old stimulus, as we expected, then the time interval between the two clicks should be reduced if visual noise arrives before the iconic image has had time to fade. Specifically, if the visual noise coincides with the end of the flash, the time interval between the clicks should be no longer than the flash itself. Conversely, if the visual noise were delayed beyond the normal persistence of the iconic image, the subject's performance should not be affected. This is exactly what was found.

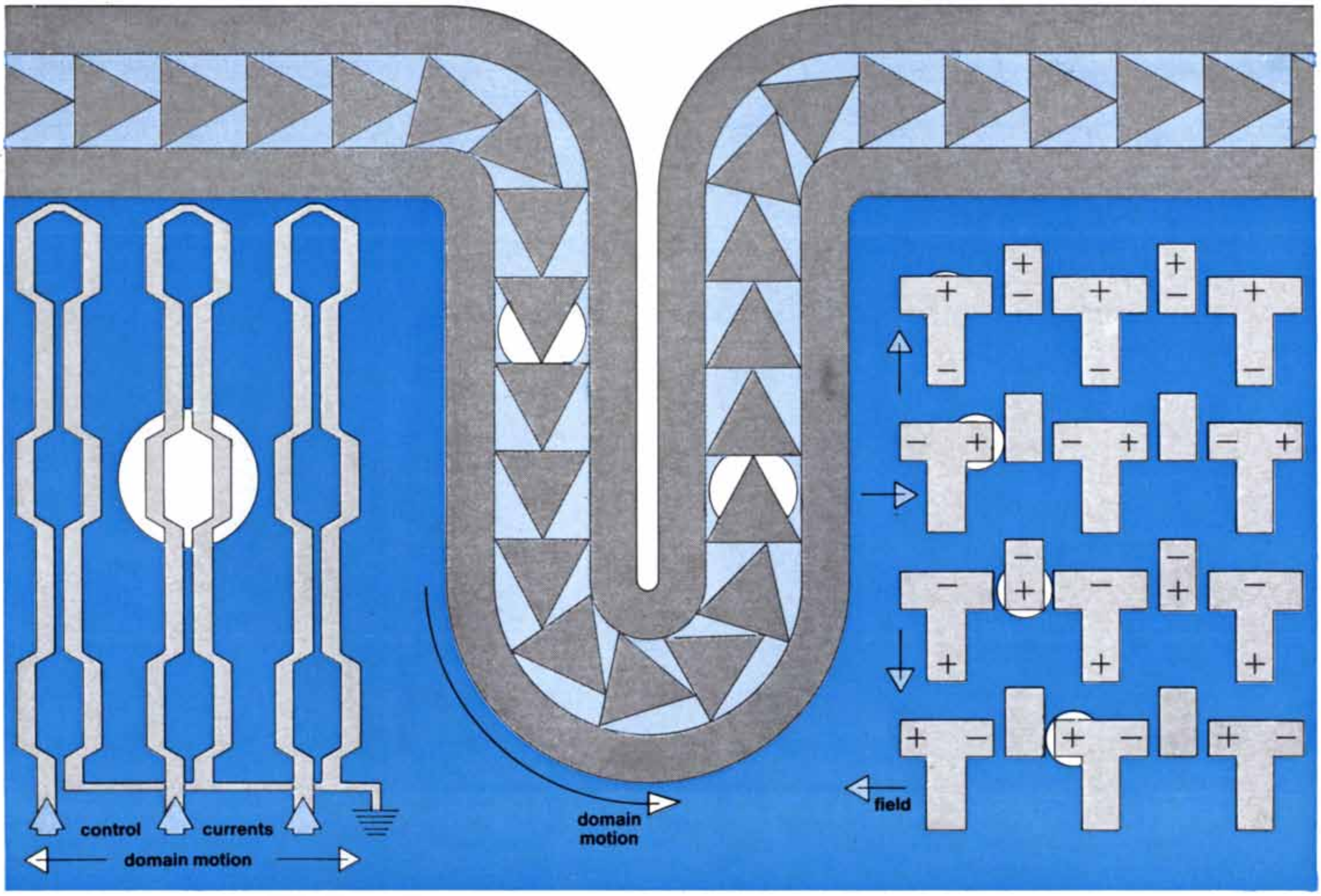
This task did not require the subject to extract information; he was asked only to estimate how much time he would need to extract the information. The results provide fairly direct support for the erasive and therefore process-stopping effect of visual noise.

Even more convincing, however, is the fact that when one display is removed and another is presented to the subject before he has time to process the image, he reports that he was aware of seeing the first stimulus but did not have enough time to recognize it. This result can be obtained whether the display is followed by visual noise or by more information. It can be concluded that the visual noise reduces a subject's time for extracting information, not the time available for perceiving the stimulus; the quarter-second occupied by the iconic image is not needed for seeing a display but for processing its content.

This effect was most clearly shown in a sequential word-recognition experiment. As the subject watched, each letter of a word appeared in succession on the screen of an electroluminescent panel, each in the same location so that the second letter should destroy the persistence of the first, the third letter the persistence of the second and so on. In this way the rate of presentation effectively controlled the time the subject had for processing each letter. The rate was varied from 20 milliseconds per letter to 300 milliseconds per letter. It was not surprising that the probability of recognizing each letter was higher for the slower rates of presentation. More important (and more relevant to this argument) was the finding that for each rate it did not matter whether the time from the onset of one letter to the onset of the next was used entirely for presenting the letter or whether the letter was presented for just a few milliseconds. Once a letter is seen, further viewing time is irrelevant as long as its persistence is unimpaired. The extra time is used to process the information that is already secured.

Finally, several experiments dating back to an earlier one of Sperling's have shown that when the interval between the onset of the stimulus and the arrival of visual noise is varied so that the time available for processing the content of the stimulus is also varied, a nearly linear function is revealed between processing time and the number of items the perceiver can recognize. In an experiment conducted in my laboratory we have shown that this relationship is much more apparent in subjects without practice in this particular task; it is attenuated after they acquire more experience. In the first few days of the experiment it appears that the perceiver needs about 10 milliseconds of processing time to recognize each letter after having some time to perceive all the letters and set up the iconic storage. For the particular displays we used, this perception and setup time was about 50 milliseconds. Thus a four-letter word requires about 90 milliseconds of time before the visual noise arrives in order for each of its letters to be correctly recognized. After several days, however, four letters require little more time than one does. This suggests that perceivers are developing more efficient strategies for processing information as they become familiar with the task and the items to be recognized.

Clearly much is happening in the first few milliseconds after the onset of a visual stimulus that is to be encoded into verbal memory. It can also be seen that the memory process can be regarded as a system concerned with information processing that consists of several stages and has its own time constants for extraction, decay, mode of persistence, susceptibility to interference or erasure, and the like. Viewing the memory process in this way is likely to lead investigators to design still other experiments that will yield a basic understanding of visual perception. Such knowledge is important for its own sake, but I hope it is also clear how much our knowledge of reading and other visual skills is ultimately related to our understanding of visual perception and information processing.



The magnetic abacus

Scientists at Bell Laboratories have invented ways to create, erase, and propel tiny cylindrical magnetic "bubbles" (domains) in sheets of orthoferrite—rare-earth iron oxide. Because the presence or absence of the bubbles at specific positions can represent binary numbers, they can perform many functions in digital data processing.

Bubbles are areas whose magnetic field is opposite to that in the rest of the material; their size and shape depend on the material and on an external magnetic "bias" field. In samarium terbium ferrite, for instance, 42 Oersteds maintains 0.0008-inch diameter bubbles. A bubble can be moved its own diameter in 0.01 microsecond, promising a data rate of over a million bits per second. We've invented three basic ways to move them:

In the first (above left), thin-film conductor loops are deposited onto the orthoferrite sheet. Currents through the loops move the bubbles from under one loop to an adjacent one. With a second pattern of loops at right angles to the first, the bubbles can move all over the sheet, like checkers.

In a second scheme (center), high permeability thin-film permalloy triangles are deposited on the sheet. A bubble "adheres" to any triangle it contacts. But, if the overall bias field is reduced, the bubble expands, and contacts the side of the next triangle. If the field is then strengthened, the bubble contracts, holding to the triangle it has contacted and sliding "downhill" off the original one. A bubble moves one step with each cycling (between 38 and 44 Oersteds) of the bias field; the permalloy "rails" confine the bubbles to the path.

A third scheme (right), a "T-and-bar" system, also uses a thin-film permalloy pattern on the sheet. Here, the bubbles are propelled by a field rotating in the plane of the sheet. The rotating field (arrows) causes changing polarities on the T's and bars; the bubbles shift in response. Rotation in the opposite direction reverses the movement.

In practical devices, we must be able to create and to detect the bubbles. We do the first by fission, from existing bubbles. We detect them by their external magnetic effects or optically.

A product of fundamental research in magnetism, the bubbles may provide compact and inexpensive data storage and processing for tomorrow's computers and telephone switching systems.

From the Research and Development Unit of the Bell System:

Bell Labs

Some new developments are changing things for the better: the computer offers the scientist relief from the laboratory grind

To the laboratory scientist the promise of the computer is relief from a growing burden of seemingly endless tabulations and computations that reduce his effectiveness as an investigator. The computer's capacity for accumulating data, plotting graphs and making complex calculations can change the obstacle course of numbers into a clear path of discovery.

The first bright promise of the computer, however, has not been fulfilled overnight. Often the pioneering computer-using scientist found that he was exchanging one form of drudgery for another. Putting the computer to work meant complex programming, interfacing of instrument and computer, of man and machine. Again, precious laboratory hours seemed to be going down the drain.

Two recent developments make the computer more acceptable to the reticent scientist. The first is the small, instrument-oriented digital computer, a relatively low-cost machine with easy-to-use controls, often pre-programmed to do a specific job . . . as in the lunar sample analysis experiment described later. Second is the shared-time computer, which reduces the physical presence of the computer in the lab to nothing more complex than a typewriter-like keyboard. When coupled with packaged programs developed by instrument manufacturers for a specific analytical purpose—as in the simulated distillation article described next—shared-time computer leasing will satisfy increasingly larger numbers of scientists. In both cases, the scientist can capture the advantage of the computer without suffering its complications.

Shared-Time Computer Helps GC Simulate Distillation

A far cry from the alembic used by the 16th century alchemist, the artful glassware used by the modern oil chemist for True Boiling Point (TBP) distillation nevertheless employs the same basic technique: boil and condense. To this day, TBP distillation remains the only accepted way to establish the basic marketing specification of petroleum products . . . and it leaves a lot to be desired. Those who refine petroleum products don't like it because it takes so long: TBP distillation of a wide-boiling distillate can take as long as 100 hours, and the results are useless in controlling the operation of a refinery. Those who buy petroleum products don't like it because the method is not very reproducible, especially as it applies to the initial and final boiling points. Those who perform the distillation don't like it because the procedure itself is a long and boring task.

A group of scientists at HP's Avondale Division have devised a completely automatic method that employs gas chromatography (GC) to simulate distillation and produces boiling point distribution data more precisely and in much less time—about 40 minutes—than TBP distillation. The new method employs the HP 7600A Chromatograph System which is capable of automatic operation from sample measurement to analytical data.

The recipe for simulated distillation with the 7600A is relatively simple. Set the GC for a linear program of 6 to 10°C/minute starting at −20°C, load the sample tray with as many as 36 different calibration and analytical samples, even of widely diverse boiling ranges up to 1000°F . . . and push the *start* button: the rest is automatic.

The 7600A automatically injects the samples and prepares a punched tape record of the GC retention time and area measurements at precise time intervals. Complete sets of programs provided with the 7600A enable any of the principal time-sharing computer services (including the HP 2000A Time-Shared System) to read the punched tape data, determine the initial and final boiling points of each sample, assign boiling temperatures to each data point and print out the analysis report of boiling point distribution of each sample at 1% increments.

No knowledge of computer programming is required by the analyst. At each stage of the computer-performed calculations, the computer asks for the information it requires and the operator answers by typing the requested number or word on the time-share terminal keyboard.

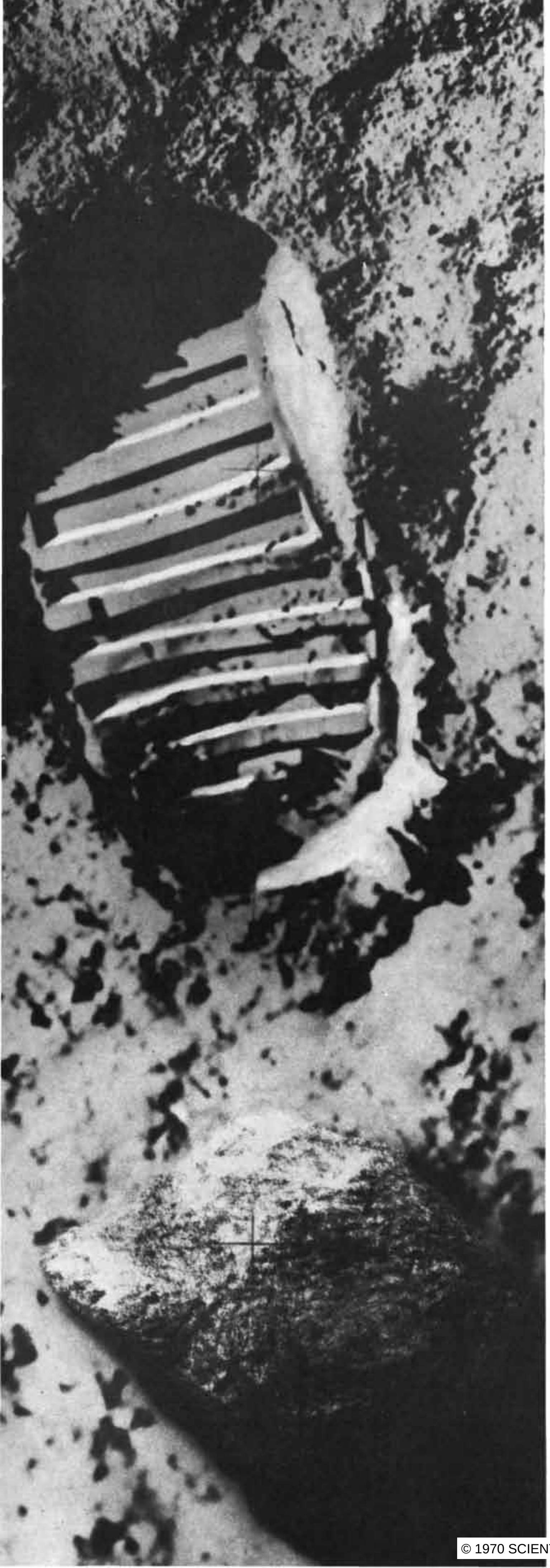
The precision of the 7600A Simulated Distillation method with wide boiling range samples is greater than is possible by any distillation method. Its speed—an average of 40 minutes per sample—completely outclasses distillation methods.

This new automated Simulated Distillation method is examined in much more meaningful detail in Vol. 2, No. 3 of *Analytical Advances*. Request your copy today.

Dedicated Computer Extracts hidden Information from Lunar sample

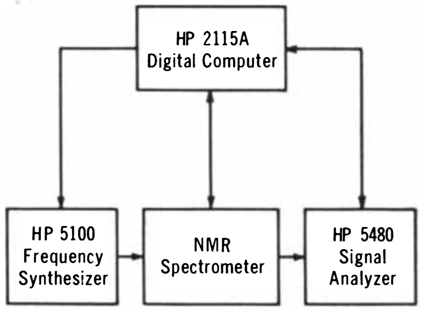
Some of the most respected scientific teams in the U.S. and eight foreign countries are performing analytical investigations on the lunar material returned to earth by the Apollo 11 crew. Among the 100-odd investigations scheduled by NASA, a nuclear magnetic resonance (NMR) analysis will be conducted by a Jet Propulsion Laboratory team headed by Dr. S. L. Manatt. Its goal is to characterize hydrogen nuclei in lunar material and attempt to establish whether any of it can be traced to free or crystalline water molecules presently on the moon's surface. The JPL scientists will also be on the lookout for heavy hydrogen whose presence will allow some conclusions about the history of the moon's surface and about the effect of the solar wind. A study of oxygen-17 may give them important clues about the current chemical environment of the moon (from surface samples) and about the presence of a lunar sea or ocean in the distant past (from core samples).

Present-day commercial NMR spectrometers are capable of accomplishing, unaided, the work assigned to the JPL team with



a creditable degree of success. But when you're analyzing samples that cost about a million dollars a gram to acquire, you're not satisfied with anything short of the best possible performance from your analytical instruments.

In the JPL team's quest for enhancing NMR sensitivity, they devised a system that combines the NMR spectrometer with a frequency synthesizer and signal analyzer under the control of a small digital computer, the HP 2115A, dedicated to this task alone.



The computer-controlled system extracts very weak NMR signals from heavy noise, enhancing instrument sensitivity as much as 100 times. It also performs fast Fourier Transforms of the NMR signal, converting it from time to frequency domain, for a further increase in sensitivity of another order of magnitude.

Here's how it works: the computer digitally sweeps both the frequency synthesizer and signal analyzer through programmed frequencies. Synthesizer output excites the NMR spectrometer which develops noise-covered resonance spikes for each nucleus in the lunar sample; under computer control, the frequency synthesizer also shifts NMR excitation between the resonance and transition frequencies of the nucleus under observation, thereby permitting measurement of relaxation or resonance decay times. The NMR output signal is fed to the signal analyzer which extracts the data from the noise and presents a calibrated display of the average signal at all times. The computer then processes the waveform, converts it from time to frequency domain by Fourier transformation and displays the result immediately in analog as well as digital form. End results of computer-controlled signal averaging and Fourier Transform is to increase spectrometer sensitivity as much as a thousand-fold. (Photo courtesy of NASA.)

Detailed information on HP Signal Analyzers and Computers is available on request. Write to Hewlett-Packard, 1503 Page Mill Road, Palo Alto, California 94304. In Europe: 1217 Meyrin-Geneva, Switzerland.

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Early Views on Forces between Atoms

Greek philosophers first conceived an atomic theory of matter and scientists after the Renaissance speculated on interatomic forces. More detailed theories awaited 19th-century experimental results

by Leslie Holliday

Is matter continuous or is it made up of discrete fundamental particles? If it is particulate, is there one kind of fundamental particle or are there many? What are the forces that bind matter together? Can the properties of matter be explained exclusively in terms of forces? Is there one kind of force or more than one? Mankind first began to ask some of these questions more than 2,500 years ago. We are still trying to answer them today.

I plan to show how ideas on interatomic forces developed from the time of the Greek philosophers until Giuseppe Belli of Italy wrote his paper "Observations on molecular attractions" in 1814. Particular interest attaches to this long span of time because the ideas on interatomic forces developed in it were largely speculative. Few experimental data were available that bore directly on what is still an extremely difficult and obscure problem. The situation changed with the dawn of the 19th century, when important new ways of observing phenomena at the atomic level were developed through the work of Joseph von Fraunhofer, Robert Bunsen and Gustav Kirchhoff in spectroscopy, of Michael Faraday in electrochemistry and of Julius Plücker on the conduction of electricity in gases. It is therefore particularly interesting to examine what progress could be made toward developing theories of matter before 1800, when there were no refined experimental techniques. To do that we must go back two and a half millenniums.

The story begins about 600 B.C. with the speculations of the Greek philosophers Thales, Anaximander and Anaximenes, who founded the world's first scientific school in the Ionian city of Miletus in Asia Minor. Thales and his successors, building on the practical experience of those who had preceded them (notably the craftsmen of the early empires of the Middle East), consequently benefited from a large legacy of technological knowledge. This legacy included a working acquaintance with the properties of natural materials (ranging from rock, bone, ivory, textiles and leather to semiprecious stones), of a limited number of metals (gold, copper, lead, silver, tin, iron, mercury and some of their alloys), and of pottery and glass. Some of these materials were known to be brittle and some ductile, some rigid and some flexible. In addition to this awareness of the mechanical differences between materials, there was available a body of craft knowledge of chemical processes and transformations such as the manufacture of glass and the reduction of iron ore and of physical processes such as the forming of metals. To a man who first set out to formulate a theory dealing with matter and its constitution, the problem was not a shortage of data but rather an overabundance of data. In such a situation the first step is the most difficult one.

Thales put forward the theory that the underlying principle of matter was water, a ubiquitous substance that could exist as a vapor, a liquid or a solid. The significance of this theory was not so much in the choice of water as in the stupendous proposal that there was a single underlying principle behind all matter, a universal substance from which all animate and inanimate things were formed. By later scientific standards Thales' theory may seem of little value because there was no obvious way to test it, but the important thing was that a question that still occupies us had been raised: What is matter? (As a corollary of this question there is a second: What forces hold matter together?) Of equal significance was the emergence, in Thales' monist theory of matter, of the yearning for simplicity that has been the hallmark of the scientific investigator ever since.

Anaximander of Miletus also postulated a single substance, something anonymous and indeterminate that could exist in four forms: Earth, Mist, Fire and Water. Anaximenes, the last Milesian philosopher of note, offered an alternative explanation: that Mist or Air (*pneuma*) was the fundamental substance and that it was transformed into various forms of matter by the twin processes of rarefaction and condensation. Rarefied *pneuma* is Fire; condensed *pneuma* becomes first Water and then Earth. Note that Anaximenes' theory represented an advance beyond the earlier theories in that it incorporated a mechanism to account for variety by explaining the change of *pneuma* into different forms.

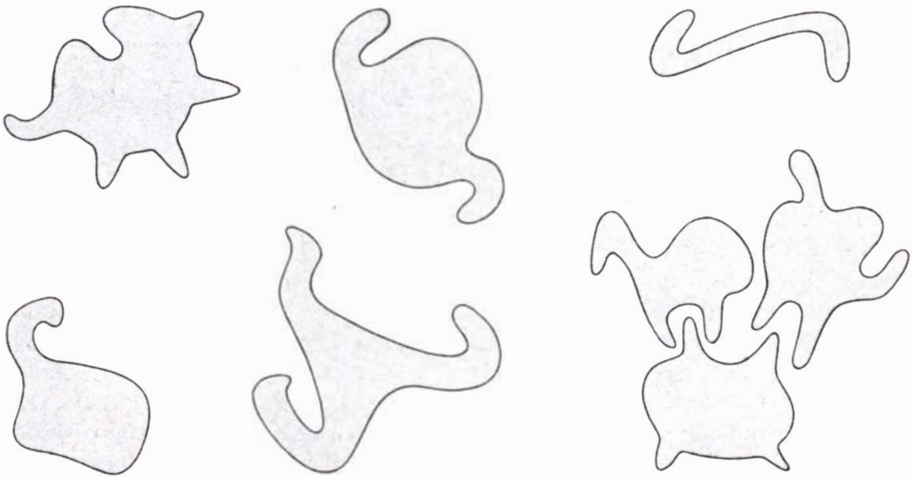
These three theories, put forward between about 600 and 550 B.C., had in common their reliance on a single fundamental substance. About 100 years later Empedocles suggested that there were four basic types of matter: Earth, Air, Fire and Water. These four elements were combined to form familiar things through the agency of two universal powers, Love and Strife. The four-element theory of Empedocles survived in one form or another for about 2,000 years, and provided the inspiration for generations of alchemists. And Empedocles' twin concepts of Love and Strife were the first hint of what are now called interatomic forces.

It is an assumption, but surely a reasonable one, that these early Greek theories were continuum theories, since it was not specified that the basic element or elements were subdivided into fundamental particles. In essence a continuum theory of matter assumes that as matter is divided into smaller and smaller pieces these pieces—no matter how small—will retain the properties of the bulk material. A continuum theory is conceptually difficult because one must imagine that the continuum exists in different states of attenuation in order to account for the various manifestations of matter, such as hard solids and thin fluids. The alternative to a continuum theory is a theory that sees matter as being ultimately composed of discrete, indivisible particles: an atomic theory.

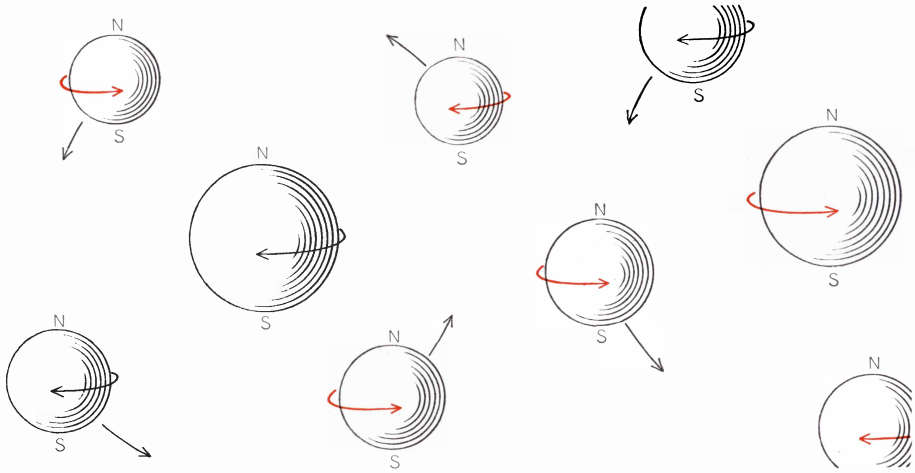
The first atomic theory was put forward by the Greek philosophers Leucippus and Democritus between 450 and 420 B.C. and was elaborated by Epicurus some 150 years later. It represented a radically different point of view, and it had the merit of explaining such processes as expansion and contraction, solution and precipitation and a wide range of other phenomena. Our detailed knowledge of the theory is based on a later source: the long Latin poem *De rerum natura* (*On the Nature of Things*), written in the first century B.C. by Lucretius, the great Roman poet and philosopher.

Lucretius set out to abolish superstitious fears about the arbitrary intervention of the gods in the affairs of men, maintaining instead that the world is governed by the laws of nature. All things, Lucretius wrote, are made up of invisible, indivisible particles called atoms (from the Greek word for "indivisible"). Atoms exist in a ubiquitous void, a void that must be inferred because one can have no direct experience of it. Atoms are small but are finite in size. They are in constant motion. There are various species, or shapes, of atoms. Although the number of species is finite, the number of atoms of each species is unlimited. Atoms are capable of combining, but the number of possible combinations is finite.

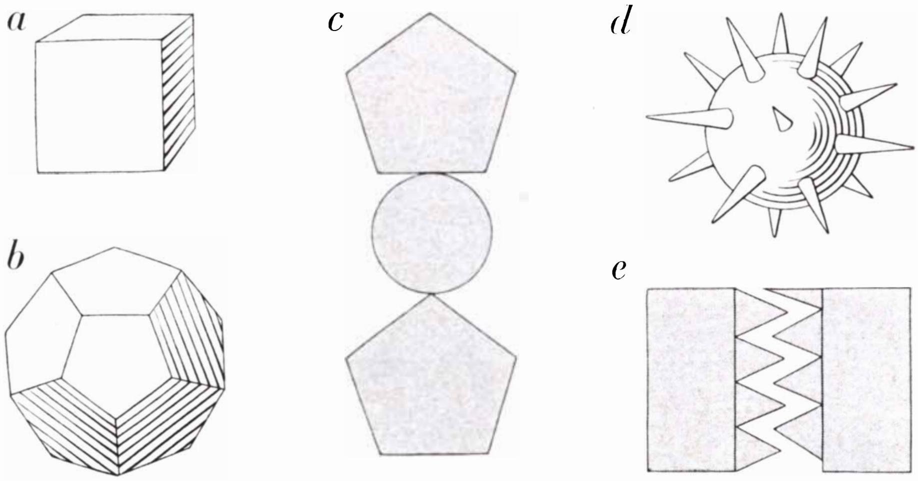
Atoms of various shapes, moving and combining in various ways, fall at last into certain arrangements of which the world of things is created. Solids exist because certain atoms unite, "entangled by their own close-locking shapes." Substances that are hard and compact (diamond, iron, flint and brass, for example) must have particles that are more tightly hooked together than others. Comparing the flowing of wine and of olive oil, Lucretius concluded that the oil must be made up of particles that are larger or "more hooked and entangled



ATOMS conceived of by the Greek philosophers Leucippus, Democritus and Epicurus were described by the Roman poet Lucretius in *De rerum natura.* They were invisible, indivisible particles of various shapes and with various kinds of projections and hooks, as imagined here. The manner in which they fitted together determined the properties of materials.



MAGNETIC ATOMS were proposed in 1674 by Sir William Petty, an English physician and economist. His atoms were invisible, immutable bodies. Like the earth, each atom had two magnetic poles; it could rotate on its own axis and also revolve around another atom. A million or more atoms combined to form a corpuscle, the smallest visible particle of matter.



FUNDAMENTAL PARTICLES proposed by Niklaas Hartsoeker in 1696 have shapes reflecting the properties of matter. A refractory metal has cubic particles (*a*), a fusible metal dodecahedral ones (*b*). Mercury's particles are spherical, and are shown mixed with gold (*c*). Mercuric chloride has sharp needles of salt inserted into a sphere of mercury (*d*). Subparticles of iron have triangular teeth (*e*); when heated, they separate, and the iron flows.

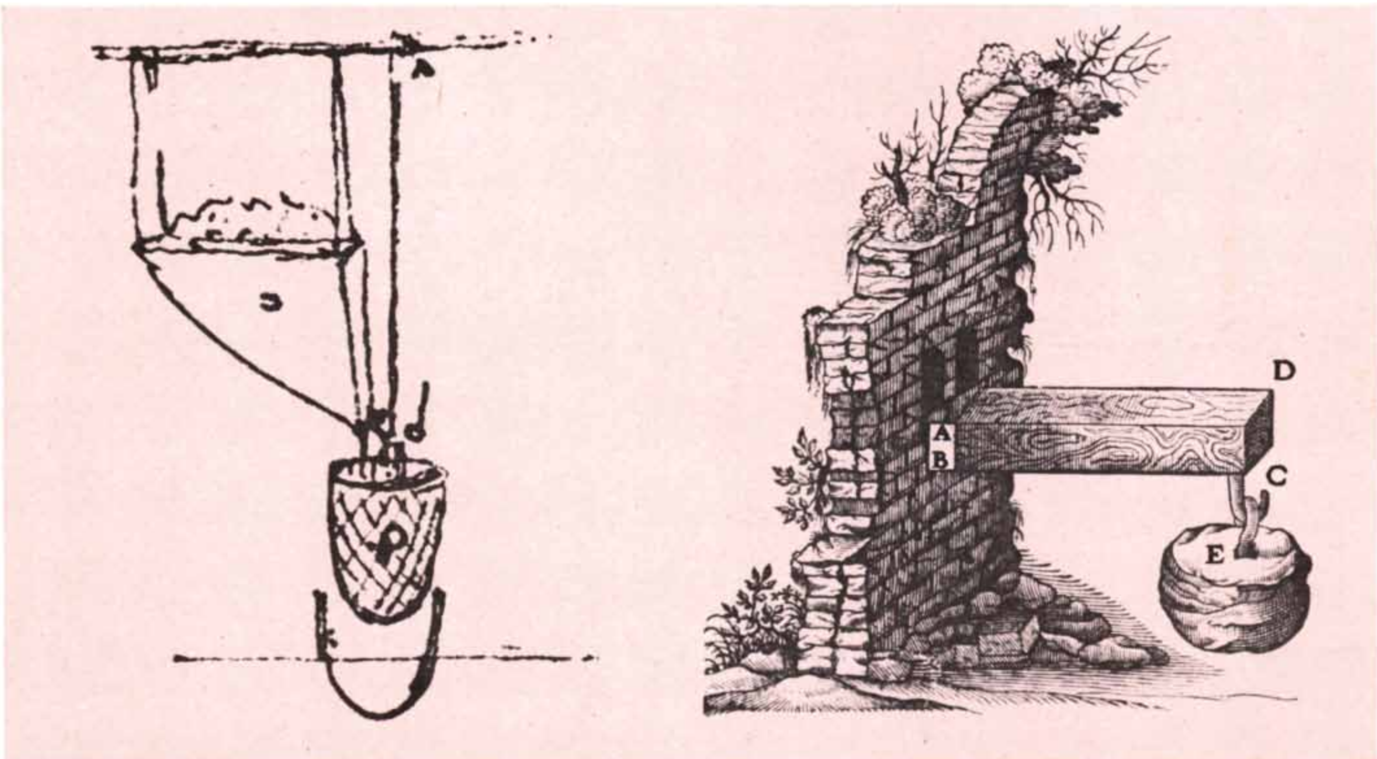
one with the other" than the atoms of wine. Substances with a pleasant taste have smooth, round atoms; those that are bitter or harsh have particles that are more irregular.

From the time of Lucretius until the revival of learning some 1,500 years later, interest in theories of matter was slight. During this period, however, the body of Greek and Roman learning proceeded, by way of Byzantium and the Islamic empire, to western Europe, along with a greatly augmented store of technological and craft knowledge. The revival of scientific interest in the properties of materials ultimately manifested itself not at the theoretical level but rather in the form of experimental inquiries. Leonardo da Vinci, for example, devised an apparatus for measuring the strength of wire. Galileo was one of the first scientists to consider the strength of materials mathematically. In his *Discorsi e dimonstrazioni matematiche,* published in 1638, he put forward 17 propositions relating to the fracture of rods, beams and hollow cylinders. A typical problem dealt with the breaking force on a wooden beam [*see illustration below*]. In dealing with this problem Galileo did not consider that the fibers in the beam might be extensible. This suggests that, although he was an atomist, he did not consider that the atoms of the material might move in relation to one another under the influence of an applied stress.

The continuum theory of matter, which continued to be advanced in opposition to the atomists, was now reasserted by René Descartes. Like Plato and Aristotle and the Scholastic school that followed them, Descartes could not accept any part of space as being empty. To account for the properties of bodies it was therefore necessary to assume that more than one kind of matter existed. One kind, "subtle" and "ethereal," was virtually weightless; the other kind, of which material objects were made, had weight and was subject to gravitation. The different densities of substances could then be explained by assuming that they contained different proportions of solid and weightless matter but no void. Although the theory of Descartes had many supporters, such a theory is much more difficult to handle quantitatively than an atomic theory, and gradually (but never completely) it lost support.

In spite of the opposition of Descartes, the idea that matter was made up of discrete atoms gained ground steadily from the 17th century on. At first the model of the atom was similar to the one expounded by Lucretius: an infinitely hard, minute, interlocking entity. Slowly, however, an attempt was made to describe the atom in terms that would better explain the behavior of macroscopic bodies. From the writings of the period I shall cite two examples that are typical of the atomic theories then current.

The first suggests that the atoms are tiny magnets. It comes from a lecture given before the Royal Society of London in 1674 by Sir William Petty, who is now chiefly known as one of the founders of the discipline of economics. Petty said that matter is made up of corpuscles (the smallest visible bodies) and that these corpuscles are made up of atoms, the smallest bodies in nature. (As a guide to the size of atoms he suggests that a corpuscle contains at least a million of them.) Atoms, unlike corpuscles, are immutable, although they are not all the same shape and size. Like the earth, an atom has two magnetic poles and a center of gravity; it can rotate on its own axis and also revolve around other atoms as the moon revolves around the earth. Atoms attract one another by their mass and are attracted to the center of the earth by gravity; they have a tendency



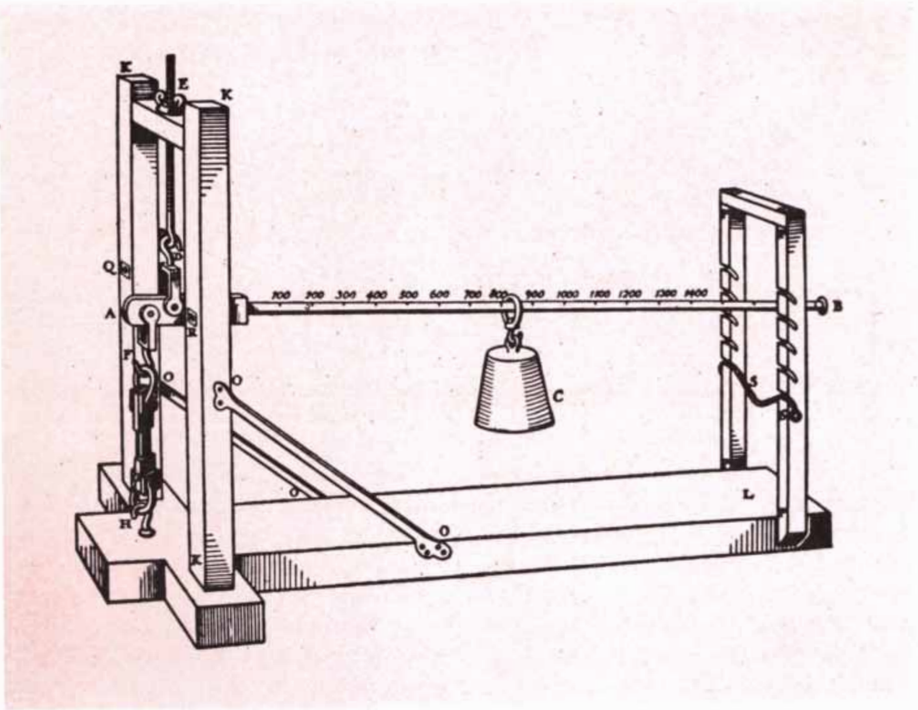
STRENGTH OF MATERIALS was investigated by Leonardo da Vinci and by Galileo. "To find the load an iron wire can carry," Leonardo wrote, attach a basket to the wire and fill it with sand from a hopper (*left*). A spring is rigged to cut off the flow of sand when the wire breaks, and then "the weight of the sand and the location of the break in the wire are to be noted." Galileo treated the strength of materials mathematically. In a series of propositions dealing with the fracturing of construction members he presented and illustrated the following problem (*right*): Find the stress that is exerted on cross section *AB* of the wooden beam by a weight *E*.

to line up in the earth's magnetic field but are prevented from doing so by their motion. They may have different velocities. (Petty also suggests that male and female atoms may exist, since the words of Genesis, "male and female created he them," may apply to atoms as well as to animals.) Petty's concept of the atom is clearly influenced by the work of William Gilbert, whose book on the earth's magnetism had been published in 1600. The analogy of the atom with the earth and the moon is interesting because it suggests a uniformity in the laws of nature in spite of the enormous difference in scale.

The other example I have chosen comes from the *Principes de Physique* (1696) of the Dutch scholar Niklaas Hartsoeker, who described the fundamental particles of a number of materials. Hartsoeker conceives of liquid mercury as consisting of spherical particles. Metals with a high melting point have cubical particles and those with an intermediate melting point are dodecahedral. Iron has particles shaped like a triangular prism, with a rough surface and a hole down the middle to account for the ease of corrosion. Mercuric chloride, a salt, has particles shaped like a hedgehog, with the sharp needles of salt inserted into the surface of the spherical mercury particles.

This theory represents a more orthodox development of Lucretius than Petty's. Yet although Hartsoeker made a real attempt to relate the shape of the atoms to properties of materials such as melting point or susceptibility to corrosion, his theory—and others like it—could not lead anywhere. Any student of nature with a fertile imagination could develop his own system of atoms with hooks and eyes or with regular or irregular excrescences. Much greater insight was required if the atomic theory was to make progress.

While theory lagged, the experimental philosophers had not been idle. Robert Hooke investigated the extension of materials under a tensile load and in 1678 published his law stating that the stress (load) is proportional to the strain (elongation). Since Hooke was anxious to obtain a patent for one aspect of his work (the behavior of springs), he originally published his theory in the form of an anagram: *c e i i i n o s s s t t u v*. He later revealed that this meant *ut tensio sic vis* or, as he put it, "the power of any spring is in the same proportion with the tension thereof." By "spring" Hooke meant any springy body, not only a spiral wire. (Hooke's law describes the elastic behavior of materials, the stage in which the strain is small and recoverable. At some point beyond this stage the material fails by excessive deformation or fracture.) Further work on the strength of materials was carried out by Pieter van Musschenbroek of the Netherlands. His textbook of physics, published in Leiden in 1729, included a section dealing with the cohesion of solid bodies that described a tensile testing machine and reported the results of experiments with it on wood and metals [*see illustration above*].



PIETER VAN MUSSCHENBROEK was concerned with the cohesion of solid bodies. He described this machine for testing tensile strength. The sample was clamped at the end of a lever (*left*) and the weight was moved along the graduated arm until the sample broke.

Isaac Newton proposed a much more useful model of the atom. He extended the idea of action at a distance from the planets to the atom—from the very large to the very small—and thus for the first time joined the concepts of the atom and of force into a single hypothesis of atomic forces. His hypothesis is described most clearly in Question 31 of the *Opticks*. As evidence that a strong attraction must exist between particles, or atoms, Newton cited a wide range of physical and chemical phenomena: deliquescence, the heats of mixing and reaction, the precipitation of metals from solution and the violent action of gunpowder and of volcanoes. Further physical evidence bearing on the nature of atomic forces included the cohesion of solids, the collision and rebound of solids, surface tension and the phenomenon of viscosity. Newton's conclusions can be summed up as follows:

1. Atoms are hard and immutable particles.

2. There are different shapes and sizes of atoms.

3. Atoms are in contact with one another at a few points. ("I ... infer from their Cohesion, that their Particles attract one another by some Force, which in immediate Contact is exceeding strong, at small distances performs the chymical Operations above-mention'd, and reaches not far from the Particles with any sensible Effect." He clearly meant that this attractive force is greater at short ranges than the force of gravity.)

4. At a greater distance the atoms repel one another. This is one possible conclusion from the fact that soluble salts "will evenly diffuse themselves into all the Water.... And does not this Endeavour imply that they have a repulsive Force by which they fly from one another, or at least, that they attract the Water more strongly than they do one another?" (Newton had already proposed a repulsive force at greater interatomic distances in gases in order to explain Boyle's law. This repulsive force varied inversely as the distance between particles.)

5. Different states of aggregation of atoms are possible. "The smallest Particles of Matter may cohere by the strongest Attractions, and compose bigger Particles of weaker Virtue; and many of

these may cohere and compose bigger Particles whose Virtue is still weaker, and so on for divers Successions, until the Progression end in the biggest Particles on which the Operations in Chymistry, and the Colours of natural Bodies depend, and which by cohering compose Bodies of a sensible Magnitude." He suggested that the largest particles were between a five-hundredth and a thousandth of an inch in diameter, several orders of magnitude bigger than the smallest particles.

It is clear from this summary that Newton envisaged an attractive force operating at very small distances between atoms or particles and changing over to a repulsive force at greater distances. It is not clear how these two forces were related to the overall gravitational attraction. Although this picture was to be drastically modified within 50 years, it represented a starting point for later theories. The following words of Newton were to bear fruit: "There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out."

The next major theoretical advance came in 1758 with the publication of the immensely influential *Theory of Natural Philosophy* by Roger Joseph Boscovich, a theory of such importance that nearly 150 years later Lord Kelvin could describe himself as a "true Boscovichean." Boscovich, born in Dubrovnik, in what is now Yugoslavia, in 1711, became a member of the Jesuit order and studied philosophy, mathematics and physics in Rome, where he finally became a professor of mathematics. He was widely traveled (he was made a Fellow of the Royal Society on a visit to London) and versatile: his biographer described him with some justice as being at once a philosopher, astronomer, physicist, mathematician, historian, engineer, architect, poet, diplomat and man of the world. It is as a physicist that we are concerned with him here, one whom the British physicist J. H. Poynting described as "amongst the boldest minds humanity has produced."

The theory of Boscovich was diametrically opposed to the theory of Newton, who had postulated an attractive force between atoms at very small distances. Boscovich said the force must be repulsive, basing his argument on what happens when two particles collide and then recoil. Could two such particles eventually meet? If they met, that is, came into physical contact, and if they were hard and impenetrable, it would imply a discontinuous change in velocity at the moment of contact. This was something Boscovich could not accept, and it led him to put forward two startling but simple proposals: that the fundamental particles were nonextended and that they never actually met. (The alternative explanation, that the particles were finite in size and compressible, he rejected as unnecessarily complicated.) The central feature of Boscovich's theory dealt with the law of force between atoms, and was based on the following assumptions:

1. The law of continuity applies. That is, any quantity (for example a force) passing from one magnitude to another must pass through all magnitudes of the same class.

2. Matter is impenetrable. Two bodies cannot occupy the same space at the same time. (James Clerk Maxwell later criticized this assumption, rather unfairly, as "an unwarranted concession to the vulgar opinion." Boscovich actually recognized quite clearly the circumstances under which the penetration of one body by another might occur.)

3. The primary elements of matter are perfectly indivisible, nonextended points.

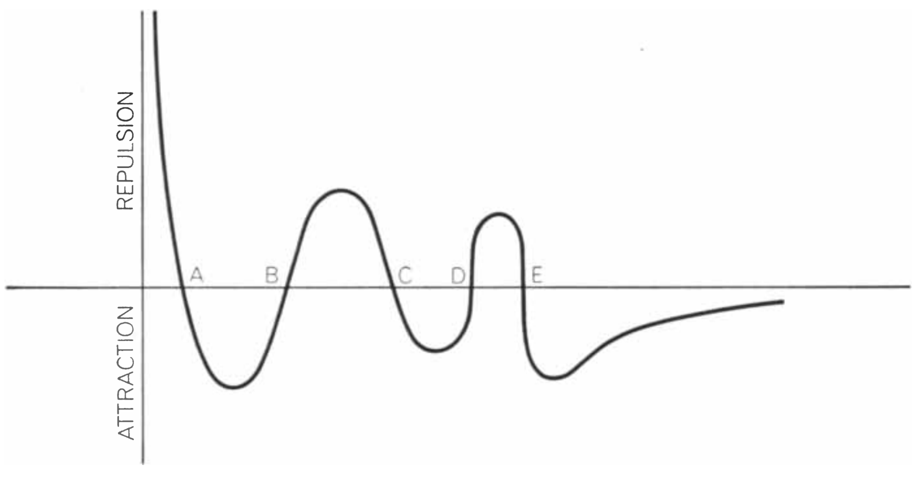
4. Immediate contact of these points is inadmissible. (This is in contrast to Newton's hard, incompressible particles in contact.) Matter is interspersed in a vacuum and floats in it.

5. The mutual force between the points is repulsive at some distances and attractive at others. At very small distances the force must be repulsive, and this repulsive force must increase indefinitely as the distance is diminished. At greater distances (beyond, say, a thousandth of an inch) the force finally becomes attractive, varying as the inverse square of the distance. Over the intervening range the force is alternately attractive and repulsive.

6. The points are never at absolute rest.

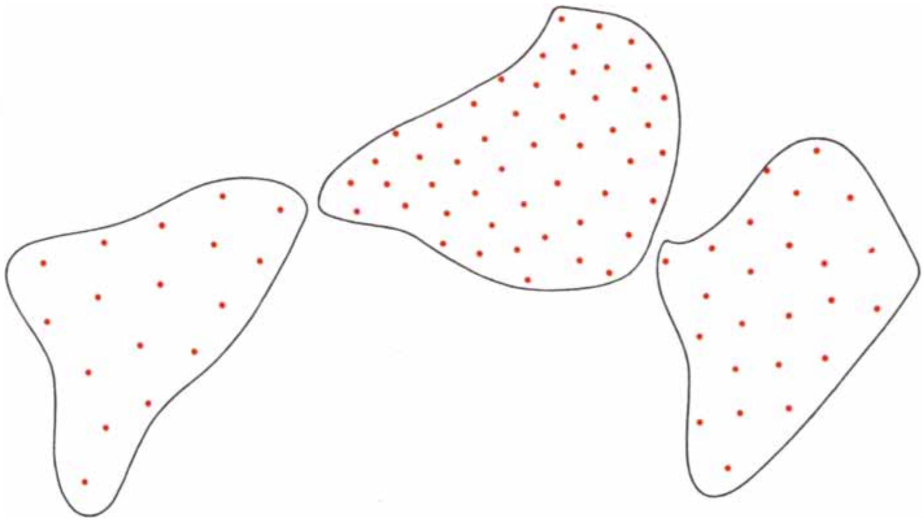
The force-distance curve on which the theory is based represents graphically the magnitude of the force exerted by a point atom along any line in three-dimensional space [*see illustration on this page*]. Forces above the horizontal axis are repulsive and forces below it are attractive. No quantities are assigned to the curve; it is the shape that matters. At imperceptibly small distances the repulsive force increases asymptotically to infinity. Beyond the scale of interatomic distances (as they are defined today) the final arc of the curve represents the curve of the gravitational force, which varies inversely with the square of the distance. Before this stage is reached there are many points of zero force where the curve crosses and recrosses the horizontal axis. Each such intersection is a "limit point" for attraction or for repulsion, depending on the sign of the slope of the curve at that point. These limit points are points of stability, or equilibrium between attraction and repulsion.

When the limit points of a number of point atoms coincide, the atoms can combine and form a stable arrangement [*see top illustration on opposite page*]. In doing so they form a particle of the first or-



FORCE CURVE of the point atom is the basis of the theory of interatomic forces put forward by the 18th-century Jesuit Roger Boscovich. The curve gives the magnitude of the repulsive or attractive force (*vertical axis of graph*) exerted by a point atom at any distance (*horizontal axis*). At vanishingly small distances the force is repulsive and infinitely large (*far left*); beyond a thousandth of an inch or so, however, it is attractive and matches gravitational force (*far right*). In between, the curve crosses the axis at a large number of points of zero force (*for example A, B, C, D, E*), the "limit points" for attraction or repulsion.

der; such particles can combine to form particles of the second order, and the process is repeated to form larger bodies. Boscovich illustrated this hypothesis with an interesting analogy, a modification of a metaphor in *De rerum natura.* Lucretius had said that atoms could be compared to letters of the alphabet: "Scattered abroad in my verses you see many letters common to many words, and yet you must needs grant that verses and words are unlike both in sense and in the ring of their sound." Boscovich goes a step further, asking us to imagine that each letter is made up of a number of identical little dots—the point atoms [*see bottom illustration on this page*]. From such letters "an incredible number of books printed in various languages could be produced."



POINT ATOMS (*color*), **according to Boscovich, combine to form a stable arrangement when their limit points coincide. In doing so they form a particle of the first order. Here three first-order particles are shown, combined to form, in turn, a particle of the second order.**

Although the Boscovich force curve is presented in two dimensions, with a succession of limit "points" of zero force along a distance axis, it is important to remember that the curve actually operates in three-dimensional space extending outward from the point atom. The point atom is thus surrounded by a series of concentric shells, like so many onion skins, which are in fact limit "surfaces" of zero force. These surfaces correspond surprisingly well to the electron orbits in the model of the atom proposed by Niels Bohr in 1913 [*see top illustration on next page*].

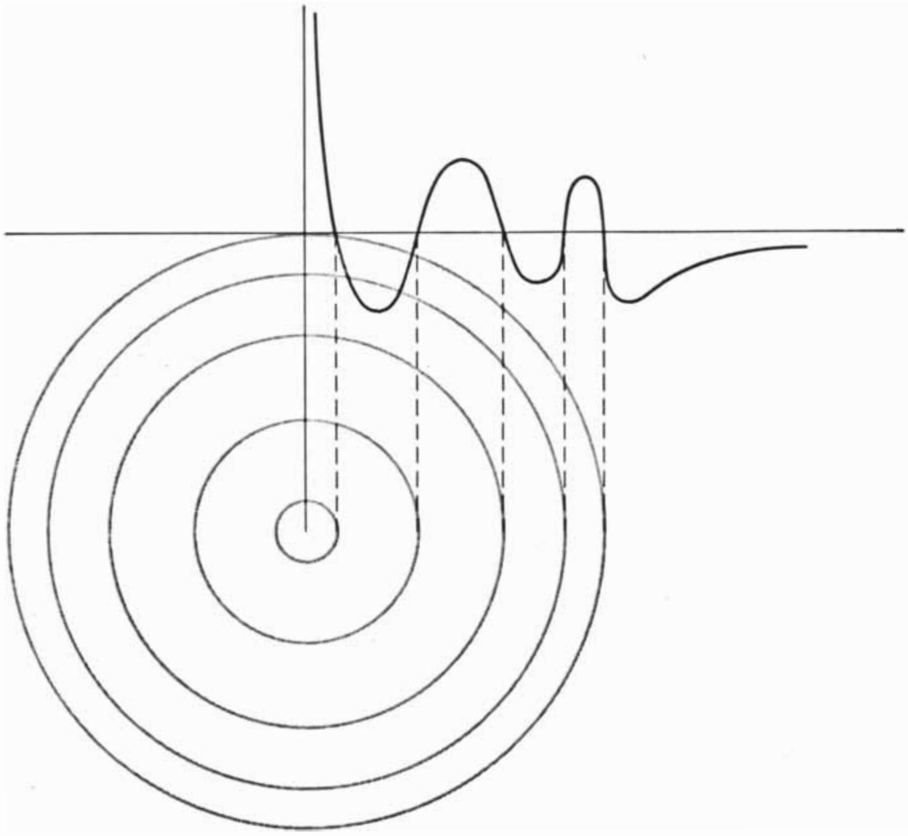
A theory that matter consists of dimensionless points, acting on one another by means of mutual forces, is as close to a continuum theory as it is to an atomic theory. Indeed, it virtually reconciles the two points of view while retaining the virtue of being susceptible to mathematical analysis. Given a sufficient number of limit points, any number of stable combinations of point atoms is possible. Changes of state or chemical changes are explained by the proposition that absolute rest is impossible in nature; particles in equilibrium do not stand still but oscillate around the limit points, and the extent of their movement can be larger or smaller depending on the slope of the force curve at the limit point in question. It also follows from the theory that absolutely hard bodies—bodies that are completely unyielding—cannot exist in nature.

So powerful were these simple basic concepts that Boscovich was led to speculate further about the cosmos. He suggested, for example, that a slight modification of the force curve at its farthest point from the origin, so that a repulsive force would operate at the limit, would make possible a number of stable universes coexisting adjacent to one another. Moreover, as long as the force curves did not mutually interfere, it was possible to envisage even coexisting, interpenetrating universes [*see bottom illustration on next page*]. This subtle thought implies that a number of worlds may occupy the same space at the same time. Boscovich also speculated that the universe could expand and contract daily without our being aware of it. He pointed out that if an object is moved, its dimensions should change because the relative arrangement of point atoms has changed; hence one cannot transfer a fixed length from one point to another.

A notable feature of the Boscovich theory was its simplicity. It made very few assumptions. Only one kind of particle was needed to explain the infinite diversity of matter. Since there was only one kind of atom, the intricacies of nature were all explained by the form of a single interatomic force curve. The curve was so flexible that any physical or chemical phenomenon could be accommodated without difficulty. The main weakness in the theory lay in the fact that it was entirely qualitative, but this was unavoidable in Boscovich's day.

Giuseppe Belli (1791–1860), professor of physics at Pavia, was deeply interested in the problem of molecular attraction. His approach can be illustrated by a paper he published in 1814, at the age of 23. (A subsequent paper of 1832 carried the argument further but along similar lines.) The work of Belli is of interest because, although he used no experimental facts that were not available

ALPHABET ANALOGIES for their atomic theories were offered by Lucretius and Boscovich. Lucretius likened his variously shaped atoms to letters that could be arranged to form words and sentences (*top*). Boscovich compared his point atoms to identical dots that could be arranged to form letters, and these in turn could make up words and sentences (*bottom*).



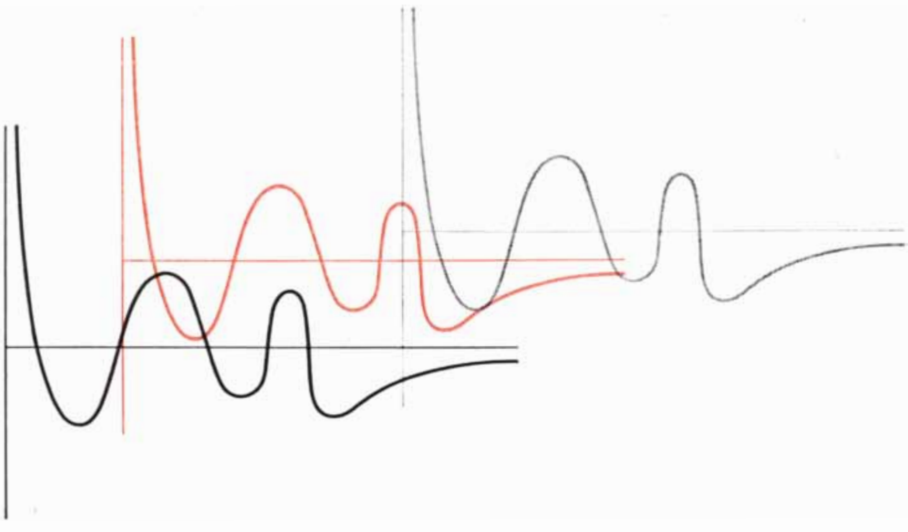
LIMIT POINTS of the Boscovich force curve define a succession of concentric shells since the force of the point atom is exerted in three-dimensional space. Illustrated in cross section, the shells look like the electron orbits of Niels Bohr's atomic model of 1913.

to Boscovich and earlier theoreticians, he nevertheless made a notable advance. Belli was concerned primarily with the attractive part of the force curve. He assumed that it could be expressed by an inverse power law: that the attraction is inversely proportional to some power of the distance between the atoms, or is proportional to $1/d^q$, where q is an integer. According to Boscovich, who did not consider the matter in detail, the integer q must be greater than 2 at very short distances.

Belli's first argument involved a drop of water hanging from a horizontal surface and in equilibrium with the attraction of the earth. Assume that the molecular attraction of the contents of the drop follows the law of gravitation (which means that q equals 2) and that the drop is spherical. The attractive force exerted by the drop on its lowermost particle must resist the attraction of the earth. Then, according to the inverse-square law, the radius of the drop multiplied by the density of water must give a product larger than the radius of the earth multiplied by the density of the earth. The radius of the drop is about a millimeter, however, and that of the earth is more than six million meters; clearly the original assumption is absurd and q must be greater than 2.

Belli's second argument concerned the mutual attraction of two circular plates of the same substance, parallel to each other. It was known that the attraction between such plates is negligible at sensible distances and becomes very great when they are almost in contact. This attraction is independent of plate thickness. Belli calculated the attraction between the plates if q were equal to 2, 3 or 4, that is, if the attraction varied inversely with the square, the cube or the fourth power of the distance. None of these agrees with the facts, since they all assign an influence to thickness. We learn from this that q is greater than 4. Using this kind of simple argument, Belli found it impossible to produce an unequivocal answer to the problem, although he showed that q might lie between 4 and 6. For further progress to be made, he wrote, it was necessary for chemists and crystallographers to elucidate the arrangement of atoms within bodies. He was right: theorists could go no further on such a slender experimental basis.

What is remarkable is how far science had got, by 1814, in understanding the forces that hold matter together. This progress was based on a belief, to which we still hold, that the secrets of nature are simple. The way to discover those secrets is to question nature in the laboratory and such questioning was the basis for the remarkable advances in physics in the 19th century, which laid the foundation of our present knowledge. Nevertheless, 212 years after the publication of the *Theoria* of Boscovich, it is clear that we still do not have a comprehensive theory. It may be that we need another Thales, Democritus or Boscovich to bring about the next major synthesis.



INTERPENETRATING UNIVERSES might coexist, Boscovich speculated. All that would be necessary would be for the force curves of each not to interfere with one another.

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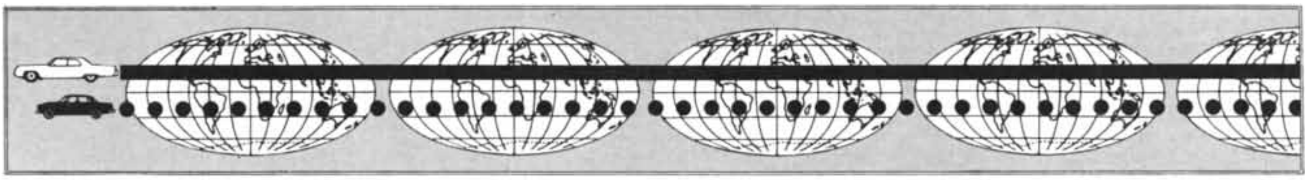

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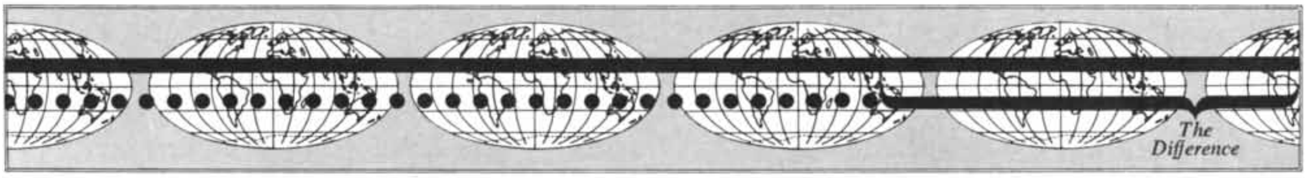

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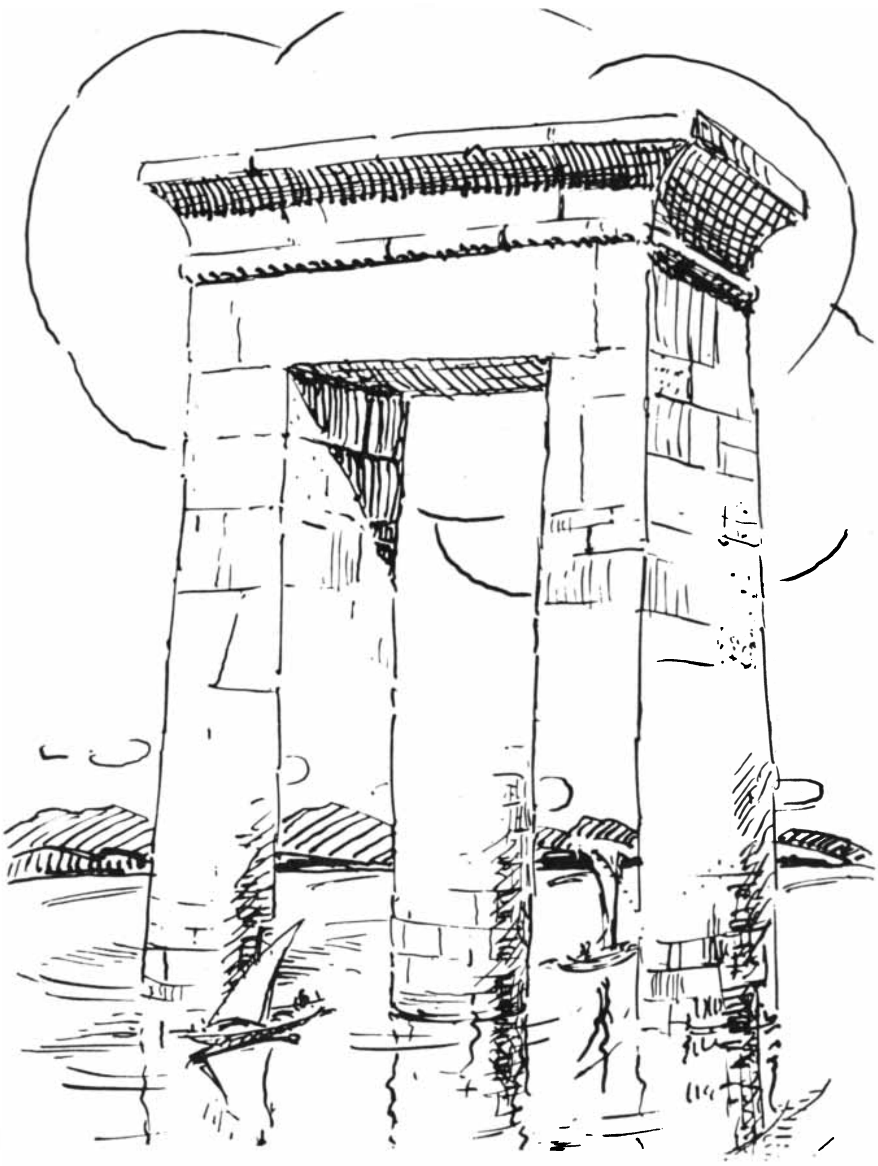
MATHEMATICAL GAMES

Of optical illusions, from figures that are undecidable to hot dogs that float

by Martin Gardner

There are so many optical illusions of so many different kinds and the literature about them is so vast that no single article can even begin to cover the field. This month we shall consider a few relatively little-known illusions that have a mathematical flavor. Readers interested in the older, more familiar examples will find most of them in Matthew Luckiesh's classic *Visual Illusions* (1922), available as a Dover reprint. For more recent work as well as current theories of why visual distortions occur there are no better references than Richard L. Gregory's *Eye and Brain,* a paperback published by McGraw-Hill in 1966, and Gregory's article in this magazine [see "Visual Illusions," by Richard L. Gregory; SCIENTIFIC AMERICAN, November, 1968]. The astonishing perspective illusions invented by Adelbert Ames, Jr., the best-known of which are his distorted room and his rotating trapezoidal window, were covered in two earlier articles published in SCIENTIFIC AMERICAN [see "Experiments in Perception," by W. H. Ittelson and F. P. Kilpatrick, August, 1951, and "Visual Perception and Personality," by Warren J. Wittreich, April, 1959].



Roger Hayward's "undecidable" monument

The process by which the brain interprets visual data is so complex and little understood that it is no surprise to find psychologists disagreeing sharply over explanations for even the simplest illusions. One of the oldest is the apparent increase in the size of the sun, moon and constellations when they are near the horizon. The late Edwin G. Boring of Harvard University wrote many papers arguing that the "moon illusion" is caused primarily by the raising of one's eyes. A quite different view, going back to Ptolemy, was convincingly defended in this magazine [see "The Moon Illusion," by Lloyd Kaufman and Irvin Rock; SCIENTIFIC AMERICAN, July, 1962]. Their "apparent distance" theory, in turn, has recently been challenged by Frank Restle in an article in *Science* (February 20).

Today's approach is to regard most visual illusions as occurring in the brain as it searches its memory for what Gregory calls the "best bet": the interpretation that best explains the visual data in terms of the brain's stored experience. Such a view is supported by recent discoveries that many animals, including birds and fish, have illusions that can be explained in this way and also by work with people in cultures that differ markedly from ours. Zulus, for example, live in an almost completely round world. Their huts and doors are rounded. They plow fields in curves. Straight lines and right angles are seldom seen and there is no word for "square" in their language. As John Updike puts it in the second stanza of his poem "Zulus Live in Land without a Square":

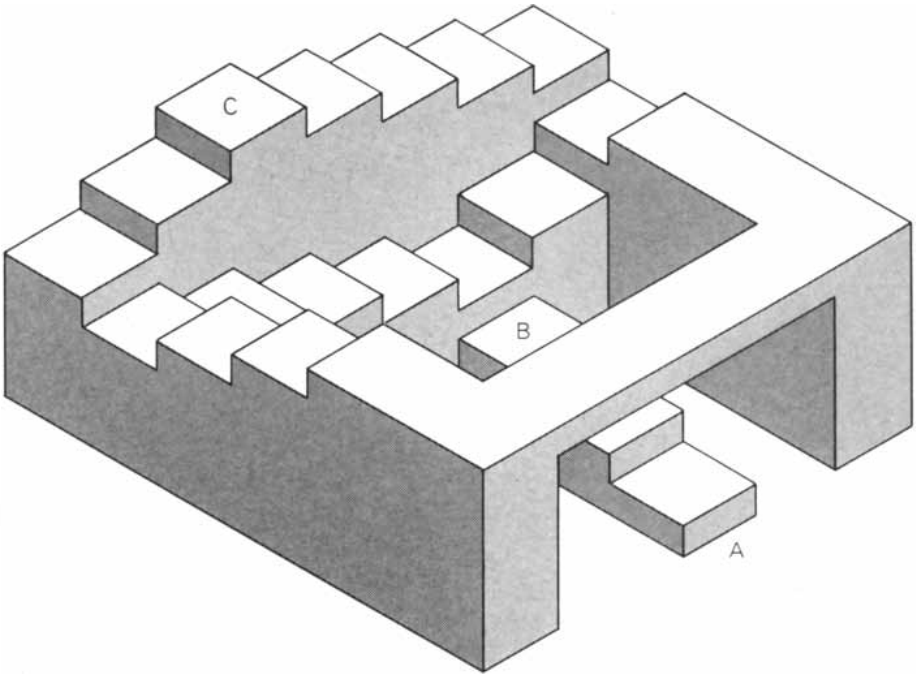
When Zulus cannot smile, they frown,
To keep an arc before the eye.
Describing distances to town,
They say, "As flies the butterfly."

Several recent studies have shown that optical illusions involving parallel lines and angular corners, so common to the rectangular world of technologically advanced societies, are difficult for Zulus to perceive. The philosophers John Locke and George Berkeley both considered the question of whether a man born blind, who suddenly gains his sight, would be able to decide, without touching them, which of two objects was a cube and which a sphere. Locke and Berkeley thought not. Gregory's book summarizes recent studies along such lines and, although they are inconclusive, they seem to support both philosophers, again providing evidence for the modern view that most optical illusions are caused by the brain's faulty interpretation of input data.

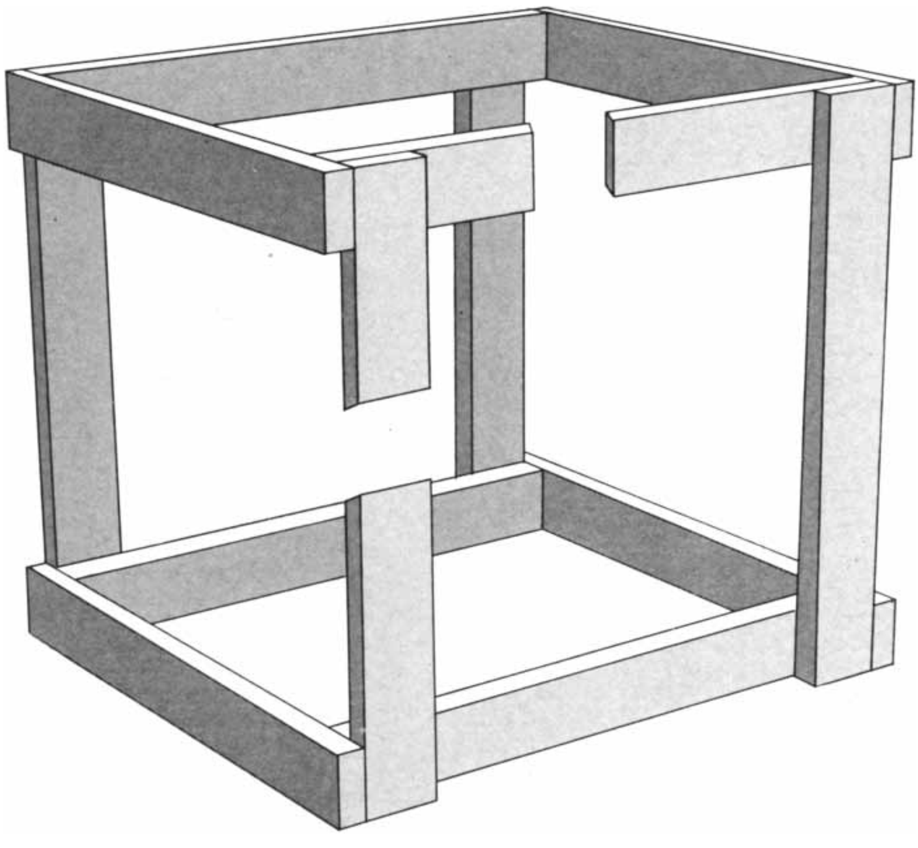
An amusing new development in visual illusions is the discovery of "undecidable figures": drawings of objects that cannot exist. The brain, unable to make sense of them, is thrown into a strange state of befuddlement. (They are analogous to such undecidable sentences as "This statement is false" or "Don't miss it if you can.") The best-known undecidable figure is the notorious three-pronged (or is it two-pronged?) "blivet," which began circulating among engineers and others in 1964. The March 1965 cover of *Mad* showed a grinning Alfred E. Neuman (with four eyes) balancing the blivet on his index finger. Roger Hayward, who illustrates this magazine's "Amateur Scientist" department, contributed an article on "Blivets: Research and Development" to *The Worm Runner's Digest* (December, 1968) in which he presented several variations [*see illustration on opposite page*].

Another well-known undecidable figure is the square staircase around which one can climb or descend forever without getting higher or lower. It can be seen in Maurits C. Escher's 1960 lithograph "Ascending and Descending" [see "Mathematical Games," April, 1966] and in the same artist's 1961 lithograph of a waterfall operating a perpetual motion machine [see "Perpetual Motion Machines," by Stanley W. Angrist; SCIENTIFIC AMERICAN, January, 1968]. This mystifying illusion, which was designed by the British geneticist L. S. Penrose and his son, the mathematician Roger Penrose, was first published in their article "Impossible Objects: A Special Type of Visual Illusion" in *The British Journal of Psychology* (February, 1958, pages 31–33).

The same two authors made use of it in their collection of original "Christmas Puzzles" for *The New Scientist* (December 25, 1958, pages 1580–1581). Assuming [*see top of this page*] that it takes three steps to go from the ground *A* to the top of step *B*, how can one get from *A* to *C* by climbing no more than 10 steps? The solution is possible only because the structure itself is not. Thomas H. O'Beirne (who devised a splendid impossible figure for the jacket of his book *Puzzles and Paradoxes*) writes that the Bell Telephone Laboratories has a film showing a ball bouncing endlessly around the Penrose staircase. At each bounce a musical note rises in pitch but the tones never seem to get any higher. After 12 rises there is a pause. The next tone drops an octave but the brain fails to realize it—an eerie undecidable sound illusion explained in *The Journal of the*



A puzzle based on the Penrose stairway



Possible model for an impossible crate

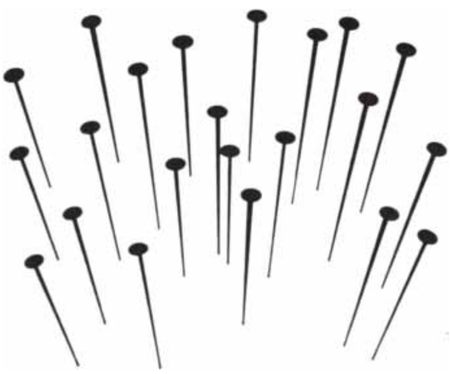
Acoustical Society of America (December, 1964, pages 2346–2353).

A third impossible object is the skeleton of the cube held by a seated figure in an Escher lithograph [see "Mathematical Games," April, 1966]. A photograph of such a "Freemish Crate" was published in this magazine's "Letters" department [June, 1966], but it was achieved by doctoring the picture. A way to build a model that produces a genuine photograph is explained by William G. Hyzer in *Photo Methods for Industry* (January, 1970, pages 20–24). Hyzer's model is shown here at the bottom of the preceding page. If the model is turned and tilted so that one open eye sees the gaps exactly coinciding with two back edges of the crate, the brain assumes that the back edges are in front, producing a mental image of the impossible cube. The same dodge is explained by Gregory (in the article mentioned earlier) as applied to a model of an impossible triangle devised by the Penroses. The basic idea goes back to the psychologist J. J. Gibson, who exploited it for many remarkable illusions in which he manipulated cardboard rectangles with portions of them cut out to make distant rectangles appear to be in the foreground. They are illustrated in Gregory's book on pages 182–183.

The fact that we have two eyes makes many curious illusions possible. Hold your extended index fingers horizontally before your eyes, tips touching. Focus through the fingers on a distant wall and then separate the fingertips slightly. You will see a "floating hot dog" between the two fingers. It is formed, of course, by overlapping fingertips, each seen by a different eye. Another ancient illusion of binocular vision is produced by holding a tube (such as a rolled-up sheet of paper) to your right eye like a telescope. Your left hand, palm toward you, is placed with its right edge against the tube. If you slide the hand back and forth along the tube, keeping both eyes open and looking at a distant object, you will find a spot where you seem to be looking through a hole in the center of your left palm.

The Canadian flag and its two angry men

A gestalt puzzle. What do the black shapes represent?



The nails that stand up

Under certain circumstances single-eyed vision gives an illusion of depth. Looking at a photograph through a tube with one eye produces a slight three-dimensional effect. One of the most striking illusions of monocular vision is shown at the bottom of this page. The page must be tilted back until it is almost flat. If the picture is viewed with one open eye from near the lower edge of the page, close to a spot above the point where all the lines would meet if they were extended downward, in a moment or two the nails will seem to stand upright. William James, in Volume 2, Chapter 19, of his famous *Principles of Psychology*, after giving an excellent explanation of this illusion proposed by Mrs. C. L. Franklin, adds the following succinct summary of the modern approach to perception: "In other words, we see, as always, the most probable object."

An amazing binocular illusion is called the Pulfrich pendulum after its discoverer, Carl Pulfrich, who first described it in a German periodical in 1922. The pendulum is simply a piece of string, from one foot to four feet long, with a small object tied to one end. Have someone hold the other end and swing the bob back and forth along a plane perpendicular to your line of vision. Stand across the room and view the swinging bob by holding one lens of a pair of sunglasses over one eye. Both eyes must remain open. Keep your attention at the center of the swing rather than following the moving bob. The bob will appear to swing in an elliptical orbit! Shift the dark glass to your other eye and the bob will travel the same elliptical path but in the opposite direction. The depth illusion is so strong that if a large object is held behind the path of the bob, the bob actually seems to pass through it like a ghost.

The Pulfrich illusion is explained in Gregory's book (pages 78–80) as arising from the fact that your dark-adapted eye sends messages to your brain at a lower speed than your uncovered eye. This time lag forces your brain to interpret the bob's movement as being alternately in front and in back of the plane in which it swings.

Similar depth illusions are experienced if you look at a television picture with the dark glass over one eye or with one eye looking through a pinhole in a card. When something in the picture moves horizontally, it seems to travel in front of the screen or behind it. It was this illusion that prompted several companies to advertise in 1966 a special pair of spectacles that, according to the advertisements, enabled one to see flat television pictures in three dimensions. The price was high and of course the spectacles were merely inexpensive sunglasses with a piece of transparent plastic for one eye and darkened plastic for the other.

A familiar category of illusions, much analyzed by the Gestalt school of psychology, concerns images capable of two interpretations of equal or nearly equal probability. The mind fluctuates, unable to settle on the best bet. The pattern of cubes that suddenly reverses, so that the number of cubes changes, is perhaps the best-known example. In recent years we all have been annoyed by looking at photographs of lunar craters and finding it difficult not to see them as mesas, particularly if the picture is turned so that the craters are illuminated by sunlight from below, an angle of lighting that is seldom experienced. The black vase with contours that can be seen as profiles of two faces, another much-reproduced illusion of fluctuating gestalts, unexpectedly popped up in the new Canadian flag when it was officially adopted in 1965 after months of wrangling in the House of Commons. Direct your attention to the white background at the top of the red maple leaf [*see top illustration on opposite page*]. You will see the profiles of two men (Liberal and Conservative?), foreheads together, snarling at each other. Once you have spotted these faces you should have little difficulty understanding the odd-shaped polygons second from the top on the opposite page.

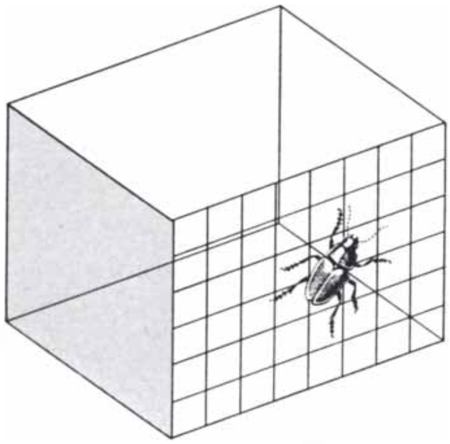
The Necker cube (after L. A. Necker of Switzerland, who wrote about it in the 1830's) is another much-studied figure that reverses while you are looking at it. The Penroses, in their Christmas puzzles mentioned earlier, had the clever idea of adding a beetle to the "cube," in this instance a rectangular box [*see top illustration at right*]. The beetle appears to be on the outside. Stare at the back corner of the box and imagine it to be the corner nearest you. The box will suddenly flip-flop, transporting the beetle to the floor *inside*.

A surprising illusion, perhaps related to the Müller-Lyer illusion (two lines of equal length that appear different because of arrow lines that point inward at the ends of one line and outward at the ends of the other) can be demonstrated with three pennies. Place them in a row [*see middle illustration at right*]. Ask someone to slide the middle penny down until distance *AB* equals distance *CD*. Almost no one slides the coin far enough; indeed, it is hard to believe, until you measure the lines, that this illustration gives the correct position. The trick can also be done with larger coins, circular coasters, water glasses and other similar objects.

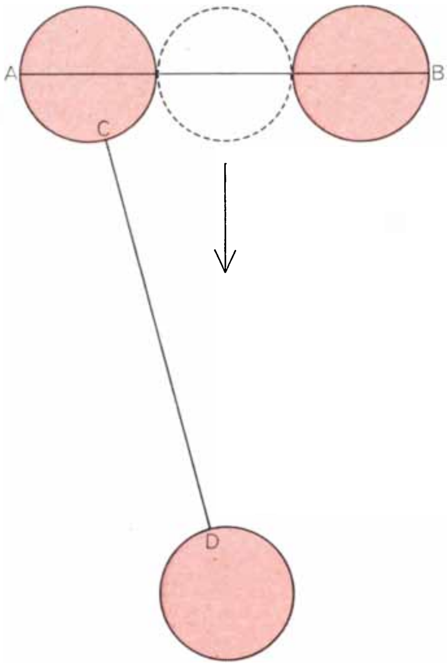
The "ghost penny" illusion, better known to magicians than to psychologists, is illustrated at bottom right. Hold two pennies between the tips of your forefingers and rub them rapidly back and forth against each other. A ghost penny will appear—but why should it be only at one end and not at the other? If any explanation of this curious asymmetry has been published, I do not know of it.

The answer to last month's first problem is that a wheel rotates three times in rolling once around a fixed wheel with twice the diameter of the rolling wheel. Since the circumference of the rolling wheel is half that of the larger one, this produces two rotations with respect to the fixed wheel, and the revolution adds a third rotation with respect to an observer from above. The general formula, where a is the diameter of the fixed wheel and b is the diameter of the rolling wheel, is $(a/b) + 1$. This gives the number of rotations for one revolution. Thus if the rolling wheel has a diameter twice that of the fixed wheel, it rotates 1½ times. The rolling wheel, as it gets larger, approaches a limit of one rotation per revolution—a limit that is achieved only when it rolls around a point of zero diameter.

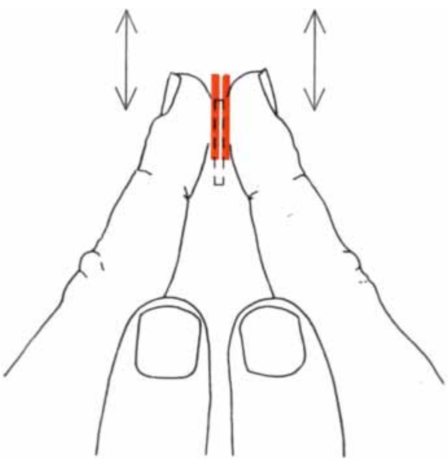
The answer to the second question, about the number of concave sections in the moon's wavy path around the sun, is that at *no* time is the path convex. The moon is so close to the earth and the earth's speed is so great in relation to the moon's speed around the earth that the moon's path (in relation to the sun) is at all points convex.



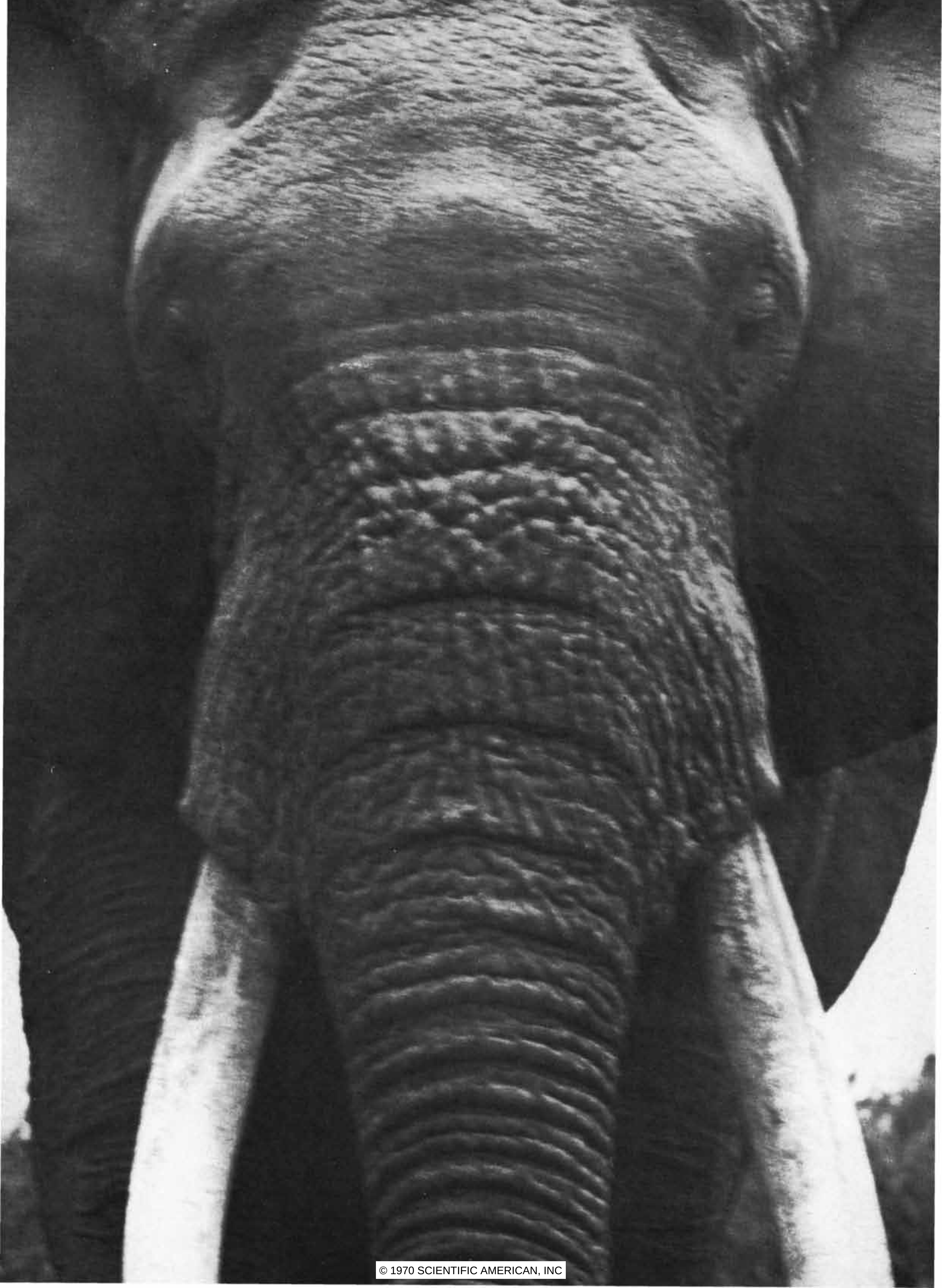
Put the bug inside the box



An equal-distance illusion



The "ghost penny"



THE AMATEUR SCIENTIST

A simple new amplifying device is adapted to driving a pen recorder

Conducted by C. L. Stong

An amplifier of some kind is an essential part of most instruments used for making fine measurements or controlling an apparatus or a process automatically. For example, the sensitivity required in an ordinary thermometer is developed by a hydraulic amplifier in the form of a capillary tube sealed to a glass bulb. Variations in temperature that cause almost imperceptible changes in the volume of fluid in the bulb appear as pronounced excursions of fluid in the capillary. Other examples include the moiré verniers of the surveyor's transit, the train of gears in a dial micrometer, the jeweled levers in a mechanical seismograph and electronic amplifiers of various kinds in light meters, ion gauges, gas chromatographs and so on.

All good amplifiers are difficult to design. They are even more difficult to make at home, a fact that has discouraged many amateurs who otherwise might enjoy experimenting with sensitive instruments. A promising solution to this problem has recently appeared in the form of the small electronic devices known as operational amplifiers. They were developed to perform arithmetical operations in computers. Experimenters soon discovered that the amplifiers make handy building blocks for constructing sensitive instruments and control devices of all kinds.

The typical operational amplifier resembles a block of plastic about the size of a cube of sugar. On the back of the block are five or more short stubs of wire; they are the connecting terminals. In a five-terminal block one terminal is the input connection, another is the output, the third is a common terminal and the remaining pair are for connecting the unit to a source of direct current, such as a small dry battery.

The gain, or amplifying power, of the units is typically several million, far more than is required in practical applications. The gain can be reduced as desired by feeding some of the output energy back into the input terminal through a resistor. A second resistor is connected in series with the input terminal. The resistors establish the "closed loop" gain of the amplifier, which is exactly equal to the value of the feedback resistor divided by the value of the input resistor. For example, if the feedback is one million ohms and the input resistor is 1,000 ohms, the amplifier will increase the strength of the input signal exactly 1,000 times. The feedback scheme not only fixes the gain but also makes the amplifier relatively insensitive to variations of loading, temperature and other external influences.

The input signal can be either direct current or alternating current. The most sensitive operational amplifier can detect an input signal of a millionth of a billionth of an ampere and deliver an output of .02 ampere at a potential of 10 volts. This is much more energy than is required to operate an inexpensive meter or to drive a power amplifier.

Some types of operational amplifier have two input terminals but only one output terminal. Such amplifiers are known as differential amplifiers. They compare two independent input signals and amplify the difference between them. The devices are used, among other things, for determining an unknown voltage by comparing it with a known voltage. The known voltage is connected to one input terminal, the unknown voltage to the second input terminal. The output voltage divided by the gain of the amplifier equals the difference. By making the gain sufficiently large the experimenter can determine the value of the unknown voltage to any desired accuracy within the limits of the amplifier.

Quantities other than voltage can be similarly determined by equipping the amplifier with appropriate sensing devices. For example, if the input voltages are derived from a pair of strain gauges, the output will be proportionate to the difference between two forces [see "The Amateur Scientist"; SCIENTIFIC AMERICAN, January, 1968]. By substituting for the strain gauges a pair of photocells, thermocouples or glass electrodes, comparisons can be made in terms of such factors as light intensity, temperature and the acid-alkaline balance of chemical solutions.

Differential amplifiers are also used as the primary functional element in servomechanisms, or automatic-control devices. The principle of these mechanisms is illustrated by an apparatus recently designed and built by J. Barry Shackleford of East Point, Ga. He writes as follows:

"For some years I have been on the lookout for a graphic recorder I could afford, or plans for the construction of one. Commercial recorders of the quality I wanted cost $500 or more. The homemade varieties that have been described are not sufficiently sensitive or versatile for recording the data I wanted to collect. Several months ago I came across a description of an operational amplifier of the differential type and decided to try one as the central element in a mechanism for converting a varying voltage into the proportional displacement of a pen. The apparatus works so well that it may interest other experimenters.

"The mechanism consists of five essential parts: a differential amplifier, a current amplifier, a reversible direct-current motor, a potentiometer and a power supply. The differential amplifier compares a signal voltage with a reference voltage and amplifies the difference. This output is then increased sufficiently by the current amplifier to operate the motor. The motor drives a train of reduction gears that rotates the shaft of a potentiometer. The potentiometer develops a voltage that is proportional to the position of its contact arm, which is fixed to the shaft. This voltage is fed back to the positive input terminal of the differential amplifier as a reference potential for comparison with the signal voltage.

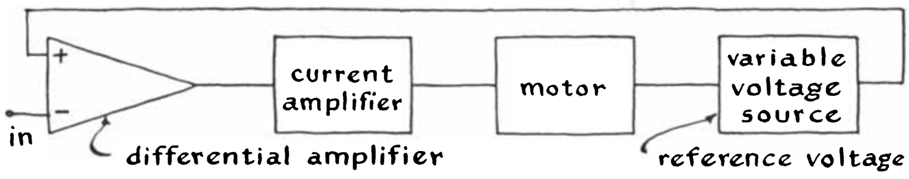
"When the signal voltage exactly equals the reference voltage, the output of the amplifier is zero. The motor receives no power and the contact arm of the potentiometer remains fixed. If the signal voltage now increases or decreases, the difference is amplified and appears across the terminals of the motor. The motor then rotates the contact arm of the potentiometer to the point where the reference voltage again exactly equals the signal voltage.

"In effect, the system converts variations of signal voltage into corresponding displacements of the contact arm. The displacements can be recorded in ink by attaching a pen to the outer end of a lever clamped to the shaft of the potentiometer. Some potentiometers are constructed in the form of a helix, so that the contact arm must make 10 or more revolutions to travel from one extreme to the other. By installing a pulley on the shaft of a potentiometer of this kind a belt can be used to displace a pen along a straight line. Other devices can be substituted for the pen, such as a valve, a rudder or a throttle.

"My differential amplifier operates from a direct-current source of 15 volts. It has six terminals: two (as a pair) for the power, one for the positive input, one for the negative input, an output terminal and a common terminal that is connected to the metal chassis on which the apparatus is mounted. Each input terminal is equipped with a pair of resistors for fixing the gain and providing negative feedback.

"In general operational amplifiers are adequately stabilized by a feedback current ranging from one microampere to 10 microamperes. I assumed a current of about four microamperes for the purpose of calculating the value of the feedback resistor. The resistance is equal to the voltage of the power supply divided by the assumed current: $15/4 \times 10^{-6} = 3.7 \times 10^{6}$ ohms. Since I happened to have several 3.3-megohm resistors, I used them because they were reasonably close to the calculated value.

"I decided arbitrarily to fix the gain of the amplifier at 100 for the initial experiment. The gain is equal to the value of the feedback resistor divided by the value of the resistor placed in series with the input. In this case the gain is $3.3 \times 10^{6}/100 = 33{,}000$ ohms. A resistor of this value was connected to each of the input terminals. Feedback resistors were then connected between the output terminal and the positive input terminal and between the negative input terminal and the chassis [*see top illustration on next page*]. The common terminal was connected directly to the chassis by a copper lead. With the exception of the two input connections and the battery connection, this completed the wiring of the differential amplifier.



Components of J. Barry Shackleford's amplifier

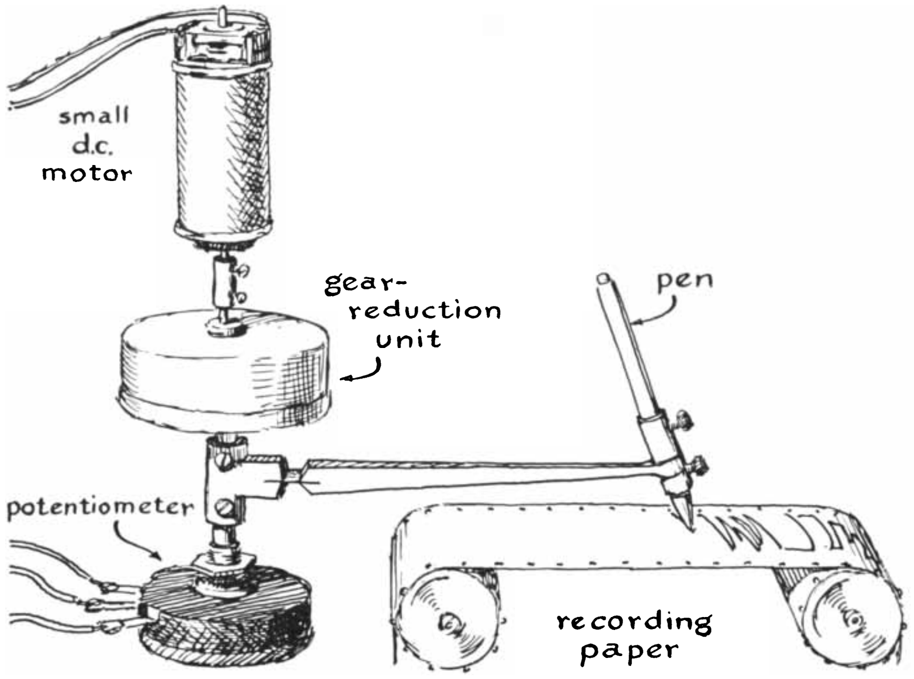
"When the signal voltage is lower than the reference voltage, the amplifier develops a negative voltage at the output terminal. On the other hand, positive voltage appears at the output terminal when the signal voltage is higher than the reference voltage. The amplifier delivers a maximum output current of .02 ampere. The motor I used requires a current of one ampere. To develop the necessary additional current I inserted a current amplifier between the differential amplifier and the motor. Current amplifiers are available commercially but can be made so easily and inexpensively that I assembled my own.

"The current amplifier uses two power transistors; they are identical except that one amplifies negative input voltage and the other one amplifies positive input voltage. Any transistors of this general type can be used provided that they are designed for an output current of at least one ampere. Each transistor must be mounted on a heat sink—a metal plate with cooling fins for radiating heat that develops internally when the device conducts current.

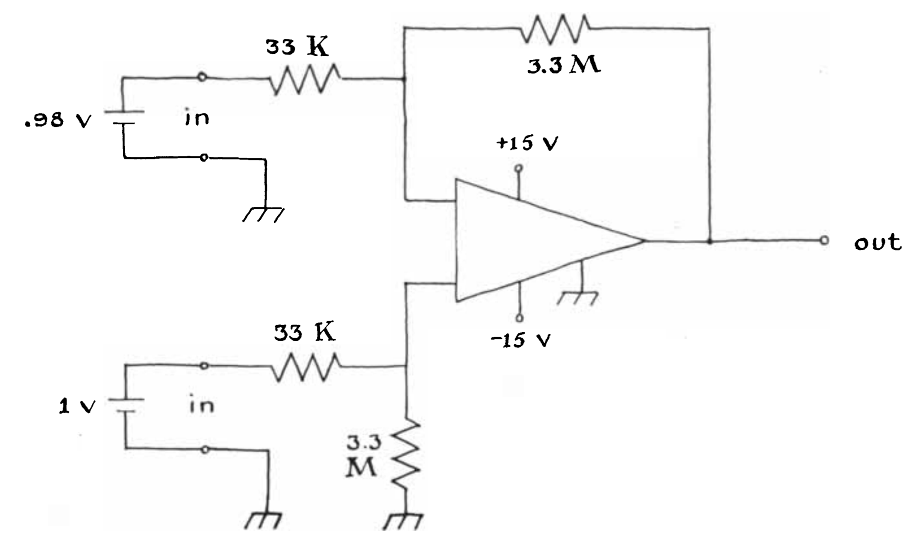
"The general wiring scheme of the current amplifier is depicted by the accompanying schematic diagram [*bottom of next page*]. The output voltage of the differential amplifier is applied to the input circuit of the power transistors through diodes connected so that positive voltage causes one transistor to conduct and negative voltage causes the other one to conduct. The polarity of the output is positive when the first transistor conducts. The motor then rotates in one direction. When the other transistor conducts, the output is negative and the motor reverses.

"The output lead of each transistor contains a 10-ohm resistor that limits the current and protects the device. Input voltage for triggering the transistors is developed across a pair of 15,000-ohm resistors connected in series with the diodes and the differential amplifier. Capacitors connected between the power-supply terminals and the chassis act as filters for suppressing spurious alternating currents.

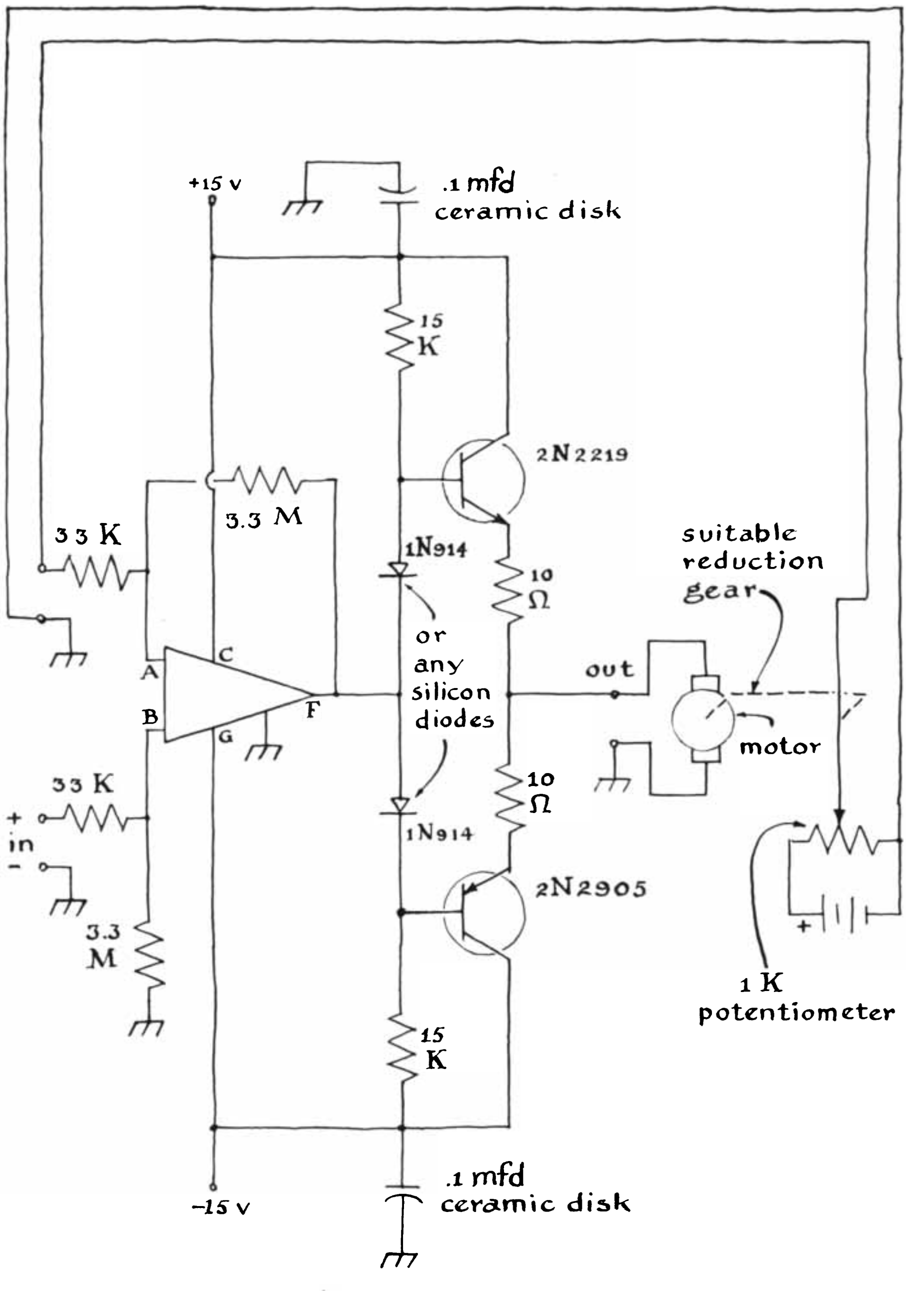
"The reference voltage is derived from the power supply, which is connected to the fixed terminals of the potentiometer. The reference voltage is applied to one



Mechanics of the pen recorder



External circuitry of the amplifier



Arrangement of the fully assembled apparatus

input terminal of the amplifier by a lead from the sliding contact of the potentiometer. The reference voltage should be somewhat larger than the expected range of the signal's voltage. For example, a reference potential of one volt is appropriate for a signal that varies from approximately .3 to .7 volt. The response of the potentiometer must be linear, that is, it must develop equal increments of reference voltage as the sliding contact advances through equal increments of arc.

"The apparatus can be operated by three dry batteries. Two of them, of about 15-volt capacity, are for supplying the amplifiers, and one 1.5-volt battery is for energizing the potentiometer. When batteries are used, the positive terminal of one 15-volt battery is connected to the negative terminal of the second 15-volt battery and to the chassis. The remaining battery terminals are connected to the apparatus.

"For reasons of economy I substituted a pair of power supplies for the 15-volt batteries. The units were regulated automatically to deliver exactly 15 volts apiece. Each unit consists of a small, inexpensive transformer that operates on house current to supply alternating current at 25 volts.

"The output of the transformer is converted to direct current by a rectifier of the bridge type that requires four diodes of the kind that will conduct an ampere and withstand a potential of 50 volts. The output of the rectifier is filtered by a pair of 500-microfarad electrolytic capacitors. Connected across the output of the rectifier is a voltage divider consisting of a 1,200-ohm resistor in series with a Zener diode.

"The Zener diode is in effect a variable resistor that automatically maintains fixed voltage in a circuit. Variations of potential cause the conductivity of the Zener diode to change in the direction required for maintaining constant voltage across its terminals. In my application the fixed voltage of the Zener diode controls the conductivity of a transistor in one lead of the power supply. Variations of the rectified voltage are instantly compensated by opposing variations of resistance in the transistor and vice versa, with the result that a constant potential appears across the output of the power supply. The power supplies are connected to the apparatus just as though they were dry batteries.

"The fully assembled apparatus performed much as I had hoped. When I applied a signal of .5 volt to the input terminal, the potentiometer promptly generated a corresponding reference volt-

How to switch from being really mean to equal tempered

You may find it hard to believe that a topic like organ tuning would ever cause people to tear their hair out. Yet, the apochryphal tale of the feud between Gottfried Silbermann, the organ builder and J.S. Bach reveals that they at least, were far from being equal tempered about the subject. Silbermann favoured mean tone and Bach equal tempered tuning. Therefore, when the latter was asked to play Silbermann's new organ, he deliberately chose a Fantasia in F Sharp Major. This key contains the largest number of false tones in the mean tone tuning method. Naturally, Silbermann became furious and, running to the organ platform, he ripped off Bach's wig!

Dr. N.V. Franssen and other members of the Acoustic Research Group of Philips Research Laboratories, Eindhoven, the Netherlands, have demonstrated a simple, accurate method of generating all the musical tones of an electric keyboard instrument, simultaneously. Its tuning system can also be varied at the touch of a switch - a feature which would certainly have mollified Bach and Silbermann.

The need for such a system arose from research into musical perception. If an instrument is not to sound off key, it must have a relative pitch accurate to within 0.05%. With Dr. Franssen's new method the tuning is automatically determined by a circuit in the organ itself and not "by ear" or with external measuring equipment.

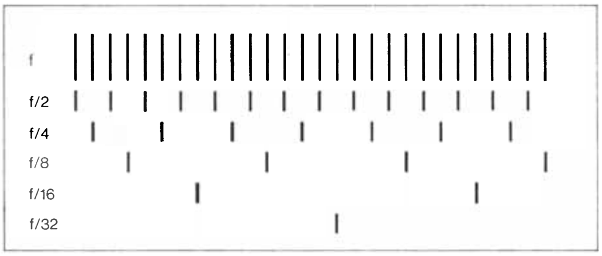
Each keyboard has a certain number of octaves. The frequencies of the highest and lowest notes of each octave are in the ratio of 2 : 1, and for intermediate notes, somewhere between 2 and 1. For example, taking the relative frequency of the top note as 2, the tenth note in the octave can be written as 1.6818. The new method of generating the notes in an octave makes use of the relative frequencies re-written in a binary scale. To achieve an accuracy of 0.05%, eleven binals are required to write these numbers (twelve for the top note). These would be 100 000 000 000 and 11 010 111 010 for the top note and tenth intermediate, respectively.

The basic circuit consists of a master pulse generator of frequency f (the supposed frequency of the top note of the octave) followed by a series of eleven scale-of-two dividers. Pulses appearing at the output terminals of the eleven dividers, are staggered and never coincide in time.

The relative values of the frequencies from the eleven dividers correspond to the relative values of the digits of the eleven-digit binary number representing a note. For every "one" in the binary number representing an intermediate tone, the corresponding frequency divider's output is fed to a pulse combiner circuit. Therefore the number of pulses appearing at the output of the combiner circuit every second, corresponds with the frequency of that intermediate tone.

As the pulses are irregularly spaced, the resulting tone sounds harsh. This is remedied by making f 2^7 or 2^8 times higher than the desired value and dividing the output frequency from the combiner circuit by the same number. This evens out the pulse spacing. (In practice, f is taken as about 2 MHz.) After producing all the tones in the highest octave on a given instrument, the other intervals can be produced by frequency division.

The automatic tuning system is yet another example of the way in which digital and integrated circuit techniques are being applied to areas normally regarded as "artistic" rather than scientific.



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.

PHILIPS

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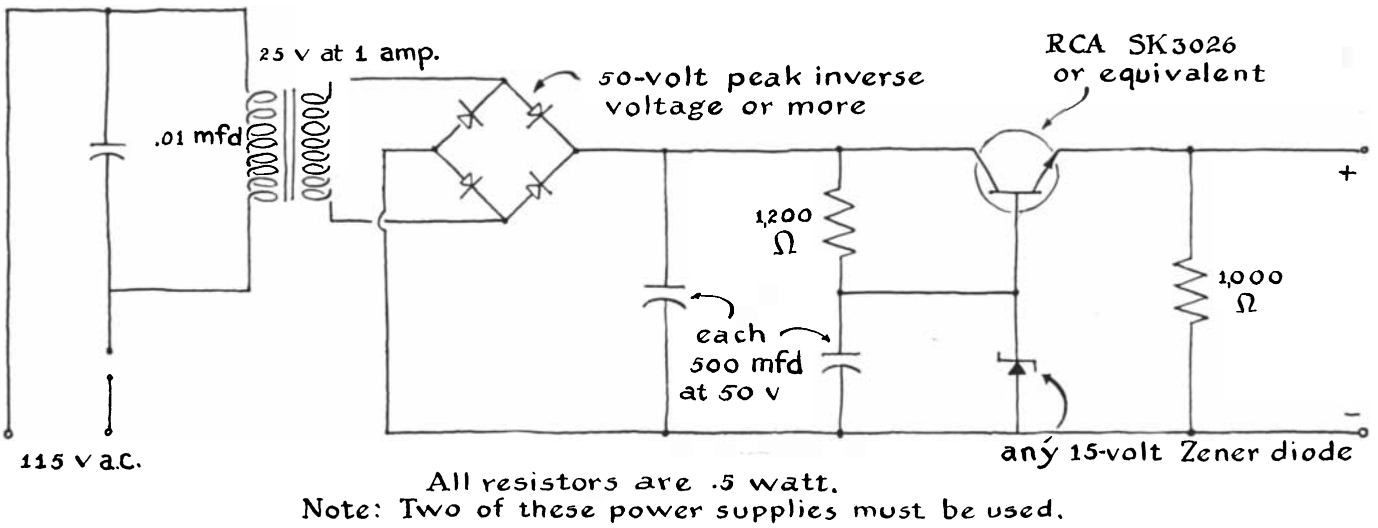


Circuitry of the power supply

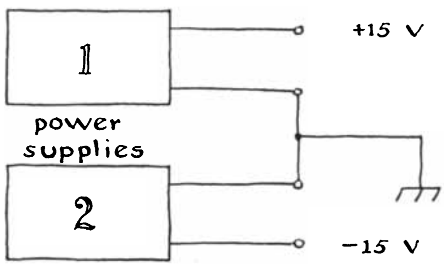
age and thereafter followed almost every variation of the signal. I say 'almost' because the device is not quite perfect. A certain minimum signal is necessary to start the motor. When the motor is at rest, the input voltage must increase or decrease slightly before the amplifier develops sufficient power to start the motor.

"I call this the 'dead zone.' It can be narrowed somewhat by increasing the gain. If the gain is increased above a certain value, however, the motor tends to overshoot: to start abruptly and coast beyond the point where the reference voltage equals the signal voltage. It then reverses, overshoots in the opposite direction and continues to oscillate for a time around the desired point before coming to rest. Insufficient gain increases the width of the dead zone.

"Optimum gain can be established most easily by providing the differential amplifier with a variable gain control. This step can be accomplished by substituting for the feedback and series resistors a dual potentiometer of about 3.5 megohms. The sliding contacts of the potentiometer are connected to the input terminals of the differential amplifier. One set of fixed terminals serves as the inputs. The fixed terminals of the other set are connected respectively to the output and to the chassis. With this arrangement the gain is adjusted to the point where the motor starts to oscillate and then is decreased slightly. The width of the dead zone could also be reduced by using a more sensitive motor.

"My motor was salvaged from a portable tape recorder that operated on dry cells. Several extraordinarily sensitive direct-current motors that are equipped with permanent-magnet fields have been made to operate from solar cells by the International Rectifier Company. Doubtless a motor of this type would improve the performance of the apparatus.

"The motor must be coupled mechanically to the reference-voltage potentiometer through a set of reduction gears. I used a surplus unit that works fine. Any gears that are relatively free of friction can be substituted. The gear ratio of my unit enables the motor to rotate the potentiometer to either of its extremes in about a second, a response time that is adequate for recording seismic waves, changes in the brightness of stars and much other information of interest to amateurs. The operational amplifier I used is Type 118-A. It is made by Analog Devices, Inc., 221 Fifth Street, Cambridge, Mass. 02142. It costs $11."



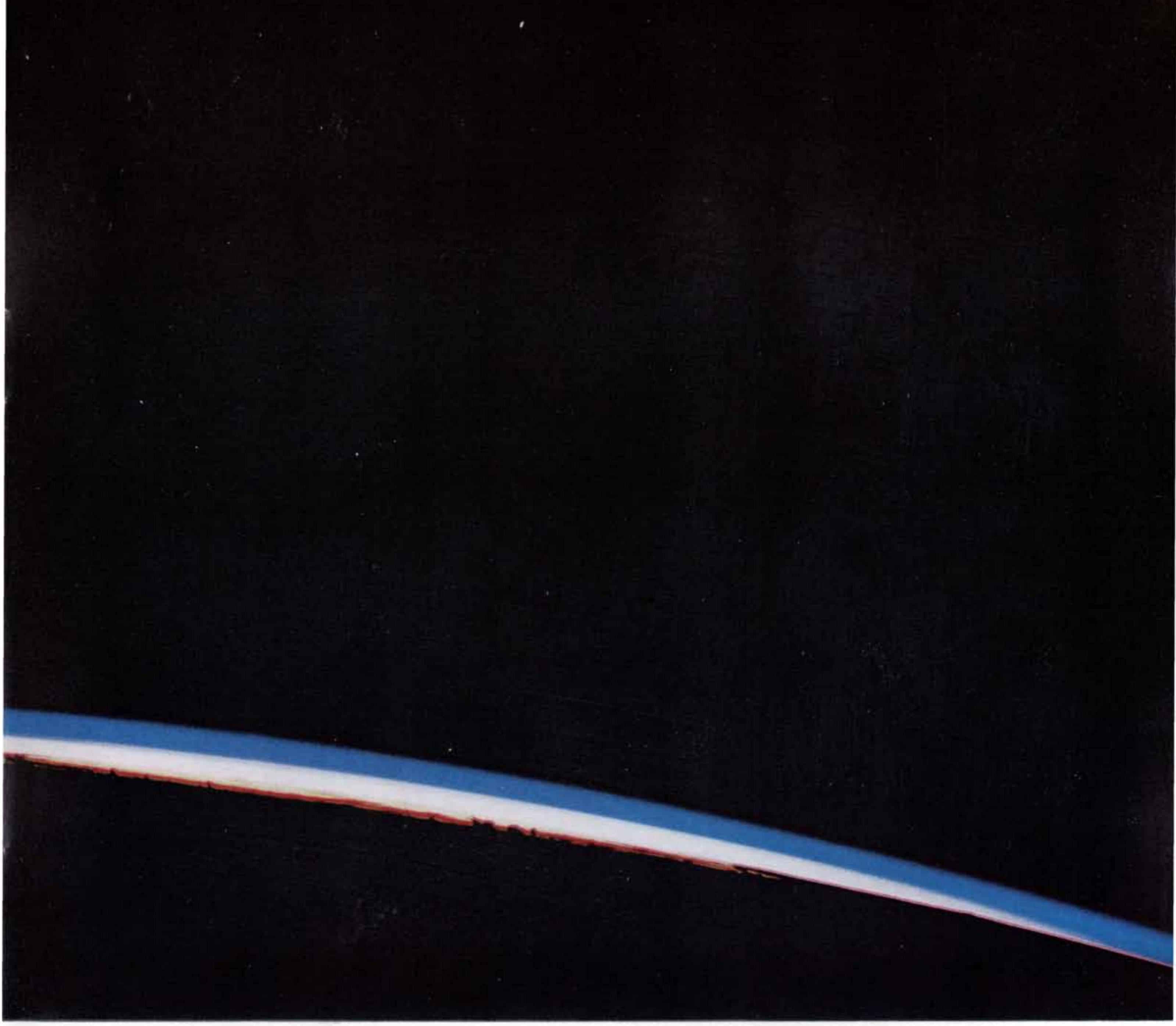
Interconnection of power supplies

Recently the editor of this department came across two other new and relatively inexpensive products of possible interest to amateurs. Both were developed for determining the acid-alkaline balance (*p*H) of materials by means of dyes that change color. The basic technique is not new. The interest of the new devices lies in the kinds of materials that can now be tested and in the accuracy of the measurements.

One of the devices measures the *p*H of the surface of such solids as paper, plastic, metal, textiles and minerals. This has not been possible heretofore. Often experimenters apply a printed circuit or some other metallic film to a substrate such as a sheet of plastic only to discover, when the apparatus fails some weeks later, that the surface was either acidic by nature or that it had been contaminated by alkali. Similarly, filter paper of the kind used for making chemical separations is supposed to be neutral but often turns out to have been contaminated by acid fumes.

The device for measuring the *p*H of solids consists of a set of four crayons contained in refillable mechanical pencils. To measure the *p*H of a surface you draw a mark on the material, dab it with a wad of cotton moistened with distilled water, wait 15 seconds and compare the hue of the mark with a scale of color that comes with the pencil. The crayons span the range of *p*H from 1 to 12.

The second product of interest is a new test paper containing a dye that is remarkably sensitive to liquids of low ion concentration. Dyes that are customarily used tend to react with the solution being tested and, if the concentration of ions is low, to alter *p*H. For this reason conventional test papers can result in an error of as much as a full *p*H unit. The new material reduces the error to less than a quarter of a unit. It consists of a roll of paper tape in a dispenser, a test tube and a color chart. The test is made by immersing a strip of the paper in a container of specimen solution and, after one minute, comparing the color of the strip with the color chart. The *p*H range of the dye is from 3 to 10. Both test kits are products of Micro Essential Laboratory Inc., 4224 Avenue H, Brooklyn, N.Y. 11210.



Photograph by hand-held camera aboard Gemini 8 shows thin veil of earth's atmosphere with towering cumulus clouds in silhouette. NASA

Five years ago the Tyonek Indians

The Tyonek Indians in Alaska used to struggle for their living. Their sole means of support was trapping and fishing.

Then one of our affiliates, Humble Oil & Refining Company, paid the Tyoneks several million dollars for the right to explore for oil on their land.

We didn't discover any oil. But we're used to that. (After all, only one out of every fifty exploratory wells drilled in the U.S. actually results in the discovery of oil in commercial quantities.)

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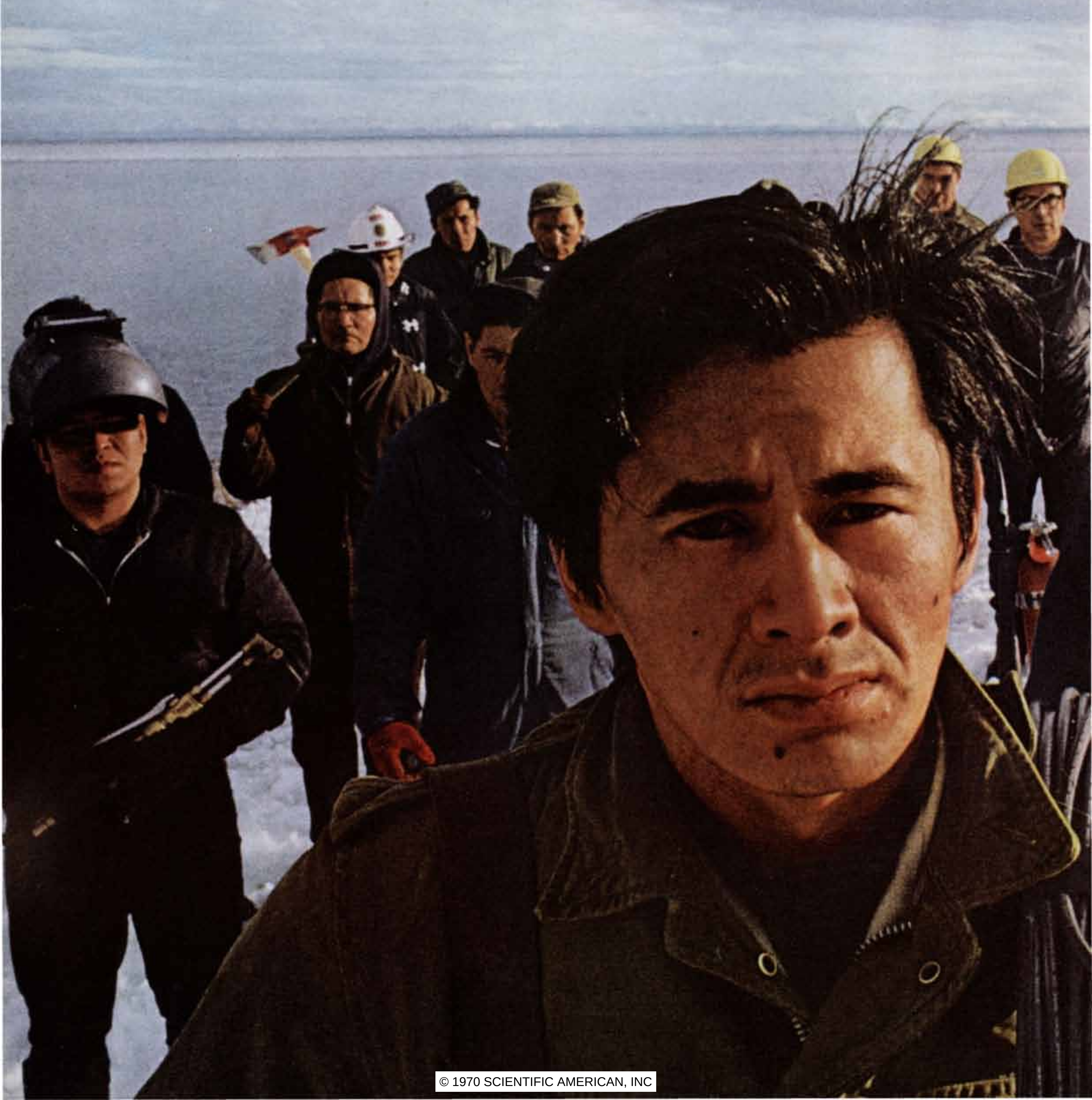

needed food. Now they need an industry.

a sawmill and a small air ine.

And they formed their own construction company, and rebuilt their village, complete with modern homes, electricity, roads and a new school.

While they were rebuilding their village, the Tyoneks learned to be welders and electricians and surveyors and technicians.

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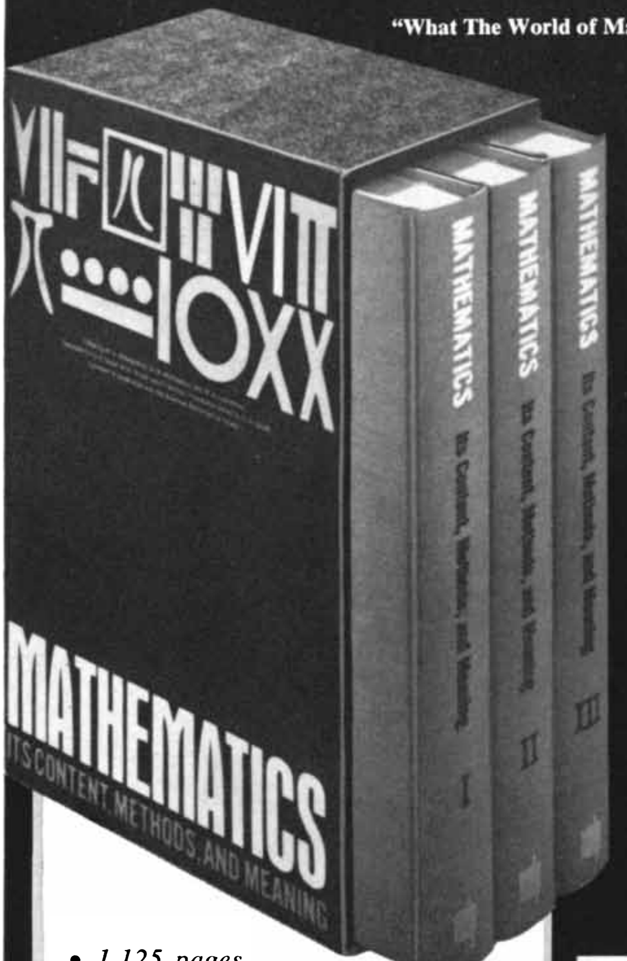

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BOOKS

Among other things, image tubes, the weather and the prevention of cancer

by Philip Morrison

PHOTO-ELECTRONIC IMAGE DEVICES: PROCEEDINGS OF THE FOURTH SYMPOSIUM, edited by J. D. McGee, D. McMullan, E. Kahan and B. L. Morgan. Academic Press ($46). The visual cortex dominates the input regions of the human brain; our minds are eye minds, and they are more so than ever these days. The two handsome volumes of this work record the present status of those new external retinas that our culture now swiftly evolves. It has been about 10 years since the first of these symposia organized by the distinguished senior editor, who came to Imperial College London out of the industry to open the narrow and proprietary history of this special branch of electron physics to the breadth and tone of international research. How much things have changed since then is shown by this report from the fall of 1968, a meeting attended by astronomers and radiologists, physicists and engineers, more than 150 strong, from Prague, Wetzlar, Meudon, Tokyo and many other centers.

The unity of the book is clear: all the work devolves on two-dimensional images produced by an organized amplification of the electron picture that a rain of photons paints on some photosensitive surface. It is remarkable that the ultimate in sensitivity, the standard of comparison for a dozen ingenious up-to-date developments, remains the electronograph. That tube was heroically developed back in about 1936 by A. Lallemand of Paris. The electronograph, called in the French contributions "la caméra électronique à focalisation électrostatique," does the job in the most fundamental way. The photoelectrons are accelerated and brought to an electrostatic focus on a fine-grain photographic emulsion directly exposed to the electron beam within the needed high vacuum. There is never any conversion to visible light. Every electron is fast enough to blacken the plate, and efficiency is limited only by the inherent atomic-lattice properties of the delicate photocathode. One can reckon about one black grain for every 10 photons that strike the surface. No other device can do better.

The cost of electronography to the user is high. Every time an exposed photographic plate is removed, the air destroys the highly reactive photosurface. The vapors of photographic film and even of photographic emulsion on a glass plate can in themselves do harm. A 10-year development at the U.S. Naval Observatory in Flagstaff, Ariz., has produced a version of the electronograph that has a gate valve able to close off the crucial volume and protect the surface during plate exchange. It is a virtuoso's tube, but it yields a signal-to-noise ratio from 30 to 50 times better than the standard high-sensitivity astronomical photographic films. Moreover, it has a nearly linear response over a wide range of intensities.

How can the image be removed from a sealed vacuum to the air world? One obvious means works well: put a very thin window—say a mesh-supported mica window about a tenth of a mil thick—to pass the electrons without much smearing by scattering. The idea goes back to World War I; it is by no means easy to realize in a practical tube. One realization is the Imperial College spectracon. Working tubes, not yet in production, have been used by several observatories. Designed for spectroscopy, this tube has a small rectangular image window. It has a gain at least two-thirds as high as the electronograph itself—until the window breaks. Round exit windows an inch in diameter are within view.

Television camera tubes, which produce an electrical wave form as an output signal, and image intensifiers, which present brightly on a glowing screen to the eye or the camera the faint scene that falls on the business end, are found in many ingenious arrangements. Some are cascades of images: photosurface, voltage acceleration, phosphor, new photosurface, more voltage, another phosphor and so on. These devices are divided into many independent sections, coupled by fiber optics or even by fast lenses. An entire series of eight sizes of such image intensifiers is produced by an American company (and is now declassified). These tubes, between four inches and a foot long, have two stages of photocathode-to-phosphor imaging, coupled by fiber-optic plates. Feed them with a battery-operated high-voltage source and you—or an infantryman—can see a target at the edge of the woods a kilometer away, where the unaided eye could make out only the dark treetops against the night sky.

Some tubes can see well in the near-infrared; one modified television camera tube has a beryllium window and looks directly at X rays. A whole class of ultrafast photographic devices is in production. One can photograph laser sparks that are bright enough with a time resolution of about a twentieth of a nanosecond. One interesting application of a cascade image intensifier is presented in a series of remarkable photographs of interference patterns, exposed at a dwindling rate of photon arrival. Interference is clearly seen even when the entire pattern is made by a few tens of photons entering the slits each second, from a few hundred excited atoms. Here, surely, the photons are independent, and "only one photon is present at a time." Yet, just as quantum physics expects, the photon can "interfere with itself." The photon gain is in the hundreds of thousands.

Two developments are foreshadowed. One is of course the general rise of solid-state devices. Various ingenious crystalline sandwiches are described that can see infrared or X rays or visible light, then display the amplified image on a glowing panel. Speed and sensitivity have not yet got ahead of the vacuum devices.

The most ingeniously simple device is the channel electron multiplier, which has been under development for a few years now. Take a glass tube 50 times as long as it is wide. Coat the inside with a smooth semi-insulating layer. Put a medium-high voltage, say three kilovolts, from one end to the other in a good vacuum. Let an electron enter the low-potential end. It will generally strike the wall of the tube a little farther on, to release a few secondary electrons. These move on to strike again, each one producing further secondaries. The entire tube is now an electron multiplier of utterly simple construction, with a gain of up to 100 million. The size of the tube is unimportant. Imagine a honeycomb made up of tiny tubes, all bundled parallel, all of a special slightly conducting glass. A typical plate of this kind is a couple of millimeters thick and contains 40,000 tubes per square centimeter. The multiplicity of tubes implies a statistical noise added to the signal, but except for single-electron applications these rugged devices should become widespread. Included here is a sharp photograph of a television image from just such a channel plate.

The imaging art is plainly in a state of mushroom growth. What the image-makers of the future will be, to set beside the commonplace wonder of the Vidicons in every brightly lighted television studio, we can only guess. Someday, perhaps, the entire computer net of the retina, and not merely the retinal screen, will become the metaphor behind development.

The Weather Business: Observation, Analysis, Forecasting, and Modification, by Bruce W. Atkinson. Doubleday & Company, Inc. ($5.95). As you read these words it is raining somewhere; in fact, there are showers at 100,000 somewheres in the thin spherical shell that is the world ocean of air. Counting ships at sea, about 10,000 stations all over the world measure a couple of dozen numbers representing their local conditions of pressure, temperature, wind, clouds, humidity and rain and feed the data eight times a day into the world network. China is not officially a member of this UN-affiliated net but her data flow in all the same. Radar, small pilot balloons, radiosonde balloons and even stratosphere-sounding rockets are routinely used at many stations. Overhead the satellites spin, reporting back the worldwide cloud cover by television. All these data are pieced together, masses of air are isolated and traced back to their origins, fronts of interaction are marked, pressure contours are drawn for various heights, winds are noted and computed, the fine structure is added, and the resulting weather maps are spread over all the world. Automatic regimes have taken over most of these tasks in some countries.

Forecasting is the goal. The classic means are extrapolation, analogues, stability analysis of local columns of air with their burden of rain and moisture, and study of the complex cover of cloud. Such a forecast is art added to science. This is a particularly noisy science, which must work like a gifted conductor in "real time," and must depend on a far-flung orchestra of observers who do not always sound the right notes. Such schemes are more than 30 years old, yet they are still useful.

The dream remains the true science of replacing the subtle and fallible forecasts by electronic integration. There are four basic equations in fluid flow: the gas laws, the heat and work relation, the equation of motion and the conservation of mass. There are four unknowns too: temperature, pressure, velocity and density. The data are taken in three dimensions. It ought to work, but of course it doesn't. Nine services in the world now extract numerical predictions day by day; they include the civil and some military authorities in Canada, Japan, Norway, Sweden, the United Kingdom and the U.S. The British use a mesh of points spaced every 300 kilometers between Hudson Bay and the U.S.S.R.; they work with three heights and some approximate model of the topography, but they neglect the important unstabilizing heat released by the condensation of water vapor. The machine output is the rough objective prediction of the general circulation a day ahead; the "weather" must still be put in by men of experience.

Even modification of the weather is routine in a few limited respects. The Russians have been seeding and clearing stagnant cold fogs at airports with dry ice or silver iodide on quite a large scale for 15 years, and they enthusiastically fire artillery shells full of silver iodide crystals into hail formations. Here and in Australia a number of special projects have inconclusively seeded cloud systems to make rain. Spectacular changes are displayed in photographs of individual cumulus clouds, but practical results remain just beyond conviction.

Right now we are approaching the climax of the first stage of the international scheme called the World Weather Watch. A large increase in stations and links is under way. By the end of 1971 a picture of the global weather will be prepared twice a day in Melbourne, Moscow and Washington and sent to all the world. The main circuits will handle 50 times the data rate of the normal teleprinter of today. The national forecast systems will begin to merge into the global one; men will begin to share the air ocean fully. Eventually 5,000 balloons will float at fixed altitude around the world, signaling the weather to three interrogating satellites at many heights, at places where a station or a ship are unknown. The data mesh will catch increasingly fine detail; still faster computers will take it all in and map the future. This well-written, attractive, map- and photograph-filled small book provides an up-to-date view of what the meteorologists do and hope to do. The photograph of John von Neumann before the tube racks of ENIAC evokes a heroic, classical past only 18 years old.

Prevention of Cancer: Pointers from Epidemiology, by Richard Doll. The Nuffield Provincial Hospitals Trust ($3.95). Redder on the world map than the provinces of the British Empire ever were, the mark of quite another rule stains three lands: Kazakhstan, especially just north of the Caspian, the mining towns of the Transkei in the Republic of South Africa and the African portion of Bulawayo in Rhodesia. There the tyrant is cancer of the esophagus. The incidence of this particular disease among middle-aged men in those three places—and nowhere else that we know of—is 200 times as great as it is in Ibadan, the capital of Nigeria, or in Holland! Smoking and alcohol are statistically linked with this cancer wherever it is found. Such factors cannot, however, explain the red patches on the map. In the Transkei the disease has appeared "in the memory of doctors who are still practicing." Soil deficiencies there affect the crops, but this is hardly convincing as a cause; moreover, the disease is newly spreading to the "Cape Colored" in Cape Town. The mystery is extreme, but unfortunately it is not unique. This clear, cool, brief book is an analysis of many such riddles, and of some solutions, by the man who has done as much as anyone to indict the cigarette as the generator of lung tumors.

Cancer is without doubt under partial genetic control; in some strains of mice all individuals die of a single form of it. Yet animals of pure lines heavily exposed to carcinogens die at different ages. Cancer deaths in children show a negligible familial linkage, and even identical twins showed no paired deaths from leukemia in the United Kingdom over a 20-year period, where 30 would have been expected if the two children were equally affected. (An American study was not in agreement.)

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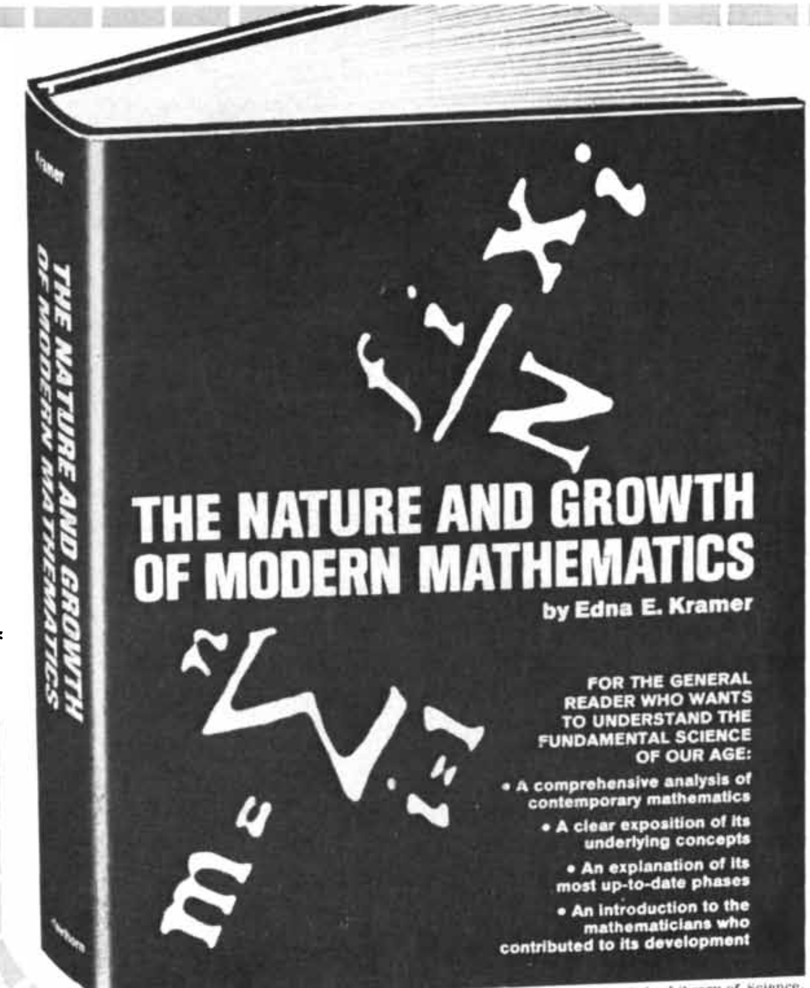

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Poker — prehistoric man and the Nielsen Ratings

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The clones of cells that form human tissues respond to a great many carcinogens, and perhaps also to specific viruses. The aromatic amines long used as intermediates in the dyestuff and plasticizer industries, present in some textile printing processes and as an impurity in rat poison, are one clear example. After a period of from 15 to 20 years men working with this class of chemicals develop tumors of the bladder. In one group of 15 men who worked as distillers of beta-naphthylamine all 15 developed this uncommon tumor. Laboratory dogs get it too, after a high enough dose, but for them the carcinogen is a metabolite of the substance ingested. Nickel refining, arsenicals in vineyard pesticides and mustard-gas manufacture have all proved specifically carcinogenic for many workers.

The only nonoccupational risk in Britain today "sufficiently serious to justify government intervention" is the risk of lung cancer. This disease can now be expected to kill one of every 12 males born. Cigarettes are mainly to blame, although it is not clear that former cigarette smokers who simply took up cigars might not continue to inhale and perhaps retain a high risk. Marihuana is no such menace.

Epidemiology throws a good deal of light on the cancer process; cancer cannot be either a one-step, all-or-none change, nor yet a general genetic predisposition, made manifest by the chance exposure of some one site to some one carcinogen. It is pretty surely a composite process. Setting early diagnosis aside, we might even now prevent about 40 percent of the cancer deaths in men, and 10 percent in women. We can hope to prevent in time a large proportion of the still unknown forms. Honest, painstaking counting and a wide-ranging analysis are shown to be forms of cancer therapy as powerful as scalpel and radium. The book has a knowing bibliography.

BIOCHEMICAL PREDESTINATION, by Dean H. Kenyon and Gary Steinman. McGraw-Hill Book Company ($4.95). Two young chemists with hope, taste and good sense have made this book both an accessible textbook for students with a little background in organic chemistry and an introduction to up-to-date work for scientists in neighboring fields. The title alone is a defect; its somewhat theological air belies the openness of the entire argument.

What the authors mean is merely that the unknown, complex early forms of life were in reality the outcome of a long sequence of natural chemical associations of the starting compounds. Life is probable, not improbable. They are not very explicit on what life is, and they are not clear on its thermodynamics either. They nonetheless know very clearly what the key topics are and what concrete work has been done on them.

The first chapters outline in convincing detail the quite subtle history, from the wheat-born mice of van Helmont to Pasteur's careful preparations, that almost barred the origin of life from scientific study from 1870 until the years between the two world wars. These authors (with excellent photographs) review modern Precambrian micropaleontology, which pushes the first living cells back at least five times the age of the Cambrian. The scenario of the early earth is written out in suitable variant versions, all leading to a generally reducing atmosphere, plenty of ultraviolet, no such fierce oxidants as molecular oxygen and a variety of special habitats, such as clay minerals or hot springs, where the early forms (and their contemporary theorists) find refuge.

The most detailed portions of the book are chemical. The storage of free energy in some special biomonomers, such as the amino acids, is necessary. The needed states can be reached in many ways. The ubiquity of the double or triple bond to carbon is striking. These bonds are most simply manifested by formaldehyde and particularly by hydrocyanic acid as the participant molecules in a wide range of syntheses, spanning many free energy sources and concentrations. Monomers, however, are not enough. How can a few molecules floating in a watery sea find one another and then combine to eliminate a water molecule and begin a long polymer chain? Many paths to this free-energy-demanding bootstrap are possible: surface concentrations, various high-energy phosphates, ultraviolet reactions using the decline of ultraviolet with depth in the water to save the products, high temperatures (as those near hot lava) and so on. The most plausible path is again cyanide-like: the energetic cyanamides, made out of a water solution of ammonium cyanide by ultraviolet, prefer to react with the dilute organic monomers rather than with the excess molecules of water.

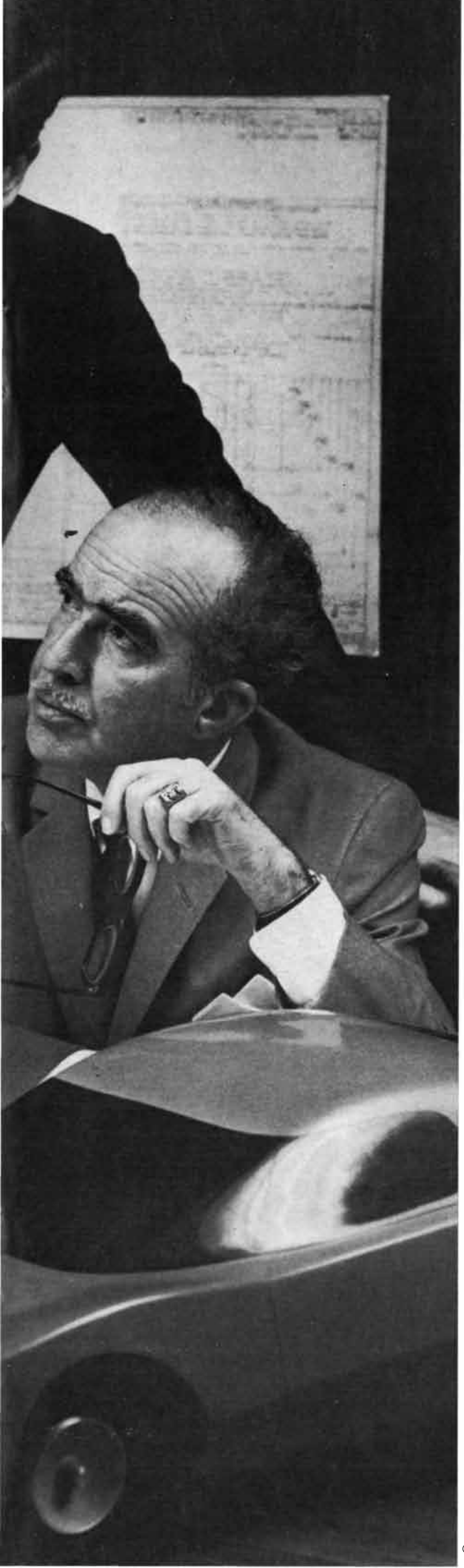
But even polymers are not enough. Life requires more concentrated units, protocells perhaps, where coupled reactions go on. Here the material is less compelling; there are plenty of photographs of the droplets and colloidal microspheres that can form out of various gluey, sugary and fatty mixtures. (One of them is even called *jeewanu,* the Sanskrit for "particles of life.") They all smell so far more of the kitchen than of the incubator. The authors rightly emphasize that these are at most models for a much more complex path. Here there is a lot to learn.

The book closes with a dialogue. It is good reading, although vulnerable to plenty of other argument. The references are excellent, up to 1968.

LIFE ON MAN, by Theodor Rosebury. The Viking Press ($6.95). Microbiologist, amusing writer and courageous social critic, Professor Rosebury has produced a book that combines his talents very richly indeed. It contains a clear nontechnical account of "microorganisms indigenous to man" (the title of his last treatise). Mostly it is an informal survey of historical attitudes toward the excretions and effluvia of mankind, and a lively study of the literature of scatology, with emphasis on Sir John Harington, Dean Swift, François Rabelais and the Gilded Age scholar–cavalry officer John G. Bourke, all on a foundation of Sigmund Freud.

A few pages outline the folly of antisepsis, tracing the ritual painting of skin wounds in America over the past few decades, from the obligate sting of iodine to the conspicuous inertness of Mercurochrome through a set of disappointing near-detergents. Only hexachlorophene remains, aimed at a special target: pathogenic staphylococci. The antiseptics we know "do no good, and they may do harm." (They still finance a lot of television, one way or another, a fact that rightly excites the author's anger.) One ethnographic citation of 1889 describes the Chuckchee, who in their double skin tents during the Siberian winter save themselves the high fuel costs of melting snow by using warm urine "supplied by any one who feels so inclined" to moisten the finger cloths and supply the dishwater with which the board and the knife are washed by the housewife. "The urine, being warm and containing a small quantity of ammonia, is particularly well adapted for removing grease." (Not a bad soft-sell commercial!) The Chuckchee are a kind and hospitable people, thrifty housekeepers, although they dwell in a "mingled odor of ammonia and rotten walrus meat." Fresh urine is usually low in bacterial content, although it is of course a nutritious culture medium.

The little book on bathroom design by Alexander Kira is given too unkind treatment by Professor Rosebury; whatever



its cultural defects, it is a data-rich and analytic guide to human engineering of a neglected kind. Microbiologist to the end, the author ignores those dear and larger creatures that live on man: he gives us nothing on the louse, the flea or the follicle mite.

COST-EFFECTIVENESS: THE ECONOMIC EVALUATION OF ENGINEERED SYSTEMS, edited by J. Morley English. John Wiley & Sons, Inc. ($13.95). This book, which seems to be cost-effective in more ways than its authors expected, is the crystallization of a one-week course on the topic for graduate engineers that was held a couple of years ago in Los Angeles. It is a clear introductory exposition of the techniques of systems engineering and the fashionable mathematical techniques used: simple probability, decision theory, simulation. You can learn the 10 steps of a "standardized approach to the conduct of cost-effectiveness evaluations" (which are not, it is fair to say, at all dogmatically set out). The authors are a microcosm, all Department of Defense or aerospace or Rand Corporation experts, plus a couple of partners in a private consulting firm.

E. S. Quade of Rand projects some future trends of the analysis: computers will become more interactive, game theory will find application beyond tactics to long-range logistics ("an optimal force mix of tactical planes") and the Delphi procedure will augment scenarios and gaming to make better systematic use of expert judgment in complex matters. Delphi is a class of routines for getting panels of experts to work anonymously together, perhaps by way of consoles, with feedback from a controlling group that compares and contrasts the answers and the relative expertise. Input-output and gaming brought us Polaris and Minuteman, although not Safeguard and Vietnam; what will Delphi bring?

The most valuable evidence for the general reader is an actual example of cost-effectiveness analysis, one carried out to find what the supersonic transport will do for the airlines. It is reported from a study by Pan American Airways, and it contains only this reference to the problem of noise, cited here in full: "It was assumed in this analysis that sonic boom will not prevent overland commercial supersonic operation. The effects of such limitation were determined by a separate analysis." By the late 1970's, says the forecaster, SST's will comprise the majority of the airplanes in service on routes longer than 700 miles. Boom.

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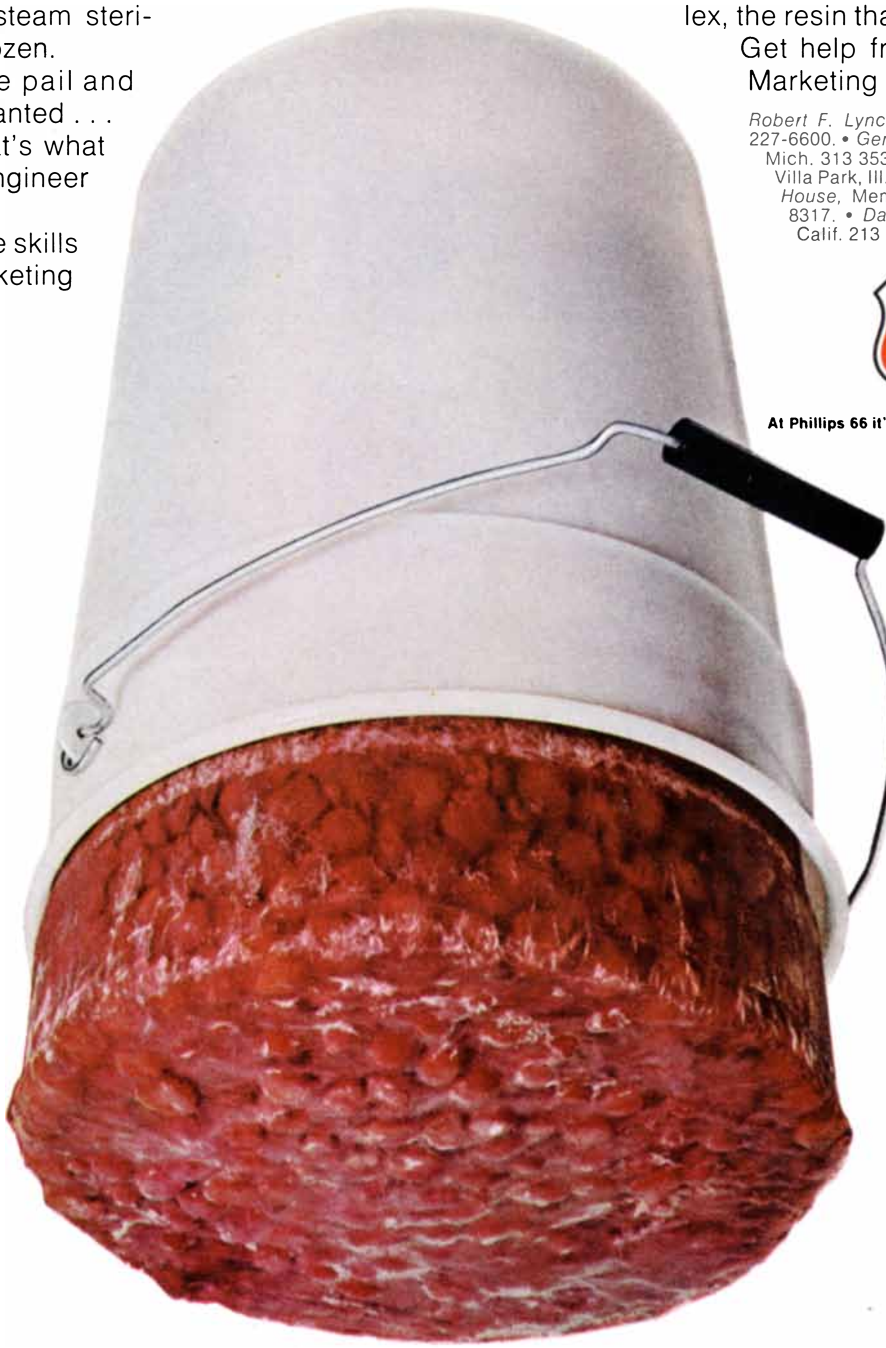

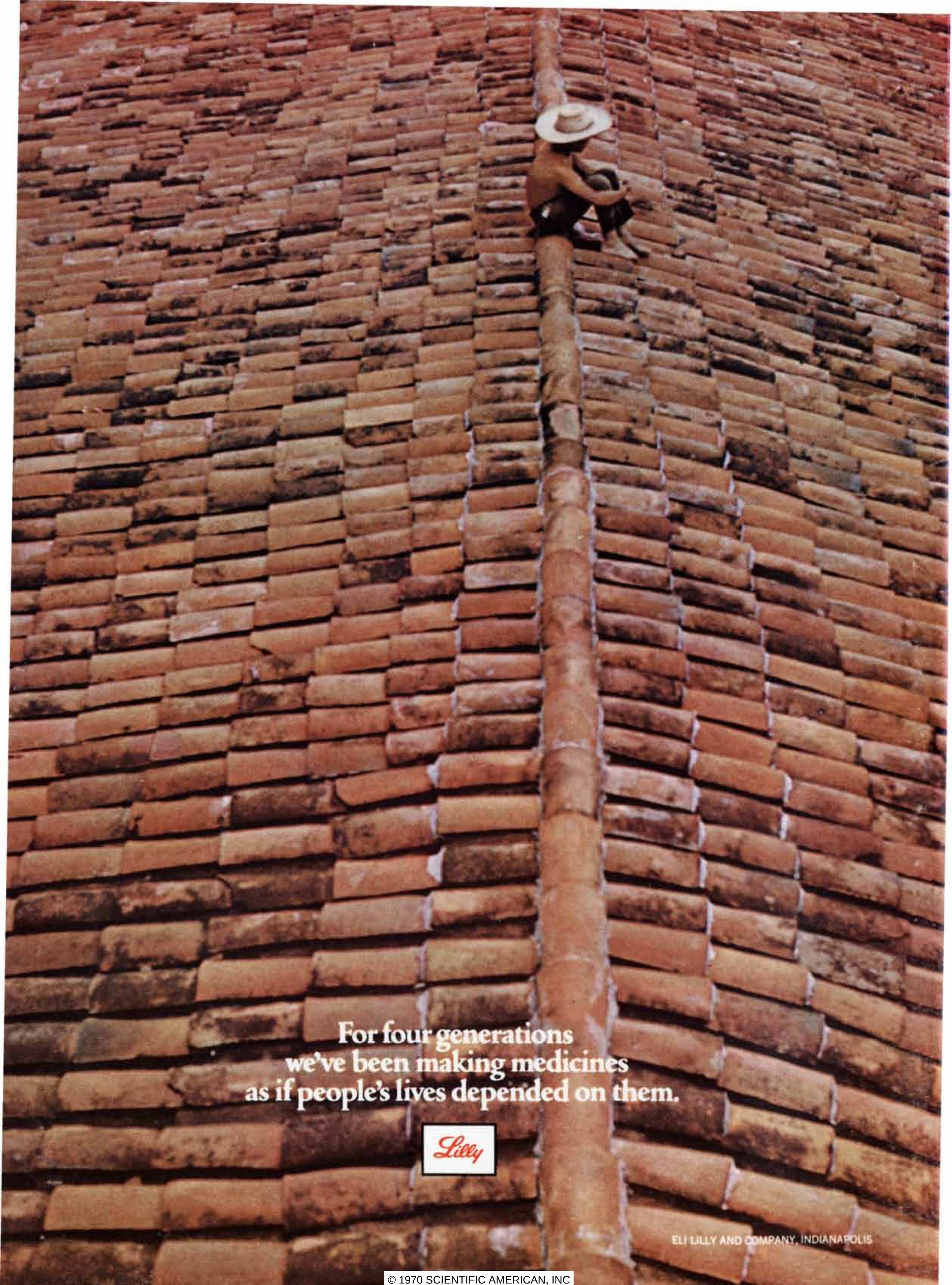
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