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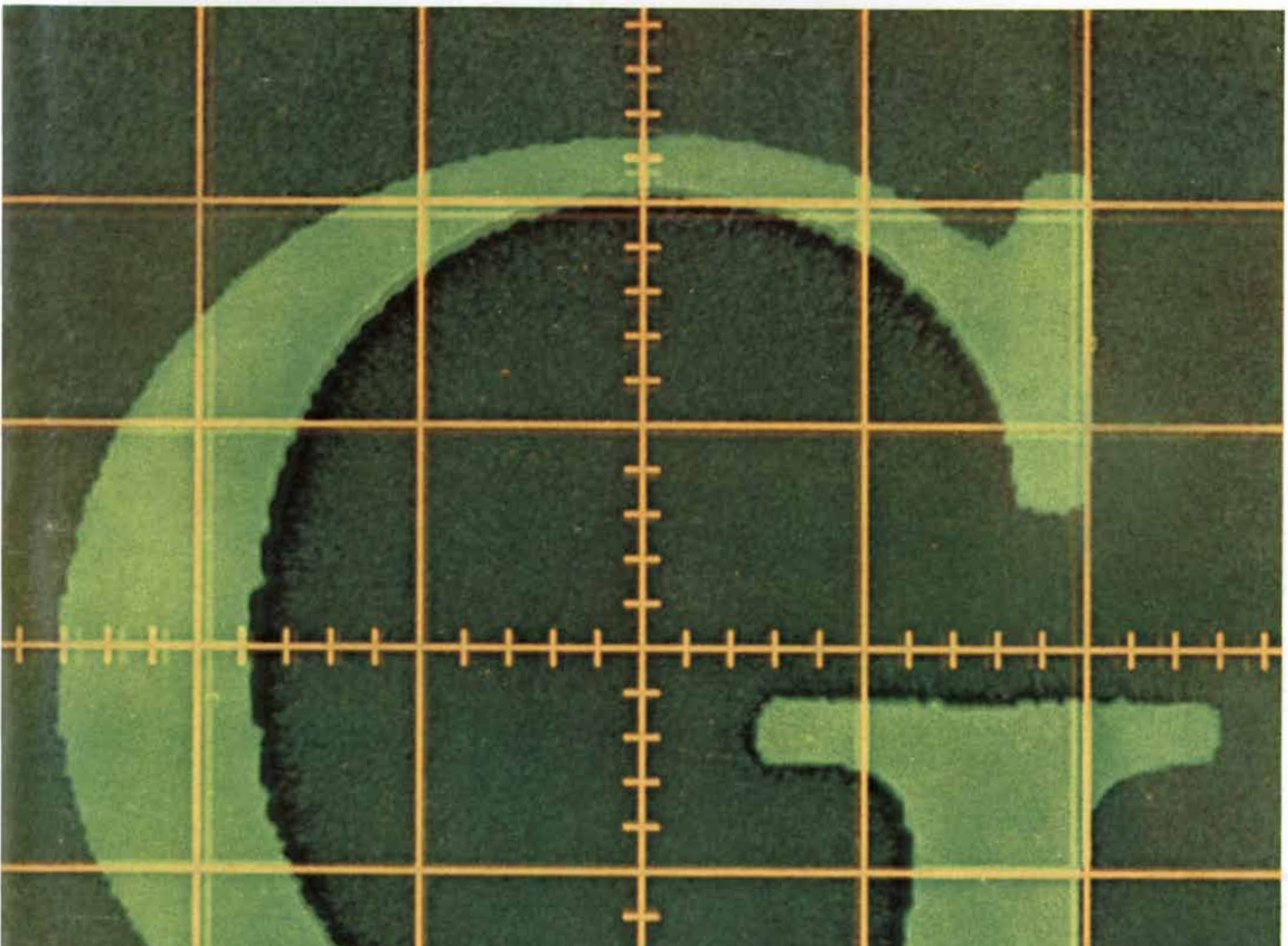

TYPESETTING

SEVENTY-FIVE CENTS

May 1969

How a 13 year old
a very peculiar

boy got us to build submarine.

In 1963, a Turkish sponge fisherman, working the reef-strewn waters of the Aegean, hauled up this statue of a 13 year old boy. Archeologists from the University of Pennsylvania realized this was part of the cargo of a ship, sunk over 2,000 years before.

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GENERAL DYNAMICS

Statue: Bodrum Archeological Museum, Bodrum, Turkey.

Established 1845 **SCIENTIFIC AMERICAN** May 1969 Volume 220 Number 5

ARTICLES

DEPARTMENTS

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THE COVER

The photograph on the cover shows an image of the capital letter *G* "painted" on the screen of a cathode ray tube by means of a moving electron beam. The image was formed by a simulated typesetting machine built by engineers at the Graphic Systems Division of RCA to demonstrate some of the capabilities of their Videocomp system for electronic typesetting (see "Typesetting," page 60). The *G* that appears in the cover photograph is about an inch and a half high on the cathode ray tube. In actual electronic typesetting machines the characters are generally smaller and the resolution is much better. Entire lines or even entire pages of type can be formed on the tube at one time. The image formed on the cathode ray tube is transferred directly to photosensitive material for use in photo-offset printing.

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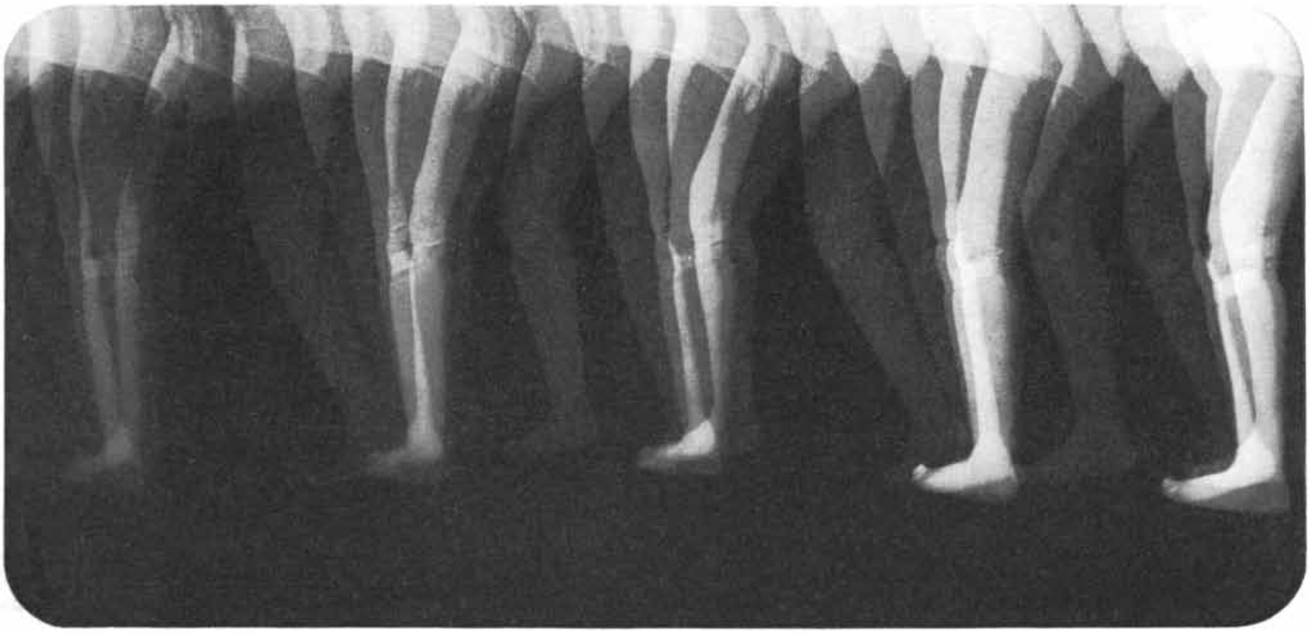


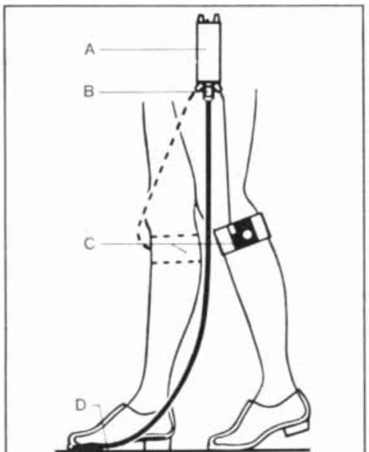
A stimulating way of taking a walk

What is so unusual about wiping your shoes on the door-mat or walking normally? Nothing, unless you happen to be hemiplegic.

As a result of certain nervous disorders or brain damage, the muscles which should lift the foot when walking, fail to function. The disability, known as hemiplegia or "dropfoot" causes the sufferer to continue standing on his sound leg until the affected foot is safely on the ground. The resulting unstable, dragging gait is both slow and tiring, even when using a walking stick.

Research into methods of overcoming this disability, suggested that a solution might be to apply electrical stimuli to the nerve causing the peroneal muscle of the affected leg to contract at the right times. W.T. Liberson of Hines, Illinois U.S.A. carried out field experiments using a portable electronic muscle stimulator with a mechanical switch placed under the heel of the affected foot. A number of patients seemed to develop an improved gait.

Subsequently, J. Vredenbregt of the Institute for Perception Research and H. J. van Leeuwen of the Rehabilitation Centre, Eindhoven, examined this method, but encountered timing problems. They noticed that the beginning and end of the swing phase of the affected foot coincided with the instants when the patient's weight was placed and withdrawn from the ball of the unaffected foot. So they placed a switch on the sole of the shoe near the ball of this foot. This was only a partial success. Normal walking was possible in many cases on hard level ground, but the vulnerable mechanical switch wore out rapidly.



Muscle stimulator

A. generator B. pneumatic switch
C. combined electrode D. insole

Vredenbregt then developed a rubber insole containing a small air chamber, which is connected via a tube to a pneumatic switch. The insole is placed in the shoe, the air chamber fitting under the ball of the foot. When the body weight rests on the insole, the switch actuates a stimulator.

The stimulator, which fits on a belt round the patient's waist, generates a 50 Hz rectangular pulse of 0,6 ms duration with a maximum amplitude of 100 V. These pulses stimulate the nerve concerned via a combined active and passive electrode on the patient's leg. This system has proved highly reliable and the switch operates on any kind of floor without damage - an essential factor in promoting the confidence of the user. Results of tests with 65 hemiplegic patients showed that all had an improved gait when using the device. It is an unexplained physiological fact that, after 3 to 6 weeks training, 55 of them walked almost normally or showed considerable improvement even without the device. Children, hemiplegic from birth and therefore never having learned to walk normally, have also given promising results after 4 to 5 months.

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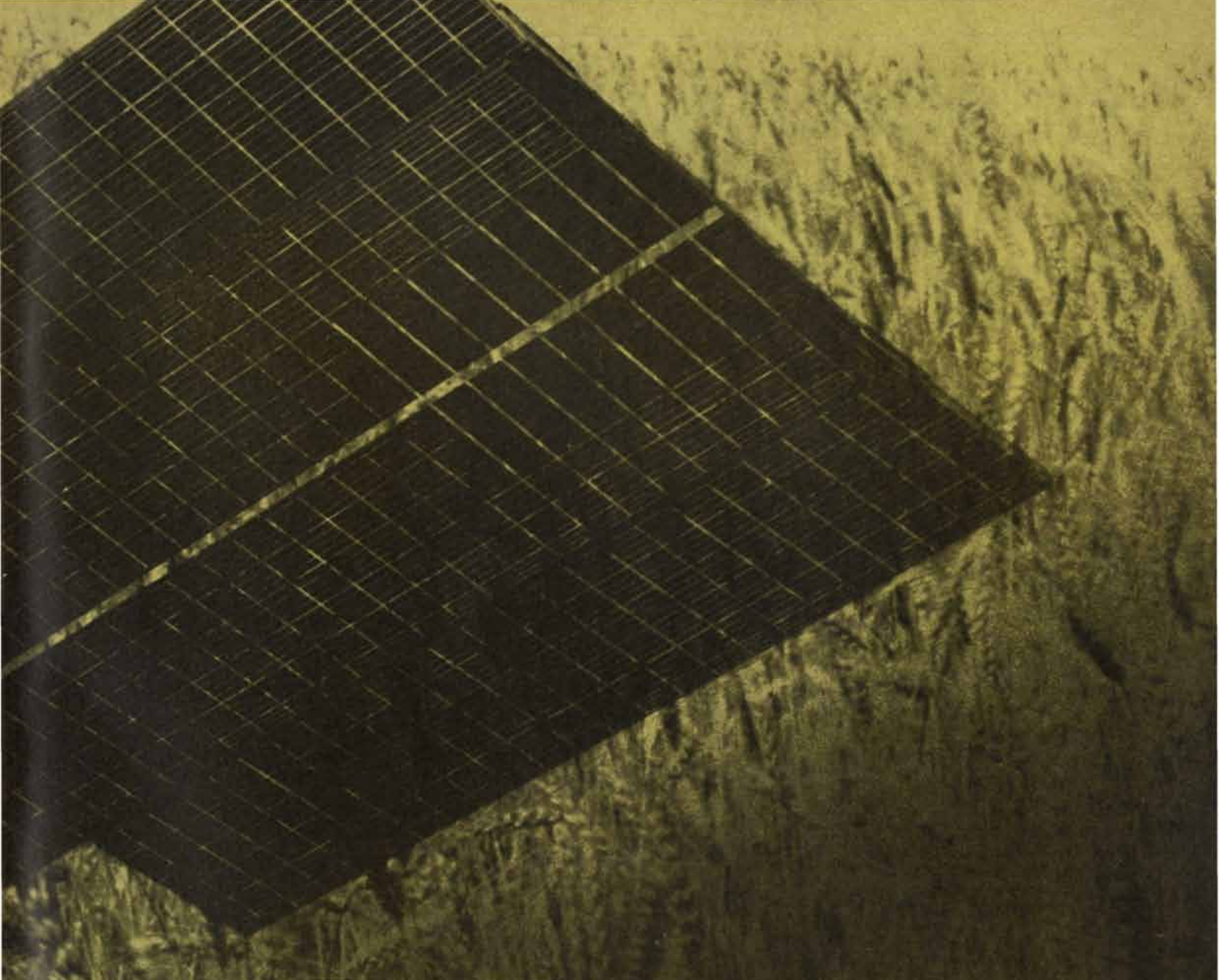

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LETTERS

Sirs:

In a recent review [SCIENTIFIC AMERICAN, March] Salvador E. Luria took "a fresh look at some aspects of teaching introductory biology" in college. We are grateful to him for expressing in his characteristically vigorous way some opinions that are widely held. Our gratitude to Luria for so flatly expressing his views does not mean that we agree with him. We do not find acceptable either his views on how biology developed or on what the present state of biology is. Luria's views on the teaching of biology are based to a considerable extent on his estimate of the significance for biology as a whole of work on bacteria and bacterial viruses. Luria (a leading investigator of bacteria and bacterial viruses) believes "any course that wishes to present biology as it really is" should recognize the role these organisms are now playing in biology: (1) "Most of our knowledge of the synthesis of proteins and nucleic acids and of the structure, function and regulation of genes comes from work on these organisms" and (2) a bacterium such as *Escherichia coli* serves as a model one-cell organism.

(1) An essential component of Luria's viewpoint is his belief that "most of our knowledge of the synthesis of proteins and nucleic acids and of the structure, function and regulation of genes comes from work on these organisms" (bacteria and bacterial viruses). The record shows, however, that this is an inaccurate statement. Knowledge of the basic molecular processes listed by Luria has in fact derived in part from studies with higher cell types and in part from studies with bacteria and bacterial viruses; the most general pattern has been one in which advances in understanding have been developed simultaneously by workers using both classes of material. Consider the discovery of DNA-dependent RNA polymerase, certainly a key step in the annals of modern molecular biology; an enzyme of this type was first reported by Weiss and Gladstone in mammalian liver-cell nuclei in 1959. The following year Weiss published a definitive report on the new enzyme and at essentially the same time Hurwitz and Stevens described an RNA polymerase in *E. coli,* and Huang, Maheshwari and Bonner reported a similar enzyme in pea tissues. DNA-dependence of the enzymic synthesis of DNA was reported by Kornberg and his associates, working with *E. coli,* in 1956. The history of our understanding of the mechanism of protein synthesis provides an excellent illustration of the dependence of modern molecular biology on studies with both microorganisms and higher cell types. Existence of a precise relationship between the genetic material and the amino acid sequence of a protein was first unequivocally demonstrated in Ingram's studies with mutant hemoglobins. This development provided a critical conceptual link in the establishment of a precise theory regarding the relation between a genetic code and the primary structure of proteins. The first demonstrations of messenger RNA and the elucidation of the triplet code were accomplished in studies with bacteria and viruses, whereas work with higher cell types was responsible for the initial development of cell-free protein-synthesis systems, the discovery of transfer RNA, discovery of amino acid activating enzymes, CCA terminal addition and most of the early information on the composition, disposition, function and so on of ribosomes. Following the correlation between RNA content and protein synthesis shown by the early work of Brachet and Caspersson, the liver-cell fractionation studies undertaken by Claude in the early 1940's resulted in the first identification of cytoplasmic ribonucleoprotein particles. The activity of the "microsomal" fraction containing these particles in protein synthesis was established in the early 1950's by workers using mammalian tissues. The requirement for ATP in protein synthesis was demonstrated by Zamecnik *et al.* in liver homogenates in 1954, and in 1955–1956 adenylation of amino acids was reported by Hoagland and his associates in rat-liver systems. In 1956 amino acid activating enzymes were found in liver by Hoagland, in yeast by Berg, in *E. coli* by De Moss and in pancreas by Davies *et al.* Transfer RNA itself was discovered by Hoagland's group in rat liver in 1957, and was reported in *E. coli* by Berg and Offengand in 1958. Knowledge of many other key areas of molecular biology has grown in ways similar to this; one could consider as further examples the enzyme-assembly units elucidated in recent elegant studies with mitochondria and the discovery of polyribosomal structures, which were first clearly recognized in reticulocytes.

To write that "most of our knowledge of the synthesis of proteins and nucleic acids" comes from studies with bacteria and bacterial viruses is thus to choose to ignore the actual history of these events, which all will agree have been of the utmost general importance. Molecular biology has advanced as one science, dependent on workers in all areas, animal, plant and microbiological, rather than as a function mainly of investigations with bacteria and bacterial viruses, with workers dealing with higher cell types waiting anxiously for the next fundamental breakthrough to come from the microbiological center of knowledge.

(2) The role of *E. coli* as a model one-cell system cannot be adequately discussed briefly. An important aspect of this problem is presented in a recent paper by Melvin Cohn: "What can *Escherichia coli*... contribute to understanding differentiation?" In answering this question Cohn (who is enthusiastic about *E. coli* lore, to which he has made significant contributions) quite properly focuses on gene regulation and control in the differentiation of animal cells. He is aware that it is not known if the type of gene control demonstrated in *E. coli* operates in higher animal and plant cells. All we have at present is his assurance that "it is more than likely that, when the smoke clears, bacteria and their viruses will have revealed a general mechanism for regulating the transcription of their genome in response to

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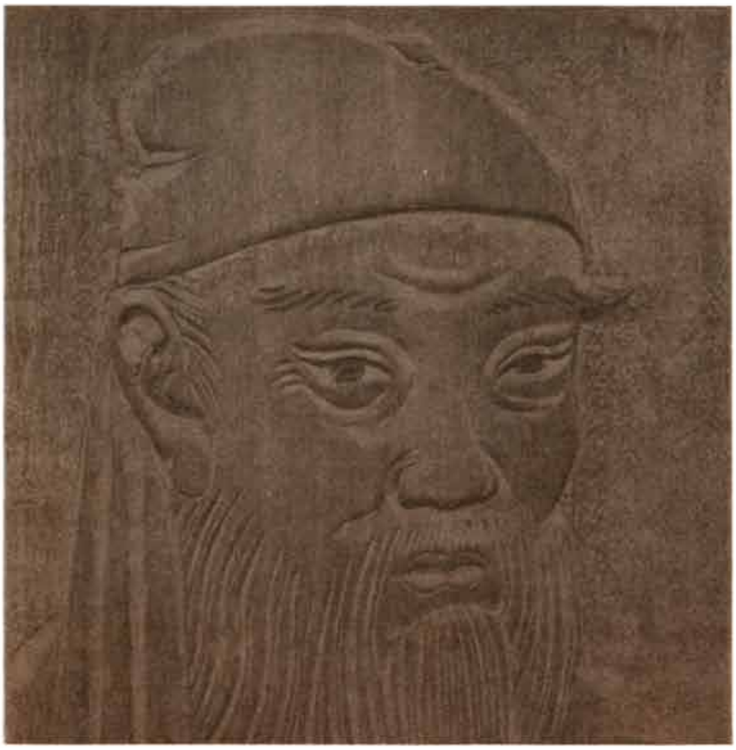
NAME

NEW ADDRESS

OLD ADDRESS



Su Sung (1020-1101)

Woodcarving by William Ransom
Photographed by Max Yavno

"[Su Sung's astronomical clock escapement] differs from the types of escapement of the later West because the action of the arrest is brought about not by any mechanical oscillation but by gravity exerted periodically as a continuous steady flow of liquid fills containers of limited size. The peculiar interest of the water-wheel linkwork escapement, hitherto unknown to historians of technology either in East or West, lies in the fact that it constitutes an intermediate stage or 'missing link' between the time-measuring properties of liquid flow and those of mechanical oscillation. It thus unites, under the significant aegis of the millwright's art, the clepsydra and the mechanical clock in one continuous line of evolution."[1]

[1] J. Needham, W. Ling, D. J. de Solla Price, *Heavenly Clockwork*, p. 59, Cambridge University Press, 1960.

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a stimulus." Without waiting for the smoke to clear, a survey of "biology as it really is" (to use a phrase of Luria's) shows that the genome of a mammalian cell is some 700 times the size of the genome of *E. coli,* that in contrast to the genome of *E. coli* there is a massive redundancy in the genome of eukaryotic cells, and that there are certain proteins associated with DNA in higher plants and animals that have no known counterparts in *E. coli.* Even if it were to turn out that the kind of gene-control mechanism found in *E. coli* exists in cells of higher organisms, it seems extremely unlikely that in the genomes of higher organisms the mechanisms now known in *E. coli* could be anything more than a minor aspect of what has evolved along with cell differentiation.

Investigation of the role of the gene in differentiation and development is an important part of "biology as it really is" today, and current work is a continuation, largely along biochemical lines, of the classical achievements in *cell biology* of the 1880's. The repository of this cell biology is E. B. Wilson's classic book *The Cell.* In 1966 H. J. Muller said, "Wilson's great book *The Cell in Development and Inheritance,* especially in its first edition (1896) here reprinted, marks him as the most constructive encyclopedist of biological science." The biology referred to here is not mentioned in Luria's remarks on 19th-century biology.

Bacteria and bacterial viruses have a place in introductory biology. Students in such a course would surely be fortunate if the lectures on microbiology that are needed were given by as lively microbiologists as Salvador Luria and Melvin Cohn.

ERIC H. DAVIDSON
ALFRED E. MIRSKY
BRUCE R. VOELLER

Rockefeller University
New York, N.Y.

Sirs:

I agree with almost everything Davidson, Mirsky and Voeller write about biology and its history. My review, however, dealt with the teaching of introductory biology. My remark that "most [I should have written "much"] of our knowledge of the synthesis of proteins and nucleic acids and of the structure, function and regulation of genes comes from work on [bacteria and bacteriophages]" was only peripheral to my argument.

In teaching I focus on the story of life, not on the history of the life sciences. My thesis is very simple: If the focus is on evolution, the central concept is the organism, not the cell. Yet the cell is the operational unit of the chemistry of life. Therefore I start from an organism that is also one cell. The only such organisms that are known well enough to be used in presenting cellular biochemistry and molecular genetics are bacteria. The more complex, multicellular organisms present problems that can be grasped more easily on the basis of principles learned in studying bacteria. That's all.

SALVADOR E. LURIA

Massachusetts Institute
of Technology
Cambridge, Mass.

Sirs:

Annemarie de Waal Malefijt's article "Homo monstrosus" [SCIENTIFIC AMERICAN, October, 1968] contains information of the greatest value. I must protest, however, that the author is at fault in claiming that "Shakespeare . . . equated the monstrous Caliban with inhabitants of the New World."

So far as the elastic geography of *The Tempest* allows localization, Prospero's island appears to be situated in the Mediterranean. The "Bermoothes" appear in the text only as an evidently distant place to which Ariel had once been sent on an errand by Prospero. Moreover, we are explicitly told that Caliban had been begotten by the devil upon the witch Sycorax, who had been deported from Argier (Algiers) and marooned on the island. Thus he belongs to a quite definite category of monsters, and is no more indigenous to the island than Prospero.

It is, I suggest, more justifiable to speculate whether the external appearance of Caliban on the stage might have owed something to the earliest travelers' tales of African or East Indian manlike apes. It is true that the first certain reference to such apes in print (in *Purchas His Pilgrimage,* 1613) is a few years later than the probable date of the first performance of *The Tempest,* but there may well have been other returned travelers besides Andrew Battell who had stories of strange beasts to tell at the Mermaid tavern or elsewhere in London.

LAWRENCE H. WELLS

University of Cape Town
Medical School
Observatory, Cape, South Africa

Painting by René Magritte, Loan Collection, Institute of Art, Rice University, Houston, Tex.

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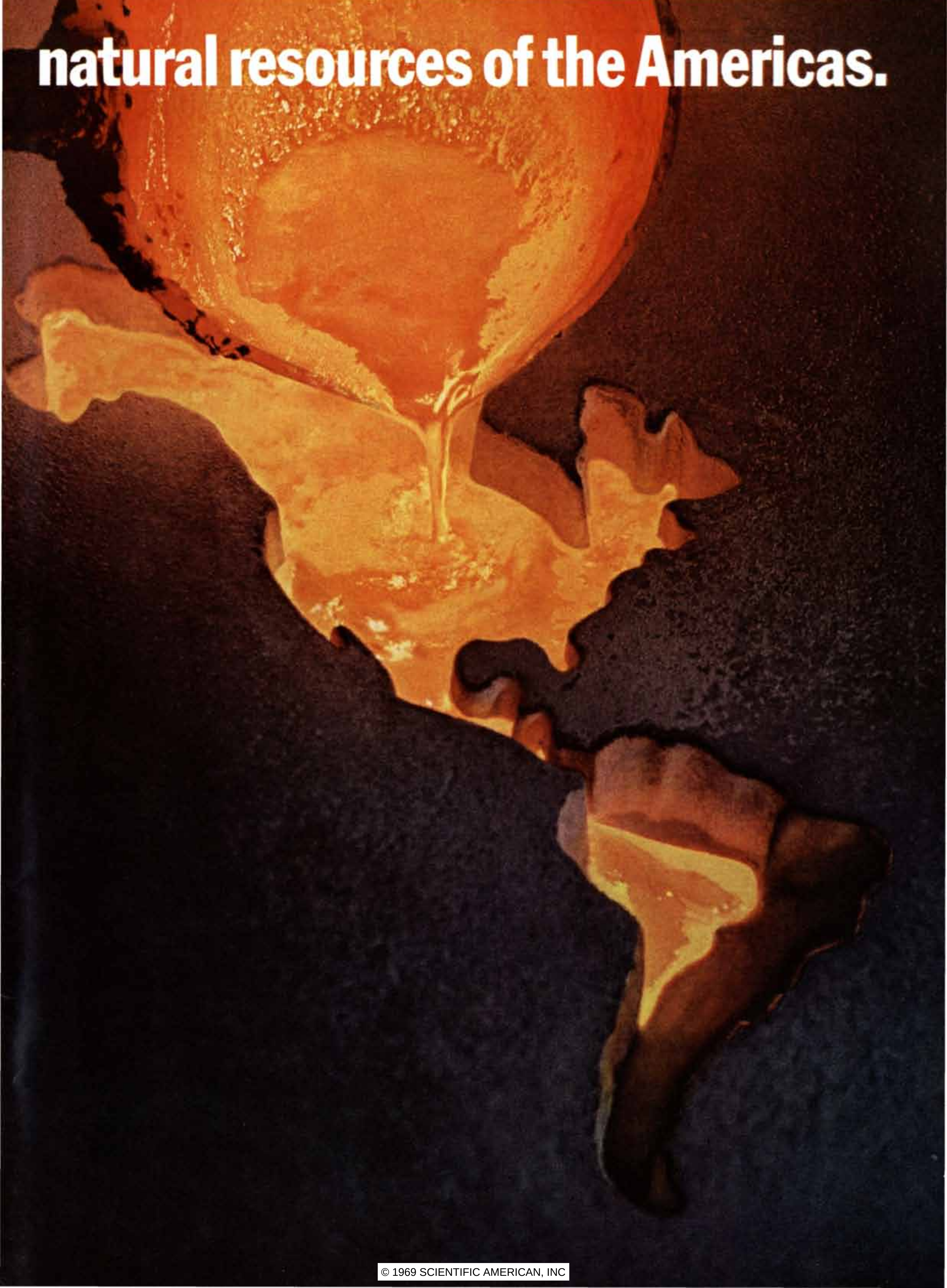

natural resources of the Americas.

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MAY, 1919: "In the arguments against the League of Nations there is to be found a vast amount of sheer nonsense. For example, a favorite plea against the League, so far as the U.S. is concerned, is that it is unconstitutional. The right to make war and peace resides, under our Constitution, with the Congress. If we enter a League of Nations, we agree not to make war, and the Congress loses its constitutional rights in the process. But what is the difference between a treaty with one nation and a treaty with a score of nations? Peace can be made only by a treaty in any event, and *our* treaties, we hope, are binding. So the moment we make peace we are bound not to make war, except in defense of the terms of the treaty. Then, whether we put the matter upon the basis of constitutionality or upon the basis of our own inherent God-given right to make war when and upon whom we please, peace is objectionable. If you can make a peace treaty with one nation, you can make one with a dozen. You can make one with the world. If you can't make a peace treaty on a large scale, you can't make one on a small scale. There is no middle ground; either peace is unconstitutional or it isn't. We had always supposed that the prime object of a League of Nations was to prevent war. It seems a trifle curious to have it violently objected to because it threatens to accomplish just that purpose."

"Now that the construction of the Channel tunnel is assured, military and commercial interests are turning their thoughts to the Straits of Gibraltar and forecasting the advantages which would be secured by building a tunnel between the European and African coasts at that point. An engineering journal in Britain states that whereas it now takes three weeks to go from London to the Cape, with the Channel tunnel and one under the Straits of Gibraltar it would be possible, when the Cape–Cairo Railway and other rail connections are completed, to go from London to the Cape in eight days. Unfortunately the Straits are about 1,200 feet deep, and unless the underlying rock is impervious to water no tunnel can be constructed there, since the limit for the pneumatic process is about 175 feet."

"The conception of a spiral nebula made possible by the recent work of the distinguished English mathematician James Jeans may justly be called magnificent. The central nucleus is a huge, lens-shaped mass of gas, containing within itself matter enough to form many thousands of systems like ours. As it rotates, the centrifugal force at its outer edge almost exactly balances the attraction of the main mass. At two opposite points of the boundary the gaseous material escapes and flows outward in enormous spiral streams. At first it is of exceedingly low density, but gradually it condenses into separate nuclei, and these shrink into stars. The boldest astronomer might well have hesitated to commit himself to so extraordinary a sequence of ideas without the steadying consciousness of a definite mathematical foundation on which to rest, but this time the process was reversed: mathematical study of a quite different problem ('What will happen to a large rotating mass of compressible gas if it is left to settle into equilibrium under its own attraction, and then to shrink slowly as it loses heat by radiation?') laid the foundation, and once this was effected the brilliant theory almost raised itself."

"An account of the discovery by Major H. Graeme Gibson, Major Bowman and Captain Connors of the Allied army medical services of what is stated to be very probably the causative germ of influenza appeared lately in the London *Times*. The germ belongs to the order of filter-passers and is grown by the Noguchi method. The discovery cost Major Gibson his life, as he fell a victim to the very virulent strains of the germ with which he was experimenting."

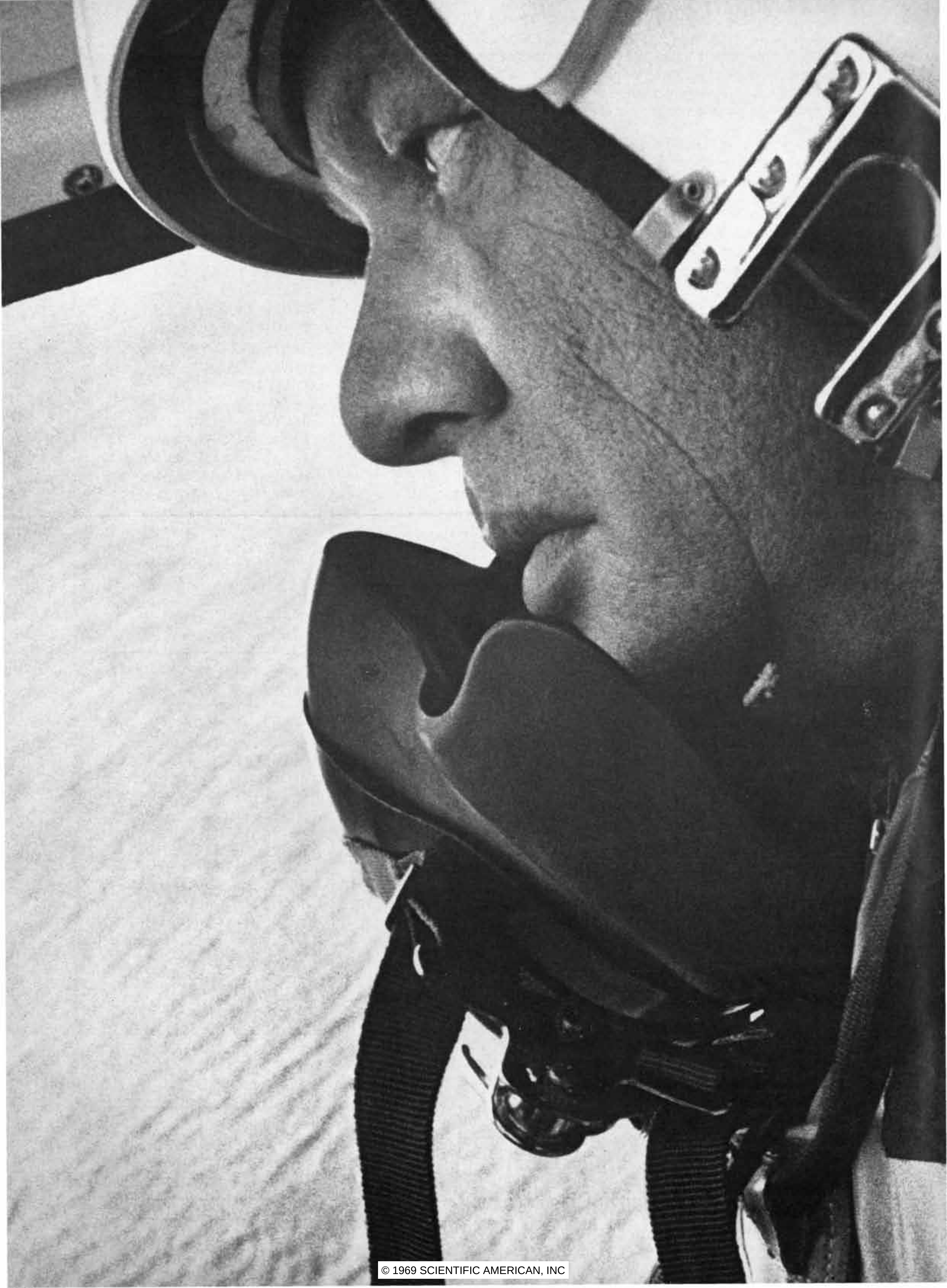
SCIENTIFIC AMERICAN

MAY, 1869: "The announcement is made that the Pacific Railroad is completed. Amid the conflicting statements in regard to the manner in which the work has been performed, we know not whether the people ought to rejoice or to feel sorry. It is generally admitted that the road has been laid in an imperfect manner. Some will even have it that it is a mere sham, only built as a matter of form to obtain the very liberal subsidies granted by the Government. This may be an extreme statement, but between those of the friends of the enterprise and its foes there is room for no little fear that the immense franchise granted to the company has resulted in no adequate return to the people at large. We are confirmed more and more by daily developments in the belief that such enterprises should be either carried forward entirely by the Government or accomplished solely by private enterprise. The system of making appropriations in aid of such works is a vicious one, leading naturally to corruption and fraud."

"A Museum of Natural History is to be established in the Central Park in New York City, $50,000 having already been subscribed for that purpose. The commissioners of the park have offered the use of the large hall of the Arsenal Building as a place where the collections may be deposited until a suitable structure can be erected. We understand it is proposed to erect a museum building on Ninth Avenue, fronting the block between 78th and 79th Streets."

"It is discreditable to the inventive genius of this country that the one great mechanical want of the time is still unsupplied. Each of the leading newspaper publishers in this city—apart from expenses for paper, press work, ink, editorial, reportorial and correspondents' salaries, and the thousand incidental demands for the production of a great daily—pays from $100,000 to $200,000 a year for composition alone. Publishers of newspapers, magazines and books throughout the country pay proportionately for this single item of type-setting. This enormous cost prevents the publishers of papers from giving their readers the literal 'volume' of matter they would gladly do from day to day were they not hampered by the delays and the cost of composition. What we want—what every large publisher in the country wants—is a type-setting machine which will both expedite and cheapen the cost of composition at least 25 per cent and perhaps 50 per cent."

"The return of Dr. Livingstone, the veteran English traveler, was expected about four months since, but up to the present moment his movements are wrapped in mystery. At last accounts, December 14, 1867, he was proceeding along the eastern shores of Lake Tanganyika, but no idea can be formed respecting his subsequent course. His fate is regarded with uncertainty."



THE AUTHORS

BYRD C. CURTIS and DAVID R. JOHNSTON ("Hybrid Wheat") are with Cargill, Incorporated; Curtis is head of the hybrid wheat development program at Cargill Research Farms in Fort Collins, Colo., and Johnston is a wheat breeder. Curtis received his bachelor's degree in agronomy at Oklahoma State University in 1950, his master's degree in agronomy at Kansas State University in 1951 and his Ph.D. in plant breeding and genetics from Oklahoma State in 1959. He was a member of the staff at Oklahoma State until 1963, working on the breeding of wheat, oats and barley; he then was appointed associate professor at Colorado State University and director of wheat research for the state of Colorado. He joined Cargill in 1967. Johnston, who was graduated from the University of Massachusetts in 1952, was a research worker at the University of Minnesota from 1956 to 1967, when he took up his present position.

LARRY FALLER ("Relaxation Methods in Chemistry") is assistant professor of chemistry at Wesleyan University. "I spring from the most fertile soil for scientists—the Middle West, a nonprofessional family," he writes. Recalling "an amusing article" in *The American Scholar* on "the conformity of supposedly nonconforming academics," Faller says that "like an embarrassing number of my colleagues, I supported Eugene McCarthy, espouse black power, read *The New York Times,* drive a Volkswagen, live in an antique house, sing Schubert lieder accompanied by my wife (when no one is listening), play tennis and squash and sail." Faller was graduated from Wabash College in 1958, received advanced degrees from Yale University in 1959 and 1963 and spent two years as a postdoctoral fellow at the Max Planck Institute in Göttingen.

HENRY DE LUMLEY ("A Paleolithic Camp at Nice") is professor at the University of Aix-Marseilles, director of its Laboratory of Human Paleontology and Prehistory in Marseilles and a senior research associate of the French National Center for Scientific Research. He has participated in a number of excavations at lower and middle Paleolithic sites in southeastern France. Of one at Vallonnet Cave he writes: "These excavations revealed for the first time man's presence in Europe at the dawn of the Quaternary." Another excavation involved caves that are now under the waters of Villefranche Bay but were above water and had human inhabitants during the last glaciation.

GERARD O. WALTER ("Typesetting") is chief engineer in the Graphic Systems Division of RCA. He writes: "I was born in Vienna, the youngest of three sons of the owner of a prominent Austrian electrical manufacturing and retailing organization, who was also a member of the Austrian cabinet. The political turmoil of the late 1930's in Europe caught up with my family and resulted in my matriculation at St. John's University in Poland rather than the Vienna Institute of Technology." Later he received advanced degrees in mechanical engineering and physics at the Institute of Technology in Zurich and at the University of Zurich. Walter came to the U.S. in 1946 and for six years operated his own engineering firm, dealing in optical tooling and automation equipment. When phototypesetting became practical, he joined a firm making automatic phototypesetting machinery. He holds a number of patents in the field and in such other areas as microfilming systems, data retrieval, image manipulation "and even," he writes, "paper-handling machinery in the printing field."

VANCE A. TUCKER ("The Energetics of Bird Flight") is associate professor of zoology at Duke University. "My active interest in bird flight," he writes, "began during an airplane trip when I saw a flock of birds flying at 12,000 feet over the Aleutian Islands. I wondered how high birds could fly, but at the time I had no way of studying flight in the laboratory. A few years later I built a small wind tunnel and found that budgerigars could be trained to fly in it. One bird learned to wear an oxygen mask when flying at simulated high altitudes. It was an easy matter to reverse the flow through the mask and measure the bird's metabolic rate." Tucker was graduated from the University of California at Los Angeles in 1958, obtaining his master's degree at the University of Wisconsin in 1960 and his Ph.D. from U.C.L.A. in 1963. Since his first experiments he has found that several kinds of birds will fly in wind tunnels, and he is investigating a number of aspects of their aerodynamics and physiology.

RONALD K. LINDE and RICHARD C. CREWDSON ("Shock Waves in Solids") are at the Stanford Research Institute; Linde is director of the Poulter Laboratory for High Pressure Research and Crewdson is chairman of the shock and high-pressure physics department of the laboratory. Linde, who joined the institute in 1964, was graduated from the University of California at Los Angeles in 1961 and received his master's degree and Ph.D. from the California Institute of Technology in 1962 and 1964 respectively. He is the author of more than 20 papers in the field of solid-state physics. Crewdson was graduated from Lafayette College in 1961 and obtained his Ph.D. at Cal Tech in 1967. In addition to his research in shock-wave physics he is interested in industrial applications of the work.

NATHAN SHARON ("The Bacterial Cell Wall") is the Joseph and Sadie Danciger Professor of Molecular Biology in the department of biophysics at the Weizmann Institute of Science in Israel. Born in Poland, he emigrated with his family to Israel (then Palestine) in 1934. He studied at the Hebrew University in Jerusalem, where he received his master's degree in 1950 and his Ph.D. in 1953. In addition to his research, which deals mainly with proteins and carbohydrates, Sharon does a great deal of science writing for general audiences, and for some time he has edited a weekly radio program on advances in science. He is also the scientific editor of *Mada* ("Science"), a general science magazine published in Hebrew. Apart from his work Sharon enjoys stamp collecting and swimming.

CHARLES R. MICHAEL ("Retinal Processing of Visual Images") is assistant professor of physiology at the Yale University School of Medicine. He received his bachelor's degree from Harvard College in 1961 and remained at Harvard for his Ph.D., which he obtained in 1965. As a graduate student he had what he calls "a rewarding experience" in his informal association with David H. Hubel and Torsten N. Wiesel, who have done much work on visual processing. For three years after obtaining his doctorate Michael was a postdoctoral fellow at Johns Hopkins University, where he worked with Edward F. MacNichol, Jr., a noted investigator of visual pigments and color vision.

DOROTHY ZINBERG and PAUL DOTY, who in this issue review *The New Brahmins: Scientific Life in America,* by Spencer Klaw, are respectively a postdoctoral fellow at the University of London and professor of chemistry at Harvard University.

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Hybrid Wheat

Many of the problems associated with hybridizing this important grain crop are being solved. The eventual introduction of hybrid wheat on a large scale will have a substantial economic and nutritional impact

by Byrd C. Curtis and David R. Johnston

So far in this century the production of two major grain crops, corn and sorghum, has been revolutionized by the technique of mass hybridization: the crossing of two dissimilar inbred lines or varieties to obtain offspring with more desirable qualities than those possessed by either of the parent lines. It now appears that another important grain, wheat, is on the verge of a similar revolution. The problems associated with the production of hybrid wheat on a commercially feasible scale have been particularly difficult, but enough progress has been made in the past few years to predict with some assurance that the eventual widespread introduction of hybrid wheat varieties will have a far greater economic and nutritional impact than the introduction of any other hybrid crop grown in the world today.

The basis of all such attempts at genetic manipulation is the phenomenon of hybrid vigor, the tendency for the offspring of crossed varieties to have greater vitality than the offspring of inbred varieties. Hybrid vigor can be manifested in a number of ways: increased yield, greater resistance to disease or insects or harsh climate, a shorter growing season and better milling or baking qualities. In the case of wheat the primary benefit being sought is increased yield.

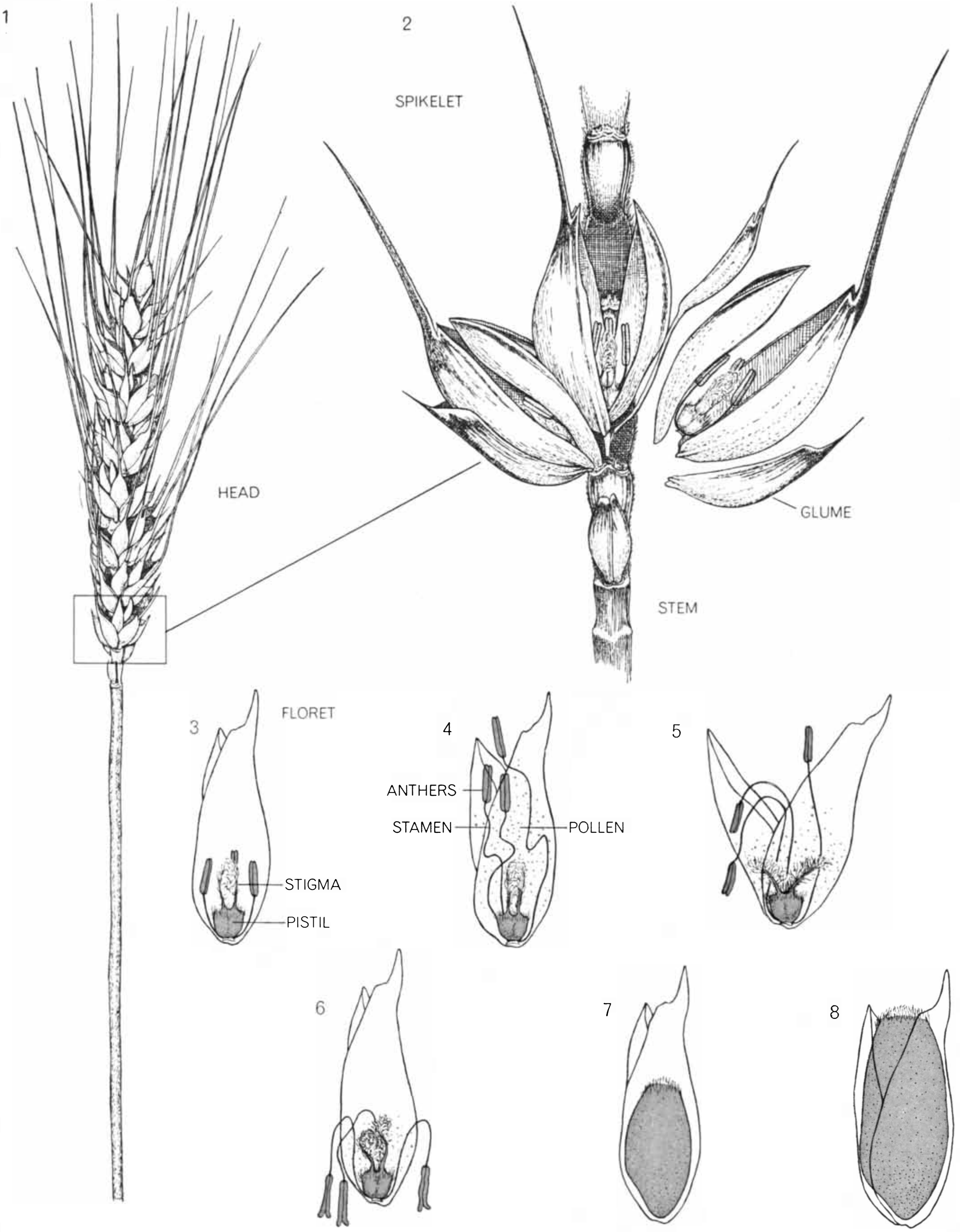
It turns out that the extra vigor of hybrids is expressed at a maximum in the first generation after the cross; later generations show a drastic reduction in vigor. Hence the object of any hybridization program is to perfect a technique for producing enough hybrid seed to grow first-generation plants on a large scale.

This was easy to accomplish with corn, because in a broad sense all corn is hybrid. Corn is a cross-pollinated species in which the male sex parts (in the tassel) and the female sex parts (in the ear) are located in quite separate parts of the same plant. Removing the tassel by hand makes the plant female and therefore incapable of self-fertilization; thus all the seed produced on the ear will be hybrid since it must be fertilized by pollen from other plants. Enough hybrid seed was produced by this method to plant the entire corn acreage of the U.S. within the first 20 years after the first hybrid varieties were introduced in the 1930's.

In the early 1950's a new technique for producing hybrid corn seed was developed. It involves a sophisticated genetic procedure for inducing male sterility in a generation of corn plants; these plants are then crossed with a variety that is capable of restoring full fertility to the first-generation offspring of the cross. This approach eliminated the need for the laborious hand-detasseling operation and is currently employed in the production of a large percentage of the world's crop of hybrid corn. A similar technique has proved successful for producing hybrid sorghum; in only a few years it has resulted in the hybridization of the entire sorghum crop of the U.S. It is basically a variation of this general approach that has been applied to the hybridization of wheat.

Unlike corn, wheat is almost 100 percent self-pollinated. Both the male and the female sex parts—the male stamens containing the pollen and the female pistil containing the egg—are located in the same floret, or flower [*see illustration on next page*]. Normally the anthers (the elongated pollen-bearing portions of the stamens) supply pollen to the stigma (the feathery portion of the pistil) before the floret opens enough to allow the entrance of pollen from other plants. To obtain a single hybrid seed it is necessary to remove the three anthers in a floret with small forceps and later apply pollen from another plant to the stigma by hand. To ensure success all these operations must be timed precisely and executed with great care. Obviously commercial quantities of hybrid seed cannot be produced in this manner.

Here it should be noted that many varieties of wheat already under cultivation are often referred to incorrectly as hybrid wheat. This misnomer arises from the fact that it is possible to derive improved varieties from a handmade hybrid several generations removed. The best descendants of the original hybrid are selected and inbred for five or six successive self-pollinated generations until a "pure line" or "true breeding" plant is obtained. Such a plant, combining the good traits of the original parents, will



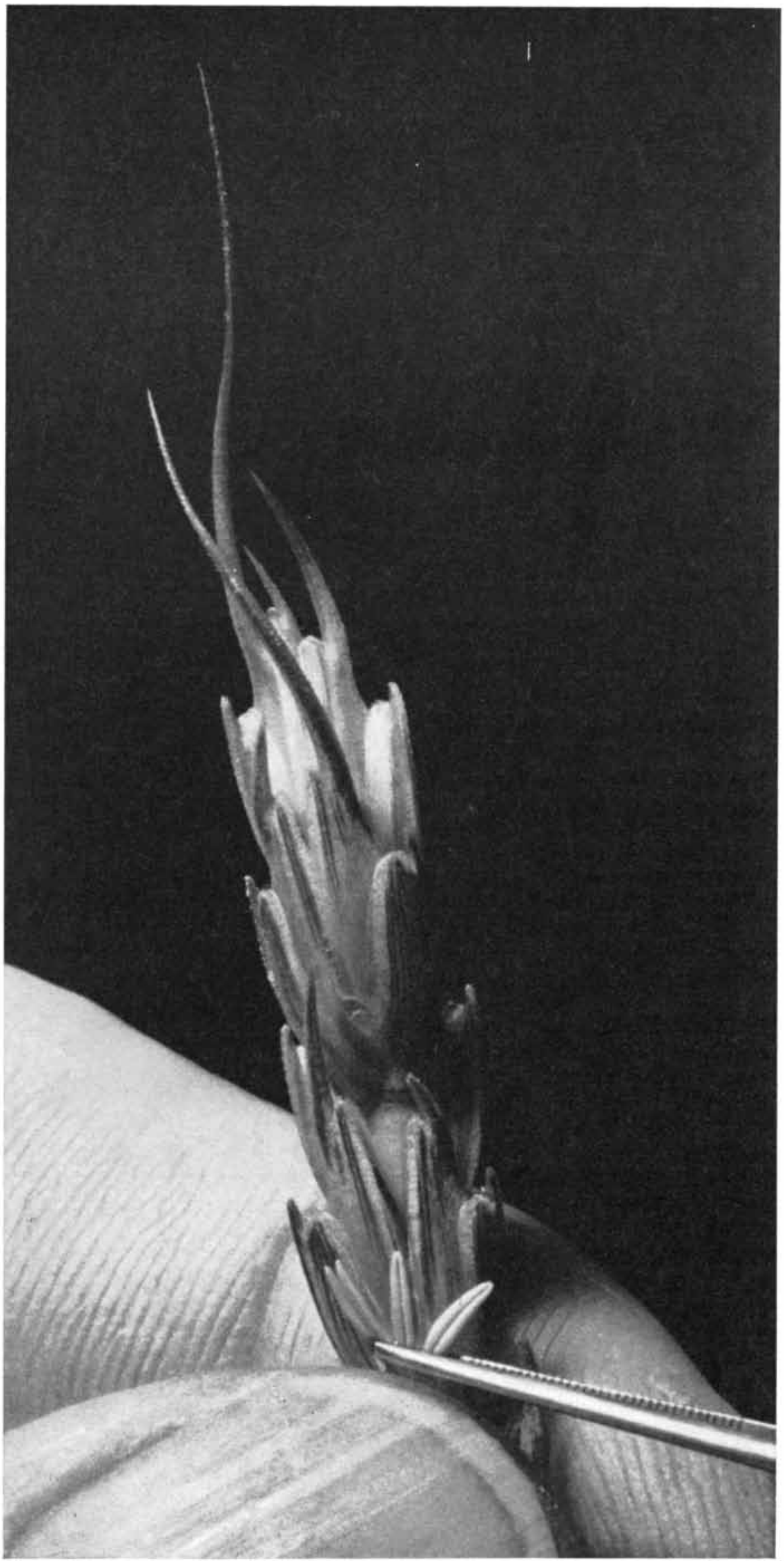
SELF-FERTILIZATION of an individual floret, or flower, of wheat is represented in this series of drawings. Drawing *1* shows a typical mature wheat spike; drawing *2* shows how the wheat head is composed of alternating rows of spikelets, each of which contains several florets (in this case three are shown). Drawings *3* through *6* show how the anthers (the elongated pollen-bearing portions of the male stamens) normally supply pollen on the stigma (the feathery portion of the female pistil) before the floret opens enough to allow the entrance of pollen from other plants. Drawings *7* and *8* show how the fertilized egg develops into the seed, or grain, of wheat. Threshing separates the full-grown grains from the rest of the plant, which is referred to collectively as chaff.

produce similar plants in all subsequent generations, provided that it is self-pollinated and that mutation does not take place. Most modern wheat varieties were obtained by some such procedure, but they are clearly not true hybrids.

The development of a technique for producing true hybrid wheat seed on a large scale began in the early 1950's, at about the same time that the male-sterile mechanism for producing hybrid corn was being perfected. The Japanese investigator H. Kihara reported in 1951 that he had succeeded in inducing "cytoplasmic male sterility" in wheat; this type of male sterility sometimes results when the nucleus of one cell interacts with the cytoplasm of an unrelated cell. Kihara had transferred the nucleus of a common bread wheat (*Triticum aestivum* subspecies *vulgare*) into the cytoplasm of a wild relative of wheat called goat grass (*Aegilops caudata*) and had found that the progeny were female-fertile but male-sterile. In 1953 H. Fukasawa of Japan obtained similar results with a different wild species (*Aegilops ovata*) as the female parent in a cross with durum wheat (*Triticum durum*), a species used primarily for making macaroni. Later Kihara developed still another male-sterile variety by crossing emmer wheat (*Triticum dicoccum*) with a species known only as *Triticum timopheevi.*

None of these developments proved successful in providing a commercially useful male-sterile mechanism for hybrid wheat, owing to adverse side effects produced by the particular lines that were crossed. The findings did, however, stimulate later and more successful experiments. In 1961 J. A. Wilson and W. M. Ross, working at the Kansas Agricultural Experiment Station, obtained stable cytoplasmic-male-sterile bread wheats by crossing *T. timopheevi* as the female or seed parent with a variety of *T. aestivum* called Bison wheat. Repeated backcrossing of the Bison variety with the male-sterile progeny plants resulted in stable, cytoplasmic-male-sterile Bison lines. These lines were widely distributed internationally and are the source of many of the male-sterile wheat varieties currently available.

For the cytoplasmic-male-sterile system to be useful in producing hybrid wheat a corresponding fertility-restoring mechanism must be found. A male-sterile Bison line, when pollinated by normal fertile Bison wheat or other normal, nonrestoring varieties, will produce offspring that are also male-sterile. This



EMASCULATION of a wheat floret is accomplished by removing the three anthers in the floret with small forceps. Pollen from another plant can later be applied to the stigma by hand in order to obtain a single seed of hybrid wheat. Such a procedure is obviously not commercially feasible as a method of producing large quantities of hybrid wheat seed.

variety called Primepi wheat by E. Oehler and M. Ingold of France. Much research is currently under way to collect enough of the restorer genes into single agronomically desirable varieties in order to make hybrids completely fertile when crossed with agronomically sound male-sterile varieties. One private seed company has announced success in this effort and has distributed several varieties of hybrid wheat seed for test planting by farmers.

The cytoplasm-nucleus reaction that leads to male sterility is not a well-understood process. In fertile plants there is apparently a good balance between the chromosomal genes and an unknown heredity mechanism carried in the cytoplasm. In cytoplasmic-male-sterile plants this delicate balance is undoubtedly upset in some way, giving rise to deformed anthers and empty or sterile pollen grains [*see illustration on page 26*]. In contrast to normal anthers the anthers of male-sterile plants are more slender and tend to curl at the base into the shape of an arrowhead. Such anthers produce little pollen, and what little is produced cannot effect fertilization. Apparently the induced imbalance has no effect on the pistil. Normal pollen applied to the stigma will function properly, and a seed will be produced. In fact, there is scant evidence that male-sterile plants are morphologically different from normal plants except for defective anthers and pollen.

Cytoplasmic-male-sterile lines can be developed, starting with a stable line such as Bison wheat or Wichita wheat, by means of the backcross method [*see top illustration on page 27*]. The final progeny will be identical with the recurrent parent in most characteristics except that it will be male-sterile instead of fully fertile. In order to prevent contamination by foreign pollen and to ensure that only pollen from the recurrent parent effects fertilization, some stratagem must be found for isolating the individual plant, such as placing a small plastic bag over its head.

A few wheat varieties have proved difficult to sterilize. These plants, which usually have a restorer gene that prevents sterilization, include several important commercial varieties. Just why these varieties have such genes is not known. Perhaps they arose by mutation or are carry-over genes from natural crosses to *T. timopheevi* in past generations.

Male-sterile varieties are maintained and increased by growing the male-ster-

MALE-STERILE SEED on the wheat head at center was obtained by hand-fertilizing the florets of an emasculated plant called *Triticum timopheevi* with pollen from a common bread-wheat variety of *Triticum aestivum*. Normal spikes of the female and male parents are shown at left and right respectively. The "cytoplasmic male sterility" of the crossed variety results from a little-understood interaction of the chromosomal genes in the nuclei of the male parent's cells with an unknown heredity factor in the cytoplasm of the female parent's cells. Repeated backcrossing of fully fertile plants of the common bread-wheat variety with the male-sterile progeny plants results in a stable cytoplasmic-male-sterile line.

outcome is of course an important and integral step in maintaining and increasing seed of the male-sterile variety, but seed used by the farmer to plant his hybrid crop must have, in the resulting plants, the capacity for male fertility. This is achieved by pollinating the male-sterile plants with a variety that restores fertility. Such varieties have in them dominant restorer genes capable of overcoming the cytoplasm-nucleus reaction that causes male sterility. Finding highly effective dominant gene systems for fertility-restoration has proved difficult indeed, but a few such systems that restore fertility well under certain environments have been reported.

In 1960 Wilson and Ross announced the discovery of partial fertility-restoring factors in bread wheat for one of the cytoplasms on which Fukasawa had worked. Then in February, 1962, Wilson suggested that restorer genes must exist in *T. timopheevi,* since it carried the sterile cytoplasm; otherwise *T. timopheevi* would be male-sterile and unable to reproduce itself. Several months later John W. Schmidt, V. A. Johnson and S. D. Mann of the Nebraska Agricultural Experiment Station demonstrated that a bread wheat derived from *T. timopheevi* was effective in restoring reasonable fertility to male-sterile Bison wheat. Shortly thereafter Wilson, working independently, reported similar results. Subsequent studies by these same investigators and others have shown that the original restorer sources were not completely effective in restoring fertility to the Bison plants and other sterile wheats in all environments.

In the years since the discovery of these partial fertility-restoring factors it has become obvious that restorer genes and modifiers of restorer genes are distributed among several of the world's existing wheat varieties. For example, Ronald W. Livers of the Kansas Agricultural Experiment Station has reported a number of common varieties that carry genes for partial restoration. An important restorer gene was also found in a ile, or *A*-line, plants in "drill strips" in the field. These are situated between drill strips of the normal fertile, or *B*-line, plants. The male-sterile plants are pollinated by windblown pollen from the fertile plants. Seed from the male-sterile plants is harvested (by combine) separately from seed from the fertile plants; after a sufficient increase is attained the male-sterile seed is ready to be planted as the female next to a restorer line as the male for hybrid-seed production.

Developing additional restorer, or *R*-line, plants from a given source is much more difficult and laborious than developing additional male-sterile lines. For example, in order to produce a restorer line of the Scout variety one must select and backcross the dominant restorer plants in later generations to the parent Scout line. After several repetitions of the cycle the characteristics of the Scout plants are combined with the dominant restorer genes, resulting in a Scout restorer variety [*see bottom illustration on page 27*].

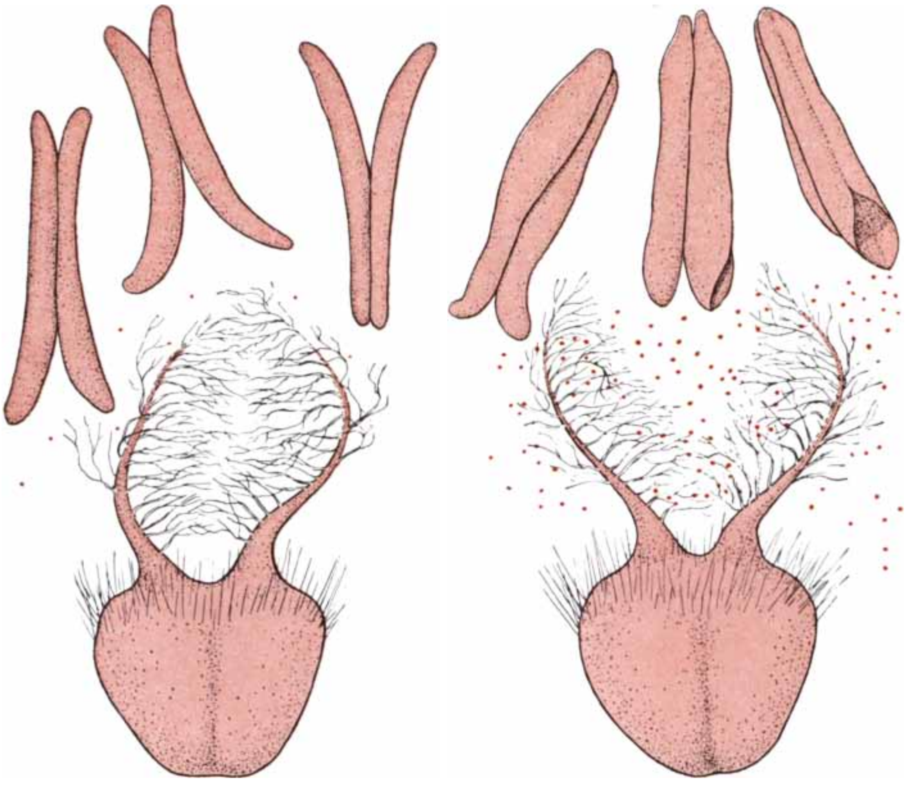
The same general procedure can be used to produce a new restorer variety with the desirable characteristics of the Scout line combined with the desirable characteristics of the original restorer source. Here, as before, the second-generation restorer plants would be selected for producing the third and succeeding generations. In each generation, however, the best agronomic plants would be selected for continuation. Thus after the fifth generation it should be possible to select plants approaching the pure-line status.

An important requirement for any breeding scheme designed to produce restorer lines is that the selected plants of each generation be crossed to a cytoplasmic-male-sterile variety to determine if the selected plants actually carry the restorer genes. The first-generation plants from these test crosses will be fully restored to male fertility if the selected plants carry the necessary fertility-restoring genes.

After a number of male-sterile and restorer lines are produced, various combinations of hybrids are made and tested under field conditions to determine which hybrids display the greatest hybrid vigor for a given production area. Once this is established the hybrid seed can be produced on a large scale for sale to farmers. Such seed will produce first-generation hybrid plants that one hopes will possess the desired amount of hybrid vigor. Obviously hybrid vigor must be manifested or the farmer gains nothing from planting the hybrid.

The amount of hybrid vigor to be gained from hybrid wheat in large-scale field plantings has not yet been established, owing to the unavailability of sufficient seed stocks for such plantings. Many reports on the gain in hybrid vigor

THREE MATURE SPIKES of Bison wheat are compared in this illustration. At left is a cytoplasmic-male-sterile spike open and ready for cross-pollination. At center is a fully fertile spike undergoing self-pollination. At right is a partially fertile spike derived from a cytoplasmic-male-sterile line; its fertility has been partially restored by crossing its male-sterile parent as the female with a variety of bread wheat derived from *T. timopheevi* as the male. The discovery of the fertility-restoring factors in bread wheat in the early 1960's stimulated a major expansion in the research effort devoted to the development of new hybrid wheat varieties.



SEX PARTS from a male-sterile plant of Bison wheat (*left*) are compared with the sex parts from a normal plant of Wichita wheat (*right*). The anthers of the male-sterile plant (*top left*) are more slender than the normal anthers (*top right*) and tend to curl at the base into the shape of an arrowhead. The little pollen produced by the anthers of the male-sterile wheat plant is sterile and cannot effect fertilization. The pistil of the male-sterile plant (*bottom left*) is morphologically identical with that of the normal plant (*bottom right*).

from small experimental plantings in various parts of the world are in the literature on wheat. One can surmise from these reports that a 20 to 30 percent increase in yield should not be difficult to obtain from large-scale field plantings. Data from such plantings should be available in two to four years; it will then be possible to ascertain the degree of hybrid vigor to be realized from wheat.

So far we have discussed only the mechanics of producing hybrid wheat plants experimentally. No mention has been made of the difficulties usually encountered in increasing the male-sterile lines or in growing hybrid seed under field conditions.

The major difficulty in producing economically feasible hybrids, other than developing adequate restorer lines, has been the failure to obtain consistently good cross-pollination in the field. Cross-pollination is affected by many factors, including the synchronization of the flowering times of the male-sterile plants and the pollinator plants. The vagaries of the weather also have a strong bearing on cross-pollination. The problem of providing receptive female florets at the time of maximum pollen dispersal depends on the relative maturity of the two parent varieties. Concurrent plantings of male-sterile and pollinator varieties, with the pollinator plants reaching the "heading" stage one to three days later than the male-sterile plants, will usually provide adequate synchronization.

Under conditions of cool weather and an adequate supply of moisture, the female sex parts will remain receptive for as long as eight to 10 days. Maximum receptivity is attained three to five days after the wheat heads are fully formed. If the pollinator variety happens to mature earlier than the male-sterile one, maximum pollen dispersal may precede maximum floret receptivity, and the result will be a reduced yield of seed. Solutions to such problems may be found in adjusting the planting times or in varying the seeding rates. Such activities will, however, add considerably to production costs and thereby increase the cost of hybrid seed. Extra seed costs to the farmer reduce the value he gains from hybrid vigor.

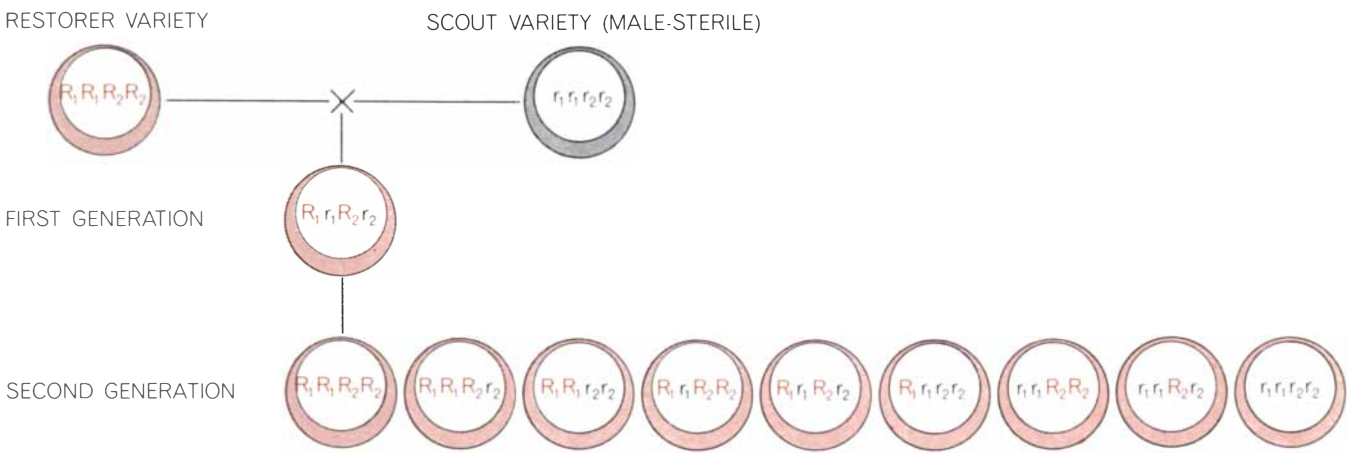
Wheat pollen is short-lived and is adversely affected by hot and dry conditions. Richard E. Watkins of Colorado State University has found under laboratory conditions that the life-span of pollen from typical wheat varieties is less than five minutes after anthesis (the opening of the anther) at a temperature of 95 degrees Fahrenheit and a relative humidity of 20 percent. At 65 degrees F. and 80 percent relative humidity some pollen remained alive for as long as an hour, with more than 60 percent still viable 20 minutes after anthesis. In addition to affecting the viability of pollen, high temperatures and low humidity reduce the pollen load in the air, since the wilting of the plant parts impedes the release of pollen.

In general the best cross-pollination has been achieved at cool (but not too cool) temperatures and medium humidity. Too much rainfall or fog also impedes pollen dispersal. Under these conditions pollen is either washed down or made so soggy that it fails to become airborne. Such weather conditions may also cause "lodging," or bending of the entire wheat plant toward the ground, another situation that could prevent cross-pollination. Gentle to strong breezes are necessary to move pollen from one plant to another, but too much wind may result in the loss of pollen. Wheat pollen is heavier than air, but it is easily borne aloft by air movement. Some workers have envisioned the use of wind machines to enhance cross-pollination, but no reports of the successful application of this technique are at hand.

Cross-pollination of more than 90 percent of the male-sterile plants has been achieved under field conditions, but much lower percentages are usually the case. It is believed that at least 70 percent cross-pollination is needed to keep the cost of hybrid wheat seed at an acceptable level. Efforts are under way to enhance cross-pollination by incorporating (through breeding) larger and more prominent anther types into pollinators and wider-opening florets with larger stigmas into male-sterile lines.

What will the advent of hybrid wheat mean to farmers, millers, bakers and the ultimate consumers of wheat products? To the farmer hybrid wheat should provide greater returns per acre of land, resulting not only from hybrid vigor but also from the more intensive and efficient management practices that seem to accompany the introduction of a hybrid crop. When hybrid corn was introduced, improved management accounted for as much or more of the increase in yield as hybrid vigor did. The production prob-

BACKCROSS METHOD is used to develop and increase a cytoplasmic-male-sterile line of Wichita wheat. The final progeny will be identical with the recurrent Wichita parent in most characteristics except that it will be male-sterile instead of fully fertile. Theoretically the genetic content of the nonrecurrent male-sterile parent will be reduced by half for each generation of backcrossing.



RESTORER LINE, consisting of wheat plants of the Scout variety, is developed by selecting and backcrossing the dominant restorer plants of later generations to the parent Scout line. After several repetitions of the cycle the characteristics of the Scout plants are combined with the dominant restorer genes, resulting in a Scout restorer variety. In this schematic representation of one such cycle the dominant restorer genes, located in the nuclei of plants derived from the original restorer plants, are denoted by R_1 and R_2; the recessive, or nonrestorer, genes are denoted by r_1 and r_2. The cytoplasm from the male-sterile variety is colored; the normal cytoplasm from the Scout variety is gray. The completely dominant restorer plant in the second generation is designated $R_1R_1R_2R_2$.

lems associated with hybrid wheat should be no greater than those encountered with high-yield pure-line wheat varieties. Hybrids must of course be acceptable in all the agronomic characteristics to which the wheat farmer is accustomed.

One specific trait that hybrid wheats must possess is good resistance to lodging, particularly in the high-yield areas. Increased grain yields of 25 to 50 percent impose a proportionately increased weight load on the wheat straw and may result in severe lodging. Heavily lodged plants result in high harvest losses in grain, manpower and harvesting-machine time. One way of increasing resistance to lodging is to breed hybrids with shorter and stiffer stems. Most breeding programs aimed at developing hybrid wheat are taking this approach to attain resistance to lodging. Sources for these hybrids include the highly productive semidwarf Mexican wheat varieties and semidwarf wheat varieties from the northwestern U.S.

Hybrids with shorter stems may not be necessary in some of the important wheat areas that normally do not support the development of tall straw. Much of the high plains of the U.S. is such an area. Irrigation is on the increase in some of the high plains areas, however, and there are indications that better lodging resistance will be needed.

Resistance to disease is an important attribute for stabilizing wheat production in many parts of the world. Hybrid wheat should offer more flexibility than pure-line varieties in the control of diseases, particularly parasitic diseases such as the rusts. When a pure-line variety that is resistant to the prevalent rust fungi is released, new rust species usually arise to attack the new variety. The same pattern will probably hold true for hybrids, except that other hybrids, resistant to the new rusts, can be easily substituted for the old hybrid. The reason is that farmers must obtain new seed for each crop from the producer of the original hybrid. Farmers growing pure-line varieties would be more likely to plant subsequent crops from the seed of preceding crops and thus perpetuate the rust-susceptible varieties. The producers of hybrid wheat have a great responsibility to keep abreast of the rust situation and to develop resistant hybrids to combat the disease.

A large number of wheat varieties are required to fit the varied ecological conditions of the areas where wheat is grown. This suggests that many different hybrids will also be required to fit many ecological niches. There is some hope, however, that one of the benefits of hybrid vigor will be increased adaptability. Some experiments have indicated that the root system of a wheat plant may be improved to allow the plant to perform better under drought conditions. Hybrids so designed will help to stabilize production in areas of the world where rainfall is highly variable from season to season.

To millers, bakers and consumers the quality of wheat produced by hybrids

IN THE FIELD hybrid wheat seed is produced by growing alternating "drill strips" of the male-sterile line and the fertility-restoring line. Cross-pollination of the male-sterile plants is effected by windborne pollen from the restorer plants. The hybrid seed from the

is of great importance. Approximately three-fourths of the wheat produced in the world is destined for human consumption. This being so, a close relation has developed between breeders and cereal chemists seeking to maintain or improve quality as new varieties are developed.

The quality of a particular variety of wheat is defined in terms of its ultimate use. Some flours require a high protein content; others do not. Some call for the ability to absorb more water than others. The large number of wheat products results in an equally large number of flour specifications. Most of the wheat produced in North America is classed as bread wheat. These wheats are generally high in protein content and have good water-absorption and gas-retention properties. The best of them are blended with poorer wheats to improve the flour quality in the making of bread.

Wheat varieties differ in their ability to confer favorable characteristics on their progeny. Studies have shown that the protein content of first-generation hybrids can be higher than that of the superior parent. This is somewhat at variance with regular varieties, in which high yield has been associated with low protein content. Conversely, some hybrids have been lower in protein (and in yield) than the inferior parent. Other crosses have produced hybrids whose protein content is intermediate between the protein content of the parents. Similar results have been obtained for water-absorption and gas-retention properties. There is still very little information on the quality characteristics of hybrid wheat, but the information available indicates that with the proper selection of parents hybrids of any desired quality can be obtained.

Research on the hybridization of wheat has been expanded on all fronts in the past decade. Much of the expansion was triggered by the discovery of the male-sterility and fertility-restoring system. Until the early 1960's wheat research was centered in the land-grant institutions and supported primarily by tax funds, both state and Federal. Credit for the discovery of the mechanism to produce hybrid wheat belongs to those institutions. The prospect of an extremely large and continuing market for hybrid wheat seed has prompted several private seed companies, most of them experienced in breeding other crops, to initiate research programs aimed at the development of hybrid wheat varieties. The combined efforts of public and private breeders have already produced dramatic results, but there is a clear need for continued research in many areas. The value of hybrid wheat can only be maintained and improved by further development of improved parental lines. These are the backbone of a successful hybridization program. The development of high-yielding, strong-strawed, disease-resistant parental lines producing grain of good milling and baking quality will ensure the success of hybrid wheat for the future.

male-sterile strips is harvested (by combine) separately from the inbred seed from the restorer strips. The photograph on these two pages shows a typical drill-strip wheat field that is located at the Colorado State University Agronomy Farm in Fort Collins, Colo.

Relaxation Methods in Chemistry

By rapidly upsetting the equilibrium of a chemical reaction one can study the important mechanisms that operate in the interval between a thousandth and a billionth of a second

by Larry Faller

When a chemist has discovered that two substances react to form a third substance, his job has only begun. His next task is to learn something about the mechanism of the reaction. Did substance *A* dissociate into two subspecies before one of them reacted with *B*? Did *A* and *B* first form a temporary complex that rearranged itself to form *C*? Did the reaction require the help of a catalyst such as an enzyme, and if so, what specific regions of the enzyme were involved in the catalytic mechanism? How fast did the reaction go? Because most chemical reactions take place rapidly, it is not easy to obtain answers to such questions. If the reaction takes place in solution, as a great many reactions do, the reaction time is often very short indeed. Hence much ingenuity has been applied to following the details of reactions on an increasingly short time scale.

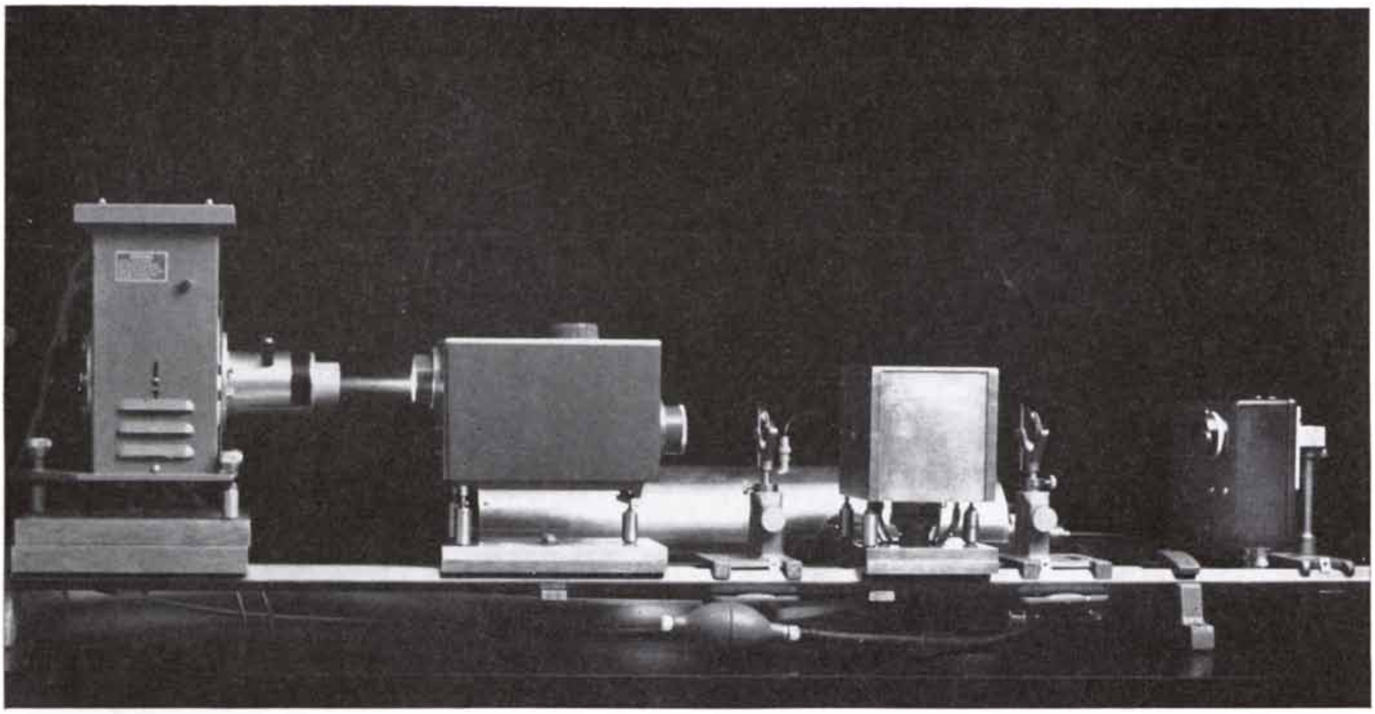
Fifteen years ago chemists thought they were doing well to study the rate of reactions in solution that were half-completed in a millisecond. Today half-times as short as a few nanoseconds (billionths of a second) can be directly measured. This dramatic progress has resulted from a new approach to the study of reaction rates to which the cryptic term "relaxation" has been applied. In this approach the equilibrium of a chemical reaction is rapidly upset by changing some important condition, such as temperature or pressure; the change in the concentration of reactants or product is monitored while the reaction reequilibrates (relaxes). This basically simple idea, which could have been implemented technically—had anyone thought of it—at least 30 years ago, was introduced in 1954 by Manfred Eigen of the Max Planck Institute for Physical Chemistry in Göttingen, who received a Nobel prize for his work in 1967. It has provided a new vision into the elementary steps of chemical reactions and is proving a powerful tool for clarifying biochemical mechanisms.

Traditionally chemical reactions have been studied by mixing separate solutions containing known concentrations of the reactants and timing either the disappearance of one of the reactants or the appearance of the product. As long as the progress of the reaction was followed by extracting samples for quantitative chemical analysis, manual mixing was perfectly adequate. The time required to mix two solutions manually depends ultimately on the dexterity of the experimenter, but it is not less than several seconds.

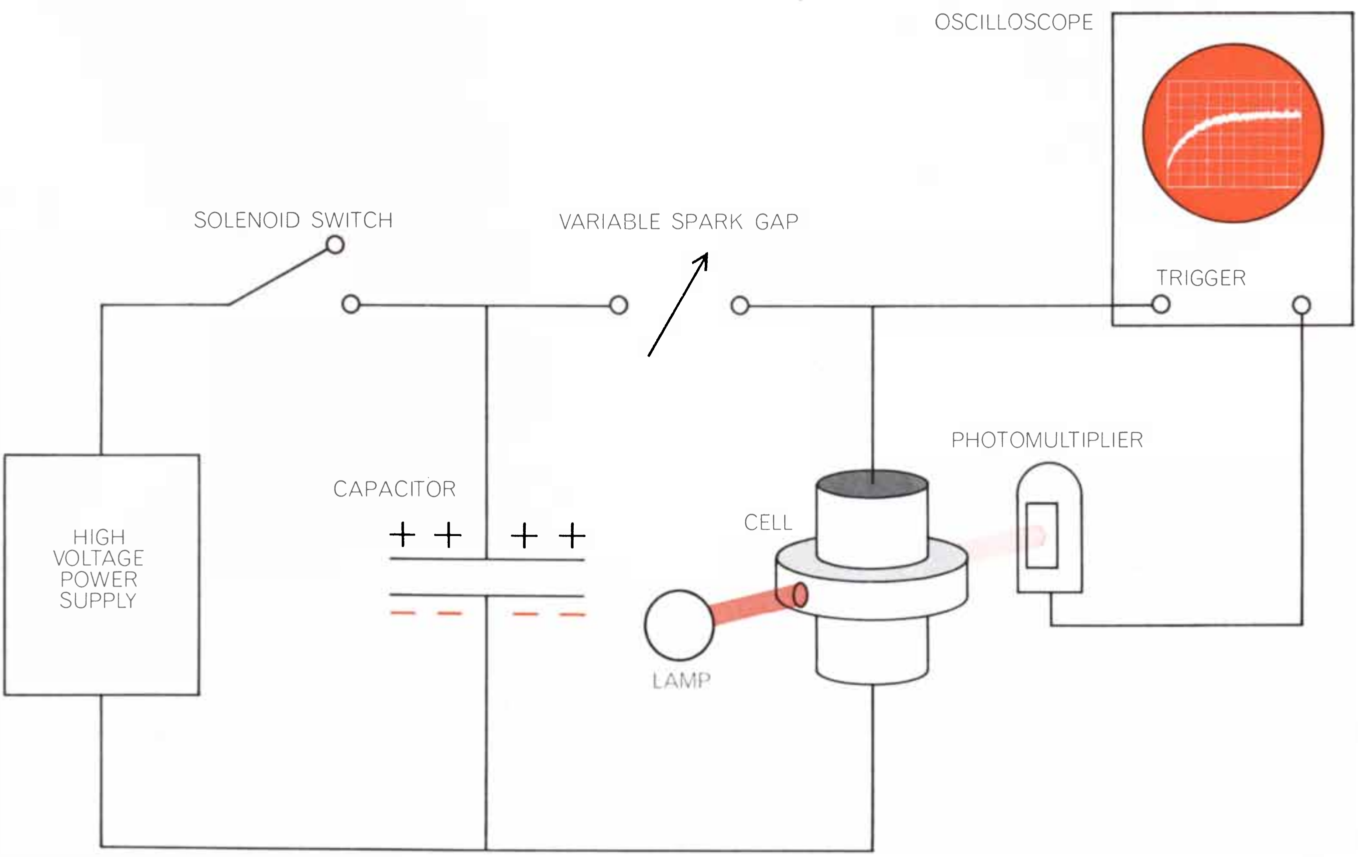
In 1923 Hamilton Hartridge and F. J. W. Roughton of the University of Cambridge devised a way to study much faster reactions. Two solutions containing the reactants were mechanically forced together in a mixing chamber from which the mixture flowed into a long observation tube. There one could measure changes in color that were related to a change in concentration of either the reactants or the product. The time from the start of the reaction depended on the distance the solution had traveled from the mixing chamber and on the velocity of flow. Hence reaction rates could be determined either by observing the extent of the reaction at different points along the observation tube or by observing the reaction at a single point and varying the flow velocity. In this way it was possible to obtain information on reactions within a few milliseconds of their starting time.

In early applications of this method a galvanometer was used to measure the response of a photocell to changes in the color of the flowing solution. Because several seconds were needed to make a measurement, a constant flow rate had to be maintained for this period, which meant that fairly large volumes of reactants were required. Therefore the method could not be employed with scarce substances such as biochemicals that were difficult to isolate. The development of cathode ray oscilloscopes that can simultaneously detect, amplify, record and time electronic signals led to "stopped flow" instruments that required much smaller quantities of reactants. In this variation of the continuous-flow method the flow was abruptly stopped after mixing and changes in the color of the stationary reaction solution were recorded spectrophotometrically. By 1940 Britton Chance of the University of Pennsylvania had developed an instrument that required only a tenth of a milliliter of reactants to produce enough readings for plotting a useful curve. Since that time there have been refinements in flow methods but none has reduced the minimum time required to mix two solutions to less than a tenth of a millisecond. Further shortening of the time in studying solution reactions required a radically different approach.

The new approach was foreshadowed in the early 1950's by measurements of sound absorption in solutions containing dissolved salts such as magnesium sulfate. Sound waves of certain frequencies were more strongly absorbed than had been expected. It is now known that the anomalous absorption results from the inability of a reaction involving the magnesium ion (Mg^{++}) to keep pace with the pressure variations in the sound wave. It is of historical interest that Albert Einstein, following a suggestion of the physical chemist Walther Nernst, had predicted in 1920 that a dissociating



TEMPERATURE-JUMP INSTRUMENT built by the author at Wesleyan University provides information about fast chemical reactions by means of the relaxation technique. "Relaxation" refers to the natural tendency of a chemical reaction to reach a new equilibrium after it has been perturbed in some fashion. In the author's instrument the perturbation is a sharp rise in temperature.



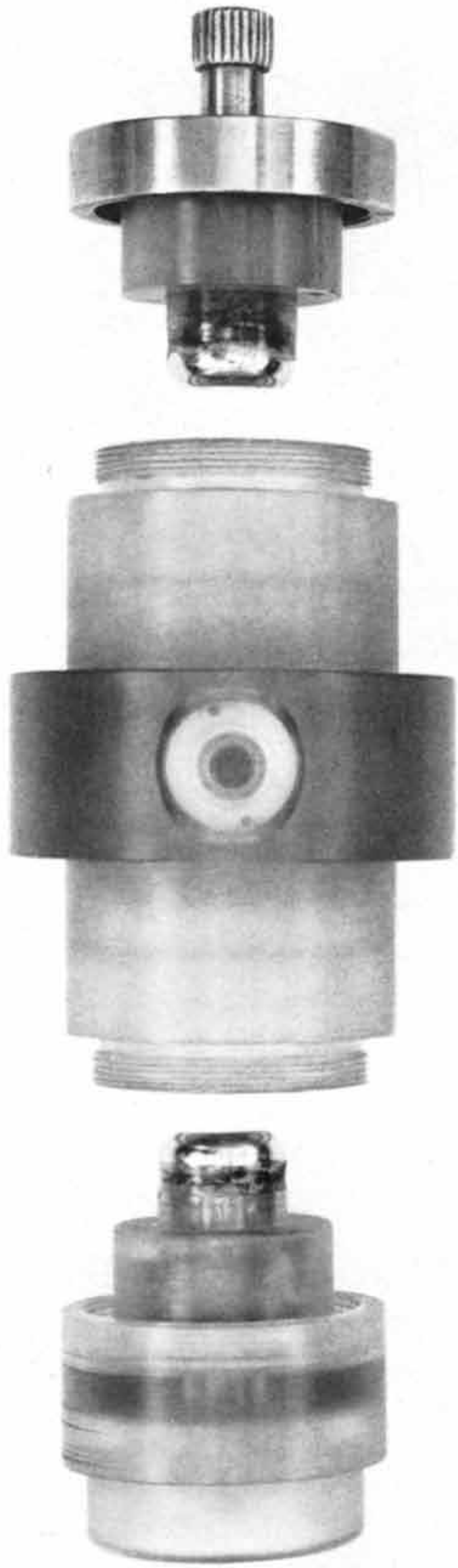
SOURCE OF TEMPERATURE JUMP in the author's instrument is a high-voltage direct-current power supply connected to a capacitor through a solenoid switch. After the capacitor is charged the switch is disconnected. By closing a variable spark gap the energy stored in the capacitor can be discharged through a cell containing the reaction under study. In solution with the reactants are salt ions that carry the discharge current, without entering into the reaction, and rapidly heat the solution. A temperature jump of six to eight degrees Celsius occurs in five microseconds. The temperature jump induces a change in the concentration of reactants and product as the reaction shifts to a new equilibrium. The shift is monitored by a photomultiplier that responds to changes in absorption of one of the reactants. The results are displayed on an oscilloscope, which is triggered by the closing of the spark gap.

gas should absorb sound at high frequencies because the association and dissociation of the gas molecules would be unable to keep pace with the sharp pressure variations in the sound waves. It remained for Eigen to recognize clearly the importance of these observations for the study of fast reactions. He perceived that fast solution reactions could be investigated by rapidly perturbing a reaction at chemical equilibrium and monitoring the rate at which it shifts to a new equilibrium.

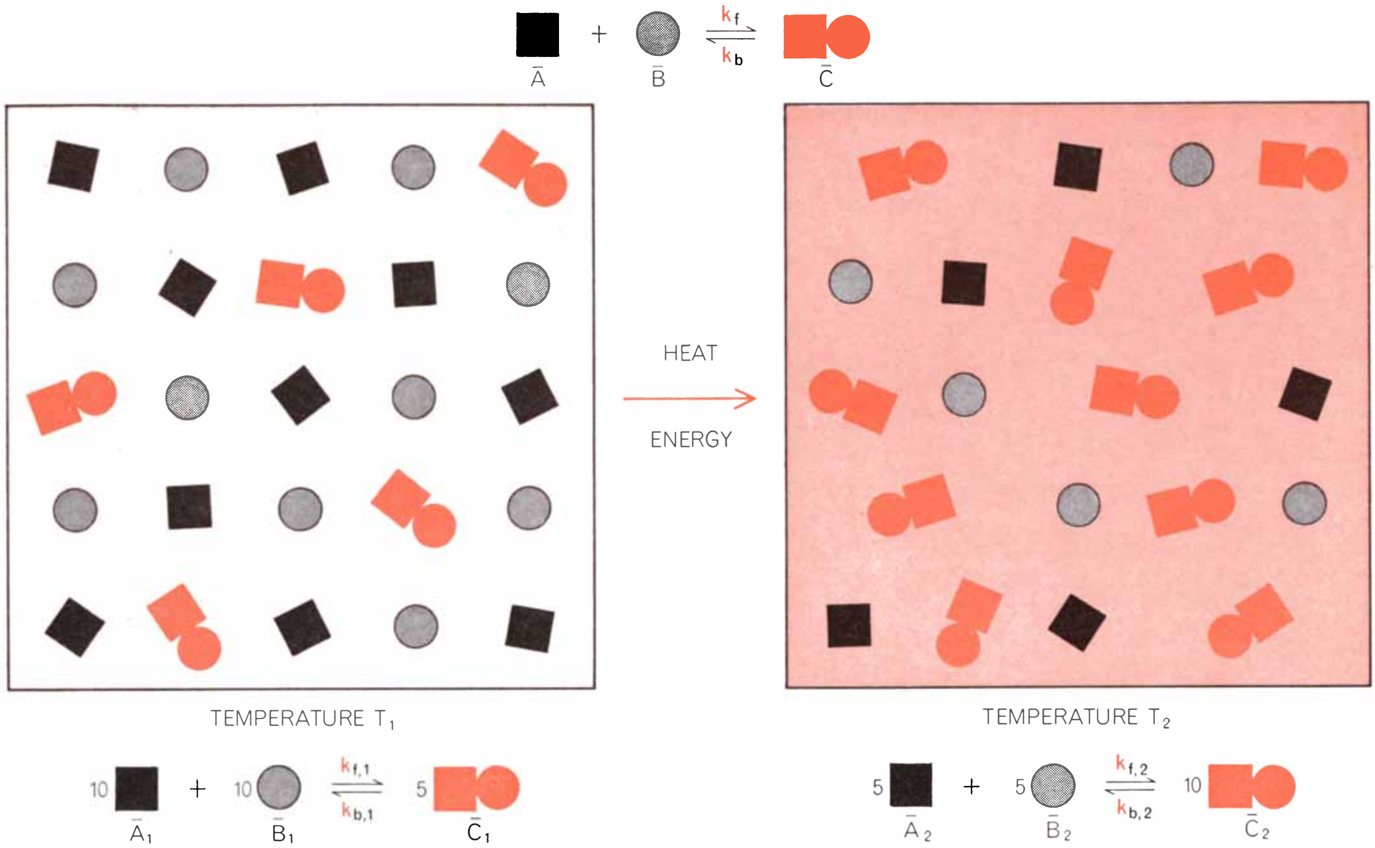
Chemical equilibrium is a dynamic state. Let us consider as a prototype the bimolecular reaction between molecules of *A* and *B* to form a new chemical species *C* [*see top illustration on opposite page*]. At each instant some molecules of *A* and *B* are combining to form *C* and some molecules of *C* are dissociating into *A* and *B*. The reaction is said to be in equilibrium when the forward and backward rates are equal. The rate at which *C* forms is proportional to the product of the concentration of *A* and *B*. The constant of proportionality (that is, the number that balances the equation) is called the forward rate constant. It is a measure of the probability that the reaction will occur. The rate at which *C* dissociates to re-form *A* and *B* depends on the amount of *C* present and on the backward rate constant. The relative concentrations of *A*, *B* and *C* are fixed by the equilibrium constant *K*, which is the ratio of the forward to the backward rate constant.

Two important properties of chemical equilibria should be noted. First, they depend on external conditions, the two most familiar being temperature and pressure. For each temperature and pressure there is a particular set of forward and backward rate constants, and therefore a different value of *K*. Second, if an equilibrium is disturbed by changing the temperature or pressure, the reaction cannot regain equilibrium infinitely fast.

Suppose our prototype reaction shifts to the right when the temperature is raised. Such a shift is reasonable, because as the temperature increases the molecules of *A* and *B* move faster. They collide more frequently, increasing the probability of reaction to form a molecule of *C*. The dissociation of *C* does not require collision with another molecule, so that the influence of temperature on the forward and backward rate constants is generally different. If the forward rate constant increases faster with temperature than the backward rate constant,



TEMPERATURE-JUMP CELL consists of a cylindrical plastic chamber and two electrodes that fit into the ends of the chamber. When a high current is suddenly passed through the cell, the temperature rises sharply and thus alters the equilibrium of a chemical reaction.



EFFECT OF TEMPERATURE CHANGE on a chemical reaction is usually to shift the concentration of reactants and product that are in equilibrium. Here reactants A and B combine to form C at a certain rate specified by the forward rate constant k_f. The dissociation of C into A and B is governed by the backward rate constant k_b. Letters with bars over them indicate equilibrium concentrations of reactants and product. At temperature T_1 10 molecules of A and 10 molecules of B are in equilibrium with five molecules of C. At temperature T_2 the reaction is driven to the right so that five molecules of A and five of B are now in equilibrium with 10 molecules of C. The values of the rate constants at each temperature can be determined by means of chemical relaxation methods.

AT TEMPERATURE T_1: RATE FORWARD = RATE BACKWARD

$$k_{f,1}\,(\bar{A}_1 \cdot \bar{B}_1) = k_{b,1}\,(\bar{C}_1) \quad (1)$$

$$1\,(10 \cdot 10) = 20\,(5) \quad (2)$$

AT TEMPERATURE T_2: RATE FORWARD = RATE BACKWARD

$$k_{f,2}\,(\bar{A}_2 \cdot \bar{B}_2) = k_{b,2}\,(\bar{C}_2) \quad (3)$$

$$8\,(5 \cdot 5) = 20\,(10) \quad (4)$$

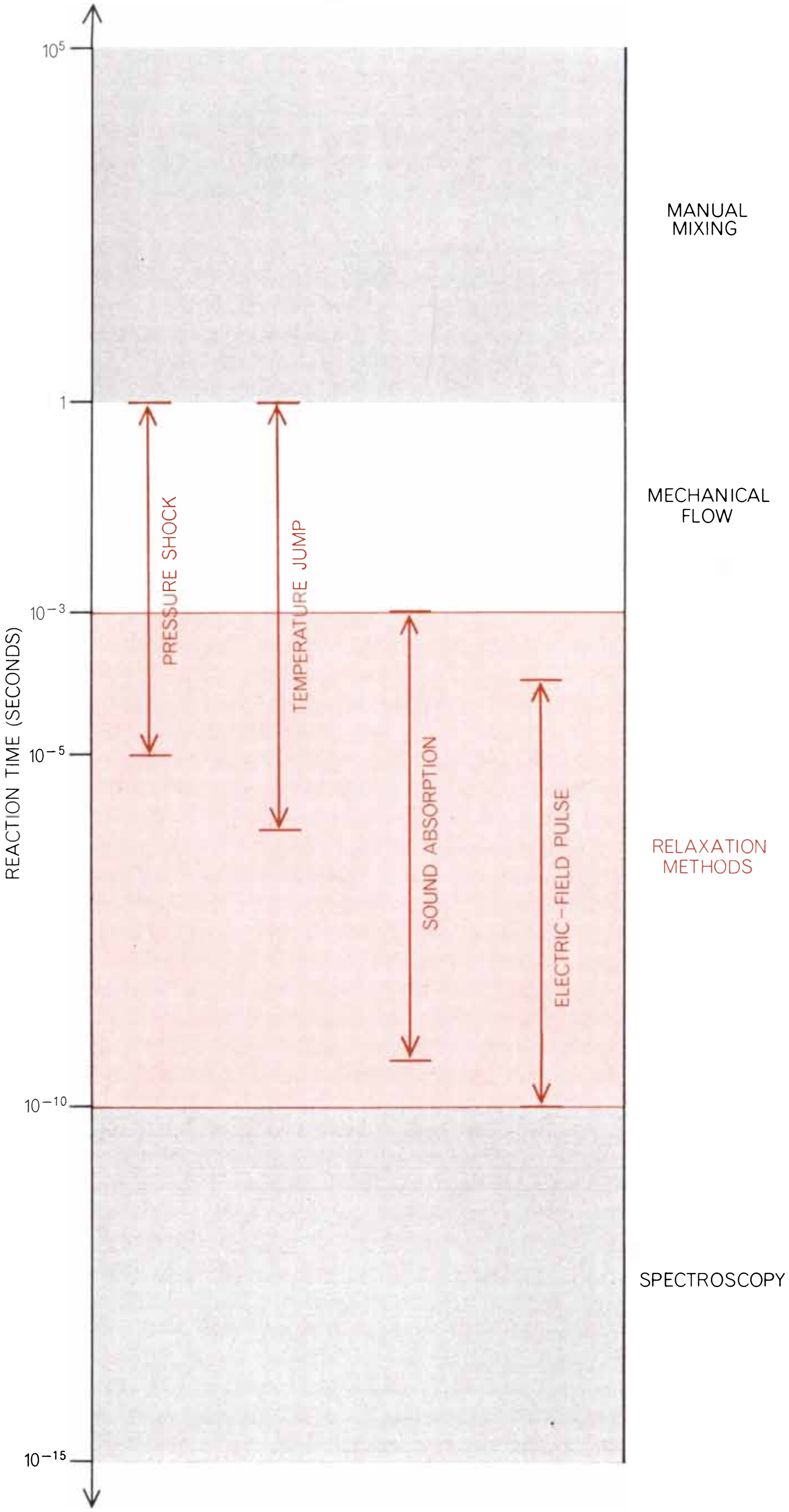
AT TEMPERATURE T_1: EQUILIBRIUM CONSTANT

$$K_1 = \frac{k_{f,1}}{k_{b,1}} = \frac{1}{20} = \frac{\bar{C}_1}{\bar{A}_1 \cdot \bar{B}_1} = \frac{5}{10 \cdot 10} = .05 \quad (5)$$

AT TEMPERATURE T_2: EQUILIBRIUM CONSTANT

$$K_2 = \frac{k_{f,2}}{k_{b,2}} = \frac{8}{20} = \frac{\bar{C}_2}{\bar{A}_2 \cdot \bar{B}_2} = \frac{10}{5 \cdot 5} = .4 \quad (6)$$

RATE AND EQUILIBRIUM CONSTANTS are computed for the reaction depicted at the top of the page. At each temperature, when equilibrium is reached, the rate forward equals the rate backward. The values of $\bar{A}_1$, $\bar{B}_1$ and $\bar{C}_1$ at temperature T_1 are substituted in equation *1*. If the forward rate constant $k_{f,1}$ is set equal to 1, it is clear that the backward rate constant must be 20 to make the equation balance (*2*). A similar substitution is carried out in equation *3* for temperature T_2, giving equation *4*. In equation *4* the backward rate constant is kept the same as in equation *2* to indicate that the tendency of molecule C to come apart is not greatly affected by a small change in temperature. The rate at which A and B combine, however, is apt to be significantly accelerated because it depends on the frequency with which they collide. Thus in this hypothetical example $k_{f,2}$ is eight times larger than $k_{f,1}$. With this information for each temperature the equilibrium constants K_1 and K_2 can be computed (*equations 5, 6*).



RELAXATION METHODS fill the gap between more traditional methods for studying the rates of chemical reactions. Reactions with half-times longer than a second can be studied by manually mixing reactants. Mechanical-flow methods extend the range of half-times accessible to study to about a millisecond. At the other extreme, spectroscopy gives information about simple radiation-absorption reactions, which can take place in less than 10^{-10} second (a tenth of a nanosecond). Relaxation techniques fill the gap between 10^{-10} and 10^{-3} second, where many of the elementary steps in chemical reactions take place.

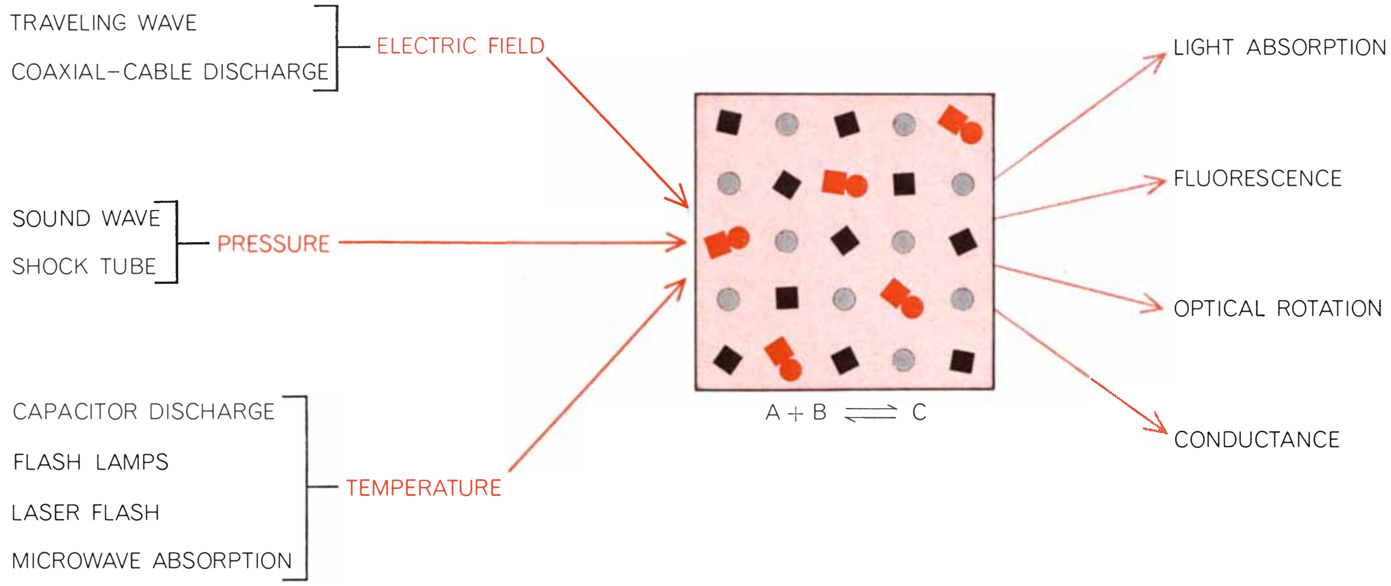
then the relative amount of C in an equilibrium mixture of A, B and C will be greater at higher temperatures.

If our prototype reaction is initially at equilibrium at some temperature T_1, the concentrations of A, B and C will be the appropriate equilibrium concentrations for that temperature [*see bottom illustration on preceding page*]. Now, suppose the temperature is suddenly increased to a new value T_2. As soon as the temperature is raised the appropriate equilibrium values for the reactants are those corresponding to the higher temperature. In contrast, the net rate at which the actual concentration of C can change is limited by the forward and backward rate constants at the higher temperature and by the instantaneous concentrations of A, B and C. If the temperature is increased rapidly compared with the rate at which the reacting system can respond, the change in the actual concentration of C will lag behind the change in its equilibrium concentration.

For small, stepwise perturbations of the temperature, the reactants are observed to approach their equilibrium values at the higher temperature exponentially, that is, the rate at which C changes is approximately proportional to the difference between its equilibrium concentration and its actual concentration. The reciprocal of the constant of proportionality has units of time and is called the relaxation time (designated by the Greek letter tau). In numerical terms it is the time required for C to approach within approximately a third of its new equilibrium value.

The exact relation between the relaxation time, the forward and backward rate constants and the equilibrium concentrations of the reactants depends on the form of the perturbation and on the reaction mechanism. For a simple bimolecular reaction the reciprocal of the relaxation time is equal to the forward rate constant times the sum of the equilibrium concentrations of A and B plus the backward rate constant. All rate constants and concentrations refer to the higher temperature. The forward and backward rate constants can be evaluated by measuring the relaxation time at different concentrations of A and B. A plot of the reciprocal of the relaxation time against the sum of the equilibrium concentrations of A and B yields a straight line whose slope is the forward rate constant and whose intercept is the backward rate constant [*see top illustration on page 37*].

If we had chosen as our prototype re-



VARIETY OF AGENCIES can be exploited for perturbing the equilibrium of a chemical reaction when employing the relaxation technique. Because chemical equilibria depend on temperature, pressure and strength of the electric field, the rates of fast reactions in solution can be studied by perturbing any one of these variables faster than the chemical system can respond. The illustration indicates some of the ways equilibria can be upset and methods for observing the speed with which equilibrium is reestablished.

action the single-molecule interconversion of two species *A* and *C*, the reciprocal of the relaxation time would have equaled the sum of the forward and backward rate constants. Here an independent measurement of the equilibrium constant would be required to evaluate the individual rate constants. More important, the relaxation time would have been independent of the concentrations of reactants [*see bottom illustration on page* 37]. Relaxation studies not only allow evaluation of rate constants but also discriminate among different possible mechanisms. If we had not known whether *C* formed directly from *A* or whether a two-molecule collision with another species *B* was involved, measurement of the relaxation time at different concentrations of *A* and *B* would provide the answer.

In multistep reactions a spectrum of relaxation times may be observed. The number of relaxation times expected depends on the number of independent reactions. If the reactions are sufficiently different, the individual relaxation times can be measured separately by simply changing the time base on an oscilloscope. If not, recourse must be taken to mathematical methods for their separation and interpretation.

The "temperature jump" instrument built by the author at Wesleyan University is illustrated on page 31. Technically it is among the simplest of the relaxation methods. It happens that it is also the most generally useful. In this instrument a capacitor is charged to a high voltage. The energy stored in the capacitor is then discharged through the reaction cell by closing a variable spark gap. The reaction cell contains a neutral salt that does not enter into the reaction but carries the discharge current through the solution, which is rapidly heated by the passage of the current. Changes in the color or transparency of the solution in the cell are monitored by a spectrophotometer and recorded on an oscilloscope. The instrument produces a temperature jump of six to eight degrees Celsius in about five microseconds.

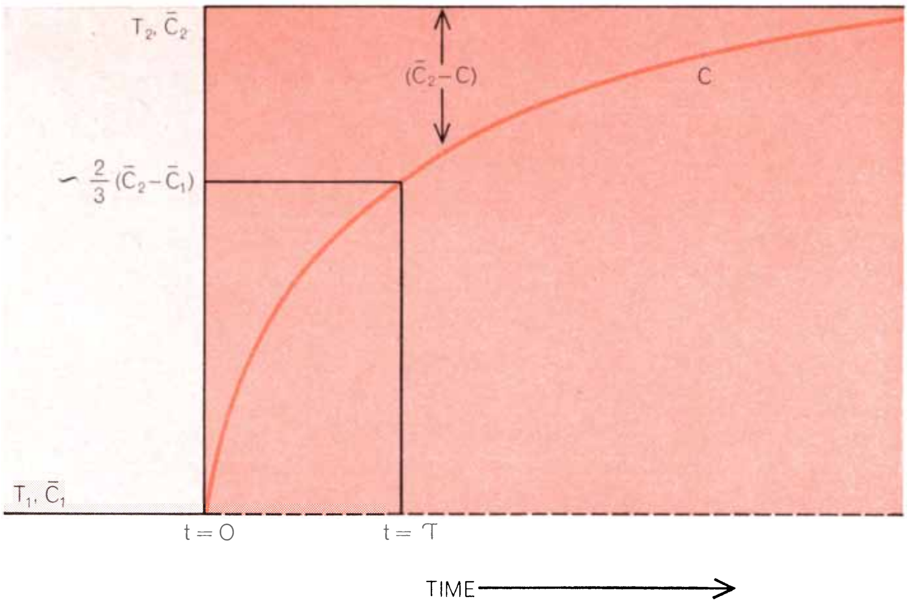
It is not necessary that the perturbation take the form of a simple step. Any perturbation that can be readily expressed mathematically can be used. For example, the pressure in a sound wave varies as a sine wave. Nor is it essential to perturb an equilibrium. Many reactions that go to completion, notably enzyme-catalyzed reactions, pass through a stationary, or quasi-equilibrium, state in which the concentrations of intermediate species are temporarily constant. The rate of formation and dissolution of those intermediates can be studied by rapidly perturbing the stationary state.

In the past decade Eigen, his co-worker Leo de Maeyer and their students have built instruments capable of measuring the fastest possible solution reactions. Instruments built at Göttingen and elsewhere have exploited a variety of agencies for rapidly perturbing chemical reactions [*see illustration above*]. For example, temperature perturbations can be produced by the absorption of microwave energy or by the absorption of short bursts of light energy, either from flash lamps or from lasers. Pressure perturbations can be produced in liquid shock tubes as well as by sound waves.

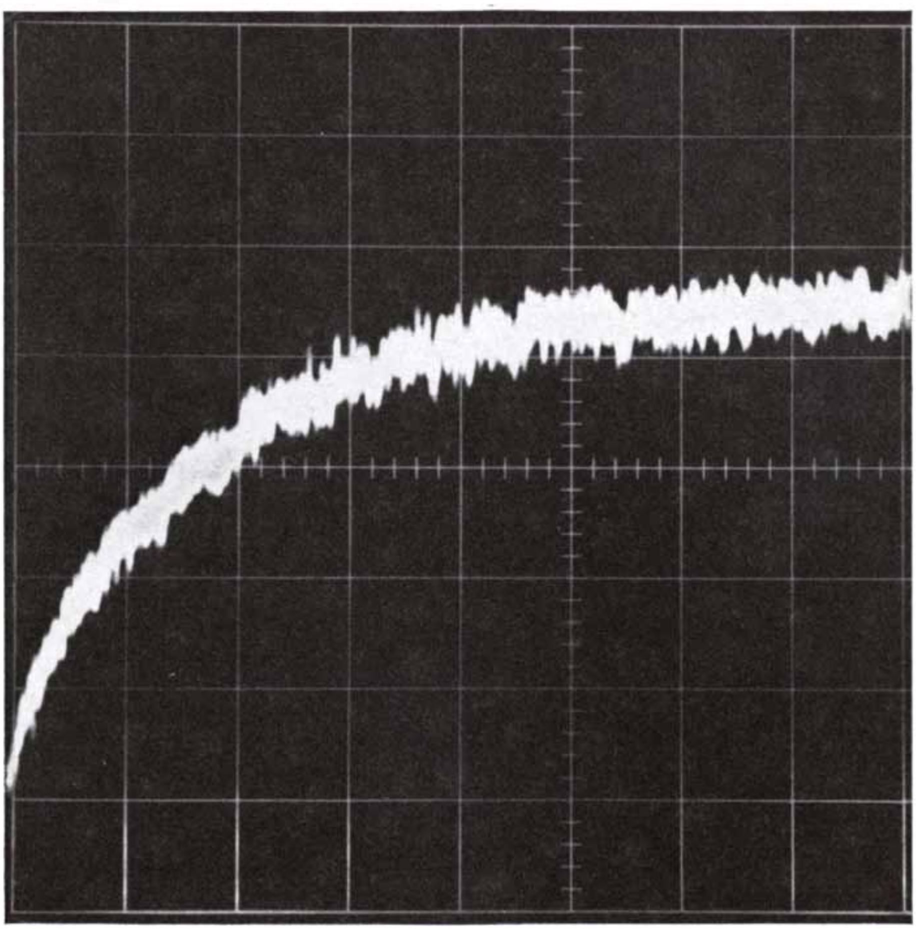
The versatility of these approaches has been extended by coupling them to diverse detection and recording systems. In addition to ultraviolet and visible-light absorption spectroscopy, changes in fluorescence, in optical rotation and in electrical conductivity have been used to follow the progress of chemical reactions. Gordon G. Hammes of Cornell University has successfully coupled stopped-flow and relaxation methods to study the stationary state in an enzyme reaction.

The chemist is not content to know the results of a reaction, the proportions in which reactants combine and the rate of the overall process. He seeks to determine the detailed mechanisms by which chemical transformations occur. It is known that complex reactions involve a series of discrete steps. A variety of techniques allow the identification of reaction intermediates. More formidable is the study of the elementary steps themselves. In general, the transfer of protons (hydrogen ions), the association and dissociation of molecules, the transfer of electrons and the rearrangement of structures—any combination of which comprises the individual steps in complicated reaction mechanisms—are too fast to study by conventional methods.

Consider the association of two mole-



TEMPERATURE-JUMP TECHNIQUE provides data from which rate constants and equilibrium constants can be determined. The apparatus used is the one illustrated on page 31. At the outset, at the initial temperature T_1, product C is present at its equilibrium concentration $\bar{C}_1$. At time zero the temperature is rapidly increased to T_2. The exponential curve (*color*) shows how the instantaneous concentration of C approaches the new equilibrium value $\bar{C}_2$. The relaxation time τ (tau) is approximately equal to the time required for product C to travel two-thirds of the way toward the final equilibrium concentration $\bar{C}_2$.



EXAMPLE OF CHEMICAL RELAXATION is shown in this oscilloscope trace made by the author. The reactants are the enzyme alpha-chymotrypsin and proflavin, a strongly colored substance that binds to the enzyme. When subjected to a temperature jump, the equilibrium amount of bound proflavin is abruptly altered, leading to a change in the amount of light at a wavelength of 460 nanometers absorbed by the solution. The trace shows the change in absorption in the 1.6 milliseconds following the temperature perturbation.

cules in water solution as forming some kind of identifiable intermediate complex. How fast can this reaction occur? Of course, since the rate depends on the concentrations of the reactants, it can be made as slow as one wishes by reducing the concentrations. Unfortunately one quickly reaches a point of diminishing returns. If the concentrations are made too small, the reaction is no longer observable. What one would like to estimate is the rate constant for association from which one could calculate the half-time of the reaction in solutions that contain detectable concentrations of the reactants. The theoretical calculation of rate constants is often prohibitively difficult. It is possible, however, to calculate the maximum rate constant for the association of two molecules by assuming that every collision results in the formation of a complex. The collision probability essentially depends on the mobility of the reacting molecules and their size. The faster the molecules move, the more probable a collision is. The bigger the molecules are, the greater the distance at which collision occurs. Both the thermal mobility and the size of the molecules can be measured by the methods of physical chemistry. For small molecules the calculated maximum rate constants range from about 10^9 to 10^{11} liters per mole per second. (A mole is the weight in grams equal to the molecular weight of a substance.) At the concentrations required for optical detection these values correspond to half-times in the microsecond range. Although such half-times are too short for continuous-flow and stopped-flow techniques, they can be measured by relaxation methods.

The study of proton transfer in water illustrates the use of relaxation methods to investigate a fast elementary process. This was one of the first reactions Eigen and his associates studied by chemical relaxation methods. They found that the rate constant for the bimolecular reaction in which protons (H^+) combine with hydroxyl ions (OH^-) to form water is 1.4×10^{11} liters per mole per second. This value was surprisingly higher than the theoretical maximum calculated by assuming that every collision leads to reaction and by using the measured mobilities of protons and hydroxyl ions. In making such a calculation one also has to assume a certain size for the reacting species. Earlier studies had suggested that a proton in water is associated with a water molecule, forming a hydronium ion (H_3O^+). Because it is much larger than a bare proton, H_3O^+ would collide more frequently with OH^-. Even this assumption, however, led to values smaller than the newly measured rate constant. It turned out that the measured value was in good agreement with the value calculated by assuming that the reacting species were the still larger ions $H_9O_4^+$ and $H_7O_4^-$.

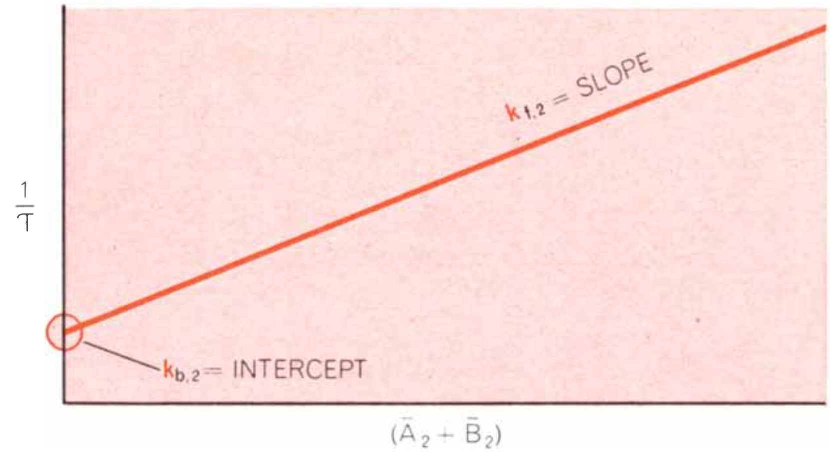
The proton in water solution can be regarded as being hydrated by four water molecules and the hydroxyl ion as being hydrated by three water molecules [*see top illustration on next page*]. Water is a polar molecule, meaning that its electric charges are not evenly distributed. The oxygen has a partial negative charge; the protons (hydrogens) have a partial positive charge. The hydrated proton complex and the hydrated hydroxyl complex are stabilized by the attraction between the charged ions and the oppositely charged ends of the surrounding water molecules. These attractions and the weak interactions between polar water molecules themselves are called hydrogen bonds. The combination of a proton and a hydroxyl ion involves the diffusion together of the hydrated complexes $H_9O_4^+$ and $H_7O_4^-$. Once collision occurs, a hydrogen-bond bridge is formed, and the excess proton is rapidly transferred from $H_9O_4^+$ to $H_7O_4^-$. In ice all the water molecules are bridged to four others by hydrogen bonds. It has been determined from measurements of proton mobility in ice crystals that the mean time an excess proton remains associated with a particular water molecule in a hydrogen-bonded structure is 10^{-13} second. Therefore the slowest step in the combination of protons and hydroxyl ions in water is the random encounter of the hydrated ions. The measured rate constant corresponds to the probability of collision between $H_9O_4^+$ and $H_7O_4^-$.

The unique ability of protons to penetrate spheres of hydration has been confirmed by comparing the rates at which protons combine with negatively charged ions in water solution and the rates at which positively charged metal ions combine with negatively charged ligands (a ligand is anything that associates with metal ions). An example of the former process is the association of acetic acid, in which H^+ reacts with CH_3COO^- to form CH_3COOH. As anticipated, the rate constant for combination (4.5×10^{10} liters per mole per second) equals the calculated collision probability. Once the hydrated hydrogen and acetate ions have collided, pro-

IF $A + B \underset{k_b}{\overset{k_f}{\rightleftharpoons}} C$

THEN, $\frac{1}{\tau} = k_{f,2}(\bar{A}_2 + \bar{B}_2) + k_{b,2}$

WHEN PLOTTED:

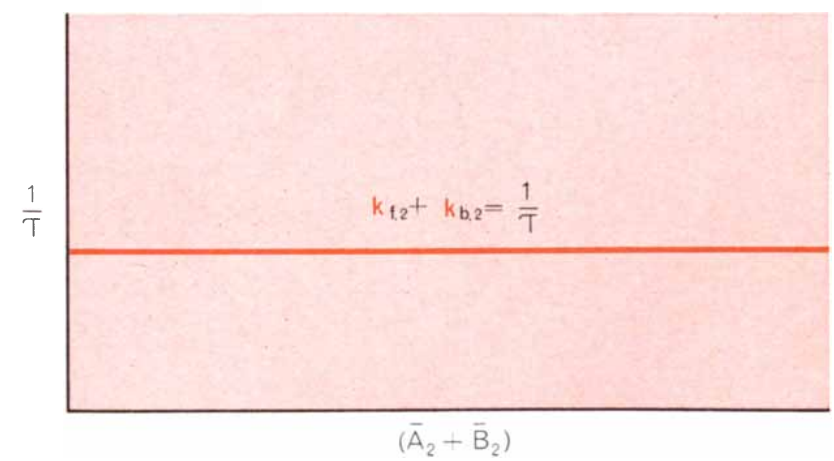


MECHANISM OF REACTION can be clarified by measuring the relaxation time, τ. If the reaction is of the form $A + B \rightleftharpoons C$, $1/\tau$ equals the forward rate constant times the sum of the final equilibrium concentrations of A and B (designated $\bar{A}_2$ and $\bar{B}_2$) plus the backward rate constant. When $1/\tau$ is plotted against $\bar{A}_2 + \bar{B}_2$, the slope of the curve gives the forward rate constant ($k_{f,2}$) and the point of interception gives the backward rate constant ($k_{b,2}$).

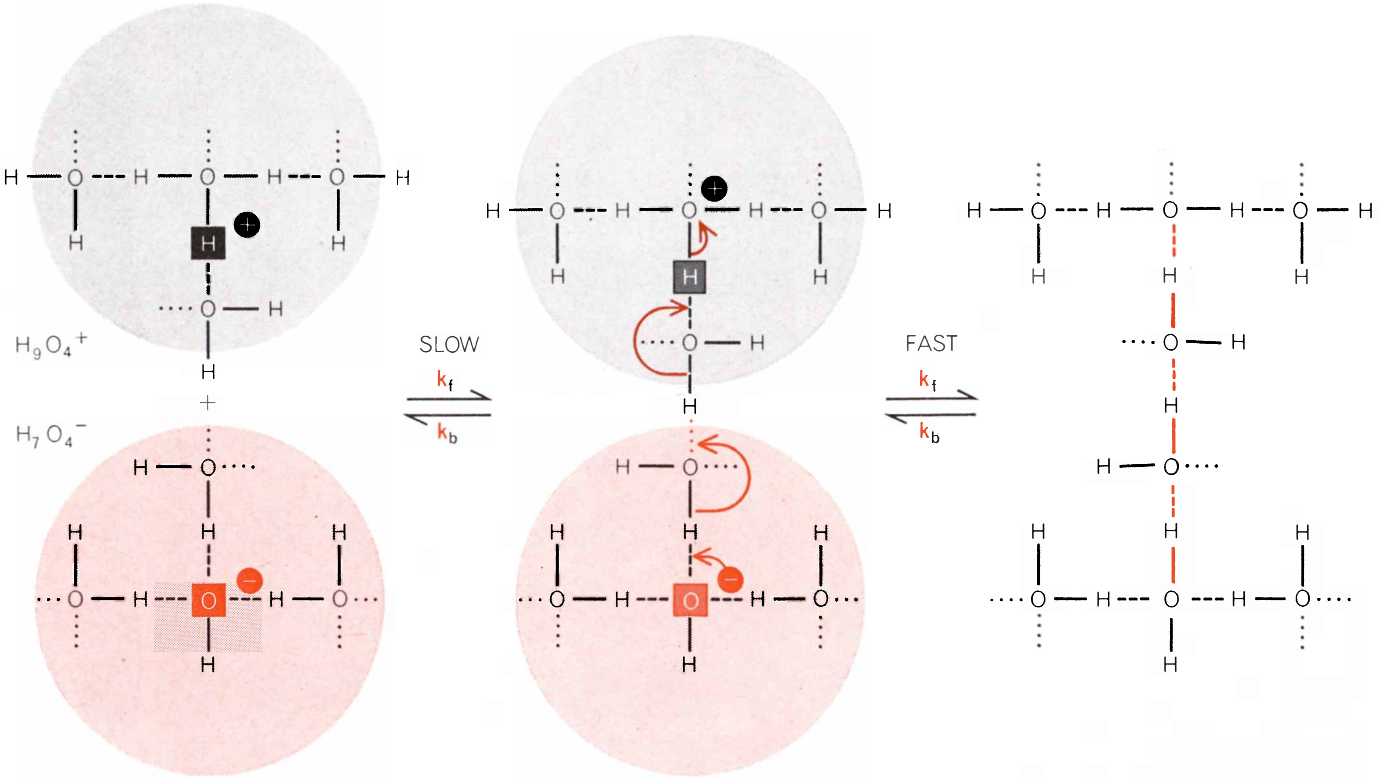
IF, HOWEVER, $A \underset{k_b}{\overset{k_f}{\rightleftharpoons}} C$

THEN, $\frac{1}{\tau} = k_{f,2} + k_{b,2}$

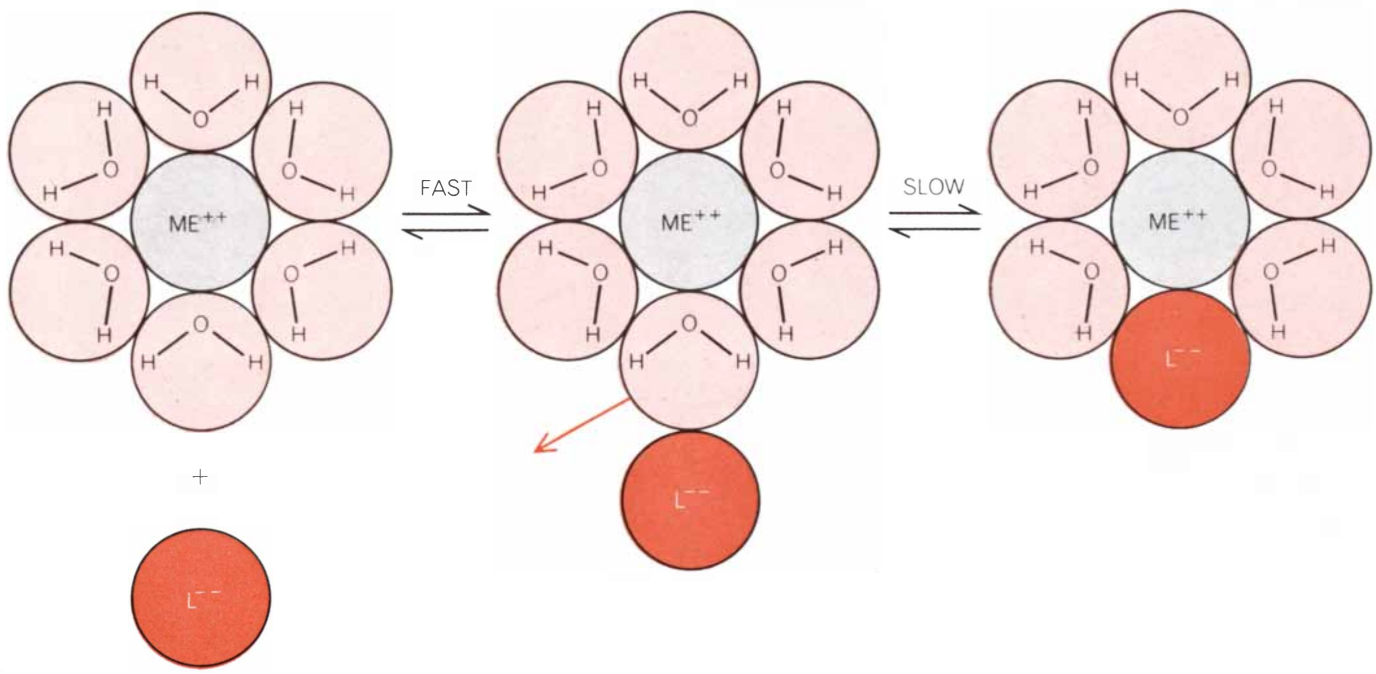
WHEN PLOTTED:



IF REACTION IS UNIMOLECULAR of the form $A \rightleftharpoons C$, it turns out that $1/\tau$ is independent of the concentrations of the reactants, so that the resulting curve is simply a horizontal line. In this case $1/\tau$ equals the sum of the forward and backward rate constants.



REACTION OF PROTONS AND HYDROXYL IONS in water can be thought of as taking place in two steps, the second much faster than the first. Relaxation experiments and other studies indicate that a proton (H^+) in water is normally hydrated, or surrounded, by four water molecules to form $H_9O_4^+$ and that the hydroxyl ion (OH^-) is hydrated by three water molecules to form $H_7O_4^-$ (*left*). When these complex ions collide, they neutralize each other and form uncharged water molecules. The neutralization actually takes place by a flow of negative charge density, which results in the flipping of weak hydrogen bonds and real bonds (*middle and right*). In the neutral structure that results, each oxygen is strongly bound to two hydrogen atoms and more weakly linked by hydrogen bonds (*broken lines*) to other water molecules. Dots on oxygen atoms represent the potential of forming other hydrogen bonds. This diagram represents in two dimensions structures that actually have three dimensions; thus the circles represent spheres.



FORMATION OF METAL COMPLEX can also be thought of as taking place in two steps, the first being faster than the second. In solution a metal ion (Me^{++}) is often hydrated by six water molecules. The ion with which it combines, called a ligand (L^{--}), is more loosely associated with water molecules (*not illustrated*). The metal ion and ligand come together swiftly (*middle*) but the step in which the ligand displaces a water molecule in the metal's inner hydration sphere takes place much more slowly (*right*).

ton transfer occurs rapidly along a hydrogen-bond bridge.

Metal complexes, for instance the combination of magnesium with sulfate ions, are not formed at a rate controlled by the rate of collision. Typically the rate constants for metal-complex formation are 10,000 to 100,000 times smaller than those for combination with protons. They are generally independent of the ligand but are correlated with the positive-charge density of the metal ion. The greater the ratio of positive charge to the size of the metal ion is, the more slowly the complex is formed. The explanation is that the metal ion and the ligand cannot penetrate each other's hydration spheres. Since the metal ion binds water more tightly, the rate is determined by the charge density of the metal ion. Before a metal-ion complex can form, a water molecule must dissociate out of the metal's inner hydration sphere [*see bottom illustration on opposite page*].

In addition to proton transfer and metal-complex formation, other elementary reactions have been studied by relaxation methods. The rates of electron transfer, of structural rearrangements and of association reactions have all been successfully measured. The use of relaxation methods to investigate processes involving a series of elementary steps is illustrated by the study of enzyme reactions.

Among the most challenging problems in biochemistry is the detailed explanation of the functioning of enzymes. It has been known for more than a century that enzymes are nature's catalysts. In their absence the myriad chemical reactions in living cells would proceed much too slowly to sustain life. In the past decade it has become clear that some enzymes also function as control units in metabolic pathways, accelerating or decelerating selected regulatory steps, depending on the abundance or deficiency of key metabolites.

Most of the enzymes involved in metabolism have now been identified, isolated and purified. The amino acid sequences of a dozen enzymes are now known. In the past four years the three-dimensional structures of five enzymes have been worked out by X-ray crystallographers. Early this year researchers at the Merck, Sharp & Dohme Research Laboratories and Rockefeller University independently completed the first chemical synthesis of an enzyme (ribonuclease) from its constituent amino acids.

The understanding of how an enzyme functions has proved to be more elusive. Detailed knowledge of the enzyme's structure is an essential first step. In fact, the X-ray analysis of the enzyme lysozyme has given a remarkably clear picture of how the enzyme binds itself to a simple molecule that mimics the structure of the cell wall of a bacterium, and clarifies the mechanism by which lysozyme catalyzes the wall's dissolution. Complete understanding of enzyme function, however, is ultimately a problem in kinetics. The role of enzymes is to regulate the speed of chemical reactions. A complete description of their functioning must therefore include both an identification of the reaction intermediates and an evaluation of the rate constants for the elementary steps in the reaction pathway. So far only three enzymes have been examined in detail by relaxation methods, but it is already apparent that such studies will play an important role in elucidating the detailed mechanisms of enzyme action.

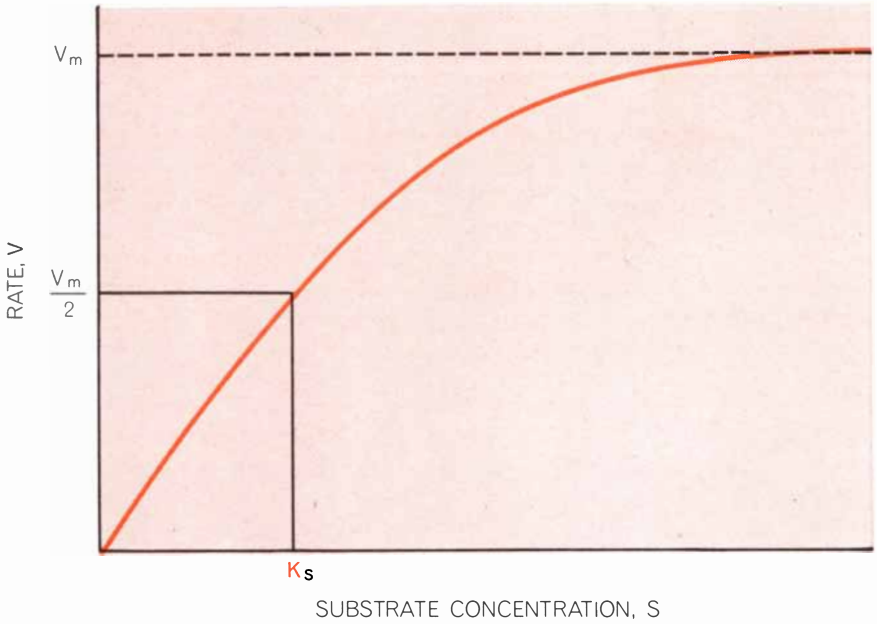
In order to appreciate the power of relaxation methods for studying enzymatic catalysis, it is helpful to understand the limitations inherent in earlier methods. In 1913, 13 years before enzymes were shown to be proteins, Leonor Michaelis and Maud L. Menten explained why the rate of enzyme reactions does not increase indefinitely in linear fashion with substrate concentration but levels off at some maximum rate [*see top illustration on next page*]. They proposed that an enzyme-substrate intermediate is formed and that it may dissociate either before or after conversion of substrate to product. Since the former is usually much more likely, free enzyme and substrate are virtually in equilibrium with the intermediate complex. The rate of product formation is proportional to the concentration of enzyme-substrate intermediate. As the substrate concentration is increased the concentration of intermediate complex approaches the total enzyme concentration and the rate approaches a maximum value. At substrate concentrations insufficient to saturate the enzyme the rate is the maximum rate times the fraction of the enzyme complexed with substrate.

The difficulty with the Michaelis-Menten formulation of enzyme catalysis is that it postulates three rate constants (k_1, k_{-1} and k_2) but supplies explicit values for only one of them (k_2). The first constant, k_1, determines the rate of formation of the enzyme-intermediate complex. The second, k_{-1}, determines the rate of dissociation of the complex. The third, k_2, determines the rate at which product is formed from the complex. As shown in the top illustration on the next page, two constants appear in the derived rate expression: the maximum rate, V_m, and the Michaelis constant K_s. After obtaining V_m one can calculate k_2 from a knowledge of the total enzyme concentration (E_0). Called the catalytic rate constant, k_2 is a measure of the number of substrate molecules that an enzyme molecule can convert to product per unit of time. The Michaelis constant (K_s) is a measure of the fraction of enzyme complexed with substrate. It is equal to the substrate concentration required to reach half the maximum rate, or $V_m/2$. The Michaelis constant is a ratio of two rate constants: k_{-1} divided by k_1. Their individual values cannot be extracted in this approach.

The problem is that information is thrown away in the derivation of the rate equation. The enzyme and the substrate are not in equilibrium with the enzyme-substrate intermediate, nor is the intermediate complex in a stationary state throughout the course of the reaction. The derivation of the rate expression without simplifying assumptions requires the solution of a second-order differential equation. The resulting rate expression includes a transient term that corresponds to the buildup of a stationary concentration of the enzyme-substrate intermediate and provides the additional information needed to evaluate the individual rate constants. Generally the transient decays too rapidly to be measured by the older kinetic methods, but even if it could be evaluated, the problem is more complex.

The simple Michaelis-Menten mechanism is chemically unrealistic. It is clear on the basis of many kinds of studies that several functional groups in the enzyme must cooperate in catalyzing the chemical transformation of substrate into product. Any realistic mechanism for enzymatic catalysis must therefore include several identifiable intermediates. It does no good simply to rewrite the Michaelis-Menten equations to provide for an extra intermediate (or more than one), because V_m and K_s then are expressed as ratios of five (or more) different rate constants [*see bottom illustration on next page*]. The physical meaning of V_m and K_s is thus quite obscure.

The solution to this dilemma is to measure directly the rate of formation and disappearance of the reaction intermediates. Such measurements were seldom possible before the advent of re-



$$E + S \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} ES$$

ENZYME SUBSTRATE ENZYME-SUBSTRATE COMPLEX

$$ES \xrightarrow{k_2} E + P \text{ (PRODUCT)}$$

$$\text{MAXIMUM RATE } V_m = k_2 E_0$$

$$\text{EQUILIBRIUM CONSTANT } K_s = \frac{k_{-1}}{k_1} = \frac{E \cdot S}{ES}$$

REACTION RATES OF ENZYMES were studied as early as 1913 by Leonor Michaelis and Maud L. Menten. They proposed that an enzyme and its substrate are in virtual equilibrium with an enzyme-substrate complex and that the complex breaks down, in turn, to release the enzyme and the product. The maximum rate of reaction, V_m, depends on the catalytic rate constant (k_2) and the total enzyme concentration (E_0). V_m is reached when the enzyme is saturated with substrate. The equilibrium, or Michaelis, constant (K_s) is equal to the substrate concentration needed to reach half the maximum rate, or $V_m/2$. Constant K_s is a ratio of the backward rate constant (k_{-1}) and forward rate constant (k_1).

$$E + S \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} ES \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} EP \xrightarrow{k_3} E + P$$

ENZYME SUBSTRATE ENZYME-SUBSTRATE COMPLEX ENZYME-PRODUCT COMPLEX ENZYME PRODUCT

$$V'_m = \frac{k_2 \cdot k_3}{k_2 + k_{-2}}$$

$$K'_s = \frac{k_{-1} \cdot k_{-2}}{k_1(k_2 + k_{-2})}$$

ACTUAL ENZYME REACTIONS are more complicated than visualized by Michaelis and Menten. If another intermediate is included in the Michaelis-Menten scheme, V'_m and K'_s can still be determined by experiment, but five different rate constants now appear. V'_m and K'_s provide only ratios of various constants whose individual values remain unknown.

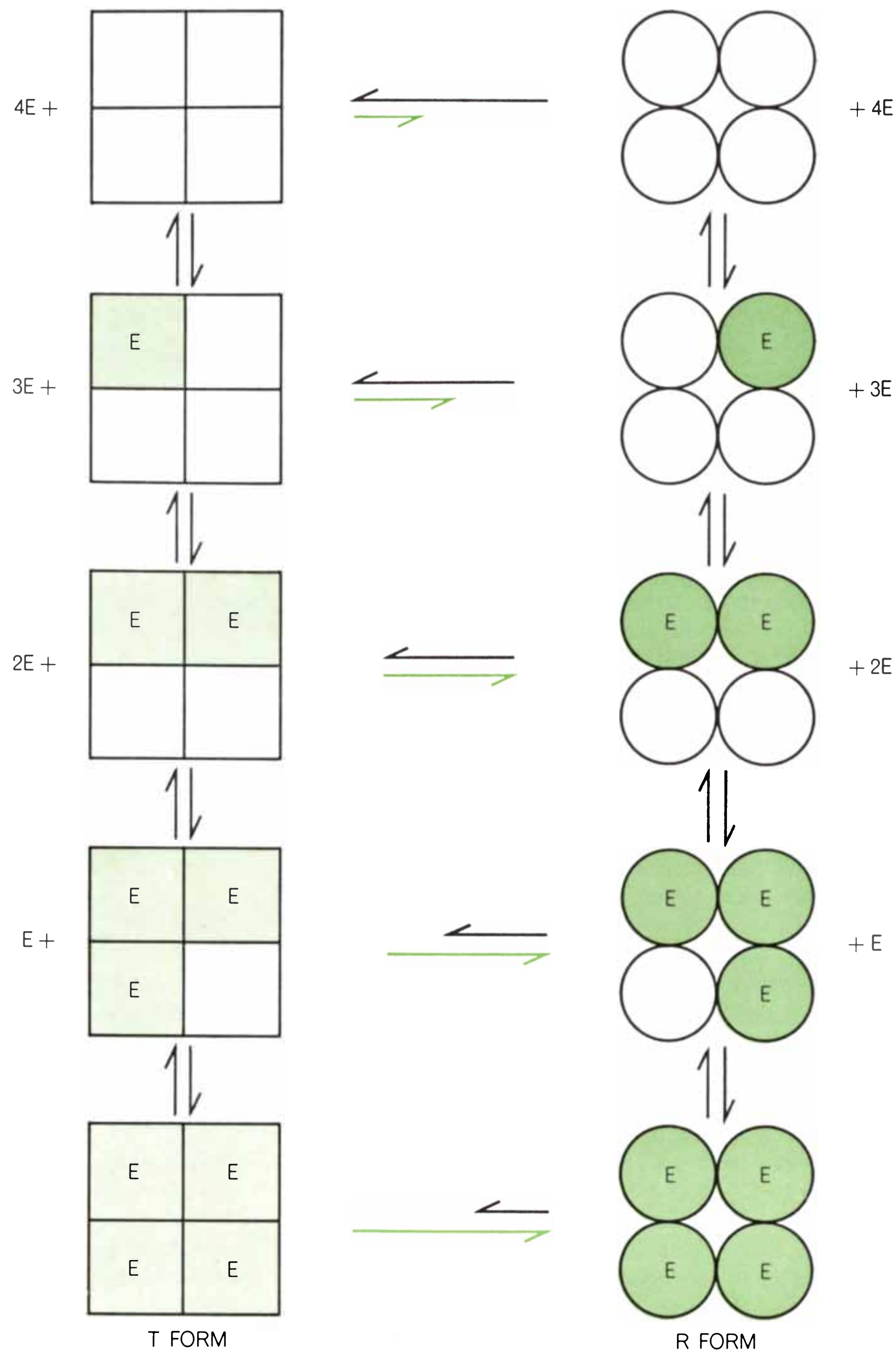
laxation methods. A single enzyme molecule can typically convert 1,000 substrate molecules to product per second. If enough enzyme were used to produce a detectable reaction, the reaction would be over before it could be measured by earlier methods. Relaxation methods now make such high-speed reactions accessible to study. The successful use of relaxation methods to explore the individual steps in an enzyme reaction is nicely illustrated by the study of the enzyme D-glyceraldehyde-3-phosphate dehydrogenase (GAPDH), which catalyzes the phosphorylation of D-glyceraldehyde-3-phosphate to form D-1,3-diphosphoglycerate, one step in the metabolism of sugars.

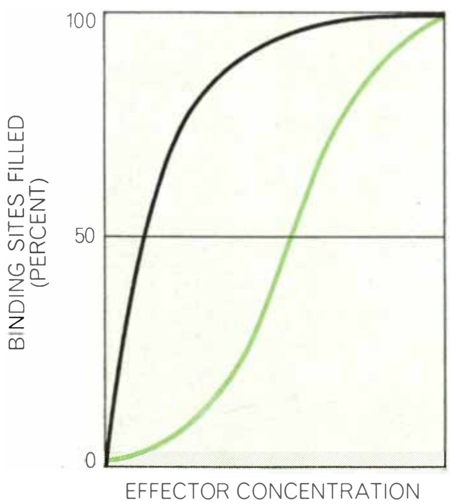
Kasper Kirschner of the Max Planck Institute in Göttingen has used the temperature-jump method to study how GAPDH is bound to the coenzyme, or cocatalyst, nicotinamide adenine dinucleotide (NAD^+). Each enzyme molecule consists of four subunits, and on each subunit is a catalytic site. The binding of the coenzyme to the enzyme is cooperative, that is, the coenzyme is bound more readily at high concentrations than it is at low ones. Since NAD^+ binds cooperatively, its availability can regulate the rate at which glyceraldehyde-3-phosphate is phosphorylated. When little NAD^+ is available, the phosphorylation goes slowly. When NAD^+ reaches a critical concentration, the reaction rate sharply increases. The coenzyme functions rather like an on-off switch.

Jacques Monod, Jeffries Wyman and Jean-Pierre Changeux of the Pasteur Institute in Paris have suggested a mechanism to explain cooperative binding. Because the structure of such a coenzyme, or other effector molecule, that binds cooperatively to the enzyme is distinctly different from that of the substrate, they call their proposal the allosteric model. ("Allo" is the Greek combining form for "other.") In the allosteric model a multiunit enzyme, *T*, is assumed to be in equilibrium with another form of the enzyme, *R*, which has a different three-dimensional structure [*see illustration on opposite page*]. Subunits in the *R* form are assumed to bind effector molecules more readily than the *T* form, but the *T* form is assumed to predominate when no effector molecules are bound. Now if the *R* form of the fully bound enzyme is favored, binding will be cooperative. At low effector concentrations most of the enzyme is present in the *T* form. The *T* form has little affinity for effector, so that most of it remains unbound. As the concentration of effector is increased, more of it is bound, and the equilibrium between *R* and *T* shifts toward *R*. At some point *R* predominates. Since *R* binds effector tightly, effector molecules rapidly saturate the enzyme binding sites. The binding process resembles a zipper. Getting it started is difficult, but once started it proceeds rapidly.

The allosteric model predicts as many as nine relaxation times for the binding of an effector to an enzyme of four subunits. Happily Kirschner found that there were only three readily separable relaxation times for the binding of NAD^+ to GAPDH. The two faster relaxation times correspond to two-molecule processes. The reciprocal of the fastest relaxation time depends linearly on the sum of the concentration of coenzyme and the concentration of free binding sites on the *R* form of the enzyme that binds NAD^+ more tightly. The other two-molecule process depends on the concentrations of NAD^+ and unoccupied *T* binding sites. Since only two bimolecular relaxation processes were observed, it could be concluded that the binding of effector to either the *R* or the *T* form of the enzyme is independent of the number of effector molecules already bound. The third relaxation time does not depend on enzyme concentration. It can therefore be associated with the conformational change between *T* and *R*. It does depend on the total concentration of NAD^+, reflecting the shift in the equilibrium between *T* and *R* with effector concentration, which one would expect if the binding is cooperative. Using the experimentally determined rate constants for the combination of effector with each conformation of the enzyme, and the rate constants for the interconversion of the two forms, Kirschner was able to construct an S-shaped binding curve that was in good agreement with the curve found experimentally.

The fact that the binding of NAD^+ to GAPDH can be described by the allosteric model does not mean that all regulatory enzymes conform to this model. It does, however, dramatically illustrate the potential importance of chemical relaxation studies to an understanding of enzyme function. The study of enzyme reactions by relaxation methods is in its infancy. Although the difficulties are formidable, such investigations promise to yield a deeper understanding of enzyme reactions and other complex biochemical processes.





ENZYME MODEL depicts an enzyme with four subunits that responds to an effector molecule (*E*) in addition to its normal substrate. Such an effector is said to be allosteric. The enzyme can exist in two configurations: *T* form and *R* form. All four subunits are assumed to change shape together. The *R* form binds effector molecules more tightly than the *T* form does. When no effector molecules are bound, the *T* form is favored. As more and more effector molecules are bound, however, the equilibrium shifts to favor the saturated *R* form. This type of binding behavior is described as cooperative and is characterized by an *S*-shaped binding curve (*colored curve at left*). When the binding is noncooperative, the binding curve is hyperbolic (*black curve*).

A Paleolithic Camp at Nice

Construction work on the French Riviera has uncovered the remains of man's earliest-known construction work: huts put up by hunters who visited the shore of the Mediterranean some 300,000 years ago

by Henry de Lumley

A Paleolithic site uncovered recently in the south of France contains traces of the earliest-known architecture: huts that were built some 300,000 years ago. The structures were evidently made by nomadic hunters who visited the Mediterranean shore briefly each year. They left behind artifacts and animal bones that, together with the plant pollen found at the site, yield a remarkably detailed picture of the occupants' activities during their annual sojourn by the sea. Because the discovery of the site and its excavation were unusual, I shall give a brief account of both before describing the new evidence the site provides concerning human life during this very early period of prehistory.

The city of Nice, in southeastern France, stands on a basement formation of limestone and marl. The bedrock is covered by layers of sand, clay and soil that mark the glacial oscillations of the ice age. During the construction of a shipyard some years ago certain glacial strata were exposed to view and attracted the attention of several scholars. In one sandy layer in 1959 Georges Iaworsky of the Monaco Museum of Prehistoric Anthropology found a few stone tools of typical Paleolithic workmanship. Two years later in another sandy section he found a tool of the early Paleolithic type known as Acheulean. Acheulean tools take their name from St. Acheul, a site in France where examples were first discovered, but since then Acheulean implements have been found at many other sites in Europe and in Asia and Africa. It had originally seemed that the sands had been deposited in the warm period between the glaciations called the Riss and the Würm, but Iaworsky pointed out that the age of the Acheulean tool indicated that these deposits were much older.

Then, in the course of foundation work during October, 1965, bulldozers cut a series of terraces into the sloping grounds of the Château de Rosemont, on the shoulder of Mont Boron in the eastern part of the city. The area of excavation, near the corner of Boulevard Carnot and an alley romantically named Terra Amata (beloved land), was scarcely 300 yards from Nice's commercial harbor and not far from the shipyard where Iaworsky and others, myself included, had studied the glacial strata. As the excavation proceeded the bulldozers exposed an extensive sandy deposit containing more Paleolithic implements. The significance of the discovery was quickly realized, and the builders agreed to halt operations temporarily. With the help of the French Ministry of Culture, a major archaeological salvage effort was mounted.

Starting on January 28, 1966, and continuing without interruption until July 5 more than 300 workers, including young students of archaeology from the universities and a number of enthusiastic amateurs, devoted a total of nearly 40,000 man-hours to the excavation of the Terra Amata site. The excavated area covered 144 square yards; in the course of investigating the 21 separate living floors found within the area the workers gradually removed a total of 270 cubic yards of fill, using no tools except trowels and brushes. The digging brought to light nearly 35,000 objects, and the location of each object was recorded on one or another of 1,200 charts. In addition, casts were made of 108 square yards of living floor and the progress of the work was documented in some 9,000 photographs.

In stratigraphic terms the deposits at Terra Amata begin at the surface with a layer of reddish clay that is nine feet thick in places and contains potsherds of the Roman period. Below the clay is a series of strata indicative of glacial advances during the Würm, Riss and Mindel periods and the warmer periods that intervened. The site embraces three fossil beaches, all belonging to the latter part of the Mindel glaciation. The youngest beach, marked by a dune and a sandbar, proved to be the site of human habitation.

When the youngest beach was deposited, the level of the Mediterranean was 85 feet higher than it is today. Soon after the beach was formed the sea level dropped somewhat, exposing the sandbar and allowing the wind to build a small dune inland. The hunters must have visited the area during or soon after a major period of erosion that occurred next. The evidence of their presence is found on or in the sands but not in the reddish-brown soil that later covered the eroded sand surface. Numerous shells of land snails, found at the base of the reddish soil, indicate a period of temperate climate.

The landscape of Terra Amata at the time of the hunters' visits differed in a number of respects from today's. The backdrop of the Alps, dominated by Mont Chauve, was much the same, but the sea covered most of the plain of Nice and even penetrated a short distance into what is now the valley of the Paillon River. The climate, though temperate, was somewhat brisker and more humid than the one we know. Pollen studies, undertaken by Jacques-Louis de Beaulieu of the pollen-analysis laboratory at the University of Aix-Marseilles, indicate that fir and Norway pine on the alpine heights grew farther down the slopes than is now the case, and that heather, sea pine, Aleppo pine and holm oak covered Mont Boron and its coastal neighbors.

In the limestone of Mont Boron's western slope the sea had cut a small cove opening to the south. Within the cove a sandy, pebble-strewn beach extended down to the sea, sheltered from the north and east winds. A small spring to one side provided a source of fresh water. A few seashore plants—grasses, horsetails, short-stemmed plantain and various shrubs—grew in the cove. The stream from the spring held water lilies of the genus *Euryale*, which, as De Beaulieu notes, can be found only in Asia today. All things considered, it appears that nothing was lacking even 300 millenniums ago to make Terra Amata a beloved land.

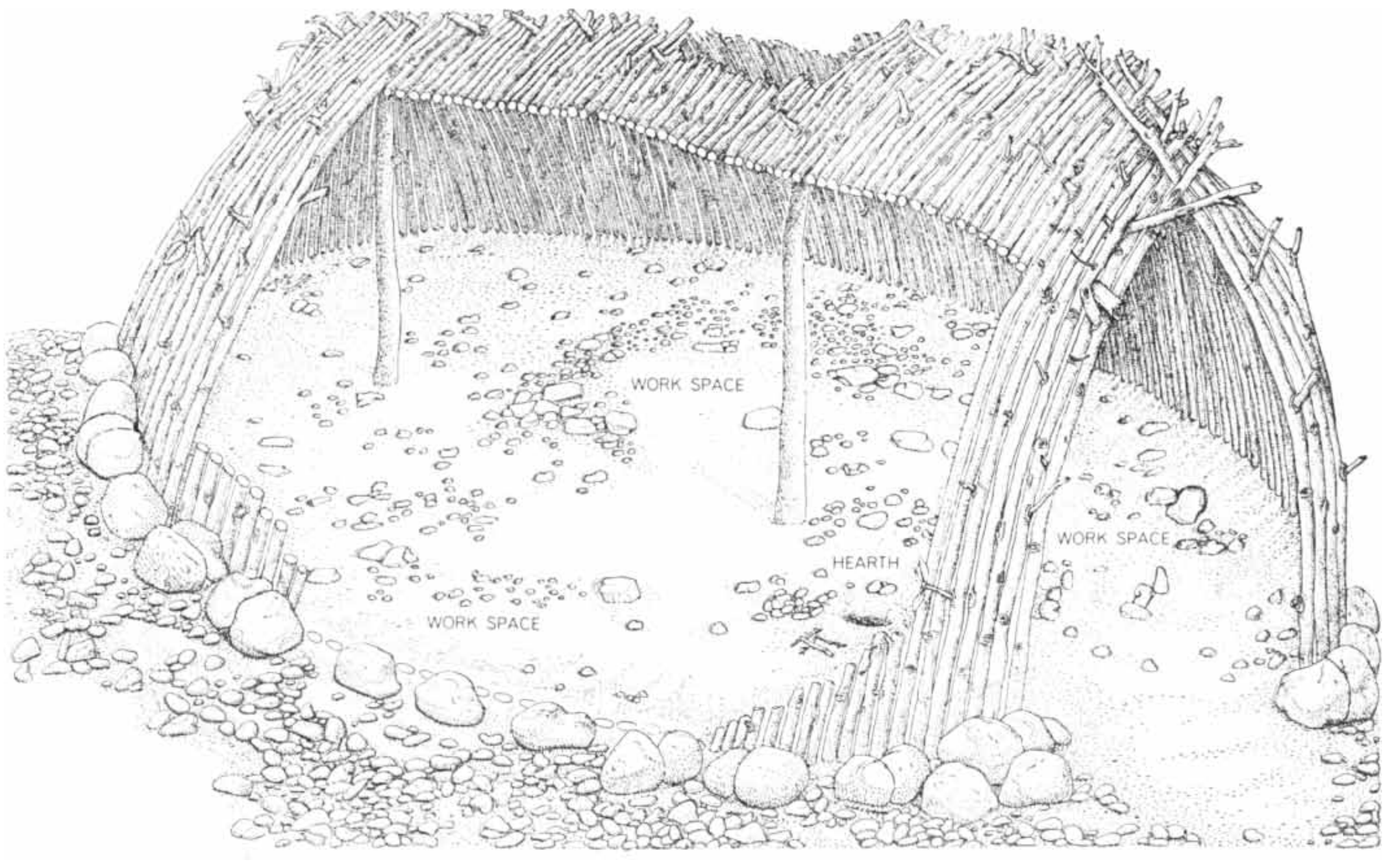
The superimposed living floors at Terra Amata are located in three separate areas. Four are on the section of beach that had formed the sandbar until the sea level dropped; six are on the beach seaward of the bar, and 11 are on the dune inland. The huts that were built on the living floors all had the same shape: an elongated oval. They ranged from 26 to 49 feet in length and from 13 to nearly 20 feet in width. Their outline can be traced with two kinds of evidence. The first is the imprint of a series of stakes, averaging some three inches in diameter, that were driven into the sand to form the walls of the hut. The second is a line of stones, paralleling the stake imprints, that apparently served to brace the walls. One of the earliest of the huts is perfectly outlined by an oval of stones, some as much as a foot in diameter and some even stacked one on the other. The living floor within the oval consisted of a thick bed of organic matter and ash.

The palisade of stakes that formed the walls was not the huts' only structural element. There are also visible the imprints left by a number of stout posts, each about a foot in diameter. These supports were set in place down the long axis of the hut. Evidence of how the palisade and the center posts were integrated to form the roof of the hut has not survived.

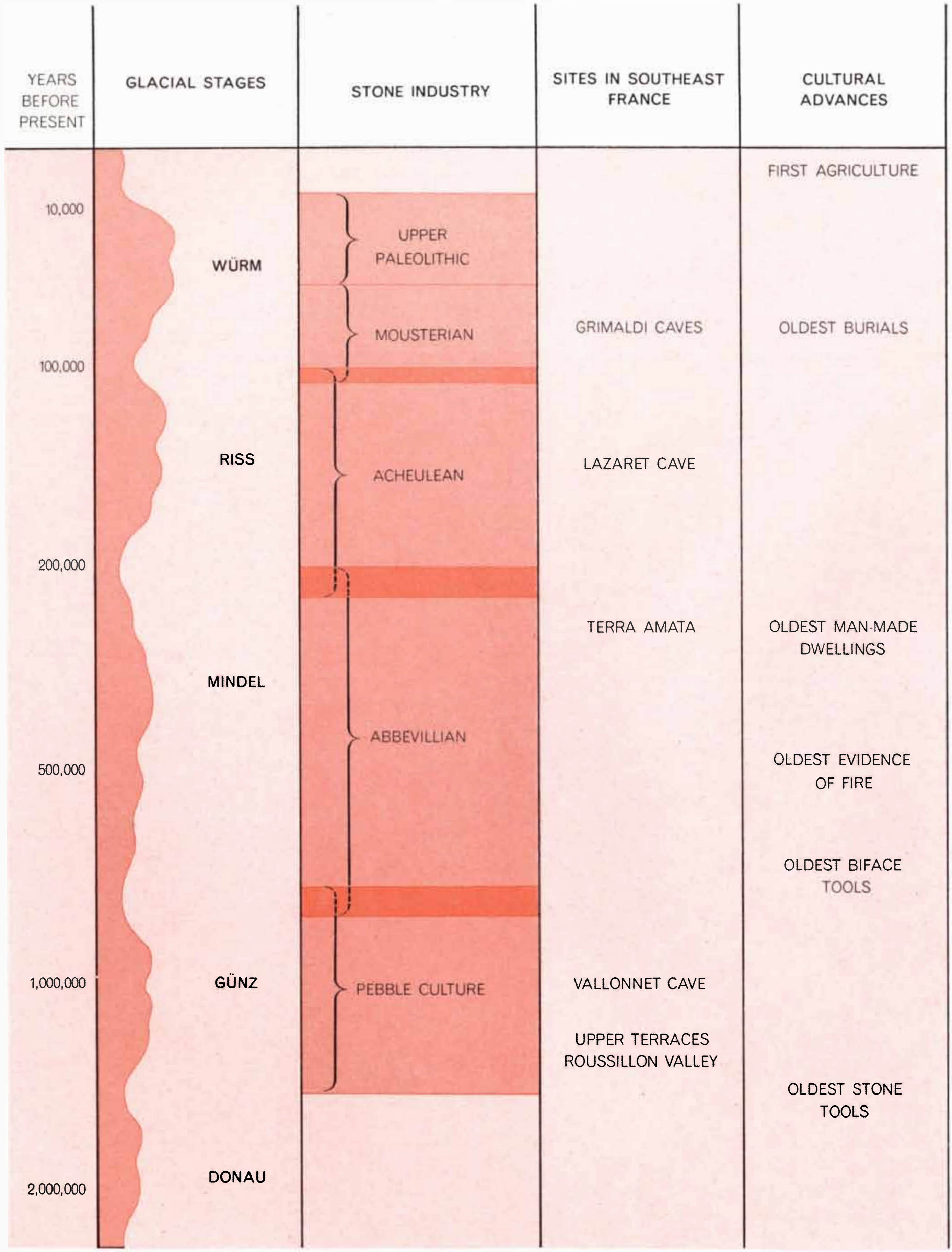
A basic feature of each hut is a hearth placed at the center. These fireplaces are either pebble-paved surface areas or shallow pits, a foot or two in diameter, scooped out of the sand. A little wall, made by piling up cobbles or pebbles, stands at the northwest side of each hearth. These walls were evidently windscreens to protect the fire against drafts, particularly from the northwest wind that is the prevailing one at Nice to this day.

The fact that the hunters built windscreens for their hearths makes it clear that their huts were not draft-free. This suggests that many of the palisade stakes may have been no more than leafy branches. Certainly nothing more permanent was required. As we shall see, the huts were occupied very briefly. As we shall also see, the time of the annual visit can be narrowed down to the end of spring and the beginning of summer, a season when such a building material would have been readily available.

In the huts on the dune the hearths were apparently designed for small fires. If one can judge from the larger amounts of charcoal and ash, the hearths in the huts closer to the sea must have accommodated much bigger fires. It is worth noting that the hearths at Terra Amata, together with those at one other site in Europe, are the oldest yet discovered anywhere in the world. The hearths that



OVAL HUTS, ranging from 26 to 49 feet in length and from 13 to 20 feet in width, were built at Terra Amata by visiting hunters. A reconstruction shows that the hut walls were made of stakes, about three inches in diameter, set as a palisade in the sand and braced on the outside by a ring of stones. Some larger posts were set up along the huts' long axes, but how these and the walls were joined to make roofs is unknown; the form shown is conjectural. The huts' hearths were protected from drafts by a small pebble windscreen.



CHRONOLOGICAL POSITION of Terra Amata in prehistory is indicated on this chart, which shows (*left to right*) the time, given in thousands of years before the present, of the major glacial advances and retreats in Europe, the successive stone industries of the Paleolithic period, sites in southeastern France where the industries have been found and early man's progress in technology.

equal them in age were found by László Vértes in strata of Mindel age at Vértesszölös in Hungary. Like some of the hearths at Terra Amata, those at the Hungarian site are shallow pits a foot or two in diameter.

Also from Vértesszölös comes a significant early human fossil: the occipital bone of a skull that has been assigned to modern man. No such human remains were found in our excavation at Terra Amata, but we came on two indirect sources of information about the site's inhabitants. One is the imprint of a right foot, 9½ inches long, preserved in the sand of the dune. Calculating a human being's height from the length of the foot is an uncertain procedure. If, however, one uses the formula applied to Neanderthal footprints found in the grotto of Toirano in Italy, the individual whose footprint was found at Terra Amata may have been five feet one inch tall.

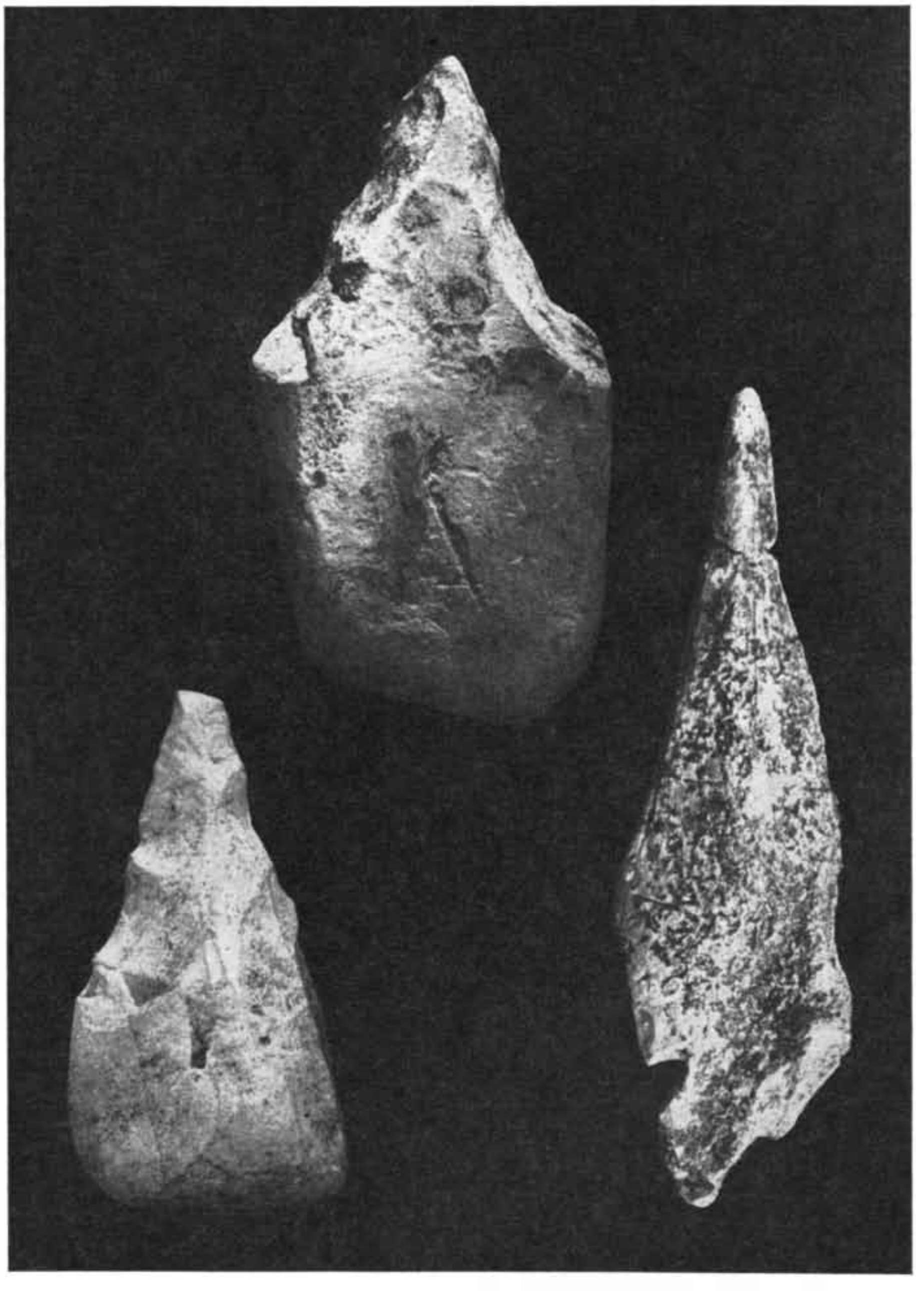
Our other indirect source of information consists of fossilized human feces found in the vicinity of the huts. De Beaulieu's analysis of their pollen content shows that all of it comes from plants, such as *Genista,* that shed their pollen at the end of spring or the beginning of summer. This is the finding that enables us to state the precise time of year when the hunters came to Terra Amata.

How did the visitors occupy themselves during their stay? The evidence shows that they gathered a little seafood, manufactured stone tools and hunted in the nearby countryside. The animal bones unearthed at Terra Amata include the remains of birds, turtles and at least eight species of mammals. Although the visitors did not ignore small game such as rabbits and rodents, the majority of the bones represent larger animals. They are, in order of their abundance, the stag *Cervus elaphus,* the extinct elephant *Elephas meridionalis,* the wild boar (*Sus scrofa*), the ibex (*Capra ibex*), Merk's rhinoceros (*Dicerothinus merki*) and finally the wild ox *Bos primigenius.* Although the hunters showed a preference for big game, they generally selected as prey not the adults but the young of each species, doubtless because they were easier to bring down.

The visitors did not systematically exploit the food resources available in the Mediterranean. Nevertheless, they were not entirely ignorant of seafood. A few shells of oysters, mussels and limpets at the site show that they gathered shellfish; fishbones and fish vertebrae indicate that on occasion the hunters also fished.

The large majority of all the artifacts found at Terra Amata are stone tools. They represent two different but closely related stone industries. Both appear to be contemporary with the earliest "biface" industries of the Paleolithic period (so named because many of the tools are made out of stone "cores" that are shaped by chipping flakes from both faces rather than from one face only). They bear certain resemblances to the tools of an early Paleolithic biface industry named the Abbevillian (after the site in France where they were first discovered) and to the Acheulean biface industry, which is somewhat more advanced. On balance, both Terra Amata industries should probably be characterized as early Acheulean.

The more primitive of the two Terra Amata industries is represented by the tools found in the huts closest to the sea. Mainly pebble tools, they include many pieces of the type designated choppers, a few of the type called chopping tools and some crude bifaces made by detaching flakes from one end of an oval cobble but leaving a smooth, unflaked "heel" at the other end. Among the other tools found in the seaside huts are cleavers, scrapers, projectile points of a kind known in France as *pointes de Tayac*



REPRESENTATIVE TOOLS unearthed at Terra Amata include a pebble (*middle*) that has been flaked on one of its faces to form a pick, another stone tool (*left*), flaked on both faces but with one end left smooth, and a bone fragment (*right*) pointed to make an awl.

FLOOR OF A HUT at Terra Amata is one of several brought to light by the excavators, revealing the ancient debris left behind by the occupants. The whole pebbles are raw material for tools; the chips and flakes, toolmakers' waste. The antler is from a stag.

and pebble tools flaked on one face only.

The stone industry represented by the tools found in the huts on the dune is more advanced, although it too includes choppers, chopping tools and cobble bifaces with a smooth heel. There are no single-faced pebble tools or cleavers on the dune, however, and tools made from flakes rather than from cores are relatively numerous. The tools made from flakes include those designated scrapers with abrupt retouch, end scrapers with toothed edges and flakes of the kind named Clactonian (after the English site Clacton-on-Sea). Some of the Clactonian flakes have been notched on one edge; others have been made into perforators by chipping out two notches side by side so that a point of stone protrudes. Projectile points from the dunes include, in addition to *pointes de Tayac,* some that are triangular in cross section and others of a kind known in France as *pointes de Quinson.*

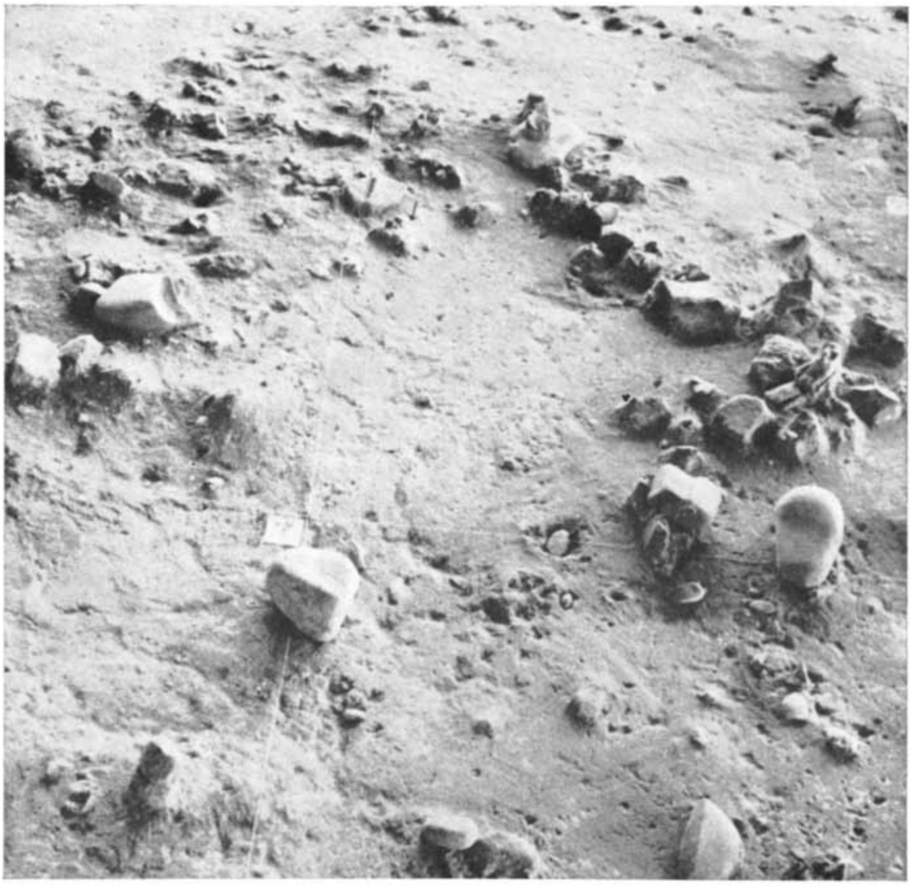
Some of the tools found at Terra Amata were probably made on the spot. The hut floors show evidence of tool manufacturing, and the toolmaker needed only to walk along the beach to find workable pebbles and cobbles of flint, quartzite, limestone and other rock. The toolmaker's place inside the huts is easily recognized: a patch of living floor is surrounded by the litter of tool manufacture. The bare patches are where the toolmakers sat, sometimes on animal skins that have left a recognizable impression.

Not all the stone debris represents the waste from finished work. In one instance the excavators found a cobble from which a single chip had been struck. Nearby was a chip that fitted the scar perfectly. In another toolmaker's atelier several flakes had been removed from a cobble by a series of successive blows. Both the core and the flakes were found, and it was possible for us to reassemble the cobble. Scarcely a flake was missing; evidently the toolmaker did not put either the core or the flakes to use.

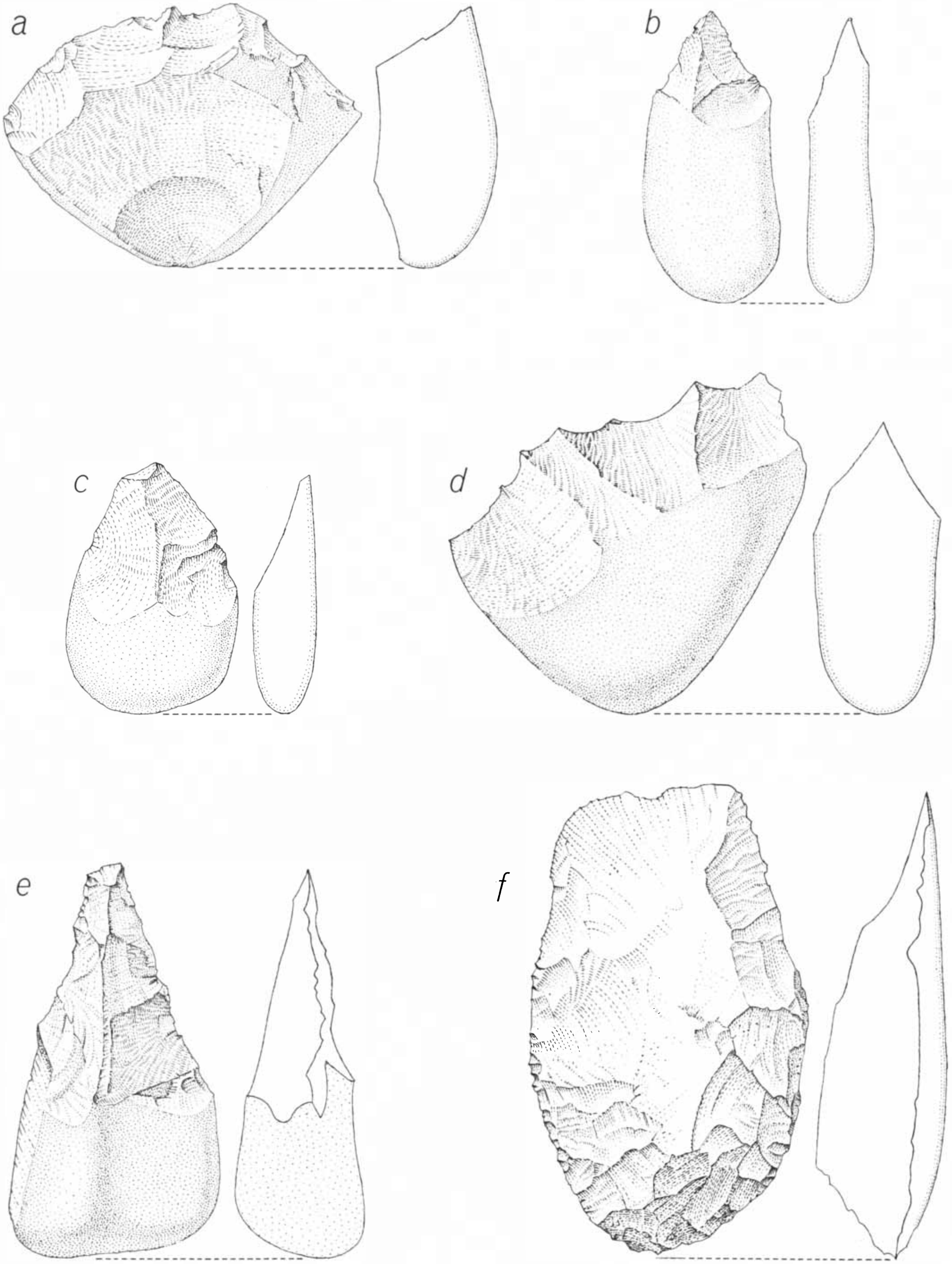
At least one of the projectile points unearthed at Terra Amata could not have been produced locally. The stone from which it is made is a volcanic rock of a kind found only in the area of Estérel, southwest of Cannes and some 30 miles from Nice. This discovery allows us to conclude that these summer visitors' travels covered at least that much territory in the south of France, although we cannot be sure how much more widely they may have roamed.

A few tools made of bone have been

FIRE PIT (*right*) was protected from drafts and from the prevailing northwest wind in particular by a windscreen built of cobbles and pebbles, seen partially preserved at left.



TOOLMAKER'S ATELIER occupies one section of a hut. It is easily identified by the debris of tool manufacture that surrounds the bare patch of floor where the toolmaker sat.



GROUP OF PRIMITIVE TOOLS was found in association with the huts closest to the sea at Terra Amata. They include choppers (*a*) and picks (*b, c*), made from pebbles that are flaked on one face only; chopping tools (*d*) that are flaked on both faces; crude bifaces (*e*), made by detaching flakes from one end of a cobble but leaving an unflaked "heel" at the opposite end; cleavers (*f*), and two other kinds of stone artifacts (*illustrated on opposite page*): scrapers and projectile points of a kind known as *pointes de Tayac.*

found at Terra Amata. One leg bone of an elephant has a hammered point at one end. Another bone has a point that was probably hardened in a fire (a technique used today by some primitive peoples to harden the tips of wooden spears). A third bone fragment has one end smoothed by wear; still another may have served as an awl, and some fragments of bone may have been used as scrapers.

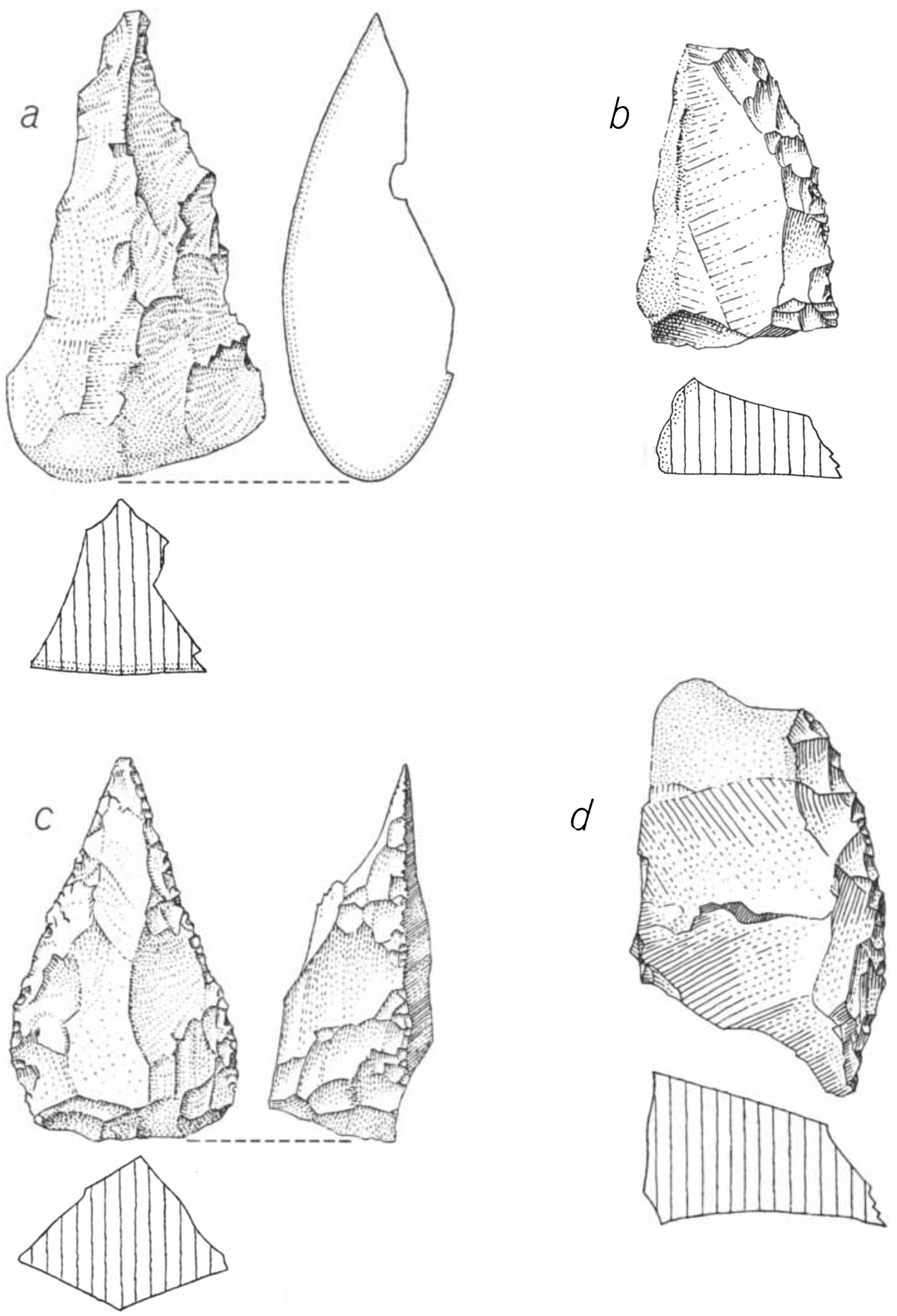
As for other kinds of artifacts, there are traces of only two. On the dune a spherical imprint in the sand, filled with a whitish substance, may be the impression left by a wooden bowl. Some pieces of red ocher found at the site obviously belonged to the visitors: the ends are worn smooth by wear. They recall the red ocher found at sites belonging to the much later Mousterian period, which François Bordes of the University of Bordeaux suggests were used for body-painting.

Let us see if the pattern of the hunters' annual visits to Terra Amata can be reconstructed. We know from the pollen evidence that they arrived in the late spring or early summer, and we can assume that they chose the sheltered cove as their camping ground as much because of its supply of fresh water as for any other reason. On arrival they set up their huts, built their hearths and windscreens, hunted for a day or two, gathered some seafood, rested by their fires, made a few tools and then departed. How do we know that their stay was so short? First, the living floors show no sign of the compaction that would characterize a longer occupation. Second, we have independent evidence that the huts collapsed soon after they were built. A freshly chipped stone tool that is left in the sun will quickly become bleached on the exposed side whereas the bottom side retains its original coloring. Many of the tools on the living floors at Terra Amata are bleached in this way. For the implements to be exposed to the full force of the Mediterranean summer sun the huts must have fallen apart soon after they were abandoned.

In the fall the winds covered the living floors, the leveled palisades and the rest of the camp debris with a layer of sand perhaps two inches deep. The rains then spread out the sand and packed it down, so that when the hunters returned to the cove the following year the evidence of their earlier stay had been almost obliterated. Only a few objects, such as the windscreens for the hearths, still protruded from the sand. The visitors then built new huts, often digging the hearth pit exactly where the preceding year's had been and rekindling their fires on the ashes of the previous season. After a day or two of hunting, gathering seafood and making tools the annual visit was ended. The 11 living floors on the dune at Terra Amata are so precisely superimposed that they almost certainly represent 11 consecutive yearly visits, probably involving many of the same individuals.

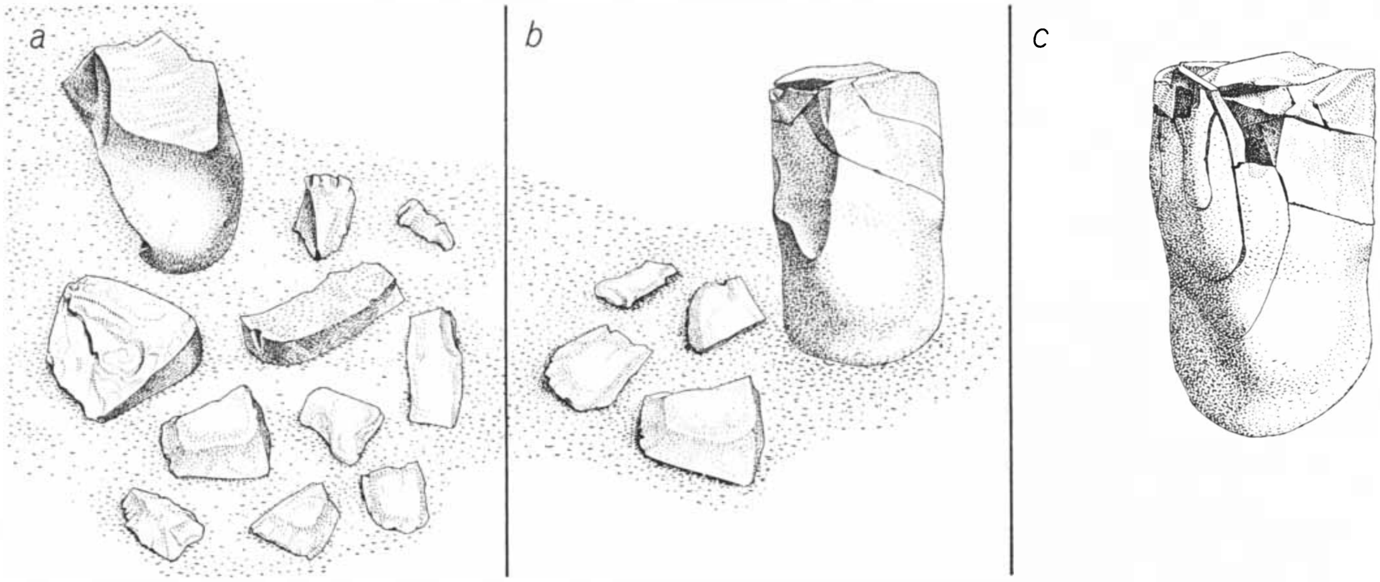
There is no older evidence of man-made structures than that at Terra Amata. Until this site was excavated the record for antiquity was held by the traces of construction discovered at Latamne, an open-air site in Syria, by J. Desmond Clark of the University of California at Berkeley. An early Acheulean site, Latamne is believed to be as old as the Mindel-Riss interglacial period. Terra Amata, which evidently was inhabited at the end of the Mindel glacial period, is therefore even earlier.

The evidence indicating that the hunt-

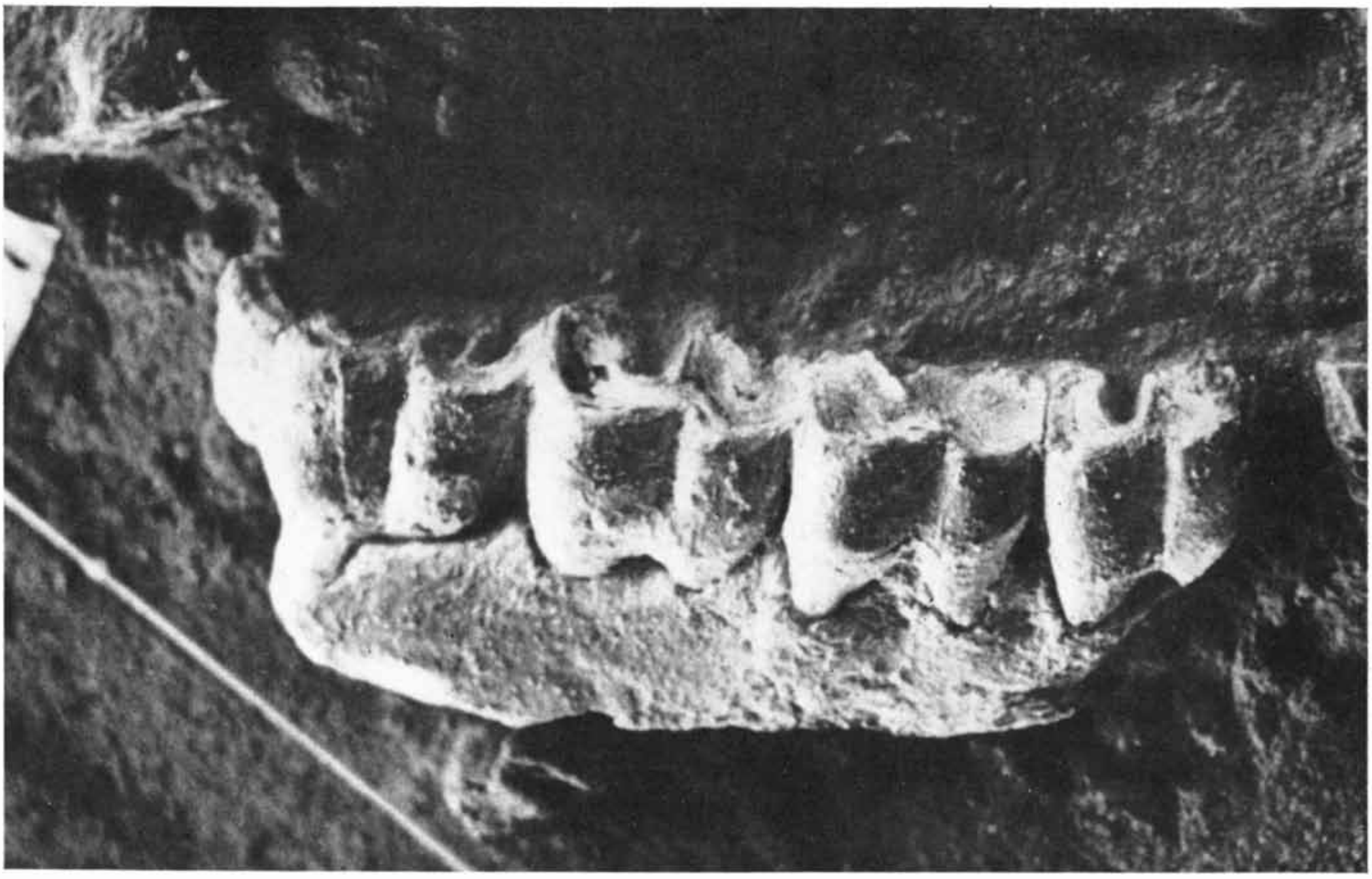


LESS PRIMITIVE TOOLS were found in the huts on the dune at Terra Amata. There were no cleavers or single-faced pebble tools and many more of the tools were made from flakes rather than from cores. Tools common to both areas are *pointes de Tayac* (*a*) and flakes made into simple scrapers (*b*), choppers, chopping tools and bifaces like those on the opposite page. Flakes were also made into projectile points (*c*) and more elaborate scrapers (*d*).

ers came to Terra Amata at about the same time year after year, together with the likelihood that the dune huts sheltered some of the same individuals for more than a decade, suggests that the visitors possessed stable and even complex social institutions. It is thus appropriate to conclude with the words of the French historian Camille Jullian, written soon after the Terra Amata living floors had been exposed. "The hearth," Jullian wrote, "is a place for gathering together around a fire that warms, that sheds light and gives comfort. The toolmaker's seat is where one man carefully pursues a work that is useful to many. The men here may well be nomadic hunters, but before the chase begins they need periods of preparation and afterward long moments of repose beside the hearth. The family, the tribe will arise from these customs, and I ask myself if they have not already been born."



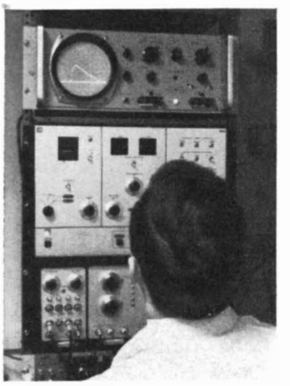
UNUTILIZED RAW MATERIAL was found in one Terra Amata toolmaker's atelier. Near the shattered half of a large cobble lay most of the fragments that had been struck from it (*a*). They could be reassembled (*b*) so that the cobble was almost whole again (*c*).



ANIMAL BONE, photographed *in situ* near one corner of an excavation unit, is a fragment of rhinoceros mandible, complete with teeth. The visitors preferred large mammals to other game. Along with rhinoceros they hunted stag, elephant, boar, ibex and wild ox.

In hope of doing each other some good

Anti-matter and industry



This is the back of the head of Joe Merrigan, candidate for the degree Master of Business Administration.

In another room where Dr. Merrigan hits the books toward his academic goal, a doctoral diploma in physical chemistry already adorns the wall. It is where he gazes at the shape of a distribution output from a multichannel analyzer that the link can be found between his seemingly divergent academic interests. Fortunately for us, *this* room we own. In all the domain of the world's manufacturing industries, few other rooms are known to be devoted to the connection between anti-matter and industrial prosperity.

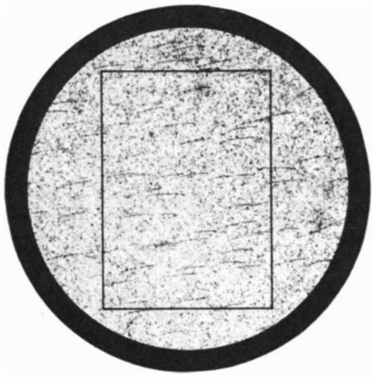
Anti-matter has taken 40 years to penetrate this far into what most men consider reality. First it appeared as a fantastically brilliant deduction knit from a skein of the thought of Einstein and Planck: that if negative energy states can have meaning, so can vacancies in these states. Vacancies are holes, but "holes" seem a shade realer. Soon their reality hardened from the merely conceptual to an actual discovery in cosmic ray showers, where they were called positrons.

After 16 more years, it was found that sometimes before a positron and electron cancel each other in a gamma ray flash they form a configuration that lasts a short time before annihilation. Actually, 140 nsec, the average lifetime in free space of one such configuration, is hardly very short today with the electronic black boxes now on the market. It's plenty of time for the positronium atom, as the configuration can be considered after its formation from positrons emitted by Na^{22}, to diffuse around before blowing up against another electron.

Therefore the scintillation-detector-fed multichannel analyzer, by holding a statistical stopwatch on the positronium between its beginning and its end, supplements and will perhaps surpass x-ray diffraction as an indicator of the degree of order in polymers or other solids. By indicating whether the electrons are tightly constrained or not, it can also be indicating progress when a lot of people are being paid to find polymers and crystals of commercial significance.

Though we sell no anti-matter, the Kodak Research Laboratories have assembled a bibliography on positrons and positronium. For a copy, write V. L. Simonetti, Mail Code 55, Eastman Kodak Company, Rochester, N.Y. 14650. Test question to warn those who cannot answer it against wasting postage: why is the reduced mass of positronium half the mass of the electron?

Nuclear structure and labor



This is a view through a microscope of deuteron tracks in the emulsion of a KODAK Nuclear Track Plate, Type NTB. Though the plate was purchased from a Kodak dealer for only \$4.15, the customer's \$3,000,000 accelerator worked 2 hours to put those tracks on it. They resulted from the reaction $W^{184}(He^3,d)Re^{185}$. Apparently a large financial commitment and a strong interest in the structure of the atomic nucleus had to precede that \$4.15 sale. One wonders of what use advertising this product can be. Here is an attempt to find a role for advertising in such a case.

You don't have to know much about what holds the rhenium nucleus together to look through that microscope in a useful way. All you need is for somebody to tell you what he wants to know about what you see there. You might not be terribly useful to him on the first plate or two, but by the time you have completed your third hour on your 200th plate, your eyes will be much better at it than his, even if your legs or some other parts of you happen to be absent or nonfunctional. Useful work brings home bacon, whether or not worker can walk out of house. Noting that our neighbors at the University of Rochester Nuclear Structure Research Laboratory send some of their plate-reading work out to the Rochester Rehabilitation Center for the handicapped, we have found an advertising idea to try:

Planning a scientific project that will generate a large volume of images to be measured or screened? Wondering where to find patient labor? Stop wondering and have a talk with the vocational director of your nearest rehabilitation center or your state rehabilitation agency.

If you can't find them or the talk gets nowhere, seek further guidance from the Rehabilitation Services Administration, Department of Health, Education, and Welfare, Washington, D.C. 20201.

Magic (for the practical-minded)

Obviously, cattle on the open range can be sexed by infrared photography. Many additional accomplishments in many other fields of endeavor, some more practical and some less, are mentioned and illustrated in "Applied IR Photography" (M-28, \$2) and "UV & Fluorescence Photography" (M-27, \$1). Lots of detail on *how* to do it. Reader already knows *what* he wants to do.

Send check with order to Eastman Kodak Company, Department 454, Rochester, N.Y. 14650.

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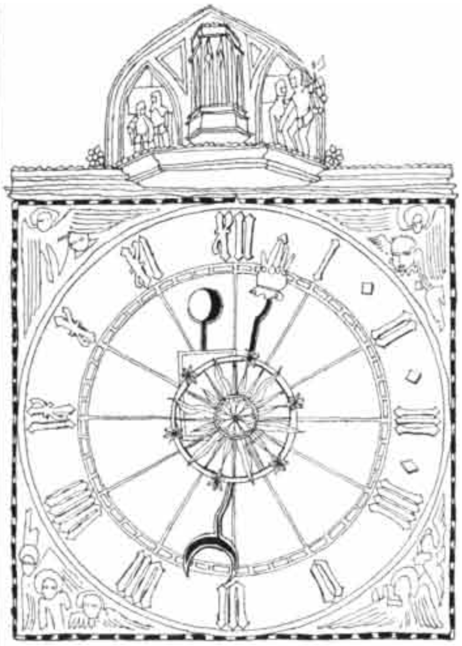

U-235 by Centrifuge

Britain, West Germany and the Netherlands have entered into a tentative agreement to build two plants that will produce enriched uranium by centrifugation. The centrifuge process for concentrating the fissionable uranium isotope U-235 was examined in the U.S. during World War II but was discarded in favor of three other processes: electromagnetic separation, thermal diffusion and gaseous diffusion. When the last proved by far the most efficient, the U.S. built two additional gaseous diffusion plants after the war and subsequently became the sole exporter of enriched uranium for use in nuclear power plants. For this purpose uranium usually contains some 2 to 3 percent U-235, compared with .7 percent in natural uranium. The three U.S. plants are estimated to have cost $2.5 billion. Their capacity is 17 million kilogram separative units of work per year (kg. s.u.w.). This unit is a measure of the difficulty of separating U-235 from U-238, which varies with the assay of the feed material; thus one kg. s.u.w. will produce one kilogram of material containing 1.4 percent U-235 from 2.35 kilograms of natural uranium.

According to the European nuclear industrial forum ("Foratom"), the total world demand in 1980 will be about 40 million kg. s.u.w. per year, of which the European demand will be between nine million and 16 million. Unless Europe is to become completely dependent on the U.S. by 1980 it will have to decide to build enrichment capacity of its own within the next few years. (Four powers in addition to the U.S. have built gaseous diffusion plants to produce highly enriched U-235 for bombs: the U.S.S.R., Britain, China and France.) The Foratom report estimates that a diffusion plant with a capacity of 2.5 million kg. s.u.w. would cost $575 million, of which $175 million would represent the cost of an electricity-generating facility. It also estimates that production costs would fall between $29 and $37 million kg. s.u.w.; the U.S. cost is reported to be $26 per million.

The attraction of the centrifuge method is that it should require only a tenth as much electric power as the diffusion method. The initial plant cost, however, would be about the same. Evidently the British and the Dutch have independently tested prototype centrifuges, machines that must rotate at 50,000 to 100,000 revolutions per minute. The Germans are also reported to have made technical contributions. The proposed plants themselves, however, would not be located in West Germany; one would be built in Britain and the other in the Netherlands. The administrative headquarters would be located in West Germany.

According to a recent issue of *Science*, the Dutch have developed a new type of bearing for the centrifuge units, which are essentially long narrow tubes revolving at high speed. A recent British development, carbon fibers, may be used to fabricate rotors that are much lighter than steel but stronger. The French news magazine *L'Express* reports that the Dutch envision a plant containing as many as a million individual centrifuges, of which 250,000 might have to be replaced each year. If the units were mass-produced on a continuing basis, their cost would be acceptably low.

Declining Curve

The trend away from cigarette smoking appears to be accelerating, as does a related trend in favor of official moves to discourage smoking. The U.S. Department of Agriculture has reported that the consumption of cigarettes declined last year for the first time since the Surgeon General's report of 1964 declaring that "cigarette smoking is causally related to lung cancer." The Harris Survey found in a recent poll that 56 percent of the adult population would support a stronger warning on cigarette packages than the present statement that "cigarette smoking may be hazardous to your health" and that 50 percent of the adult population would support a prohibition of cigarette advertising on television and radio.

The figures from the Department of Agriculture showed that the domestic consumption of cigarettes last year was 523 billion, a decline of .6 percent from the total of 527.8 billion in 1967. The trend away from cigarette smoking was borne out by the Harris Survey, which found that the number of adults who smoke cigarettes has declined from 47 percent of the population in 1965 to 42 percent now. During the same period, according to the survey, the proportion of adults regarding cigarette smoking as "a major cause of lung cancer" rose from 40 percent to 49 percent. The survey also found that people under the age of 30 smoke the least and that the largest concentration of heavy smoking is in the group aged 35 to 49.

Formaldehyde in Space

Until a few months ago radio astronomers had succeeded in detecting only one molecule—the hydroxyl, or OH, radical—in interstellar space. Then in rapid succession a group at the University of California at Berkeley announced the discovery of two more molecules—ammonia (NH_3) and water (H_2O)—in a number of different interstellar gas clouds. Now the first organic molecule—formaldehyde (H_2CO)—has been added to the list. Microwave radio signals characteristic of absorption by formaldehyde molecules were detected from 15 of 23 sources surveyed recently by a group working with the 140-foot radio telescope at the National Radio Astronomy Observatory in Green Bank, W.Va.

In addition to being the most complex molecule ever discovered in space, formaldehyde has a special significance for workers concerned with the origin of planetary life. Current models of the development of complex organic molecules in primordial atmospheres postulate the existence of four basic atmospheric gases: hydrogen, water, ammonia and methane (CH_4). The first three have now been detected directly in interstellar gas clouds by the techniques of radio astronomy. The importance of the latest finding lies in the fact that formaldehyde is chemically related to methane (which does not have a molecular structure that makes its detection with radio telescopes possible). Hence the detection of formaldehyde in certain regions of space can be regarded as strong indirect evidence of the presence there of methane.

The detection of the formaldehyde signals was reported in a recent issue of *Physical Review Letters* by Lewis E. Snyder and David Buhl of the National Radio Astronomy Observatory, Benjamin Zuckerman of the University of Maryland and Patrick Palmer of the University of Chicago. They believe it is possible that all four of the molecules detected to date (OH, H_2O, NH_3 and H_2CO) will be found together in the same interstellar gas cloud. So far hydroxyl radicals have been observed in the company of each of the other three molecules, and water and formaldehyde have been detected in common sources. Ammonia has not yet been clearly identified in the same clouds as water or formaldehyde, although one ammonia source near the galactic center may be the same as a formaldehyde source.

Silent Epidemic

Although lead pigments were eliminated from interior paints in the U.S. some 20 years ago, multiple layers of lead-based paint still cover the walls and woodwork in many old houses and apartments. Therefore lead poisoning, once an occupational hazard for painters, is now primarily a disease of small children: toddlers between one and five who live in slum housing and nibble steadily at the paint that flakes off dilapidated walls and can be gnawed off peeling windowsills. At a conference at Rockefeller University in March participants estimated that lead poisoning in children is much more prevalent than is generally assumed, but they pointed out that the "silent epidemic" could be eliminated by aggressive medical, social and legal action.

The habit of eating nonfood substances (known as pica, from the Latin name for the magpie, a scavenger) is common in young children. A few small chips of old paint can contain more than 100 milligrams of lead, according to J. Julian Chisolm, Jr., of the Johns Hopkins University School of Medicine; the safe long-term daily intake of lead is less than half a milligram, and so a child who eats two or three paint chips a day for three months can accumulate a potentially lethal dose. Lead poisoning often goes unrecognized. The acute symptoms in small children are like those of many ailments: stomach ache, nausea, lassitude, anemia, convulsions. Often there are merely behavioral manifestations: fits that simulate epilepsy, hyperactive behavior or mental retardation. A urine test (for a metabolite that accumulates in the presence of lead poisoning) and a blood test are required to establish the diagnosis.

The mortality from the severe brain disease that can arise from lead poisoning used to be about 66 percent, Chisolm said. In the 1950's this was reduced to about 30 percent by the advent of chelating agents, drugs that combine strongly with the lead atom, removing it from the proteins to which it tends to bind (see "Chelation in Medicine," by Jack Schubert; SCIENTIFIC AMERICAN, May, 1966). Still, severe permanent brain damage occurs in more than a quarter of those who survive, and reexposure to lead poisoning increases the incidence to almost 100 percent.

Mass screening for lead poisoning can be undertaken on the basis of the urine test, spectrophotometry of hair samples or blood tests. None of these measures is simple, however, and experts at the conference urged that preventive measures be instituted instead: the eradication of slum housing or at least the removal or covering of dangerous painted surfaces.

More Brain, Better Brain?

Animals with more than the normal amount of brain tissue may learn more quickly than normal animals. This is the striking implication of preliminary results of an experiment conducted by David E. Bresler of the University of California at Los Angeles and M. E. Bitterman of Bryn Mawr College. If part of the brain of an animal is removed, the function of the missing tissue can be inferred from the animal's subsequent learning behavior. For example, if a portion of the cortex of a young rat is excised, the grown rat will perform certain learning tasks more as a fish would than as normal rats do. Bresler and Bitterman undertook to turn the experiment around by implanting extra brain tissue in fishes.

They worked with a tropical fish, the African mouthbreeder (*Tilapia macrocephala*). They took material from early mouthbreeder embryos and implanted it in other embryos in the region destined to become the optic tectum, a portion of the fish brain comparable to the cortex of mammals. Of the 10 embryos that developed to maturity, they were able to train six in a series of habit-reversal tasks devised by Bitterman to establish differences in learning behavior among species (see "The Evolution of Intelligence," by M. E. Bitterman; SCIENTIFIC AMERICAN, January, 1965). In habit-reversal experiments an animal is rewarded first for choosing one of two alternatives. When the preference for this rewarded alternative has been established, the conditions are switched so that the other behavior is rewarded. Trained in this way, rats or pigeons show steady improvement in reversing ability; fishes show no such improvement.

In the case of the implanted mouthbreeders, Bresler and Bitterman report in *Science,* three kinds of learning behavior were found. Two of the fish showed the inefficient performance typical of normal mouthbreeders. Two of them, however, showed marked progressive improvement at a level ordinarily seen in rats. The remaining two showed unusually low error scores (quick learning) throughout the test. Moreover, the fishes' behavior was correlated with their brain structure as revealed on dissection. The two animals that behaved normally had normal brains; for some reason the implanted tissue had not become engrafted. In the brains of the two animals that showed progressive improvement, however, the tectums were enlarged; in one of them what appeared to be a new tectal structure was added, and in the other the tectum was generally thickened. In the two fish with unusually low scores but no progressive improvement there was some thickening of the tectum but it was restricted to the rear part of the brain.

Sleeping Easy

How does the sleep of animals compare with man's? Noting that sleep is an active rather than a passive function, H. Hediger of the Zurich Zoological Gardens concludes that man has lost some animal abilities. The sleeping animal, he reports in *Proceedings of the Royal Society of Medicine,* is protected from visual and auditory disturbances in a variety of ways. All animals whose anatomy permits it, for example, close their eyes when they sleep, but many mammals in addition cover their eyes with their paws or tail. Animals with especially sensitive hearing, such as the bush baby and the big-eared bat, sleep with their outer ears folded.

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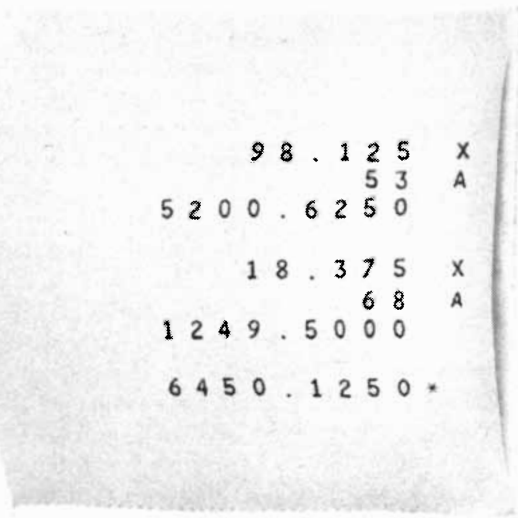

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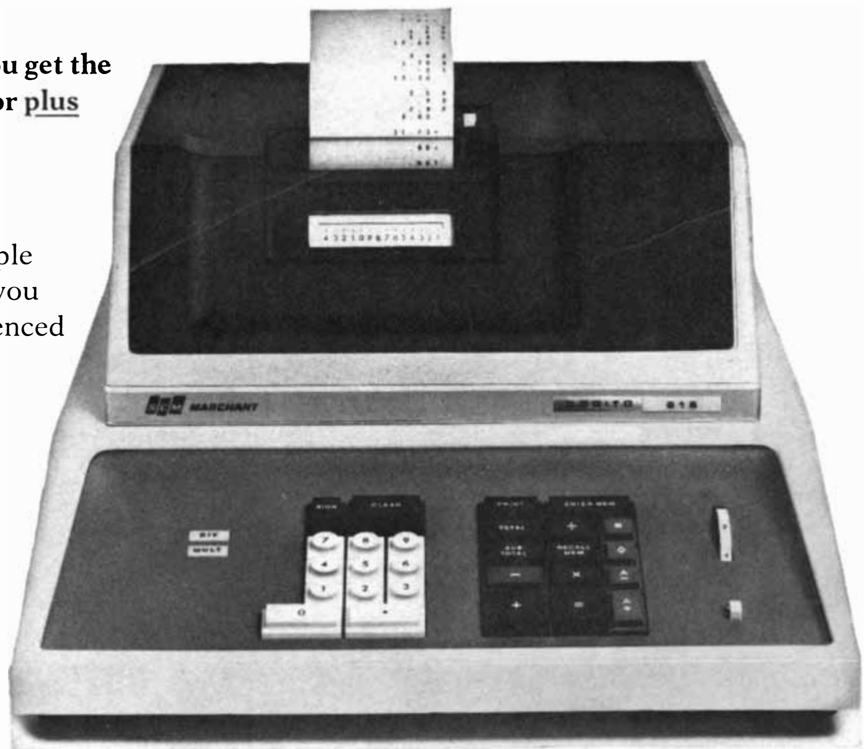

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deepest sleep. The most profound sleeper is the sloth bear of India, a savage fighter that even tigers avoid. Animals with safe refuges—the fox in its den, the mouse in its hole, the hippopotamus in the water and tree-living birds, monkeys and apes—are also sound sleepers. Many animals, however, cannot burrow, swim or climb. Of these, the ones that live in herds take turns sleeping. A common sight at noon in Africa, Hediger reports, is part of a zebra herd reclining asleep on the ground while the rest of the herd remains alert. Some solitary antelopes, he suggests, may never sleep or may, as has been observed among deer, sleep very deeply but only for a few minutes at a time.

One animal attribute that man has lost, Hediger notes, is a "sort of filter" in the central nervous system that distinguishes between harmless and potentially dangerous stimuli. A circus elephant, he points out, will not rouse even if another elephant's leg is rested on its head but wakes immediately on hearing the slightest metallic sound. Hediger concludes, however, that what disturbs human sleep most is not the loss of such protections but the fact that, unlike other animals, man broods over the past and worries about the future.

Buckled Buildings

Single-piece plastic roofs bent or buckled into a variety of shapes are being tested at Purdue University. The work, which is based on a conception by Joseph Waling and is directed by V. J. Meyers, is described in the annual report of the National Science Foundation. "Results of research to date," the report says, "indicate that the process has great potential for producing buildings as large as sports arenas or airplane hangars" and that it also "shows promise as a means for building low-cost housing, as well as intermediate-size structures such as school buildings, office buildings or covers for recreational areas."

In the buckle-shell technique the first step is to assemble at the building site a flat plate of a fairly soft plastic material, such as urethane foam. Before or after buckling a thin stiffening layer of a material such as fiber glass impregnated with polyester resin is sprayed on the upper side of the plate. The plate is buckled upward by the application of force inwardly at a number of places on the perimeter, and finally a stiffening skin is put on the bottom of the plate. The Purdue group believes that on a large scale the technique will be comparable in cost to conventional flat-roof construction and that the buckle-shell roofs will offer better weathering qualities and a better appearance than conventional roofs do.

Split Concept

Solid-state physicists at New York University have witnessed the splitting of an exciton, a conceptual entity consisting of the temporary union of a negative electron and a positive electron "hole" in an excited crystal lattice. The particular exciton that was split, an extremely short-lived type called the singlet exciton, immediately formed two other excitons, both of them the relatively long-lived triplet excitons. The result may have important biological and technological implications.

The experiment that led to the fission of the exciton is part of an extensive investigation under way at N.Y.U. and elsewhere into the electrical properties of crystals of conjugated aromatic hydrocarbons (see "Electric Currents in Organic Crystals," by Martin Pope; SCIENTIFIC AMERICAN, January, 1967). The organic crystal used in the exciton-splitting experiment was tetracene ($C_{18}H_{12}$), a benzene derivative. The experiment was described in a recent issue of *Physical Review Letters* by the N.Y.U. investigators: Nicholas E. Geacintov, Martin Pope and F. Vogel.

A singlet exciton is produced in an organic crystal when a photon of light striking a molecule in the crystal is energetic enough to excite an electron to an upper energy level termed the first excited singlet state. In the brief interval before the electron recombines with the "hole" it left in the "ground" state of the molecule, the hole-electron pair (the singlet exciton) can travel as a unit through the crystal from one molecule to another.

Normally, because of the extremely short lifetime of singlet excitons, the concentration of such excitons generated in any crystal is very low—roughly the same as the concentration obtained by putting a teaspoonful of sugar in a million gallons of water. Hence any coordinated movement of singlet excitons in a crystal could not produce a detectable macroscopic effect.

What the N.Y.U. investigators succeeded in showing in tetracene was that the fission of short-lived singlet excitons would produce pairs of much longer-lived triplet excitons. In view of the efficiency of this method for generating large densities of triplet excitons, they believe it should be possible for the first time to observe coordinated exciton effects on a macroscopic scale.

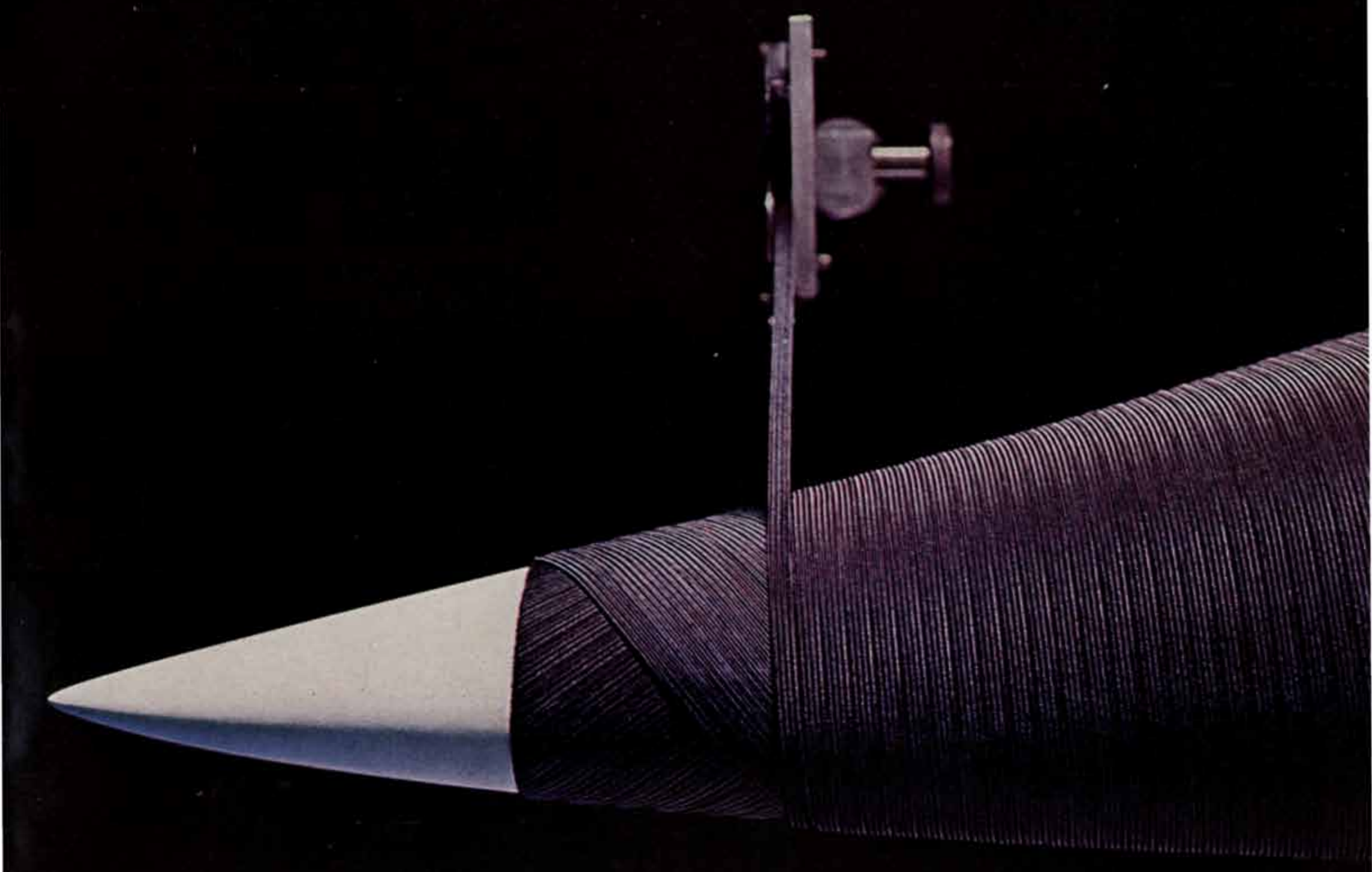
The N.Y.U. team has suggested that one such effect might be magnetic. They base their surmise on the observation that triplet excitons have a magnetic moment whereas singlet excitons do not. This suggests that macroscopic magnetic effects could be induced in organic substances by shining light on them.

Much of the research done by the N.Y.U. group is based on theoretical work by Richard E. Merrifield of E. I. du Pont de Nemours & Co. Recently Merrifield, P. Avakian and R. P. Groff observed the same exciton-fission effect in tetracene. Merrifield has proposed the term "excitonics" to describe this new field. The recent developments in excitonics could have an important bearing on the study of energy-transfer mechanisms such as those involved in photosynthesis by living plants.

The Oak Ridge Silver Mine

More than 2,100 tons of silver worth $124 million have been removed from the electromagnetic separation plant at Oak Ridge, Tenn., and returned to the Department of the Treasury. The silver was part of nearly 15,000 tons lent to the Manhattan project in 1942 and 1943 to be converted into windings for the huge magnets that were part of the "calutrons" used to separate fissionable uranium 235 from nonfissionable uranium 238. The silver, then worth more than $400 million, was used as a substitute for copper, then in short supply.

The calutrons were essentially enormous mass spectrometers in which ions of a uranium compound were made to travel in the field of electromagnets 19 feet square. In a magnetic field ions of different mass execute arcs of slightly different radius. In this way ions comprising U-235 could be separated from ions comprising the slightly more massive U-238. The process was beset by many technical difficulties but helped to produce the highly purified U-235 in the atomic bomb that destroyed Hiroshima. Subsequently the gaseous diffusion process proved much more efficient in producing U-235, and most of the calutrons were dismantled. In the 10 years following World War II more than 12,500 tons of silver were returned to the Treasury. A few of the calutrons were kept in operation, however, to produce small quantities of natural isotopes other than U-235. After the current return of 2,100 tons of silver only about 70 tons will remain at Oak Ridge; it too will soon be returned to the Treasury.



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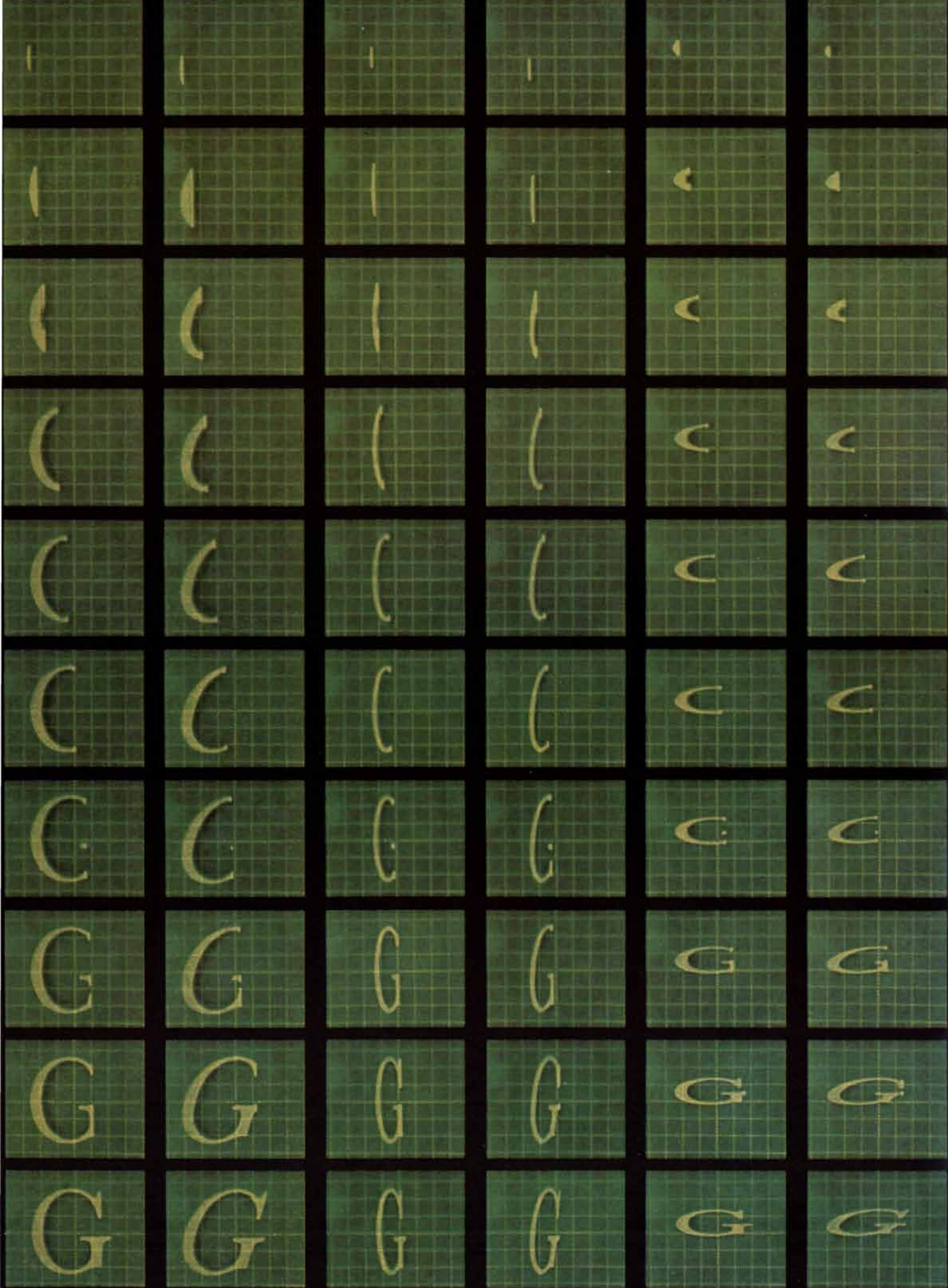


TYPESETTING

Electronic typesetting systems capable of "painting" as many as 10,000 characters per second on the screen of a cathode ray tube promise to have a revolutionary effect on the printing industry

by Gerard O. Walter

The art of printing is at least 1,200 years old, and in general practice it still follows basically the original method. Characters or images are formed in relief on supporting blocks or plates; the composition is then inked and printed on paper. The invention of movable type and stereotypes and the mechanization of the various steps in the printing process facilitated these operations but did not fundamentally alter the method. Printing is now, however, undergoing radical innovations, particularly in typesetting. Since 1948 we have seen the application of photography to this operation, leading to the wide use of photo-offset printing. Within the past three years a much faster technique has been developed: "typesetting" by an electron beam.

In the days of setting type by hand highly skilled compositors achieved remarkable speeds as high as one character per second; mechanical typesetters built since the turn of this century cast about five characters per second. Nowadays photographic typesetting machines that select the characters mechanically are capable of setting as many as 500 characters per second. In contrast, the new electronic method can produce up to 10,000 characters per second. In conjunction with a computer directing the operation this system is introducing a new order of speed and capability in the printing industry.

PHOTOMONTAGE on the opposite page was assembled in order to provide a demonstration of the technique employed to "paint" a character on the screen of a cathode ray tube by means of a moving electron beam. The photographs were selected from film strips of single letters formed by a simulated typesetting machine built by engineers at the Graphic Systems Division of RCA to demonstrate some of the capabilities of their system for electronic typesetting. In the actual RCA Videocomp machine the resolution is much better and the formation of the characters is too fast to capture photographically in this manner. Reading from left to right, the six capital *G*'s in the photographs at bottom are called roman, italic, condensed roman, condensed italic, expanded roman and expanded italic.

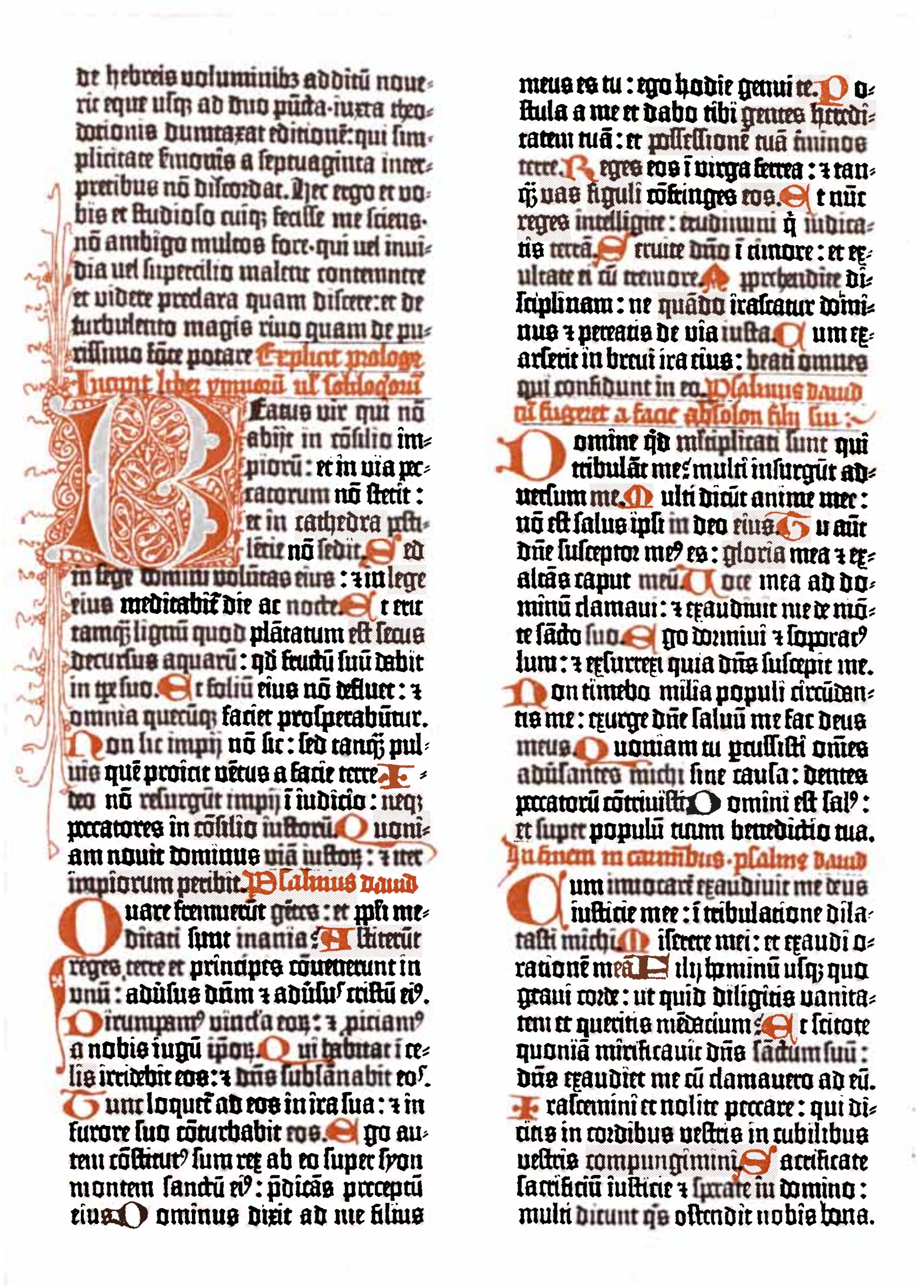
Early Printing Techniques

For background let us take a brief look into the history of the development of typesetting. Printing originated in China and was not introduced into Europe until several centuries later. The earliest printing tools and printed documents, found in China and Japan, are from the eighth century, and the oldest-known printed book is a Chinese work dated May 11, 868. The early printing was done from clay plates or wood blocks. The clay plates were made by scribing ideographs—symbolic pictures—in a flat slab of wet clay, drying the slab in an oven and then pressing soft clay into this hardened mold to form the "positive," or raised image, that was used for printing. Wood printing blocks were made by carving the surface of the block to produce the image in relief. Essentially these two elementary principles have been the bases for the various methods of producing type masters up to the present day.

In the 11th century a Chinese printer named Pi Shêng introduced flexibility into the composition of type masters by inventing movable clay type. Each unit was a small clay tablet bearing the relief image of a single ideograph. The type units were assembled for printing on a tray coated with resin that held them in place. Printers could now compose any message from the store of ideographs and use the units again and again to produce other compositions. Thus by the 11th century the basic devices for founding a printing industry had already been invented by the Chinese, and these developments soon became known in the West through Chinese contacts with the Arabs. Yet the Europeans did not take up and develop printing until more than 400 years later!

Curiously, it appears that a seemingly minor language technicality may have been largely responsible for this lag. The Chinese ideographs are all of about the same width; consequently Pi Shêng was able to make his clay type blocks of uniform width and use uniform spacing, so that they could be laid out simply and neatly in a regular order that formed a tastefully balanced plate, or page. In the Western languages the irregularity of the letters and other characters does not allow making the type size uniform. The characters vary in width, in height and, because of their different shapes, in their spacing.

To appreciate the importance of this complication, examine the page you are reading. You are quite aware of the visible type (there are about 6,000 characters in black on a full page of this magazine), but in all likelihood you are not aware of the fact that the page also contains a great deal of invisible type—the white spaces between letters, the spaces between words and the spaces between lines. For a compositor these spaces are as important as the characters themselves. He must produce them somehow by material means. The white space around each letter is provided by the fact that the type body (the block that carries the letter) is slightly larger than the letter itself, and the size of this body must vary with the letter so that the



HAND COMPOSITION of movable type was the technique devised by Johann Gutenberg to set the type for his 1456 Bible, a section of which is shown in this photograph. Gutenberg cast each character in relief on a metal block in a position such that when the blocks were put side by side, the spaces between the characters were tastefully balanced. The lines were "justified" by using blank blocks of various widths for the space between words.

spacing between letters fulfills requirements of legibility and aesthetics. The spaces between the lines are provided by leading. The spaces between the words present a prime problem of management for the typesetter: they are by no means standard but in each line are finely tuned—by the process called justification—so that the line comes out even at the right margin.

It was the skillful solving of the spacing problem that made Johann Gutenberg the most famous name in the history of printing and even gained him the reputation of being printing's inventor (at least in the West). The Gutenberg Bible, which he printed in his native city of Mainz in 1456, is a model of accurate and tasteful composition [*see illustration above*]. Using the Gothic style (derived from manuscript writing), Gutenberg produced movable type by casting each character in relief on a separate metal block. The character was not centered; each was cleverly placed on its block in a position such that when blocks were put side by side, the spaces between the characters were well balanced and there were no "holes" or concentrations of black in a word. This is indeed an art, requiring an aesthetic eye and meticulous care; even today, with all our technology, the placement of characters on their blocks is determined empirically by trials involving closer and closer approximations. Gutenberg also introduced the justification of lines of type by using blank blocks of various widths for the space between words. To set up a page he laid the blocks in a chase: a viselike holder that clamps all the blocks together.

Gutenberg's alphabet (in Latin) consisted of 73 characters (letters and numerals) and punctuation marks. Modern fonts of type usually contain 126 characters. A font is a complete collection of symbols in a particular design and size; its elements are the lowercase letters, capitals, small capitals, ligatures (letter combinations such as fi, ffi and fl), accented letters, numerals, punctuation marks, reference marks and other symbols. The size of the type is measured in "points"; in the U.S. a point measures approximately 1/72 inch. Each size of type comes in various thicknesses, ranging from light to bold. And a given design also embraces other variations, such as "condensed" and "expanded," roman (upright) and italic.

Among the creative printers who followed Gutenberg the names of several are immortalized in the designations of the type styles, or typefaces, they invented. Around 1470 a French printer, Nicolas Jenson, originated the Venetian style, which has since been developed in many variations. Between 1720 and 1726 William Caslon, an English artist, architect and stonemason, developed the typeface that bears his name. Another famous type style was designed by a similarly versatile Englishman, John Baskerville, about 1750. Perhaps the most distinguished of all type designers was Giambattista Bodoni of Italy, who in 1768 produced the type style, notable for its simplicity and cleanness, that is the most popular today.

Printing is now an industry of many separate crafts and specialties, which include the production of paper and inks, typesetting, engraving, press operations and of course the vast enterprise of publishing, to which the printing industry is intimately related. Although this article is primarily about typesetting, I should like to touch briefly on some of these related developments.

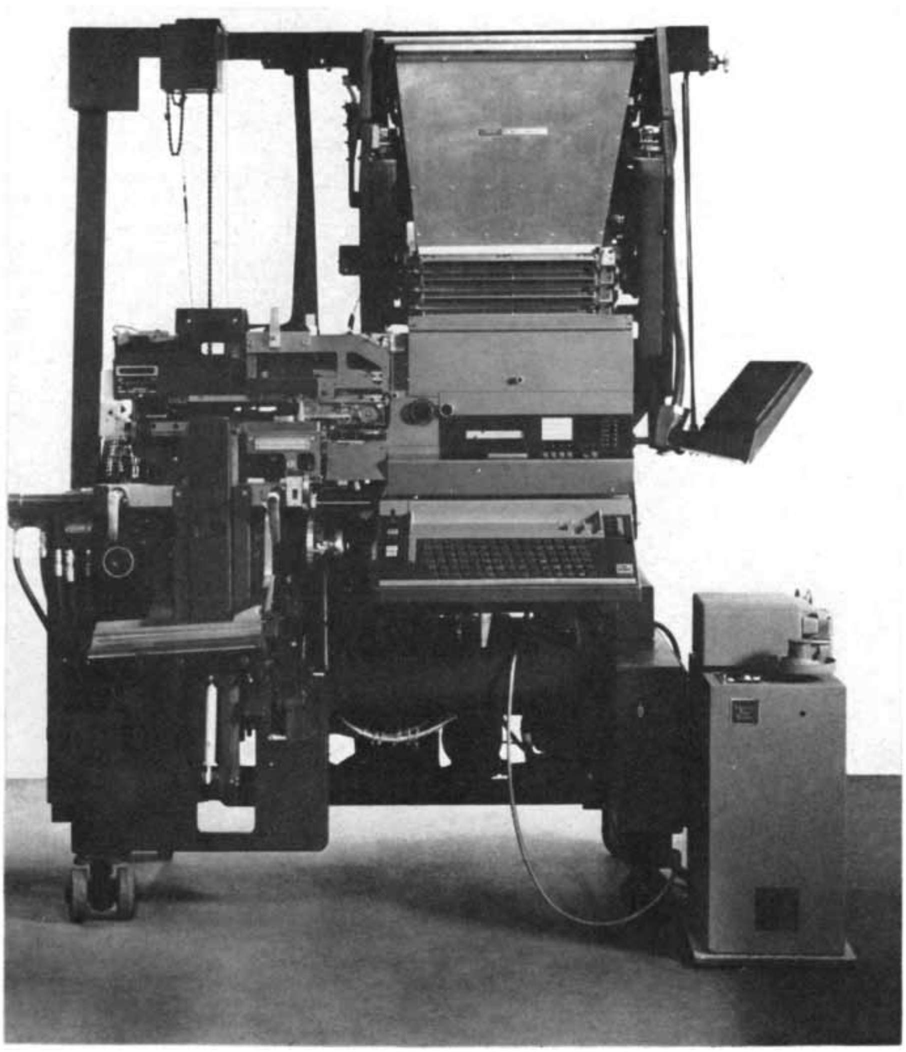
Paper, Ink and Type

The invention and manufacture of paper had its beginning nearly 2,000 years ago in what is now a small, dirty pool of water at Leiyang at the foot of Heng Mountain in south central China. There the world's first papermaker, whose name is lost to history, originated the material by boiling bark, rags and discarded fishing nets and beating the stuff into a pulp. From the first century until the eighth papermaking was scarcely known outside China, but in the middle of the eighth century the Arabs learned the craft from Chinese prisoners captured in a battle at Samarkand. The Arabs rapidly substituted paper for parchment as a writing material, as is evidenced by many Arabic manuscripts on paper that date back to as early as the ninth century. They produced paper from linen at first and then from flax and other plant fibers, supplemented by rags. By the 12th century the manufacture of paper was established in Europe by the Moors who invaded Spain, and paper was being produced and used in Britain by the 14th century. The popularity of newspapers, pamphlets and letters of correspondence in the American colonies spurred papermaking in the new world; the first paper mill was built in Germantown, Pa., in 1690 by an ambitious papermaker from Prussia, William Rittenhouse, to supply the Philadelphia printer William Bradford. The U.S. has become the world's leading producer and user of paper, primarily for the publishing of newspapers, magazines and books.

Ink is considerably older than paper; it was produced in Egypt and China as early as 2500 B.C. The ancients at first made ink by mixing lampblack with a solution of glue or gum; later they resorted to a variety of other plant, mineral and animal substances, including "dragon's blood." Modern inks consist of a pigment such as a mixture of iron salt and tannin in a vehicle such as linseed oil, with an addition of oxygen-absorbing materials to hasten drying of the ink. For magazine publishing, where the printing must be done at high speed and on less absorbent paper, fast-drying inks that are dried by heat and evaporation have been developed. The composition of ink and its application have become a sophisticated technology with a considerable bearing on type design, as the flow of ink affects the thickness of the type image impressed on the paper.

In typesetting the first important physical improvement arrived in the 15th century: metal began to replace wood blocks for the type. The switch to metal type soon led to the use of matrices. Since the high cost of metal type made it impracticable to stock enough type to print an entire book, printers resorted to using their type to make a replica in lead for each page. The page was set in type, this assembly was pressed into a sheet of papier-mâché, the impression was then filled with hot lead, and the resulting plate of characters in relief served as the print master. The type itself, not having been inked, could be re-sorted and used again without cleaning. In the 19th century the invention of the rotary press for faster printing brought about the development of curved stereotypes, made in essentially the same way as the flat matrices, to fit on the cylinders of the rotary press. Machines for making matrices and stereotypes were built, and in 1837 a German physicist, Moritz Hermann Jacobi, invented the process of electrotyping, which by depositing a coat of copper or nickel on the print master improved its durability.

Meanwhile progress was being made in increasing the speed of typesetting. Gutenberg's idea of ligatures was extended to putting commonly used combinations of letters (such as ed, er, st, wh) and even entire syllables on a type



MECHANICAL COMPOSITION, an innovation introduced largely in the 19th century, has reached its highest point of development in modern typesetting machines such as the Mergenthaler Linotype Company's Elektron, depicted here. The Elektron, like the original Linotype machine invented by Ottmar Mergenthaler in 1885, can be operated directly by means of a keyboard; the modern version can also be driven by information on paper or magnetic tape. When the operator (or the tape decoder) depresses a key, the matrix for the indicated character (or a blank for the space between words) is delivered from an overhead rack to a line-collector. The line is justified by inserting expandable wedges. After the line measure has been filled the line of matrices is locked and transported to a chamber where molten metal is introduced under pressure. From the matrices as a mold the metal is cast into a line in one piece; after cooling the cast line is ejected into a tray. The matrices that formed the line are then returned to their individual compartments in the overhead rack through a sorting machine. Mechanical typesetters can cast five characters per second.

block, constituting what is known as a logotype. Using logotypes, a Viennese compositor named Leopold Weiss set type at the rate of 3,500 characters an hour in a contest in 1883. His typecase had 668 compartments (as against the ordinary font of 126). Only a genius could work with such a monster of a case, and one must marvel at the accomplishments of Chinese compositors, who even today have to work with a case containing up to 10,000 ideographs.

Other devices for accelerating setting by hand came into use. The inventive Danish compositor Christian Soerensen conceived the idea of tying the composing stick to his waist so that he could work with both hands. A Swedish engineer, Albert Lagerman, went a step further and placed under the typecase a collector that conveyed the types to the line-holder by way of a funnel; the compositor, using both hands, simply threw the types into the funnel.

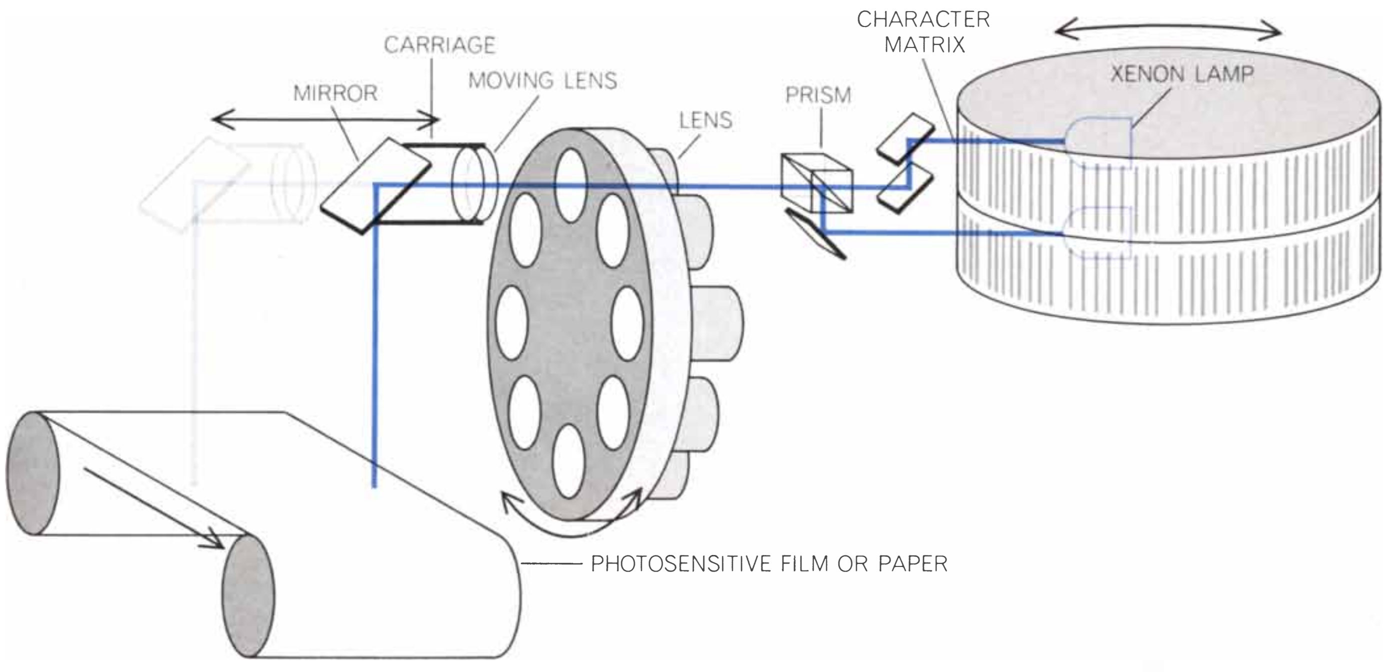
Mechanical Typesetting

Soerensen became one of the pioneers in the mechanization of typesetting. Throughout the 19th century many inventors sought to devise a machine that would select type from a magazine, assemble it in a justified line and return the types to their proper places in the magazine after the line was cast. Elaborate machines (one of which required no fewer than seven operators!) were built, but they fell short of acceptability. One of the main difficulties was the problem of mechanical identification of the types for setting and for later return to the origin. In 1849 Soerensen produced a device that essentially solved this problem. He notched each type body in a way that identified the character and used brass rods to select and guide the transport of the type. Soerensen's was the first machine that could both set and return type, and his notching idea is still used in typesetting machines today. His machine did not, however, work well enough to be adopted by printshops.

A successful machine, the Linotype, was finally produced in 1885 by Ottmar Mergenthaler, and the Linotype is still one of the most widely used typesetting machines. It is operated by means of a keyboard. When the operator strikes a key, the matrix for the indicated character (or a blank for a space between words) is delivered from an overhead rack to a line-collector. The operator justifies the line by inserting expandable wedges. After the line measure has been filled, the line of matrices is locked and transported to a chamber where molten metal is introduced under pressure. From the matrices as a mold the metal is cast into a line in one piece, and after cooling the cast line is ejected into a tray. The matrices that formed the line are returned to their individual compartments in the overhead rack through a sorting machine. While the metal line is being cast, the compositor is already assembling the next line with the keyboard.

The Linotype machine is well designed for tasks such as setting a newspaper, consisting of regular columns and relatively simple text; it is not well suited, however, for handling complicated, irregular formats, and it becomes a slow, cumbersome instrument when many special symbols must be inserted in the text or when many corrections are required. The machine is noisy and emits considerable heat from the molten metal. The latter inconveniences were avoided in the Monotype machine, which was developed at the turn of the century. In the Monotype instrument the typesetting is done in the first instance on paper tape.

The inventor of the Monotype was Tolbert Lanston. A clerk in the U.S. Pension Bureau, he took a cue from Herman Hollerith's development of punched cards for machine tabulation



PHOTOCOMPOSITION, a development of the 1940's and 1950's, is represented here by a schematic drawing of the Photon 713 optical system, a product of Photon, Inc. A cylindrical matrix containing all the characters in the form of photographic images carries the images past a stroboscopic lamp, which flashes the successively selected characters through a moving-lens system onto a photosensitive film, from which an offset printing plate is exposed. After the plate is developed only the desired character images remain. The plate is treated so that ink will be deposited only on the images; it is then inked and run against a rubber blanket that picks up the images and serves as the printing surface. This method is known as photo-offset printing. Phototypesetting systems can be operated either from a keyboard or from data on paper or magnetic tape. Fastest systems can set type at rates up to 500 characters per second.

of the 1890 Census and set out to apply the idea to typesetting. He reasoned that holes punched in a paper tape could represent the matrices for individual type characters and could specify the position in which each character should be placed in a line. The tape, punched by an operator at a keyboard, would be fed into a machine that would cast the type units and set them in the line according to the tape's instructions. With the help of John Sellers Bancroft, an engineer, Lanston eventually produced a successful machine. An operator punches the holes for the successive characters with the tape-perforating machine; the machine automatically adds up the width units as he proceeds and, before the end of the line is reached, it informs him what keys he must strike to insert word spaces of a width that will produce a full, justified line. When the line is completed, the punched tape is inserted in the casting machine tail end first (so that the line will be cast from right to left). In the casting machine the information in the tape selects matrices one at a time and causes each matrix to be pushed into a mold where a squirt of molten metal is injected to form the character or word space; the cast line is finally deposited on a galley. One such machine can keep up with two keyboards.

The Monotype machine owes much of its success to beautiful type designs by Frederic W. Goudy and Sol Hess. Several other machines, some successful and some not, contributed to the advancement of mechanical typesetting, among them the McMillan composing machine, the Rogers Typograph, the St. John Typobar, the Ludlow Typograph and the Intertype. Let us go, however, to the next major development in typesetting: the introduction of photographic processes in the 1940's and 1950's.

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SAMPLE TYPEFACES produced by the RCA Videocomp include the commonly used fonts represented here. Electronic typesetting systems such as Videocomp can also generate tabular or columnar displays, drawings and eventually halftone pictures for printing.

Photographic Typesetting

There are several varieties of machine for phototypesetting, or photocomposition, as it is called. They differ in method of operation but all are based on the same principle. A matrix containing all the characters in the form of photographic images is scanned in one way or another with a stroboscopic lamp that flashes the successively selected images of characters through a lens onto a photosensitive plate [*see illustration on opposite page*]. After development of the plate only the character images remain. For photo-offset printing the plate is treated so that ink will be deposited only on the images; it is then inked, and the plate is run against a rubber blanket that picks up the images and serves as the printing surface. This system does away with the casting of raised characters in metal and the letterpress method of printing. A photo-offset plate can be produced quite quickly.

The use of the lens makes it possible to magnify the image and thus project the characters in various sizes from the same master matrix. The matrix can contain sets of characters in various typeface styles, any of which can be used simply by dialing to a desired setting. The machine can readily be operated by taped instructions, either from a keyboard or from a computer.

Phototypesetting machines can set type at rates of up to 500 characters per second. With a human operator at the keyboard, however, the machine is obviously limited to the rate of input by the operator. Including the various kinds of command that must be given the machine, a good keypunch operator cannot do much better than about one and a half characters per second. It is possible to multiply this rate by hooking several keyboards into the machine with operators working simultaneously, but even so their combined input will use only a small fraction of the machine's speed capacity. The two limitations—the limited speed capacity of the machine itself and the limited rate of input by human operators—prompted the current new development: typesetting by electronics with a computer providing the input.

Electronic Typesetting

Suppose one designed a cathode ray tube (similar to the kind used in television sets and other display devices) that would paint characters on the screen and produce lines of text that in turn would be recorded on film for printing by the photo-offset method. Characters could be formed by swinging the electron beam to make short, parallel strokes so fine and spaced so closely together that the image would appear solid [*see illustrations on page 68*]. Several companies in the electronic and printing fields began to explore this inviting concept almost simultaneously, and since 1966 a number of successful machines have been produced and demonstrated. The companies include RCA (which has produced several systems based on machines first developed by the Dr.-Ing. Rudolf Hell Company in Germany), the Mergenthaler Linotype Company (marketing a machine developed by K. S. Paul of Britain and one developed in cooperation with CBS Laboratories), the Intertype Company and the International Business Machines Corporation (distributing a machine developed by Alphanumeric Incorporated).

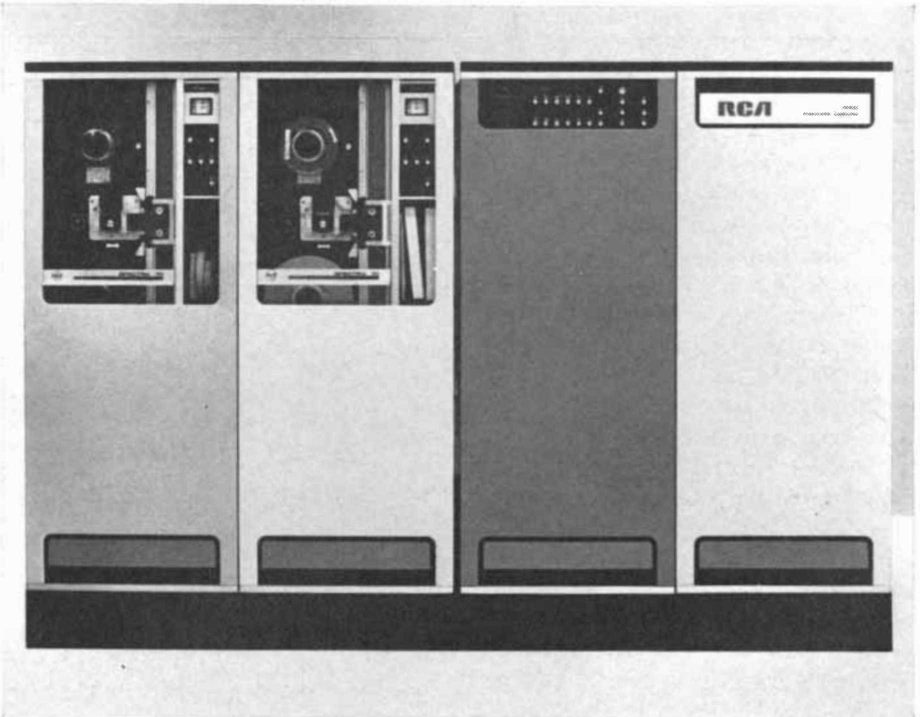
In some of these machines the character is painted with vertical strokes, in others with horizontal strokes. The screen is an optically flat disk coated with layers of aluminum and phosphor. With each stroke the electron beam produces an extremely fine line, less than a thousandth of an inch wide, on the screen; some systems pack the lines as closely as 1,200 strokes to the inch. The stroke, produced by switching the moving beam on for a brief instant, is of course very short—no longer than the height or the breadth of the members that form the type character. Since the beam can move at speeds as high as 10,000 inches per second or even faster, it paints the characters very rapidly.

The RCA machines, some of which can generate characters as large as an inch and a half in height, operate at speeds from several hundred to several thousand characters per second, depending on the model and the size of type. A number of the RCA machines are already in use in the printing industry. The Alphanumeric machine generates type at up to 6,000 characters per second. One of the Mergenthaler Linotrons can compose 10,000 characters per second. It will probably be possible to develop electronic typesetters with speeds of 60,000 or more characters per second.

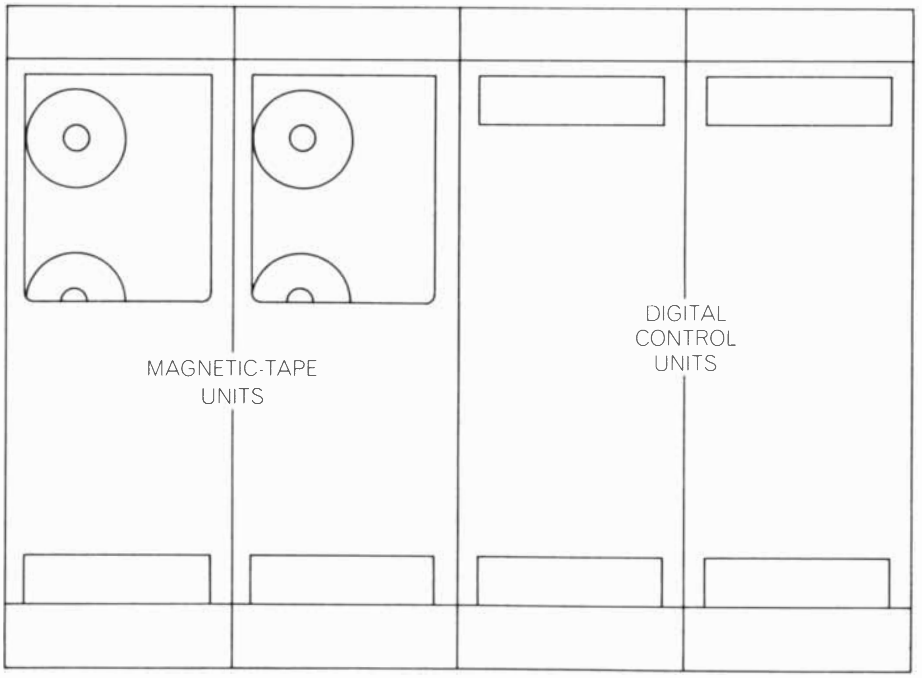
The machines record the electronically produced characters on film by various methods. For projection to the film some machines use stationary lenses and others moving lenses to pick up the characters as they are painted on the screen; some use continuously moving film; some photocompose an entire page of text at a time on stationary film; others advance the film for every line. One of the virtues of the electronic system is that the beam can paint not only type characters but also any kind of graphic material; it can easily generate tabular or columnar displays, drawings and eventually even halftone pictures for printing.

The high-speed electronic typesetter not only lends itself to operation by computer but also actually demands it. To begin with, the system requires a computer-type memory bearing fully detailed instructions for the printing of each character, so that the keyboard operator need not punch in on-off signals for the multitude of strokes the electron beam must make to form the character. Thus one "box" in the memory carries the instructions for forming the letter *a*, another for *b*, and so on. Entire fonts of type in various styles are stored in the memory, and any font can be selected simply by pressing the proper identifying keys.

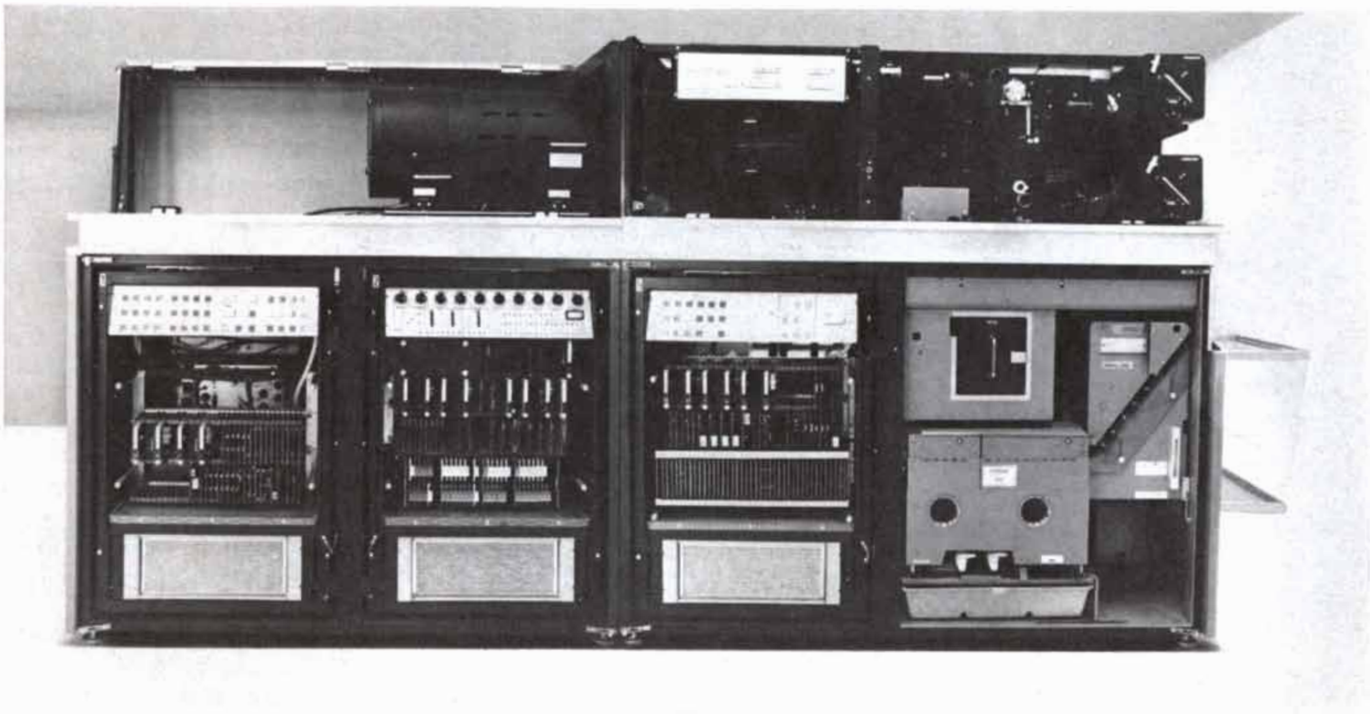
This is merely the first step in the



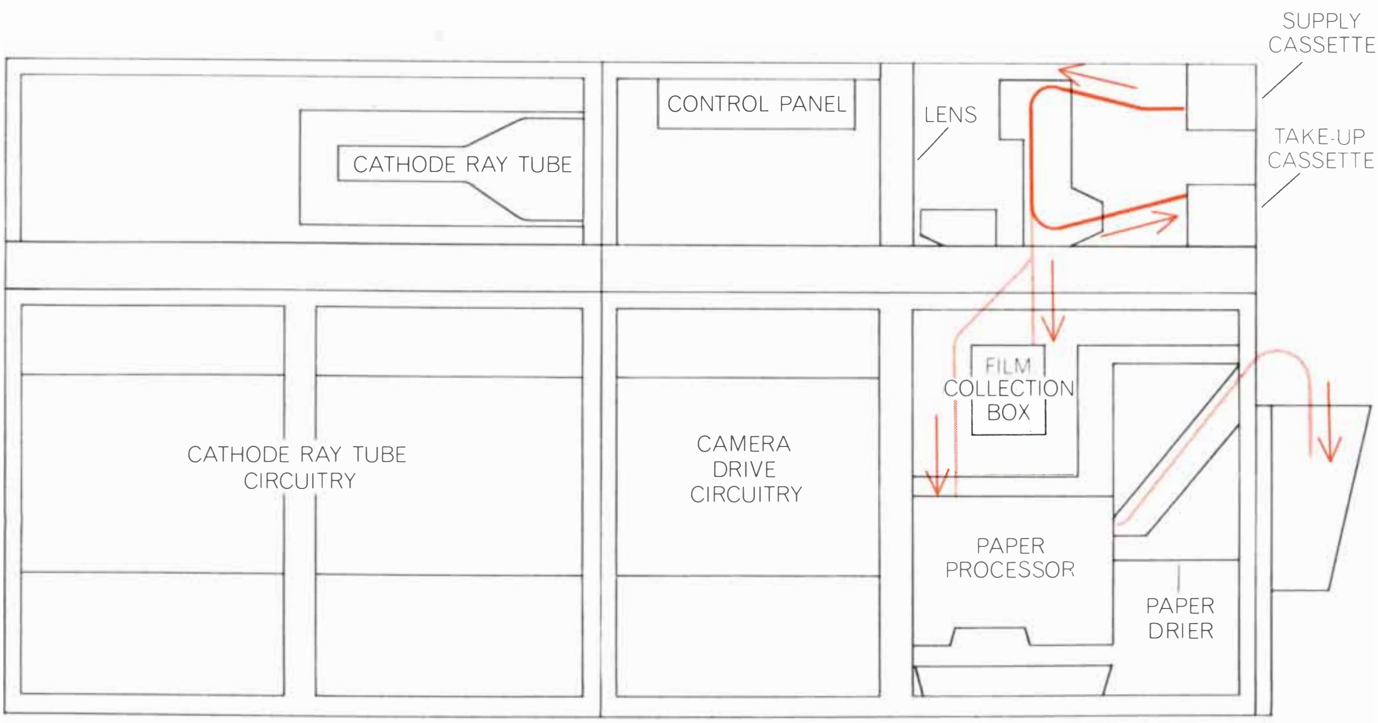
RCA VIDEOCOMP is a high-speed electronic typesetting system based on machines first developed by the Dr.-Ing. Rudolf Hell Company in Germany. Machines such as the Video-



SCHEMATIC DRAWING of the Videocomp system shows the relationship of the essential components. The two tape units at extreme left submit the text in digital form to the system. The system can also handle an input of digitized information from as many as 32 keyboards at a time. The next two units comprise a digital computer and a memory, which contains computerization of the machine's operations. In composing text the keyboard operator need only type on steadily as if he were writing one long line; the computer, which has the width of each character, a word dictionary and a set of rules stored in its memory, will break up the typed text into justified lines, even hyphenating a word at a proper syllable break when it would run over the line. With a brief signal identifying a stored string of commands the operator can cause the computer to start a new chapter in a book, calling for the start of a new page, selecting the style and size of type for the chapter head, specifying the placement of the head and the spaces around it and indenting the first line of the following text. The computer can perform almost all the functions of formatting, creating runarounds for illustra-

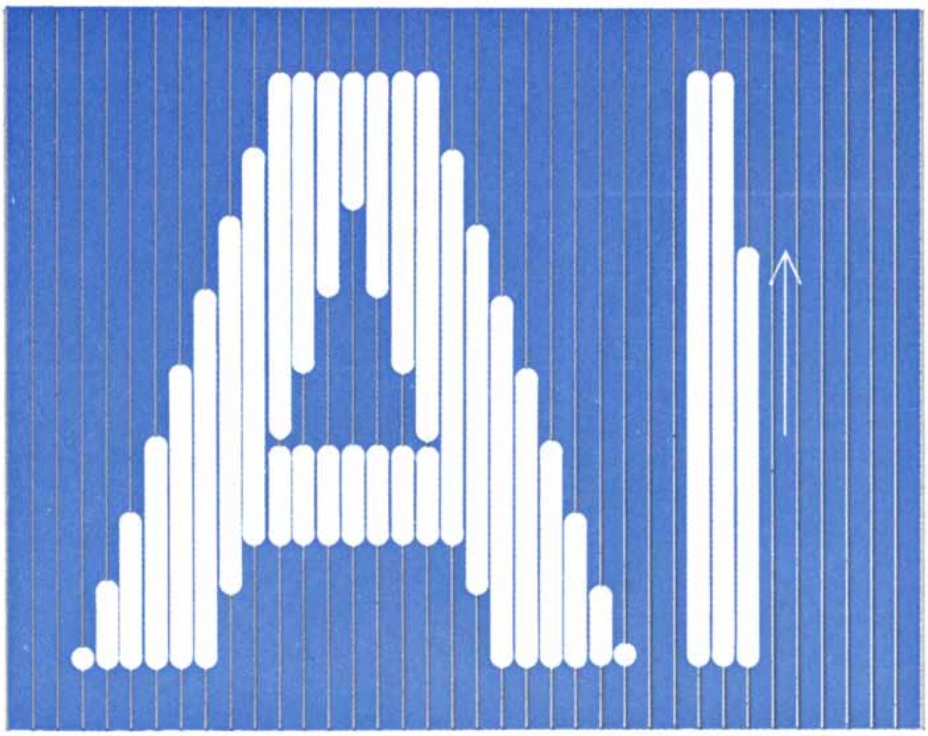


comp operate at speeds from several hundred to several thousand characters per second, depending on the model and the size of the type. A number of electronic typesetting machines, made by various companies, are already in use in the printing industry.



stored programs for printing each character. The computer can also break the text into justified lines, hyphenate words at proper syllable breaks and carry out other tasks of makeup and editing. The electronically produced characters are painted on the cathode ray tube (*right*). The images on the tube are projected by means of a stationary lens onto photosensitive film or paper, which advances line by line or page by page. The developed paper is used mainly for proofs; developed film is suitable for making printing plates.

CHARACTERS APPEAR on the cathode ray tube of this Videocomp system one line at a time. The screen is an optically flat disk coated with layers of aluminum and phosphor. The photograph was made with the aid of a mirror inserted between the screen and the lens.



CHARACTER IS PAINTED on the cathode ray screen with closely spaced vertical strokes. With each stroke the electron beam produces an extremely fine line, less than a thousandth of an inch wide; the lines can be packed as closely as 1,200 to the inch. The line is produced by switching the moving beam on for as long as it takes to traverse the height of the character at that point. The beam can move at speeds greater than 10,000 inches per second.

tions, dividing the text into columns and pages, inserting page numbers and carrying out other tasks of makeup.

Considerable work has been done on the development of detailed programs for typesetting and other functions, and RCA has invented a special language that enables printers to communicate with the computer in the terms of their trade. Moreover, the input of information to the machines has been speeded up greatly. Besides simplifying the work of the individual operator, the stored programs and the rapidity of the typesetting machine's operations make it possible to feed commands into a machine from 32 keyboards at a time.

The computer has begun to perform some editing functions. It can be programmed, for example, to compile indexes, bibliographies, lists of footnotes and other specified lists for books or technical publications. As the setting of the text proceeds, the computer notes the key terms or other specified items of information, stores the places of their occurrence in its memory and at the end automatically sorts them in alphabetical order and directs the setting of the list it has compiled.

There are other interesting applications of this capability. For example, after a telephone directory has been set in the usual form with the subscribers' names in alphabetical order, the computer, with the list stored in its memory, can sort the information to produce other editions in which the entries are listed by districts and street numbers or by the telephone numbers in numerical order. The periodic updating of editions of the main directory, with additions and changes, can be produced simply by putting the new information into the computer, which automatically places it in the correct alphabetical order. Another operation of a similar nature that has already been carried out is the selection of sections from an encyclopedia for separate publication. After the encyclopedia, consisting of many volumes, has been keyboarded into the computer, the computer under instruction withdraws the material on a specified subject from its memory storage and sets it up for publication as a separate book or pamphlet, complete with its own index, list of references and so forth.

Effects on Publishing

The effects of electronic typesetting *cum* computer on publishing are likely to be substantial. The public hunger for printed information is seemingly insatiable; historically the supply has generally run behind the demand. Within the past decade book publishing has doubled in the U.S., and the sales of newspapers and periodicals have increased by 50 percent or more. Printing, the eighth-largest industry in the nation, is growing faster than other manufacturing industries. Its total sales now amount to more than $15 billion a year, of which $5.5 billion is spent for newspapers, $5.3 billion for general printing, $2.5 billion for periodicals and $2 billion for books.

Electronic typesetting will undoubtedly foster a considerable increase in the demand for and volume of printed material, since it reduces the cost of printing and speeds up the output. One can foresee other consequences, however, that will be more dramatic. These have to do with a predictable acceleration of the pace of printing.

The new electronic techniques have cut the publishing time for a complicated college text or a technical book from a year or more (after submission of the completed manuscript) to less than three months. This means that up-to-date texts can now be made available rapidly to universities, colleges and schools, and technical handbooks can carry current information. For newspapers and periodicals the effects of rapid printing will be even more significant. It has already been demonstrated that a full newspaper page, including pictures, can be set up electronically in less than five minutes; thus the news can become available in print almost as quickly as the bulletins on the radio or television.

There is a prospect as exciting as rapid printing itself. The electronic system makes it possible to distribute publications speedily on a continental scale without the need of shipping them in the form of vast, slow-moving quantities of paper. The content of a newspaper or a magazine, composed electronically in a central office, can be transmitted by means of telephone lines or wireless channels to satellite plants around the country, or even around the world, where local electronic typesetters, activated from the central source, will produce plates for printing on local stocks of paper. Thus readers in New York, Chicago, San Francisco, Honolulu, London, Tokyo and other points will be able to read the same newspaper or magazine at the same time. Truly national dailies, which in each city will include local news and features in space reserved for the purpose, will become a practicable proposition in the U.S. for the first time.

The Energetics of Bird Flight

The metabolism of gulls and parakeets is measured during ascending, descending and level flight in the wind tunnel. The results show how flying birds can husband their "fuel"

by Vance A. Tucker

How hard must a bird work to fly? The speed and endurance of birds in flight have always challenged the curiosity of students of animal physiology. Even the smallest birds not only stay in the air for hours but also travel without stopping for hundreds or even thousands of miles at speeds well above those attained by all but the fastest ground animals. In my laboratory at Duke University I have been examining how birds accomplish these feats by measuring the power expenditure of budgerigars (the common parakeet) and laughing gulls flying at various speeds and attitudes in a wind tunnel. These are the only birds for which direct information is available, and they are among the few birds for which there are any such data at all.

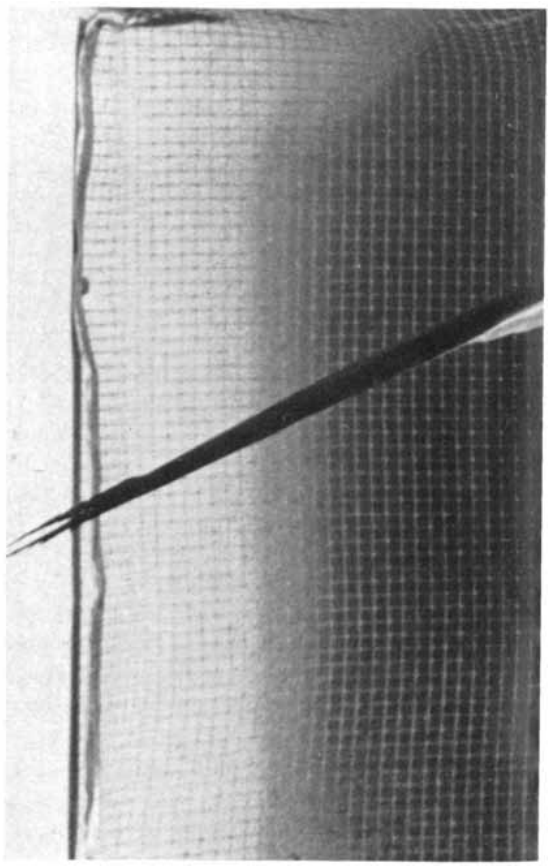
The speed and endurance that make bird flight so interesting also make measurements of the energetic cost of flight difficult to obtain. Many methods for estimating the cost of free or hovering flight have been used, including aerodynamic calculations, measurements of weight loss during flight, studies of the washout rates of radioactive compounds and studies of the rate of oxygen consumption. The last method is more accurate than the others, which depend on more or less tenuous assumptions. All these techniques, however, have a common failing when applied to free-flying birds: they do not allow experimental manipulation of the speed, duration and direction of a bird's flight so that such factors can be related to metabolic data.

This is precisely the advantage of the wind-tunnel method. At the beginning of an experimental run a budgerigar or a gull is placed in the test chamber of the wind tunnel so that the bird flies into the stream of air [*see illustration at right*]. In this way the bird can be made to fly as rapidly in relation to the air as it does in natural flight, while remaining stationary from the observer's point of view. The bird's flight in the wind tunnel can be likened to the progress of a sailboat heading into a strong tide; although water moves rapidly past the boat's hull, to someone on the shore the boat may seem to be standing still. The experimenter can select the speed of the bird's flight by controlling the air velocity. He can also set the duration of the flight and determine whether the bird is flying on a level path or on an ascending or descending one.

To simulate ascending flight the tunnel is tilted so that its forward end points upward. A downward tilt creates the conditions of descending flight. Ideally the aerodynamic and gravitational forces on a stationary object in a wind tunnel are exactly the same as if the object were moving through still air. This is why I refer to a bird as ascending or descending when the wind tunnel is tilted, even though the bird's actual position does not change.

While flying, the bird wears a clear plastic mask over its head to collect exhaled gases. An elastic band around the back of the bird's head holds the mask in place, and a vacuum pump draws the exhalations down a flexible plastic tube to gas analyzers so that the rate at which the bird obtains energy from fats and carbohydrates can be measured. Oxygen consumption and carbon dioxide production are determined by measuring the concentration of these gases in the air entering and leaving the mask, and also by metering the total flow rate of air through the mask. In addition to providing gases for the analyzers the vacuum pump system draws fresh air in through the back of the mask.

The budgerigar was chosen for the experiments because it is tame, is readily available in pet stores and is a steady flier. (An early attempt to work with a sparrow failed when the bird, instead of flying on a level path, tried to escape and dived and turned inside the wind tunnel.) A small bird such as the budgerigar, which weighs 30 to 40 grams, was the only one that could be accommodated in the wind tunnel available at the time, a nine-foot-long affair with a somewhat cramped test chamber. When I



LAUGHING GULL flying in the experimental chamber of a wind tunnel wears a

sought to study a larger bird, I chose the laughing gull, which weighs 300 to 400 grams; it happened that one of my colleagues had a number of gulls at hand for other work. To accommodate them I had a larger tunnel built.

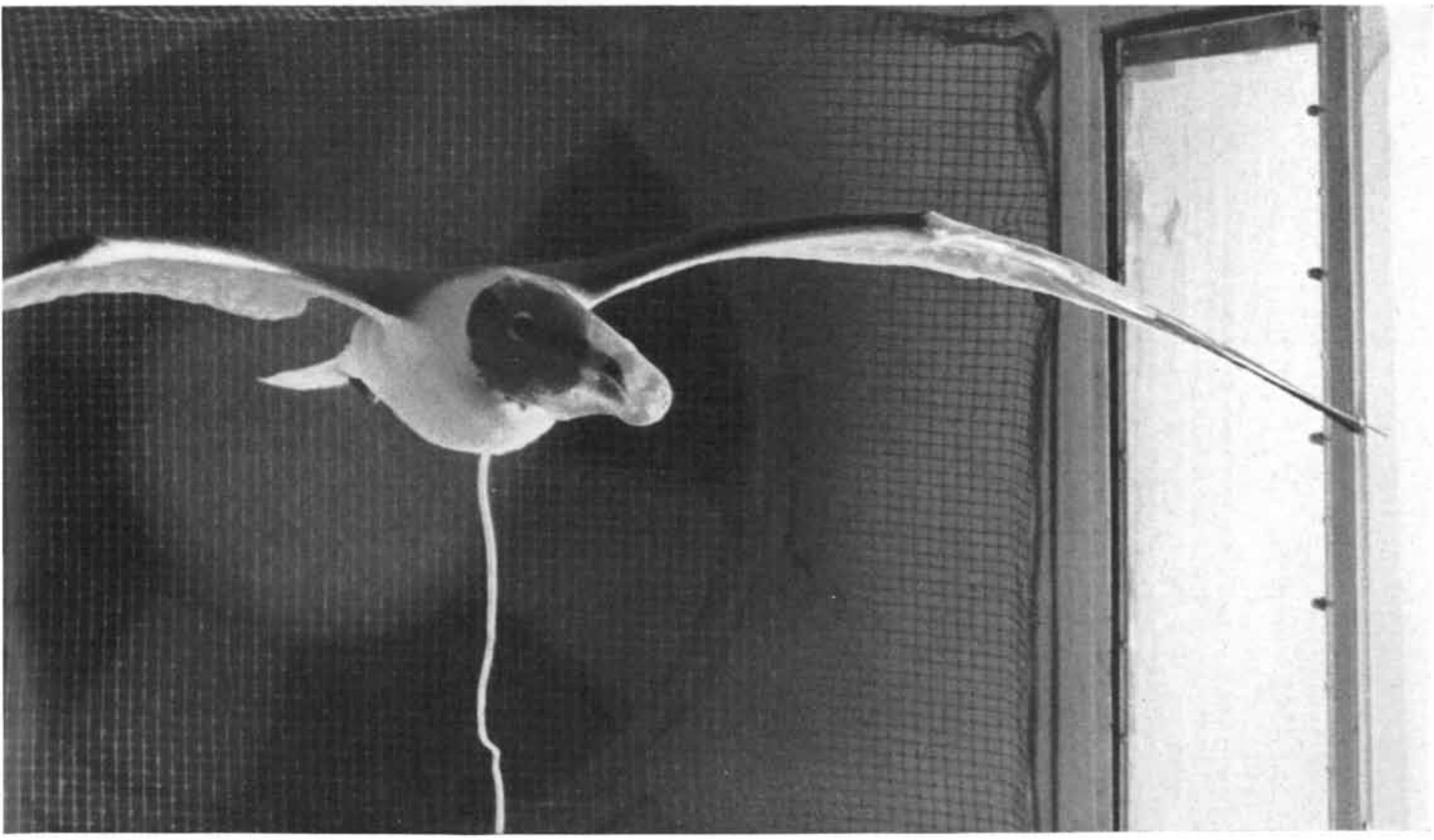
Training birds to fly in a wind tunnel is a lengthy process. My basic approach is simply to punish the bird mildly if it does not fly and reward it if it does. The punishment is an electric shock (detectable by humans but not painful) administered when the bird lands on the floor of the tunnel. The reward is the presentation of a perch on which the bird can rest after a successful flight. As the bird learns to control its movements in the confines of the test section and improves in physical condition, it will fly for steadily lengthening periods before it will risk a shock. In fact, gulls can be trained to fly in the wind tunnel without the use of electric shock; they will fly when nudged with a stick. After several weeks of training both budgerigars and gulls had reasonable endurance, even when they wore masks. They could fly at least twice as long as a typical half-hour experimental period without stopping. One herring gull flapped and glided almost continuously in the wind tunnel for 10 hours!

Once trained, both the budgerigars and the gulls "liked" to fly in the sense that they flew voluntarily as soon as the tunnel was turned on. During the training period, however, the budgerigars cleverly frustrated the observer. One bird avoided both flying and being shocked by hanging on to every protuberance in the test section. As these were discovered and removed, the bird finally learned to hold on to the electric grid with one foot to avoid completing the circuit. Another bird accomplished the same thing by rolling over on its back on the floor and keeping both feet in the air. When the birds could fly well in the tunnel, they were trained to wear the transparent mask.

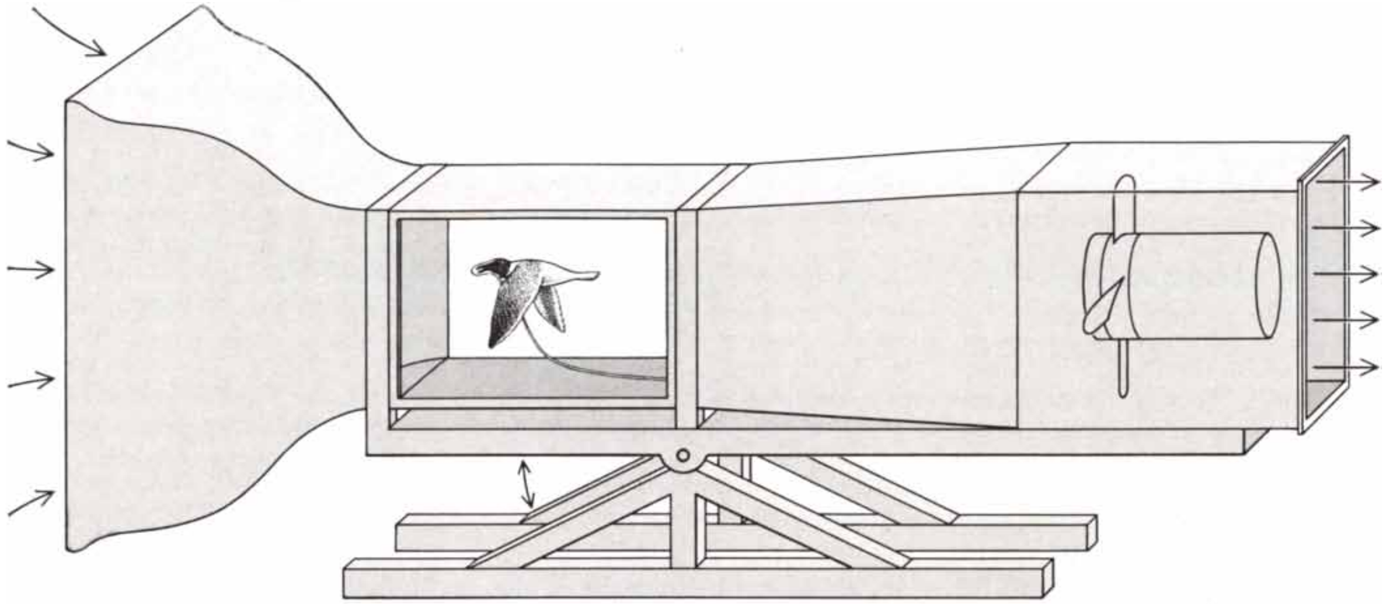
Whether in wind tunnels or in natural flight gulls and budgerigars, like other animals, obtain power for sustained work from reactions that combine oxygen from the air with fats, carbohydrates and proteins to produce carbon dioxide, nitrogenous wastes, water and usable energy. Of these sources fat, many investigators have concluded, probably provides most of the power for flight. Fat is certainly the best source of fuel in terms of weight. Gram for gram it contains almost as much energy as gasoline, more than twice as much energy as protein and eight times more energy than stored carbohydrate.

My research confirms that fat is the main source of energy in bird flight. When fats are burned in a calorimeter, they yield .7 milliliter of carbon dioxide and 4.7 calories for each milliliter of oxygen consumed. The experimental birds exhibited almost exactly the same exchange rates: the ratio of carbon dioxide exhaled to oxygen consumed by budgerigars and gulls was always between 1 : 0.7 and 1 : 0.8 during sustained flights. Animals normally do not use protein for fuel, and if the birds had been metabolizing carbohydrate, they would have consumed and produced equal quantities of oxygen and carbon dioxide. It can be calculated that more than 70 percent of the energy for flight came from fat metabolism, and that 4.8 calories of energy are released for each milliliter of oxygen consumed. This caloric equivalent of oxygen consumption offers a convenient way to determine the power expenditure of flight at different speeds and angles of ascent and descent.

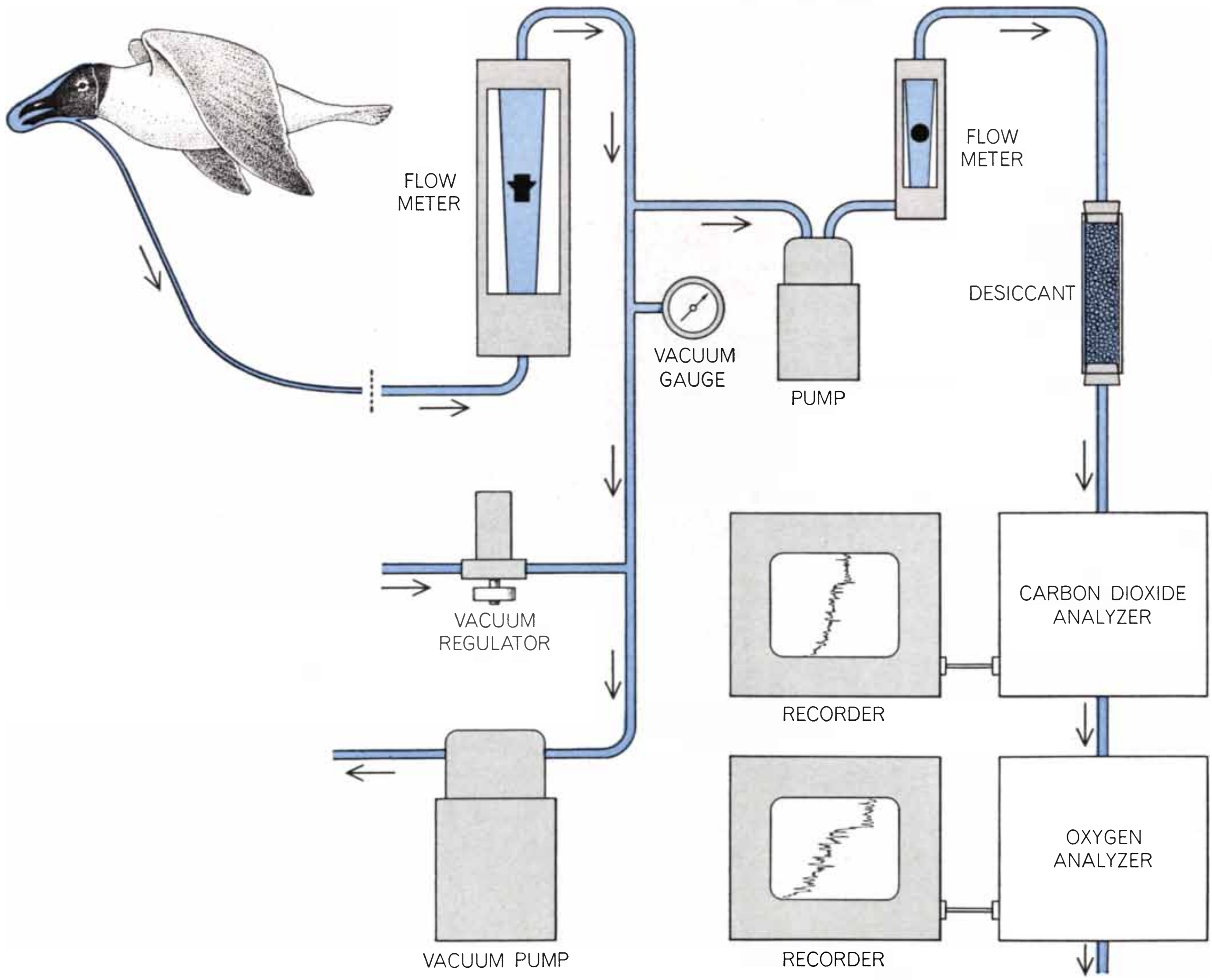
The wind-tunnel experiments show that there is no simple answer to the question of how hard a bird works to fly. The power expenditures of the budgeri-



plastic mask that captures its exhalations. A pump draws gases through tube to analyzers so that the gull's rate of fat and carbohydrate metabolism can be measured. Because the bird flies into the airstream it appears to stand still. In the rear is the tunnel's fan.



WIND TUNNEL designed for author's experiments can hold a flying laughing gull or other large birds. The 25-foot device can be tilted eight degrees to simulate ascending or descending flight. Speeds above 40 miles per hour can be achieved in the tunnel.



ANALYZING EQUIPMENT measures the carbon dioxide and oxygen exchange rates of a bird as it ascends, descends or flies a level course in the wind tunnel. The energy costs of the different kinds of flight can be calculated from the exchange rates. A vacuum pump draws gases from the mask while a smaller pump samples the flow continuously for the analyzers. Desiccant absorbs water vapor.

gar were markedly dependent on flight speed and angles of ascent and descent. For example, in level flight a budgerigar flying at 12 miles per hour expends energy at a rate of 152 calories per gram hour (the number of calories needed to move each gram of body weight at a given speed for one hour). As the bird's flight speed increases to 22 m.p.h. its power expenditure declines to a low point of 105 calories per gram hour. At higher speeds the power expenditure rises, reaching a high point of 165 calories per gram hour at 30 m.p.h.

When the budgerigar climbs at an angle of five degrees, its power expenditure is 140 calories per gram hour at 15 m.p.h. and rises slowly with flight speed to a maximum of 170 calories per gram hour at 26 m.p.h. When the bird is descending at an angle of five degrees, its power expenditure drops precipitously as its flight speed increases from 12 to 22 m.p.h. [*see illustration on next page*].

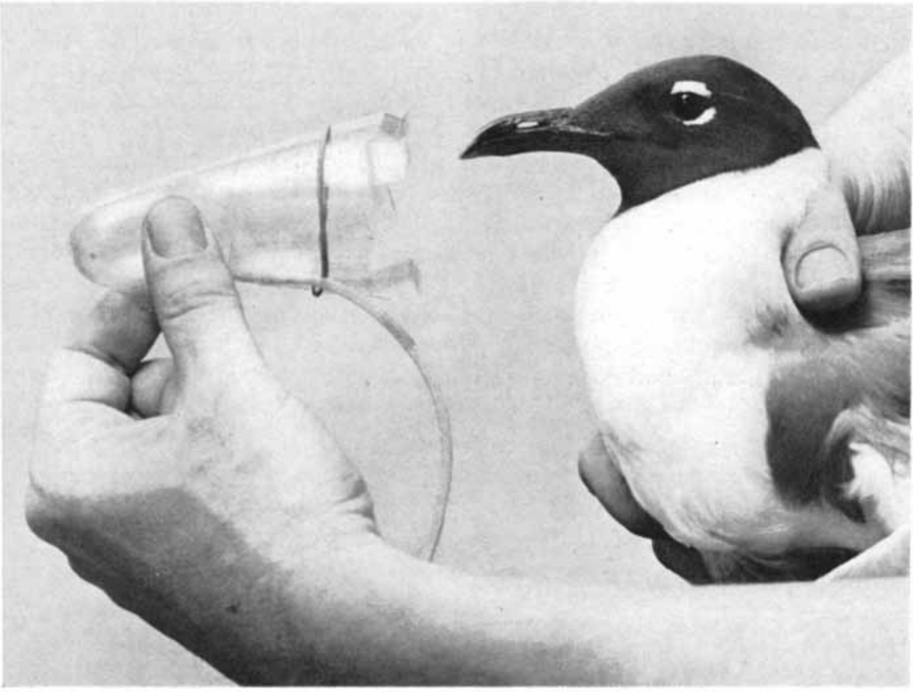
In evaluating the performance of the gull it should be noted that the animal was in some respects noticeably hindered by the mask. Its top sustained speed of 28 m.p.h. increased by almost 15 percent when the mask was removed. Moreover, the masked gull usually flew with its beak open, which wild gulls seldom do. This may mean that the bird was working unusually hard, or that the mask induced panting by interfering with the airflow that normally cools the beak.

Nonetheless, the wind-tunnel results are similar to the bird's performance in nature. The range of speeds at which the gull flew most economically in the tunnel (19 m.p.h. for endurance, 28 m.p.h. for distance) was about the same as the usual range of airspeeds for free-flying gulls. Laughing gulls have been tracked at 29 m.p.h. by a double-theodolite system. Radar tracking of ring-billed gulls and herring gulls respectively yielded mean airspeeds of 23 and 25 m.p.h. It should also be mentioned that the gull would not fly on an ascending path in the tunnel for more than a few minutes. This behavior, however, is not unusual in nature, where gulls prefer to gain altitude by soaring rather than flapping.

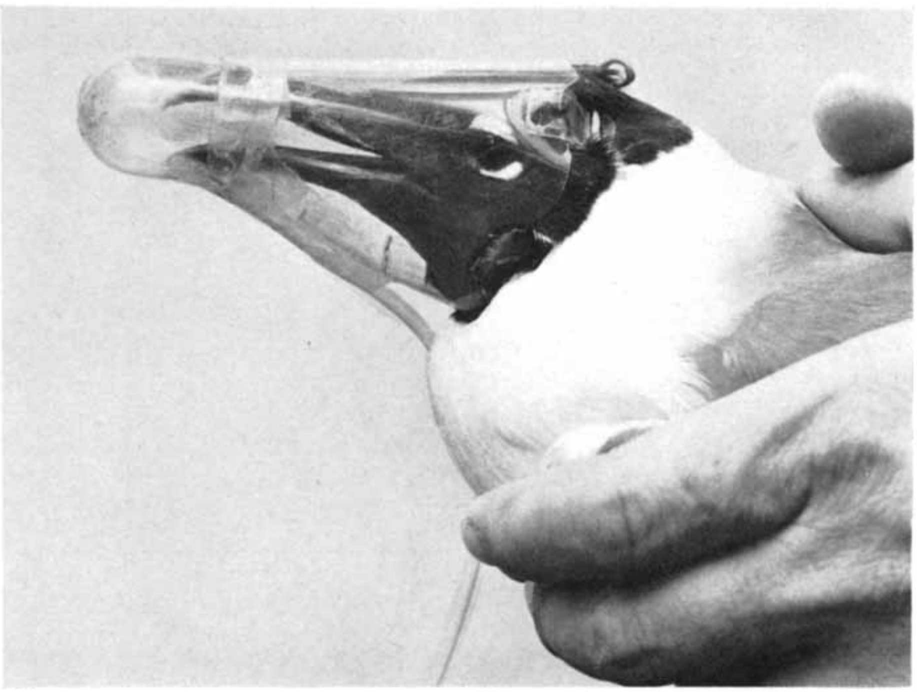
In level flight the power expenditure of the laughing gull, in contrast to that of the budgerigar, remains quite constant. It stays between 50 and 60 calories per gram hour whether the bird flies at 15 or 29 m.p.h. Both birds can expend power at much the same multiple of the basal, or resting, metabolic rate. The multiple is 13 to 20 for the budgerigar and 11 to 14 for the gull. Some mammals can do as well, but only for a short time. For example, a well-trained human athlete can expend power for a few minutes at 15 to 20 times his basal rate.

Power requirements in the wind tunnel obviously are related to the speed and angle of flight. This fact suggests that a bird in its natural environment could save energy by flying in such a way that minimal demands would be made on its metabolic resources. It is interesting to consider the various flight requirements a bird may encounter and how the animal could meet them with the lowest possible expenditure of energy.

A bird might, for instance, need to stay aloft for as long as possible, as



TO MASK A GULL the experimenter waits for a moment when the bird has stopped moving its head and then slips the mask over its beak. A rubber band secures mask to bird's head.



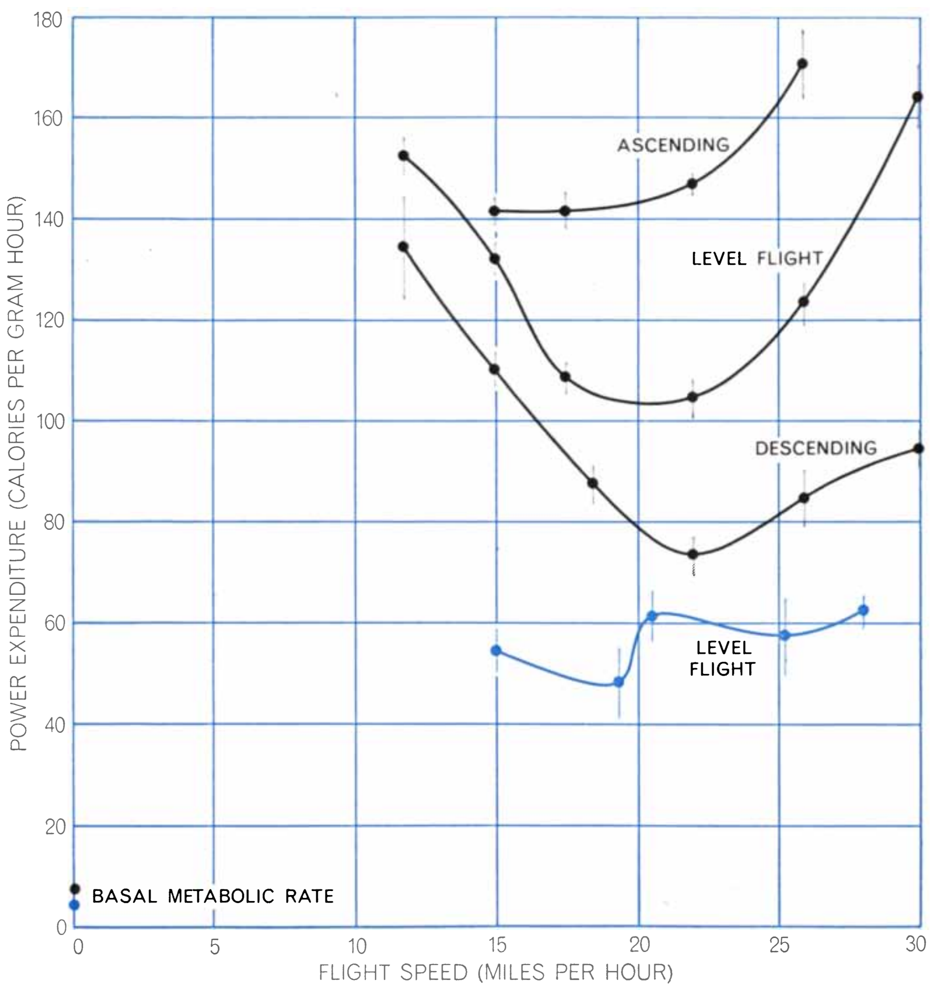
MASKED GULL, somewhat impeded by the weight and drag of mask, can fly at a steady top speed of 28 m.p.h. Without the mask the bird can increase its speed to 32 m.p.h.

in the case of a gull searching for food over the water. Here the bird might maintain a constant altitude and fly at a speed where power requirements would be at a minimum. This speed is 19 m.p.h. for the laughing gull and 22 m.p.h. for the budgerigar. At 22 m.p.h. a budgerigar consumes 1.1 percent of its body weight each hour as fuel when it metabolizes fat, and the gull uses half this proportion at 19 m.p.h. Since some birds can accumulate fat until it comprises half of their total body weight, they should have enough fuel to fly nonstop for tens of hours. Their precise endurance, however, is hard to estimate because not all the fat is available for fuel. Furthermore, the power requirements of flight probably decrease as the bird uses up its fuel supply and becomes lighter.

A migrating bird such as a budgerigar might also need to cover the maximum possible distance with a given amount of fuel. This would be accomplished at the speed where the ratio of power expenditure to flight speed is smallest. Budgerigars travel most economically at 22 to 26 m.p.h., at which speeds they consume .05 percent of their body weight in fat for each mile traveled. The laughing gull travels most economically at 28 m.p.h. and consumes only .024 percent of its body weight in fat for each mile traveled. These figures confirm that some birds can fly 2,000 miles without feeding. Indeed, the golden plover migrates 2,100 miles without food from Alaska to the Hawaiian Islands, and other land birds fly without food from the northeastern U.S. to Bermuda, and from Africa across the Sahara and the Mediterranean to Europe.

It is not surprising that both the budgerigar and the laughing gull have about the same speeds for maximum endurance and range in spite of the tenfold difference in their weight. In nature both are exposed to the vagaries of the ambient wind, and both must fly faster than ordinary wind speeds if they are to reach their destination against a head wind. In fact, the airspeed of almost all migratory birds, large or small, is more than 20 m.p.h.

Birds may also save energy during ascending or descending flight by seeking the speed where the ratio between the rate of climb and power expenditure is highest. To determine this point for budgerigars I used data from experiments where the wind tunnel was tilted at five degrees to simulate ascending or descending flight conditions. The rates of climb or descent were calculated by multiplying each bird's airspeed by .087, the number of feet its altitude changed (in effect) for each foot traveled forward. Finally these data were compared with the records of each animal's energy expenditure during the flight. I concluded that both ascending and descending flight were most economical at the speed where budgerigars have their maximum range: 26 m.p.h.



ENERGETIC COST OF FLIGHT for gulls and budgerigars is plotted. The steep curves represent a budgerigar's power expenditure in three kinds of flight. The gull produces a curve only for level flight (*color*) because it will not ascend in the tunnel and it behaves so erratically during descending flight that no valid data can be taken. When flying, budgerigars and gulls expend energy at 11 to 20 times the rate at which they metabolize while at rest.

Thus far I have discussed the economics of avian flight but have not mentioned its efficiency. Whereas flight economics involves the fuel costs of flying for various lengths of time and various distances, efficiency measures the relation between power input (power expenditure) and power output. The efficiency of a machine expresses the power output of the machine as a percentage of the power input. It shows how much of the energy put into the machine appears as useful work.

Several kinds of efficiency can be calculated, including the relation between total input and total output. In the case of the budgerigar, however, it is revealing to consider another kind of efficiency: the relation between the changes in power output that occur when the bird departs from level flight to ascend or descend and the accompanying changes in power expenditure or input. This approach makes it possible to compare the bird's efficiency with that of other animals. It also leads to a hypothesis that may explain why some birds swoop in flight instead of pursuing a level course.

Power output is the product of the speed of the bird and the thrust force it exerts. The bird also expends energy to create a lift force, but this force is essentially constant as the tunnel is tilted to represent ascending and descending flight. Therefore when the bird ascends from its level flight path at a given speed, its power output increases over power output in level flight solely because of changes in thrust, and when it descends, its power output decreases for the same reason. This increase or decrease in power output exactly equals the rate at which a bird would gain or lose potential energy if it actually changed altitude.

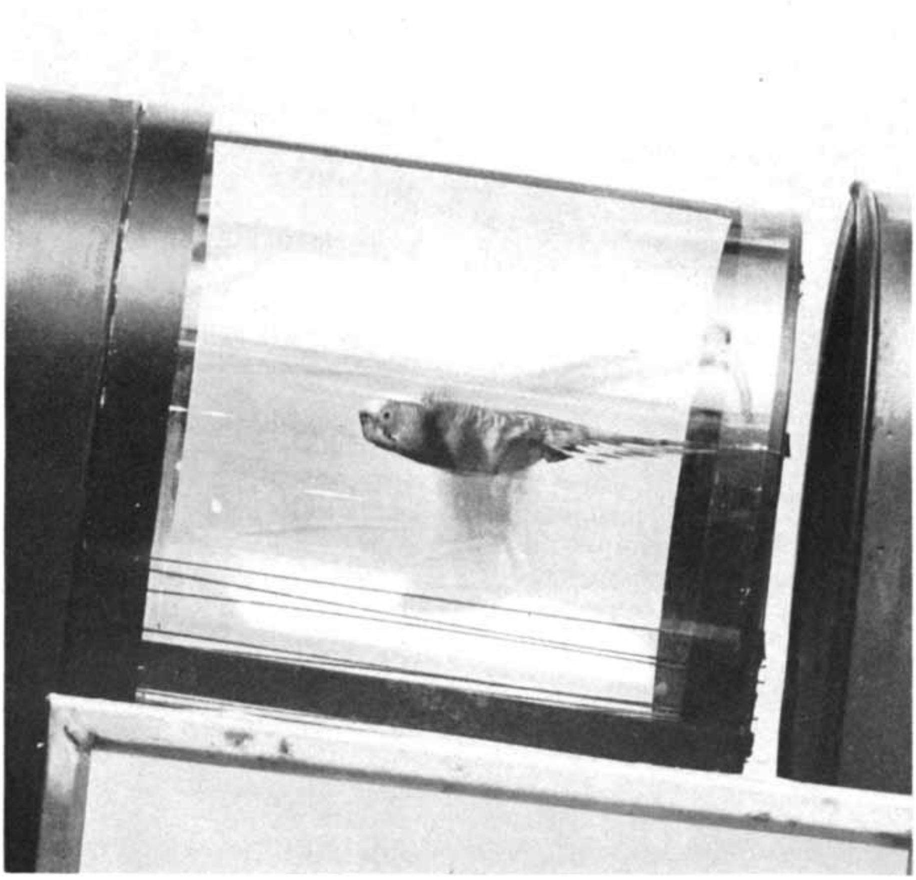
Once the power output changes have been derived, calculations of efficiency can be completed by using the measured increases or decreases in power expenditure for climbing or descending at a particular speed. For an ascending budgerigar the efficiency is more than 50 percent at the lowest speed of 12 m.p.h. The efficiency then drops to between 15 and 18 percent as the speed reaches and exceeds 17 m.p.h. Efficiency during descent is more constant, changing from 14 to 24 percent between speeds of 12 and 30 m.p.h. At 17 and 27 m.p.h. the efficiency of ascent and descent are equal.

Since the efficiencies for ascent describe a bird working to increase thrust, they are comparable to efficiencies for increased work rates in other animals walking up inclines or pulling loads. Appropriate measurements under these conditions are available for men, dogs and horses. All have efficiencies between 30 and 35 percent (that is, the change in power output is 30 to 35 percent of the change in power input). The budgerigar over most of its range of flight speeds is about half as efficient as these animals, but at low flight speeds it is more efficient.

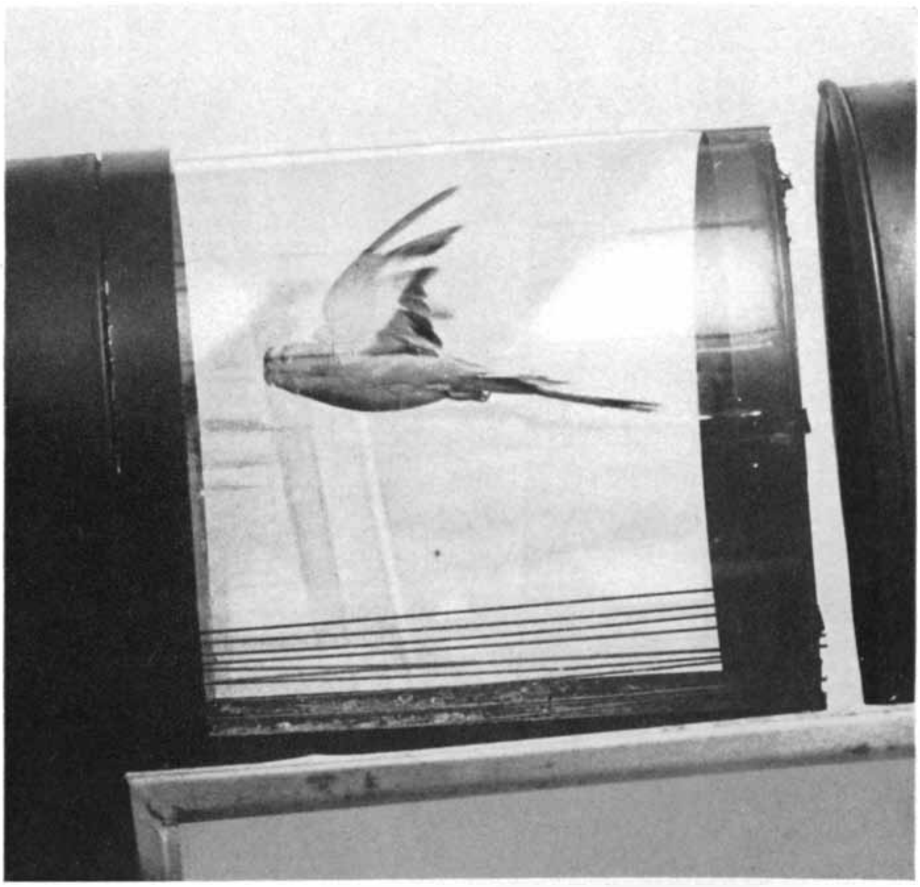
High efficiency for increasing thrust at low speed is consistent with the fact that in nature budgerigars often feed on the ground. Since the budgerigar must take off from the ground, it must simultaneously accelerate and gain altitude. (If it took off from a tree it would already have altitude and would need only to accelerate.) Because of the efficiency with which the bird utilizes energy at low speeds it can both get into the air and reach cruising speed at a cost that is little more than that of slow and level flight.

The reader should not conclude at this point that a bird gains altitude most economically at low speeds. I have already mentioned that the best speed for climbing is 26 m.p.h. Slow flight for the budgerigar is a costly process, but as long as the bird must fly slowly it might as well go up. The extra cost is small. At speeds above 17 m.p.h. the efficiency of ascent has dropped, but so has the total cost of flight. As a result the bird gains altitude with increasing economy as it approaches its optimum climbing and cruising speed of 26 m.p.h.

These studies of the budgerigar's effi-



ASCENDING FLIGHT can be simulated in the wind tunnel by raising the front end. To "climb" at a given speed the budgerigar increases thrust while lift remains almost constant.



DESCENDING FLIGHT is simulated when the tunnel is tipped downward. As the bird "climbs" or "falls," aerodynamic and gravitational forces are identical with those in nature.

ciency suggest that the swooping flight of some finches and woodpeckers and the slowly undulating flight of migratory birds (which may ascend and descend as much as 20,000 feet during long journeys) may represent an energy-saving stratagem. When the efficiencies of ascending and descending flight are the same at a particular speed, as they are for the budgerigar at 17 and again at 27 m.p.h., the extra power expenditure during ascent is just equal to the saving during descent. Thus the bird could climb to a given altitude and descend at no extra cost over level flight for the same length of time.

It follows that if the efficiency of ascent is greater than the efficiency of descent, the bird can actually save energy by flying in a swooping or undulating path. In fact, the lower the efficiency of descent, the more energy the bird saves. Since the efficiency of descent for the budgerigar is always less than 25 percent, one can speculate that if this bird could ascend (that is, increase its thrust) at cruising speeds with efficiencies as high as the 30 to 35 percent values for man, the dog and the horse, it could save energy by flying in a swooping pattern. One would predict, however, that in nature the budgerigar cruises on a straight path because in actuality the efficiency for ascent is less than the efficiency for descent between speeds of 17 and 27 m.p.h.

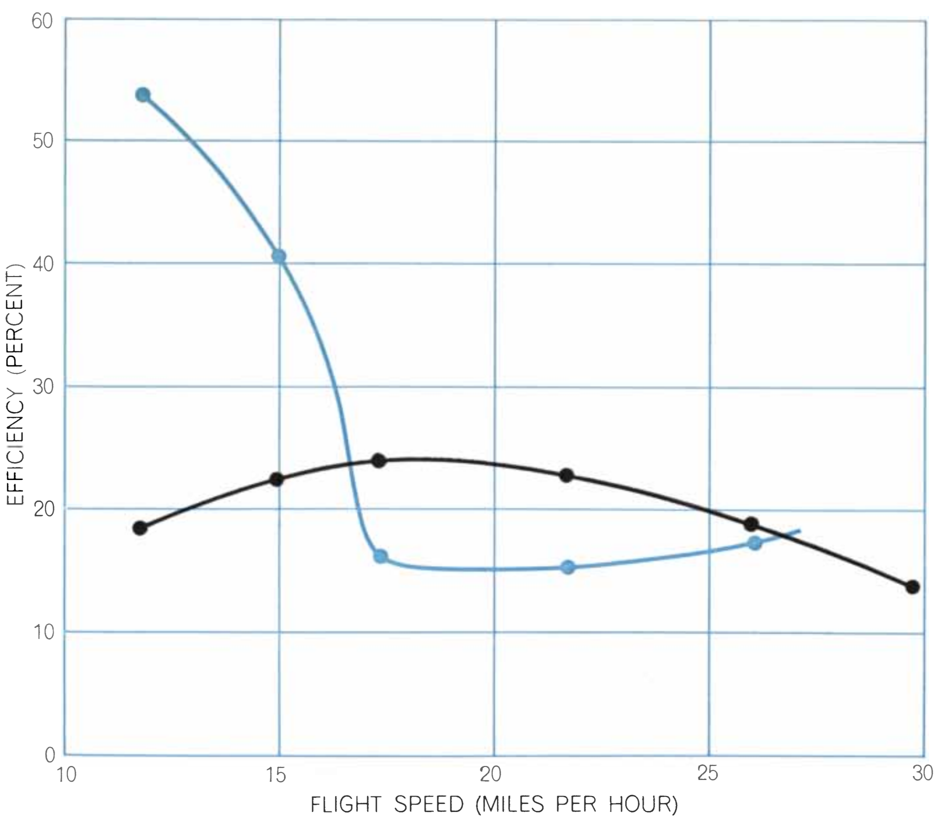
How does flight compare as a form of locomotion with walking or running, or with the flight of aircraft? Two points of comparison are speed and endurance. In these respects birds are clearly superior to ground animals. Even small birds fly for hours at speeds in excess of 20 m.p.h., and larger birds such as ducks can cruise at 40 to 50 m.p.h. A few large ground animals such as antelopes, the ostrich and the cheetah can attain these higher speeds, but none can maintain them for long. I have mentioned that some birds are able to fly without feeding for tens of hours and for 1,000 miles or more. No walking or running animal can equal these feats, which in terms of endurance are respectable even for aircraft.

Another point of comparison is the energetic cost of transport, measured in units of calories required to transport a gram of body weight one kilometer. These units have the advantage that, whatever the size of an animal, they indicate the cost of moving a given mass a given distance. For example, the cost of transport for a flying bee is about the same as the cost for a running rat weighing 3,000 times as much. Thus when 300 grams are moved one kilometer, either in the form of a swarm of 3,000 bees or a single rat, the caloric cost is the same.

When measured in this way, the cost of transport for various swimming, walking, running and flying animals generally goes down as body weight goes up. A fruit fly, for instance, expends more energy to move each unit of its weight a given distance than a locust does [*see illustration on page 78*]. When walking, running and flying animals are compared with one another, however, flying animals prove to be much more economical than ground ones. A walking or running mammal expends 10 to 15 times more energy to cover a given distance than a bird of the same size does. It is no wonder that small mammals do not undertake long seasonal migrations! Some birds can even travel more economically than some machines. For example, a pigeon flies more economically than a light plane. Moreover, a Canada goose may be able to perform better than a jet transport.

Although the wind-tunnel experiments yield interesting information about metabolism and flight, it must be remembered that these experiments reproduce only certain aspects of natural flight conditions, never their entire rich variety. In addition, the experiments introduce some unnatural conditions. Although the aerodynamic forces in the test chamber ideally are the same as those in still air, the flow of air in the tunnel is more or less turbulent, and the walls of the test chamber may interfere with the flow of air around the bird. The effect of these distortions can be hard to determine. Relatively small amounts of turbulence, for instance, can improve the aerodynamic performance of model birds and model airplane wings, but extreme turbulence increases the power expenditure of flying budgerigars. Furthermore, a bird flying in a tunnel and wearing a mask has limited room to maneuver, and its shape, weight and weight distribution differ from those of a free-flying bird.

Even if one could be certain that a bird flying in a wind tunnel utilized energy at exactly the same rate as a bird flying through still air, there is a degree of uncertainty in any estimate of the cost of flight in the natural environment. This is particularly true of long migratory flights. The air in which a free bird flies is not still but moves in a complex manner. It is heated at the surface of the earth, rises and is replaced by descending air. Superimposed on these thermal currents are wind currents that flow hor-



EFFICIENCY OF FLIGHT varies at different speeds for the budgerigar. At 17 m.p.h. and again at 27 m.p.h. the efficiencies of ascending (*colored curve*) and descending flight are equal to each other, indicating that at these points swooping costs no more than level flight.

■ Counting the Mzma and the Peykan and the Warzwa, there are about 150 makes of automobile running over the world's roads today. They pass each other, in the foothills of the Andes, in the Loire Valley, in the streets of Istanbul, on the string-straight roads of Texas, as anonymously and as indifferently as subway riders—all except one. Porsche. When Porsches pass, their headlights flash.

Why? Someone has said that the wealthy and the talented are comfortable only in each other's company. Men in risky occupations—high-wire performers, hard-hat divers, fighter-pilots—tend to feel the same way. Members of some select groups can identify each other by sight (a karate-player's hands) or by sound (a Cambridge graduate's accent). Some wear identifiers (an Esperanto speaker's lapel button, the rosette of the Legion d'Honneur). Some nod. Some speak. Porsche owners flash their head-lights.

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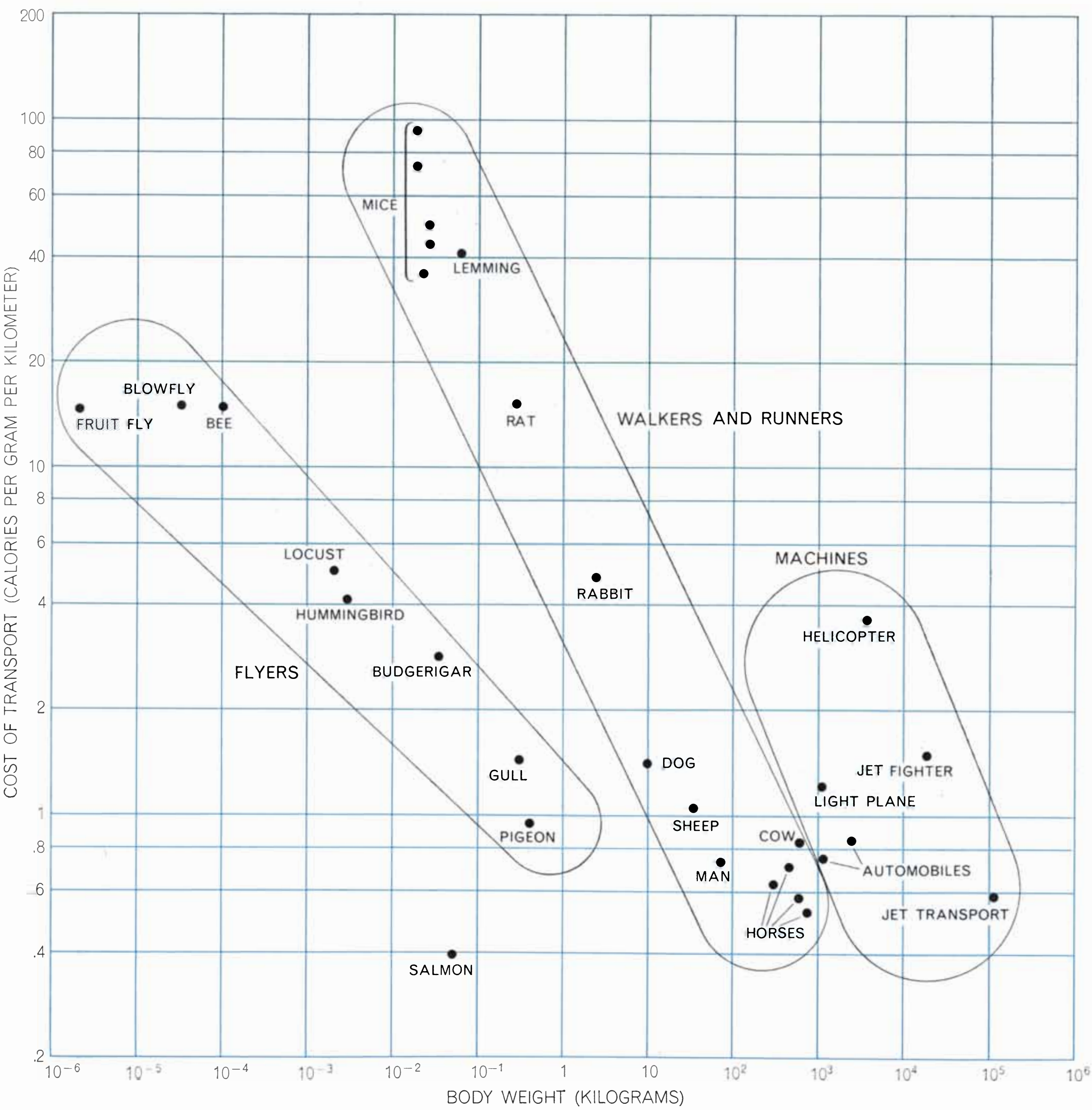
PORSCHE

Greetings from one insider to another

izontally over flat surfaces but develop vertical components when they encounter other wind currents or surface features such as trees and hills. Such drafts and currents are strong enough to influence the power expenditures of flying birds. Since most birds fly at airspeeds of 20 to 30 m.p.h., even everyday winds could change their ground speed by 50 percent.

Vertical currents can be strong enough to hold a bird aloft, as is demonstrated by birds soaring in thermals, over ridges or over ships at sea. Even in the absence of vertical currents birds are accelerated upward or downward by changes in either the speed or the direction of the wind. The albatross in particular is reputed to remain aloft indefinitely without flapping its wings by moving through wind-velocity gradients over the sea. Changes in horizontal wind velocities large enough to influence bird flight in this way are ubiquitous on windy days. They occur with gusts of wind, in the wake of surface features such as trees and in the wind boundary layers above the surface of the land and the sea.

I have commented here only on the energetics of avian flight, but I have also used the wind tunnel to investigate other aspects of flight physiology: respiratory mechanics, water and heat budgets and responses to simulated high altitudes. In addition the wind tunnel is useful for aerodynamic investigations. In this connection my colleagues and I have studied the flapping flight and the gliding flight of vultures and hawks. Over the next few years we hope to use our wind tunnel to investigate other areas of avian biology.



BIRD FLIGHT, when compared with other kinds of animal locomotion, generally is more economical than walking or running. Large flying birds can even travel farther for each calorie per unit of weight than a light plane or jet fighter. The young salmon's performance shows, however, that a fish can travel more economically than gulls, pigeons, horses or any other kind of animal.

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These events have taken place within milliseconds and the image is now being recorded on the film.

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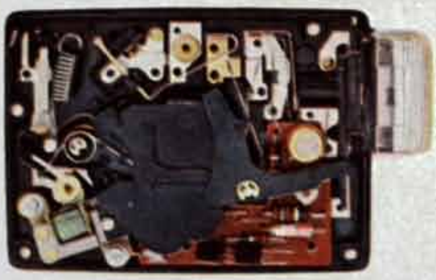
The system works so quickly that it actually measures the burst of light of a flashbulb during the split-second of its existence and simultaneously regulates the shutter for an unerring exposure. Every time.



Anthropologically based rangefinder.

A transparent red square in the Colorpack II viewfinder shows you when you're 5 feet from your subject. And since that's Colorpack II's optimum distance for all flash shots, and most daylight pictures of people, the red square is a very handy device.

This is how it acts as a simple, but accurate, rangefinder:

The red square is a stadimeter (it measures distance by measuring the known size of a reference object as it appears in your field of vision).

Our reference object is the distance from the top of the head to the chin-tip. And we obtained it with the help of a little anthropology. This science tells us that the head-top to chin-tip dimension is remarkably constant in *homo sapiens* over the age of three. And since picture subjects very often turn out to be *homo sapiens* over the age of three, our reference object is a most appropriate one.

To find the distance, simply set the Colorpack II lens to the 5 foot click mark. Then look in the viewfinder and move backward or forward until the red square covers the subject's face from head-top to chin-tip and you're set to shoot.

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The desired focal length of the Colorpack II lens was the equivalent of the lenses in the more expensive Polaroid Color Pack Cameras (about 114mm).

This new lens would be mounted on a small, rigid camera body. And, ideally, it would not require a monstrous front housing.

The only way to achieve the ideal lens for this set of conditions was to design a semi-telephoto lens system (that is, a lens in which the distance from the front element to the film plane is slightly shorter than its effective focal length). The task was complicated by the fact that the desired lens would have to be a wide-angle telephoto. And telephoto lenses don't lend themselves to wide field angles (in this case, 56° full field).

The solution to the problem was obtained by feeding a series of design constraints into a computerized lens optimization program.

The result of this collaboration between man and machine is a compact, front element focusing, brilliantly sharp, triplet lens. A color-balanced, telephoto-type lens that provides a combination of optical qualities unique in its price range.

Because it's a precision lens, we've precision-mounted it on the camera with an ultrasonic welding technique that assures accurate seating and secure attachment.

*Suggested list price. Polaroid®

Hand-held instant darkroom.

Of course, one of the most improbable aspects of Colorpack II is the Polaroid Land film it uses. It develops the print outside the camera in your hand. Even in bright sunlight. Without fogging.

This is even less probable when you consider that one of the films (our 3000-speed black-and-white) is the most light sensitive general purpose film in the world.

How did we do it?

By opacifying the outer surface of our positive-negative film packet with a thin coating of carbon particles, suspended in a polymer.

Sealing the edges of the packet was more of a problem:

As the film is pulled out of the camera, it squeezes between two bars, breaking a pod containing the developer. This reagent contains suspended carbon particles which further inhibit light transmission. The developer spreads between the positive and negative film layers until it is trapped by a special mask, laminated around the edges. When this happens, the packet becomes light-tight.

More and less.

What's *more* is:

Flashcube capability that lets you take four indoor shots as fast as you can pull the film packets out of the camera. And when the last flash has been used, the dead cube stops at an angle to remind you to replace it. (You'll never lose a great flash picture because you forgot to put a fresh bulb in your camera.)

A lightweight stainless steel developer spreader that can be removed to facilitate cleaning.

Pack film that loads in seconds. The pack film lets you take rapid sequence shots, too. (Since you pull each film packet out of the camera after the shot, you can take another picture immediately, while the first one is developing outside.)

A shutter lock. A turn of the shutter release button locks it to prevent accidental exposures.

An incredibly tough, durable camera body.

And alkaline batteries for the electric eye and flash systems that last a full year.

What's *less* than you'd expect is the weight:

Twenty years ago, our original Polaroid Land camera weighed 4 pounds, 5 ounces. And delivered a sepia print. In 60 seconds.

Colorpack II weighs just 20 ounces. And delivers a rich color print. In 60 seconds.

What else is less is the work you do. Because this camera was designed to make taking a picture almost as easy as wishing for it.

Last and least.

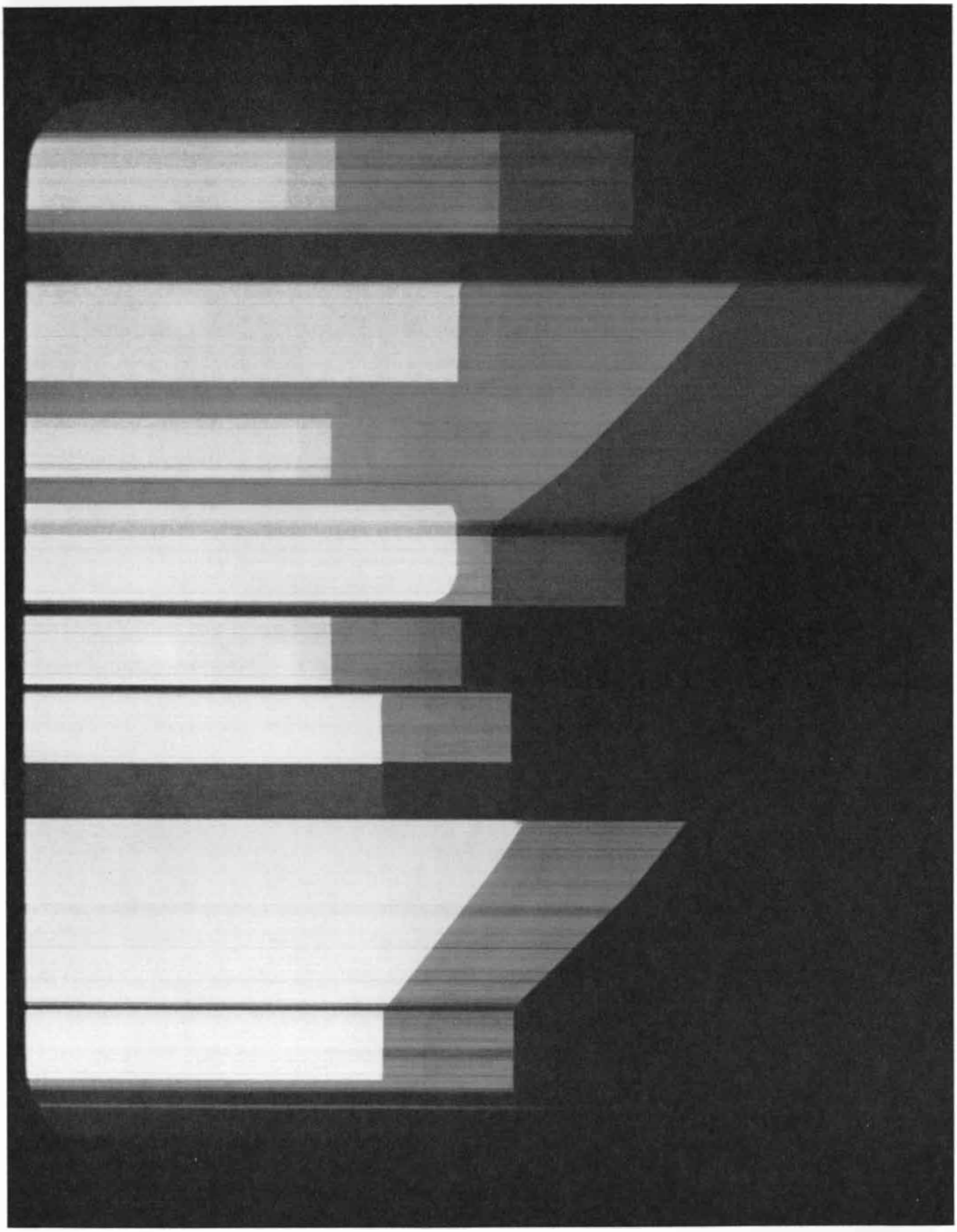
$29.95*

That's all you pay for the camera that has all these features:

Colorpack II.

Impossible? No.

Improbable? Yes.



OPTICAL RECORD of a shock wave in a solid was obtained by photographing light reflected from mirrors mounted on the specimen and on the plate holding the specimen. A bright light directed at the mirrors is transmitted through one or more slits as shown schematically in the illustration on the opposite page, and the images of the slits are swept rapidly across a film by means of a rotating mirror. In this case there were three slits that had different filters; the filters account for the different degrees of darkness in the bars. When a shock wave, here originated by an explosion, reaches a mirror, the mirror loses reflectivity and the photographic image is cut off, vertically in the case of mirrors mounted flatly and obliquely in the case of mirrors mounted obliquely. Through interpretation of the photograph the experimenter can determine the velocity of the shock and of motions on the surface of the specimen.

SHOCK WAVES IN SOLIDS

When an explosion or a projectile is directed against a solid, an intense wave of pressure and stress passes through it. Such waves can be used to study materials and also to process them

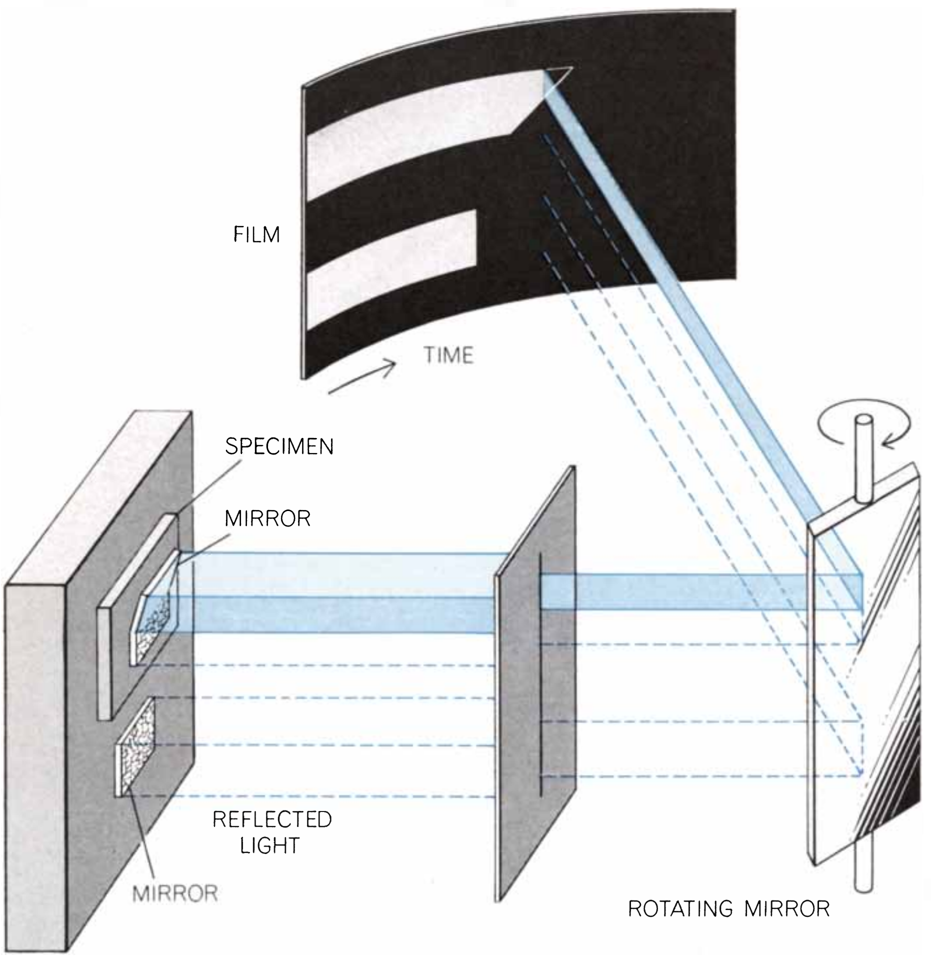
by Ronald K. Linde and Richard C. Crewdson

A shock wave is a pulse of pressure or stress that moves through a medium at a speed faster than the medium can transmit sound and produces a steep, almost instantaneous rise in stress at the points it reaches. The wave delivers a large amount of energy, as anyone knows who has experienced even the relatively mild sonic-boom form of shock wave generated by an airplane flying at supersonic speed. Until rather recently the behavior of shock waves was studied mainly in gases. Now, however, shock waves are being used to produce dramatic changes in solid materials.

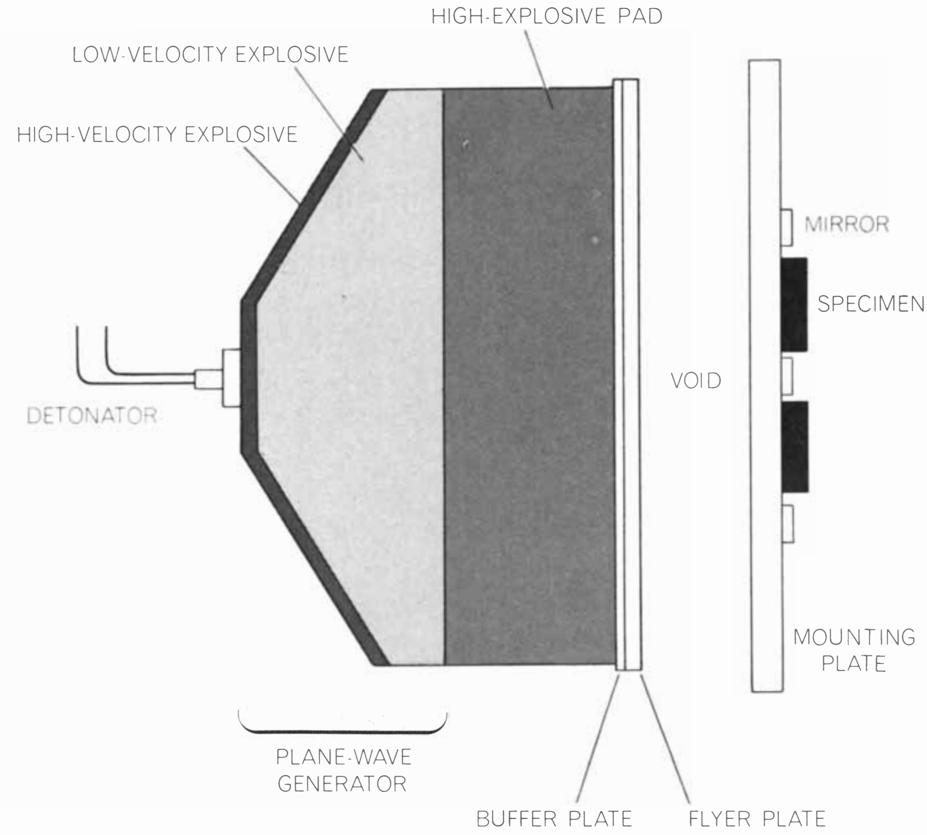
Much of the interest in this subject has arisen from recent improvements in the techniques of creating shock waves in solids and in the instrumentation for recording the behavior of the waves. As a result the study of shock waves in solids has made valuable contributions to solid-state physics and to the understanding of the properties of materials. Moreover, the fact that it is now possible to control quite precisely the extreme conditions of pressure, temperature, shear stress, strain rate and compression created by a shock wave in a solid has given rise to a number of commercial applications of the technique. Among the notable examples are the direct conversion of graphite to diamond, the creation of new polymer forms and the bonding together of layers of materials in a few millionths of a second with a single shock.

Our group in the Poulter Laboratory for High Pressure Research at the Stanford Research Institute has been involved with both the exploration of the subject and the applications of it. We create a shock wave in a solid either by firing a flat-faced projectile at it with a gas gun or by detonating an explosive that can be directly in contact with the specimen or in contact with a flat metal plate that is propelled against the specimen by the explosion. Some of the changes produced as the wave travels through the solid are so transient that they must be observed and measured in less than a millionth of a second; others are more permanent and can be studied in specimens retrieved after shocking.

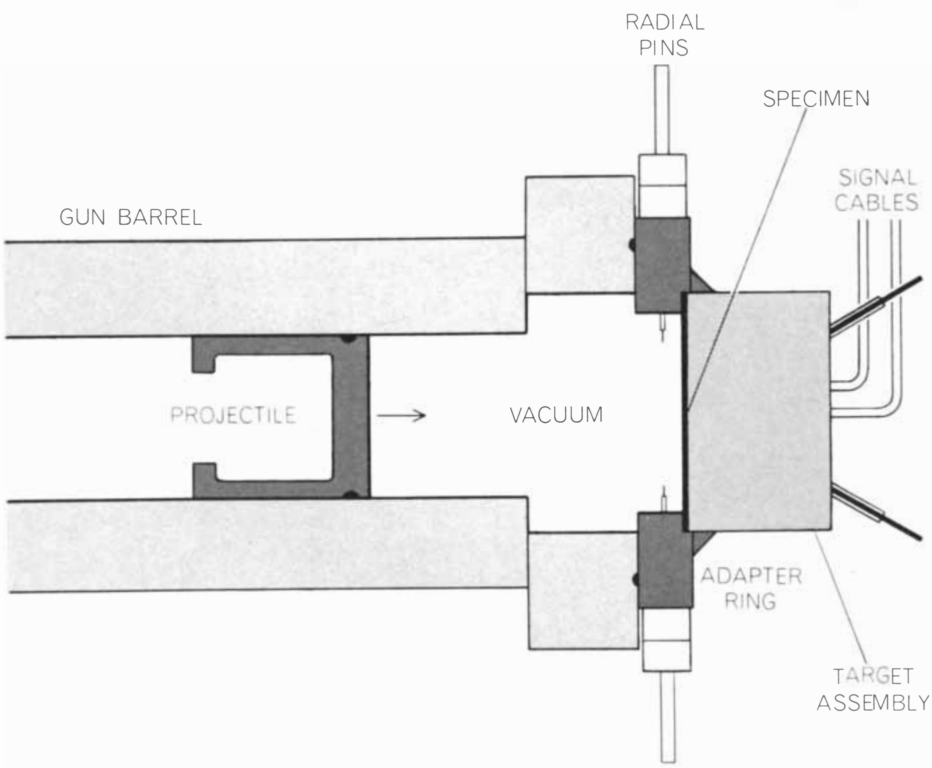
In many respects the behavior of a shock wave in a solid is much the same as it is in a gas or a liquid. The chief difference is that the shock pressures attainable in solids are far higher than those attainable in gases and appreciably higher than those obtained in liquids. Although solids and liquids are usually regarded as being incompressible, it is possible with present shock-wave technology to compress many of them to more than twice their original density.



MIRROR TECHNIQUE involves reflecting light, originated by an intense source, from mirrors placed on the specimen and on the mounting plate. Reflected light goes through the slit to a rotating mirror, which sweeps an image of the slit along the film at high speed.



EXPLOSIVE SYSTEM for creating a shock wave in a solid is depicted for a typical experiment. The conical shape of the explosives adjacent to the detonator is designed to form the detonation front into a flat plane before it reaches the high-explosive pad. In this way the flying plate can be directed at an accurately flat attitude toward the target array.



ALTERNATIVE MEANS of creating a shock wave in a solid is a gas gun, which fires a flat-faced projectile against the specimen. With this apparatus the experimenter can achieve more precise control over the attitude and speed of the projectile than he can with an explosive system, but for large samples the explosive system generates more intense shocks.

Under such extreme conditions even the strength of steel is for most purposes negligible. The passage of a shock wave through a solid can rearrange the atomic lattice in the solid, alter the configuration of electrons around the atoms, change the physical properties of the material and modify its internal balance of energy.

What happens as a shock wave passes through a solid can be visualized in an analogy with a railroad train made up of boxcars coupled by springs instead of the usual inelastic couplings [*see illustration on page 86*]. The boxcars represent atoms in a solid, and the springs represent the elastic interaction of atoms. If two such trains were to collide, a shock wave would pass through each of them in an essentially linear or one-dimensional way. The wave travels at a velocity much greater than the velocity of the individual boxcars.

As the illustration suggests, the important quantities in shock-wave physics are the velocity of the shock, the increment of velocity given the atoms or particles by the shock, the density of the particles and the axial stress, which is the component of stress in the direction of shock propagation. Since the laws of conservation of mass and momentum apply, the four quantities can be related by two simple equations, which are called Hugoniot equations: the initial density times the shock velocity is equal to the density under compression times the difference between the shock velocity and the particle velocity [$\rho_0 U = \rho(U - u)$], and the axial stress is equal to the product of the initial density, the shock velocity and the particle velocity [$\sigma = \rho_0 U u$]. For a given material initial density is fixed, so that the equations contain four variables; measurement of any two of the variables makes it possible to compute the other two.

The shock front is the part of the wave that does the compressing. Behind the shock front is a region where the stress decreases rapidly from its peak value. This part of the pulse is called the rarefaction front. Rarefactions serve to transmit a reduction in stress at one position in a material, such as an edge where stress can be relieved by bulging, to the rest of the material. The shock and rarefaction processes are generally assumed to be adiabatic, meaning that they occur so rapidly that no flow of heat takes place, even though large changes of temperature may result from the conversion of one form of energy into another one.

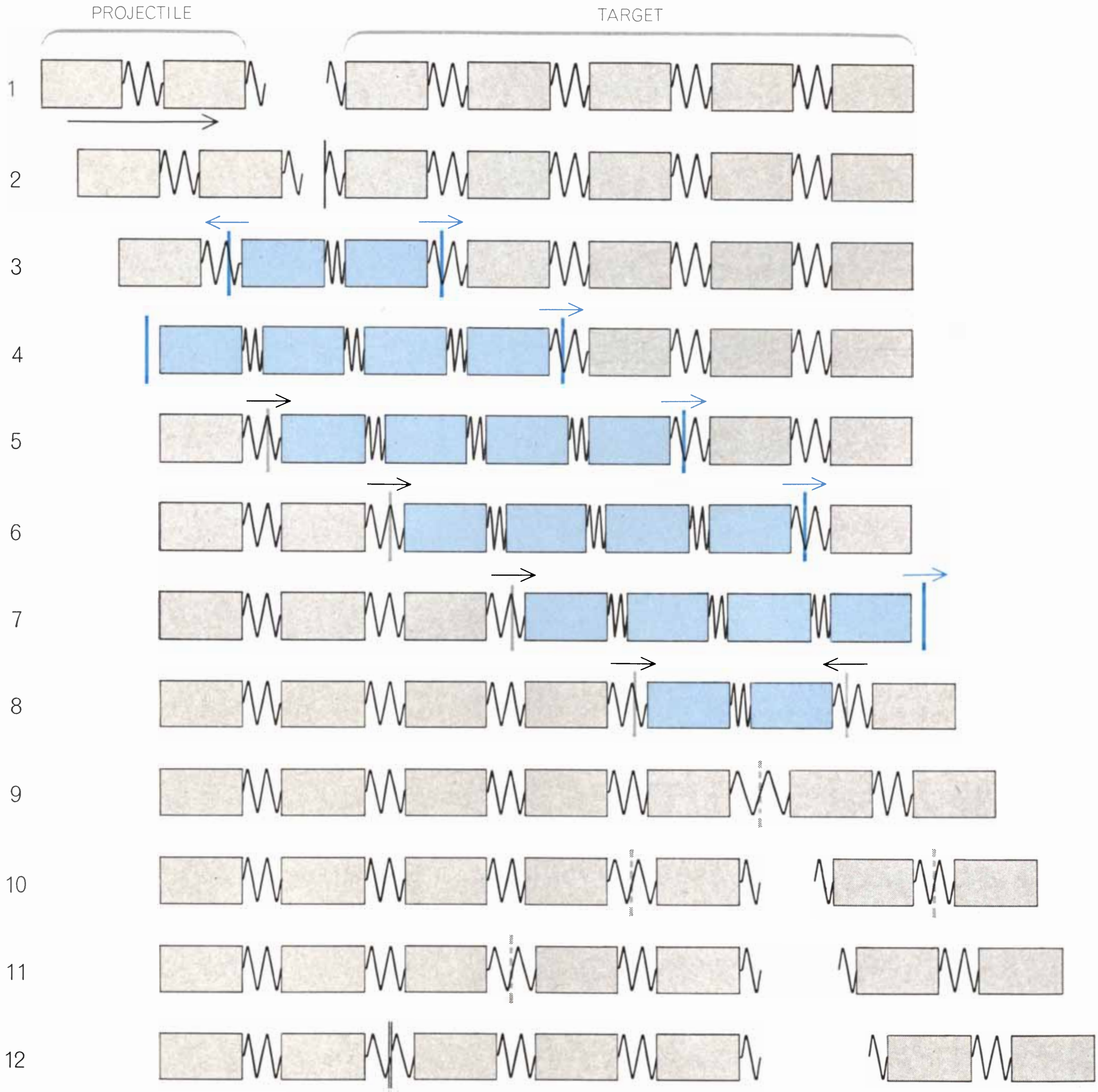
DETONATION of an apparatus such as the one shown in the top illustration on the opposite page produces a substantial explosion. It destroys the apparatus, but not before the specimen's response during the first moments is recorded by streak camera in bunker.

For simplification of the theoretical analysis, and for an understanding of a number of subtle effects produced, it is of considerable importance that the solid can be treated as one-dimensional. The opportunity for doing so arises in the following way. A typical specimen is a slab of material that is wider and longer than it is thick; it might be several inches wide, several inches long and half an inch thick. When a shock wave of uniform lateral extent moves through the thickness of the slab, rarefactions originating from the edges will tend to communicate to the center the fact that the slab is of finite width. Because the plate is thin in relation to its width, however, the message does not actually reach the center during the time it takes the shock to pass through the thickness of the slab, so that the effect is the same as if the slab (and thus the shock pulse) were of infinite lateral extent. The result is that each small region of the slab experiences exactly the same stresses as its neighbor and must undergo the same deformation as its neighbor. The only way this can occur is for deformation to take place solely in the direction of the shock pulse, and so the experimenter effectively has a one-dimensional condition to consider.

The boundary conditions that enable us to treat the solid as one-dimensional are referred to as plane shock conditions. Plane shock waves can be produced most effectively by either the gas gun, which makes it possible to control precisely the attitude of the projectile directed at the target, or by detonation of a special plane-wave explosive system [*see illustrations on opposite page*]. Only the axial stress is measured in shock experiments. The lateral stresses are inferred from the properties of the material.

Measurement of the rapid transformations that take place in a solid during the passage of a shock wave requires a number of sensitive and quick-acting devices. Shock stress, for example, can be measured with stress transducers. The most versatile stress gauge now available, which was developed at the Stanford Research Institute, is one made of Manganin, an alloy consisting of 84 percent copper, 12 percent manganese and 4 percent nickel. This alloy is particularly useful because the change in its electrical resistance is directly proportional to the stress it is sensing but is essentially independent of the temperature. By means of this gauge it is possible to record the stress as it changes with time; the resolution is usually as high as 10^{-8} second.

Shock velocity can be measured electronically or optically by recording the time required for a shock to pass through a known thickness of material. Optical techniques often make use of a "streak camera," which records an image swept across a strip of photographic film at a speed of 45,000 miles per hour [*see illustrations on pages 82 and 83*]. The film records light reflected from mirrors mounted on the specimen or on the plate holding the specimen. When a shock wave reaches a mirror, the mirror loses reflectivity. The photograph gives a continuous record of the intensity of the light reflected by the mirror over a period of time; the resolution is on the order of 10^{-7} second or better. (The event shatters the mirror, but not before the desired information has been obtained.) The way the photograph enables the experimenter to measure shock velocity is exemplified by the top two bright streaks with vertical ends in the photograph on page 82. The top streak is from a mirror mounted on a plate that held several specimens; the lower streak is from a mirror mounted on a specimen. The difference in the length of the streaks is re-



EFFECTS OF A SHOCK WAVE are shown in a trainlike arrangement wherein the boxcars represent atoms in a solid and the spring couplings represent interaction of atoms. Train at left (*1*) is analogous to a projectile hitting a solid target. On collision (*2*) the springs are compressed and the cars of each train are compressed into a denser array. A shock front (*colored arrows*) that transmits the compression from car to car moves at a velocity much higher than the velocity of each car within the shocked region (*light color*). When the shock front reaches the end of the projectile (*4*), a rarefaction or unloading wave (*black arrows*) begins moving in the opposite direction. A similar event takes place when the shock wave traveling through the target reaches the end. Where the two rarefaction waves meet (*9*) a tension (*broken line*) is created; if it is large enough, a fracture can occur (*10*). If the spring there has any strength in tension before it breaks, it will transmit tension waves (*11*) that could cause more fractures. The trains finally separate (*12*) because the interface where they met cannot support a tension. Oscillations behind tension fronts have been ignored.

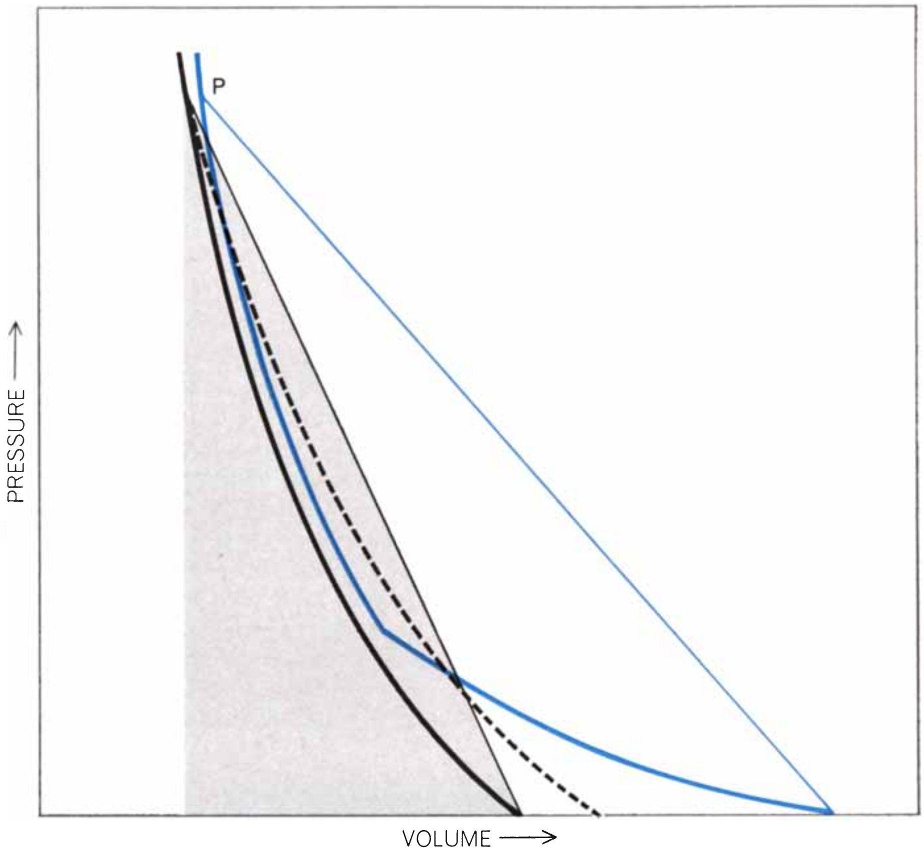
lated to the time required for the shock wave to pass through the specimen and therefore to the shock velocity.

Although shock stress and shock velocity are the most easily measured of the four basic quantities related by the Hugoniot equations, it is also often desirable to measure the particle velocity or density. Recent advances in measurement techniques have made it possible to measure the particle velocity directly by detecting the motion of a thin conducting foil embedded in a nonconducting specimen. This is done by placing the specimen in a magnetic field and measuring the electromotive force induced in the foil as the shock wave passes through the specimen. More typically particle velocity is inferred from an optical measurement of the surface velocity of the specimen. One method employs a laser interferometer to monitor surface motion by observing changes in interference fringes over time. Another method utilizes the streak camera to observe the behavior of a mirror placed at an angle to the surface of the specimen. The surface velocity of the specimen can be computed from the angle at which the streak cuts off on the photograph and the original angle of inclination of the mirror.

Changes of density can be observed radiographically with the aid of "flash X ray" equipment, which is a system of one or more high-current X-ray tubes that emit very intense pulses of X rays lasting for 10^{-7} second each. The equipment makes pictures similar to medical X rays. The pictures show conditions in the interior of the specimen as the shock passes through [*see upper illustration on next page*].

Another observing technique employs high-speed framing cameras that make a series of individual photographs at a rate of up to 2.5 million frames per second (with exposure times as short as 10^{-7} second). The photographs are useful for observing a number of phenomena such as fracture, jetting (of which we shall say more later) and luminescence.

In an experimental setup for the analysis of a shock wave one knows the conditions existing before the shock is generated. The severity of the shock can also be predetermined by the setting of the gas gun or the nature and the amount of explosive used. The states that can be reached in a given target material as a result of a steady shock wave will always fall along a single curve (plotting stress against volume) that is unique for the given starting conditions. The curve is called the Hugoniot.



PRESSURE AND VOLUME relations in shock-wave work are depicted for a solid material (*solid black curves*) and a porous one (*color*). Heavy Hugoniot curves plot final pressure against final volume. Pressure-volume path taken by either material as it shocks up to a pressure *P* will lie on Rayleigh line (*thin*). Release curve (*broken line*), which is often nearly the same for both materials, describes path taken during rarefaction or unloading wave that follows shock. Work done during shock compression is area under Rayleigh line.

The Hugoniot curve usually becomes steeper with increasing pressure [*see illustration above*]. This shape results from the fact that at higher pressures a greater additional increment of stress is needed to compress the material by a given additional increment of volume. With diminishing compressibility the velocity of a sound wave or of a small pulse of pressure through the material becomes greater. Hence if a shock wave were to start as a series of little increments, each successive increment would be traveling in somewhat stiffer material and would tend to overtake the earlier increments. This steepening process cannot continue indefinitely, however, because it is limited in a solid by such conditions as the bulk viscosity and the inhomogeneity of the material.

The rise in internal energy and hence in the temperature of a material under shock compression is highly sensitive to compressibility and to specific heat. For a shock wave with a pressure of 500,000 atmospheres, for example, the rise in temperature would be less than 200 degrees Celsius for a relatively incompressible material such as tungsten but perhaps as much as 10,000 degrees C. for cesium iodide, which compresses to almost twice its original density. Larger temperature rises can be obtained for a given material and shock pressure if compressibility is artificially increased by the introduction of porosity.

A physical effect that has to be taken into account in shock-wave experiments is the tension that arises at the point where a rarefaction wave reflected from a face or an edge of the material intersects the rarefaction wave that follows close behind the shock front. The tension may be strong enough to cause the target plate to fracture. Such a tension can be troublesome when the experimenter wants to recover the specimen after the shock. One way to overcome the problem is to surround the specimen with a momentum trap: a supporting material arranged in such a way that rarefaction waves combine only in the trap and cannot travel back into the specimen. The idea is simple in principle, but in practice it is difficult to build a perfect momentum trap.

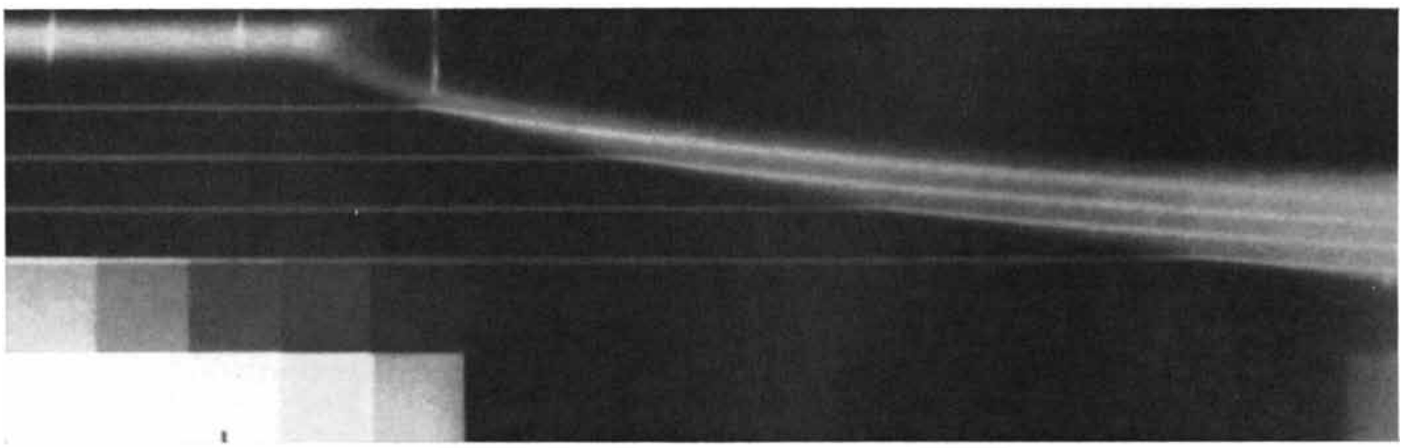
In view of the fact that with present

shock-wave technology it is possible to achieve shock pressures up to several million atmospheres, temperatures up to tens of thousands of degrees C., strain rates as high as 10^8 per second and shear stresses close to the ultimate theoretical limit for short times in many solids, it is hardly surprising that shock waves will alter the nature and properties of materials. In actuality much less extreme shock conditions are sufficient to produce many of the significant effects. The types and magnitudes of effects produced are markedly influenced not only by the peak stresses resulting from the shock but also by the shape and duration of the shock pulse, the rise in temperature and the physical arrangement of the experiment.

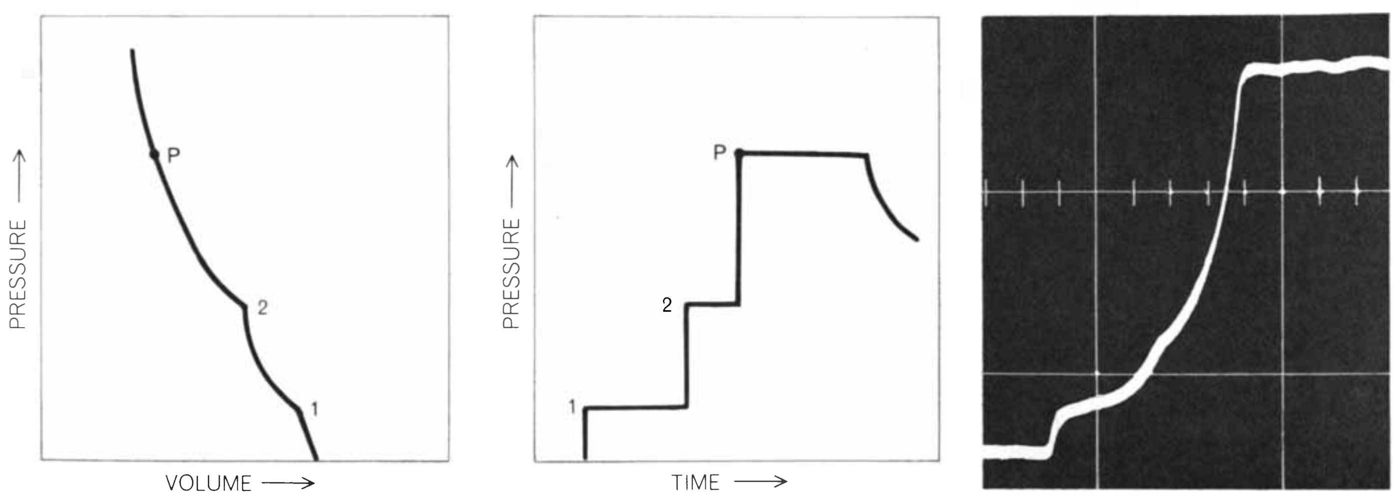
Shock methods are a convenient way, and in some cases the only way at present, to produce and investigate high-pressure transformations of phase, or crystal structure, in a material. A previously unknown phase of iron has been detected by the technique, and the existence of still another unsuspected phase of iron has recently been suggested by shock experiments. It is of considerable theoretical interest that such changes in crystal structure can take place within the submicrosecond span of a shock experiment.

An interesting example of shock-induced transformation is found in titanium dioxide, a compound that is often used as a pigment in paint and enamel. Normally the compound has one of three crystalline structures: rutile, anatase or brookite. Measurements made during shock-wave experiments have shown that when the rutile form is shocked to very high pressure, it changes to a form of titanium dioxide that is about 20 percent denser than any previously known form. The exact crystalline structure of this phase is unknown because it has not been possible to retain the phase long enough to examine it; when the pressure is released, the unknown structure is transformed either back to the rutile form or to a new phase with the same crystal structure as a common form of lead dioxide. The pressure-release transformation is particularly interesting, because apparently the orientation of the original crystal planes, with respect to the directions of the shock and rarefaction waves, is important in determining whether it is the rutile or the lead-dioxide form that is produced when the pressure is released.

In contrast, many of the phase transitions that take place under high-pressure shock treatment of a material can be retained at low pressure. Diamonds made from graphite by shock are an example, and they also appear to have resolved an argument that began many years ago when diamonds were found in the Canyon Diablo meteorite that cre-



SHOCK WAVE moving through a solid is depicted by means of an X-ray technique that makes a series of radiographs in 10^{-7} second each. In this one a sheet of explosive, set off at far right, accelerated a flier plate that hit the specimen, which is layered polyurethane foam with thin sheets of metal foil sandwiched between layers to provide contrast in the radiograph. Shock front is the bottom of the curving light region. The "calibration wedge" at bottom provides a way of estimating changes in the density of the specimen.



MATERIAL PROPERTIES are reflected in curves and wave forms. Hugoniot curves (*left*) show material's elastic limit (*1*) and a phase transition (*2*). If material were shocked to pressure *P*, a stress gauge in it might yield the simplified stress-time profile at center; steps correspond to cusps in Hugoniot. Actual wave profile recorded by a Manganin gauge appears in oscilloscope trace (*right*).

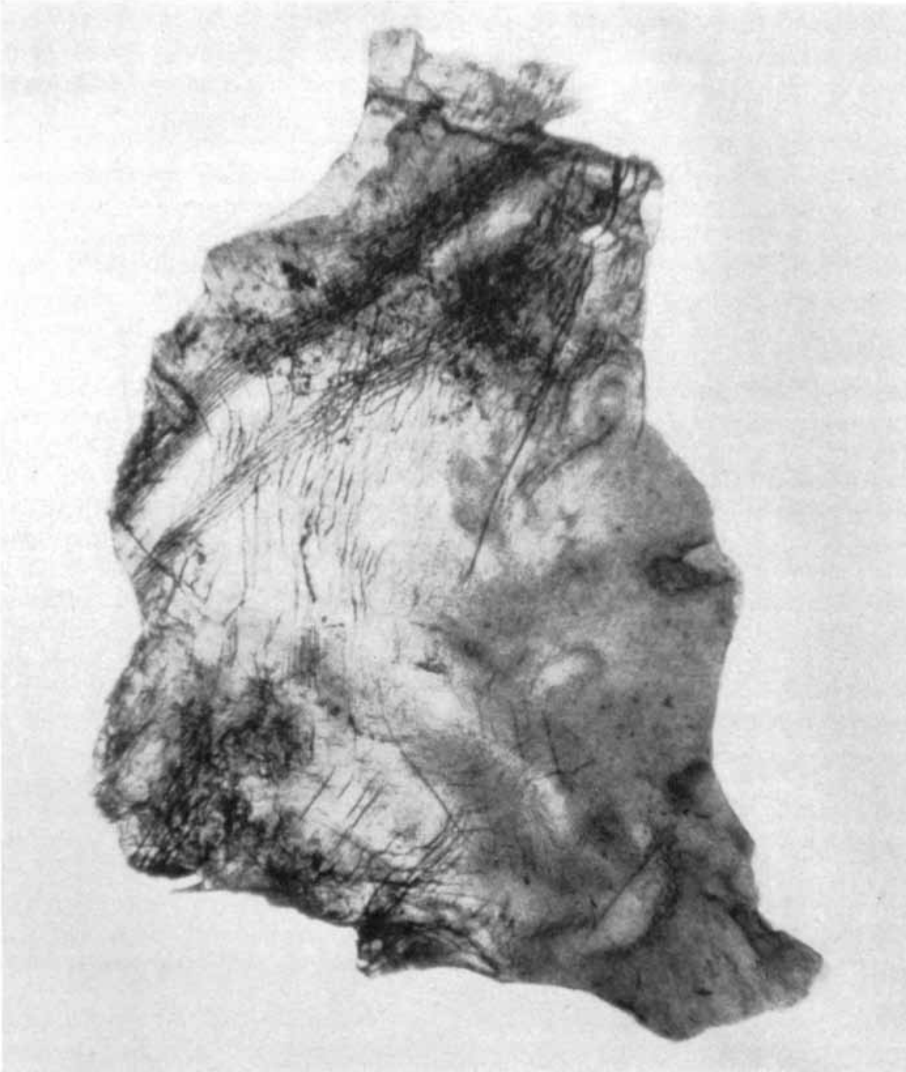
ated the famous Meteor Crater in Arizona. The question was whether the diamonds were formed in the shock resulting from the impact of the meteorite with the earth or whether they resulted from static high pressure in the parent body of the meteorite. Eventually a dramatic experiment at the Stanford Research Institute showed that diamonds can be made (cheaply and in quantity) by shock. This experiment and further investigation of the Canyon Diablo diamonds led to the now generally accepted opinion that those diamonds were formed by shock when the meteorite hit the earth.

Another example of a new phase created in a material by shocking is borazon, which is a high-pressure form of boron nitride that does not occur naturally. Borazon has a crystal structure similar to the structure of diamond, and it rivals diamond in hardness. It was originally discovered by workers at the General Electric Company who were using static high-pressure techniques. Indeed, the crystallites, or coherent crystalline regions, found in borazon produced by static high pressure are still much larger than the crystallites formed by shock.

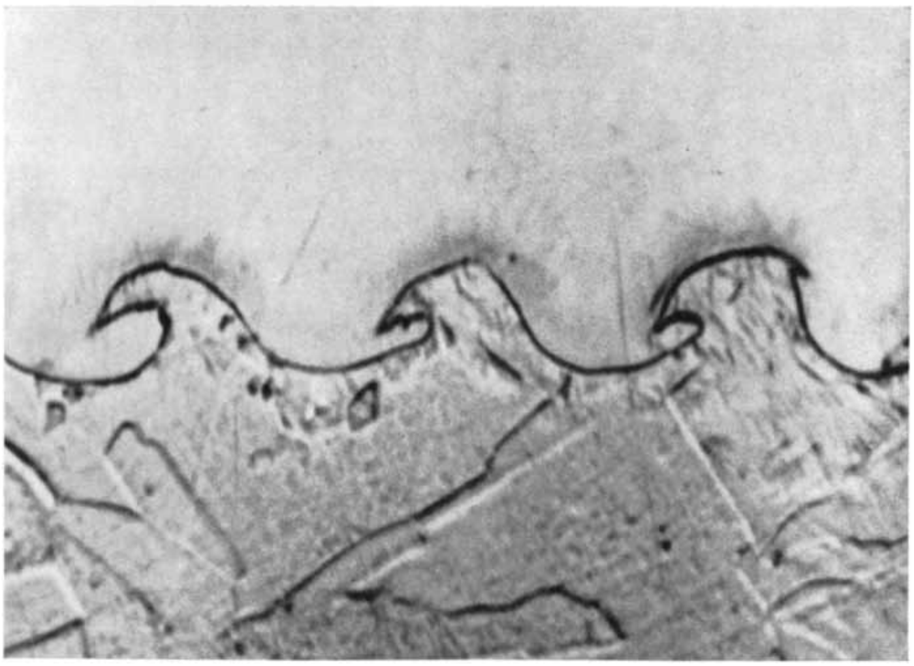
Success in using shock waves to polymerize a number of monomers and to create new polymer forms has been reported recently by workers in the U.S.S.R. Shock-wave vulcanization of several elastomers has also been described. Although other examples of the synthesis of new materials by shock could be cited, the fact is that this promising field has been relatively unexplored.

Shock treatment does not always result in the synthesis of a new material, but it may nonetheless effect significant changes in the properties of a material. For example, deformation by shock makes many metals and alloys harder and stronger than an equivalent amount of static or quasi-static deformation does. The explanation probably lies in the number and movement of dislocations, which are discontinuities in the regular crystal structure of a material. When the dislocations in a material are mobile, the material is plastic and deforms easily. The dislocations can be made less mobile by work hardening, in which the material is repeatedly deformed; this creates more dislocations (and also other defects) that tend to block the movement of any one dislocation. Work hardening can be done by shock; indeed, shock can produce many more dislocations than other methods can.

Dislocations and other defects pro-



ARTIFICIAL DIAMOND was created by passing a shock wave through graphite. The diamond flake is about one millimeter long at its greatest length and about 50 microns thick.



SHOCK WELDING bonded copper (*top*) to nickel. The welding did not give rise to melting at the junction of the two materials, as would have been the case with conventional welding techniques. The enlargement of this photomicrograph is about 600 diameters.

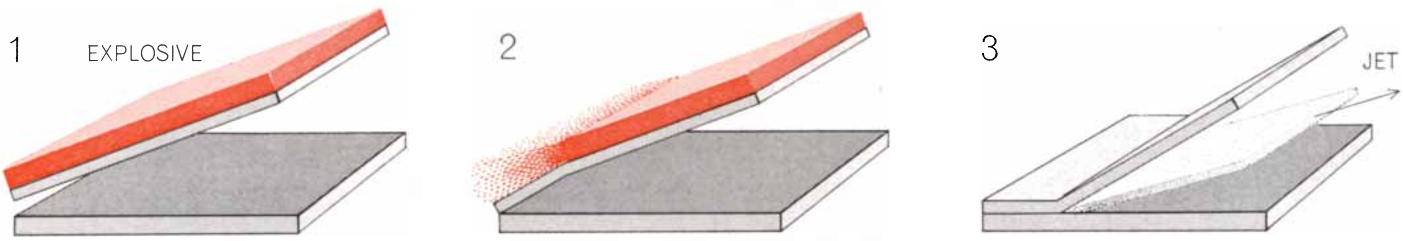
duced in the lattice structure of a crystal by shock can have consequences beyond those affecting mechanical properties. Such defects, for example, can change the surface properties of crystals, sometimes dramatically. An apparent example is the increase of two or three orders of magnitude in the rate at which certain catalysts function after they are subjected to shock-wave treatment.

Among the transient effects of shock waves are changes in the electrical properties of materials. Materials that are electrical insulators at atmospheric pressure become electrical conductors under shock-wave compression. As the shock wave passes, the cloud of electrons surrounding an atomic nucleus in the material is briefly pushed into the cloud surrounding a neighboring nucleus; the effect is to raise the temperature and decrease the electron "band gap," thereby shifting electrons from the "valence band," where they cannot conduct electricity, to the "conduction band," where they can. Conversely, materials that are electrically conductive at atmospheric pressure usually decrease somewhat in conductivity under shock. The major causes are normally the increase in temperature and the introduction of large concentrations of lattice defects that serve to scatter the conduction electrons. (Such thermal and defect scattering of electrons is also introduced in insulators, but at very high pressures and temperatures the effect is greatly overshadowed by the shift of electrons to the conduction band.)

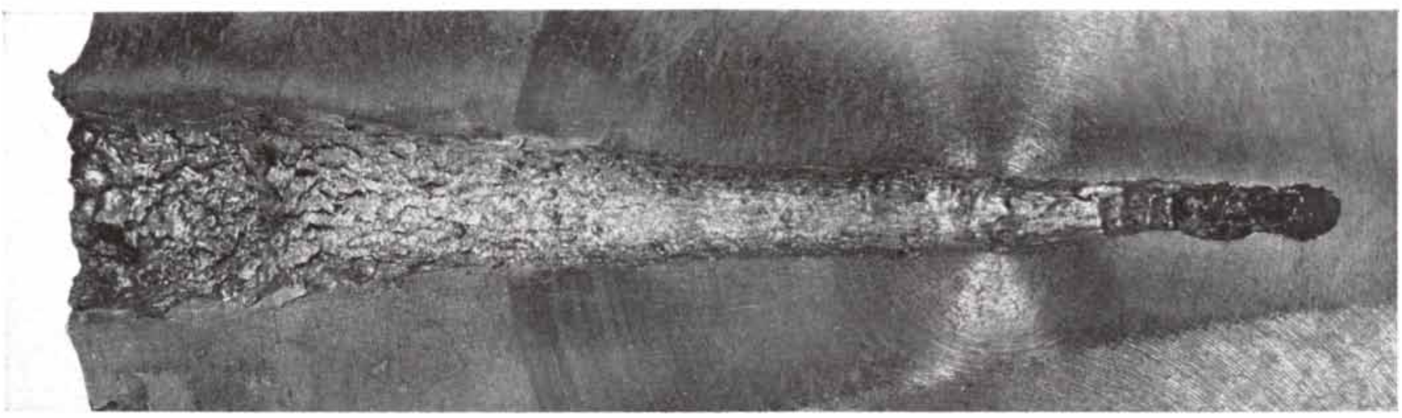
A spectacular effect sometimes results when a shock wave impinges on two inclined plates or on a groove in a solid; it is the creation of a fluid-like jet or spray consisting of tiny particles of material moving at high velocity. To achieve a jet the two plates or the two sides of the groove must be at an angle to each other such that (1) the shock stress substantially exceeds the yield strength of the material so that the material will flow and (2) the point of contact where the plates or the sides of the groove collide moves at a speed less than the speed of sound in the material. (This "collision-point velocity" depends on the strength of the shock and the angle between the two plates or the two sides of the groove.) Since the shock pulse itself is traveling faster than the speed of sound, it preconditions each point to accommodate the fluidity that will result when the two plates or the two sides of the groove collide at that point [*see upper illustration below*]. A high-velocity jet of this kind is impressive in its ability to pierce an object. The principle is put to use in perforating the pipe in an oil well to gain access to oil-bearing strata and in armor-piercing weapons such as the shaped charge.

High-explosive techniques are also coming increasingly into favor as means of fabricating materials. The applications include hardening, strengthening, welding, the forming of wrought metals and the compaction of powder into solid parts. Explosive forming, which can produce one-piece aluminum domes 10 feet in diameter, has been the best-publicized application, but the most rapidly expanding one is explosive welding. Some 10 years ago it was found, in studies of the penetration of metal plates by projectiles, that the projectile will be welded to the plate if the angle of incidence is right for the formation of a jet.

Since then three distinct types of explosive bond have been recognized. A direct bond, flat or rippled, can be formed if a jet removes the surface oxides and adsorbed gases to enable adhesion or cold-welding to take place. The second type of weld is made when a jet is trapped between the welded parts. The significant difference between it and the first type of weld is that here there is a localized layer of solidified melt at the



FORMATION OF JET can take place if two plates are placed (*1*) at a certain angle to each other. When the explosive (*color*) is detonated (*2*), the top plate is collapsed against the bottom one in such a way that the speed of closure is less than the speed of sound in the material. The shock stress, which exceeds the yield strength of the material, travels faster than the speed of sound and so preconditions each point it passes to yield and become fluid (*3*) when the region where the two plates are colliding reaches that point.



EFFECT OF JET, in this case a cylindrical one, was to bore a hole in steel. Penetration is about six inches, although much greater penetration could be achieved. A jet created by a shock wave consists of a spray of fine particles moving at a very high velocity.

weld interface. The third type of weld results from oscillations in the jet flow, which cause the formation of a rippled interface with alternating regions of solidified melt and direct bond.

One of the major advantages of explosive bonding is that it offers a relatively inexpensive way of producing strong bonds even between dissimilar and normally incompatible materials, such as aluminum and steel. Many of the new "sandwich" coins issued by the U.S. are made in this way; copper billets are explosively clad with a nickel-copper alloy and rolled to sheets from which the coins are stamped. In cases where a conventional welding process will form brittle or otherwise undesirable compounds, or where excessive heat is harmful, explosive bonding is often the only welding technique that can be used. Moreover, it is likely to be the most economical method of bonding when unusual shapes are involved or large surface areas of plates or sheets are desired. Because the technique does not require heavy equipment and can function in a vacuum, it is being considered for the fabrication and repair of structures and equipment on space missions.

Within the past few years methods have been developed for studying materials under static high pressures up to 500,000 atmospheres, thus overlapping part of the pressure range studied with shock-wave methods. In addition, material can be held at static high pressure for an unlimited time, whereas in shock work the duration of pressure is usually not more than 10^{-5} second and is often much less. On the other hand, stresses can be applied and relieved at much higher rates in shock work than is possible in static high-pressure work. Furthermore, with pressures above 150,000 atmospheres the volume of a specimen cannot be much more than 10^{-3} cubic inch in static experiments, whereas specimens in shock work can be any size. Static methods are likely to be cheaper than shock methods for small-scale experiments, but the situation is reversed when large amounts of material are involved. Finally, shock methods offer the only way to achieve a number of the transient phenomena we have described and such processes as jetting and explosive bonding. For these reasons it can be expected that during the next decade shock waves will become both increasingly useful in research and increasingly important in the processing of materials and in the development of new materials.

THE BACTERIAL CELL WALL

The tough, inflexible envelope that surrounds a bacterium is a single giant molecule made up of amino acid and sugar units. Its formation is blocked by drugs such as penicillin

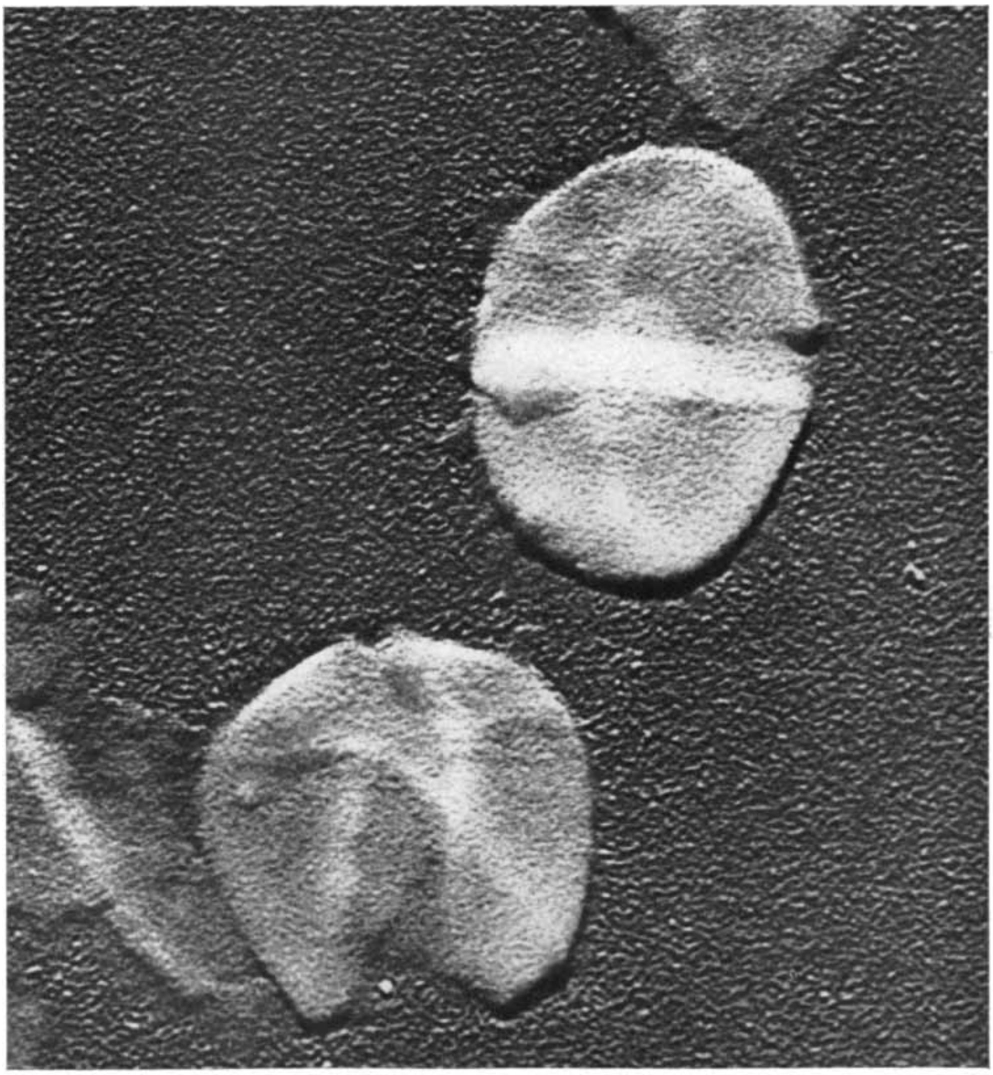
by Nathan Sharon

The pioneer microscopist Anton van Leeuwenhoek, who in the 17th century was the first to observe the one-celled organisms later called bacteria, made sketches showing their shapes. In this way he identified the major classes from which bacteria derive their names: cocci (spherical), bacilli (rodlike) and spirilla (helical). It is evident from van Leeuwenhoek's writings that he realized bacteria have a structure of some kind that holds the organism together and preserves its shape.

This structure is known to us as the bacterial cell wall. It surrounds the fragile plasma membrane of the bacterial cell and protects the membrane and the cytoplasm within from adverse influences in the environment. The rigid wall structure is characteristic of bacteria; the cells of animals are enclosed only by the plasma membrane. Plant cells have a rigid or semirigid envelope, but the structural material of plant cell walls (with the exception of a few seaweeds) is cellulose. The bacterial cell wall is made up of a different material whose composition and structure are far more complex than those of cellulose. Indeed, studies of the bacterial cell wall's molecular architecture have revealed substances and structures found only in bacteria and not in plants and animals.

The composition of the cell-wall material is of particular interest because the cell wall and certain substances that are attached to it are largely responsible for the virulence of bacteria. The symptoms of a broad spectrum of bacterial diseases can be produced by the injection into animals of cell walls rather than whole bacteria. Similarly, animals can be immunized against certain bacteria (for example enteric bacteria, brucellae and pasteurellae) by means of the bacterial cell walls rather than whole killed cells.

The bacterial cell wall became the subject of intensive study about 10 years ago, when it was discovered that certain antibiotics, notably penicillin, kill bacteria by interfering with the synthesis of the cell-wall material. Bacteria that lack cell walls can be grown in the presence of penicillin under certain conditions. Such naked cells, called protoplasts, can also be prepared by means of enzymes, such as lysozyme, that normally kill susceptible bacteria by lysing, or dissolving, their walls. The substances that are stripped from bacteria to expose the na-



ROUND CELL WALLS were isolated from the spherical bacteria known as *Micrococcus lysodeikticus*. The wall structure is responsible for the characteristic shapes of bacteria.

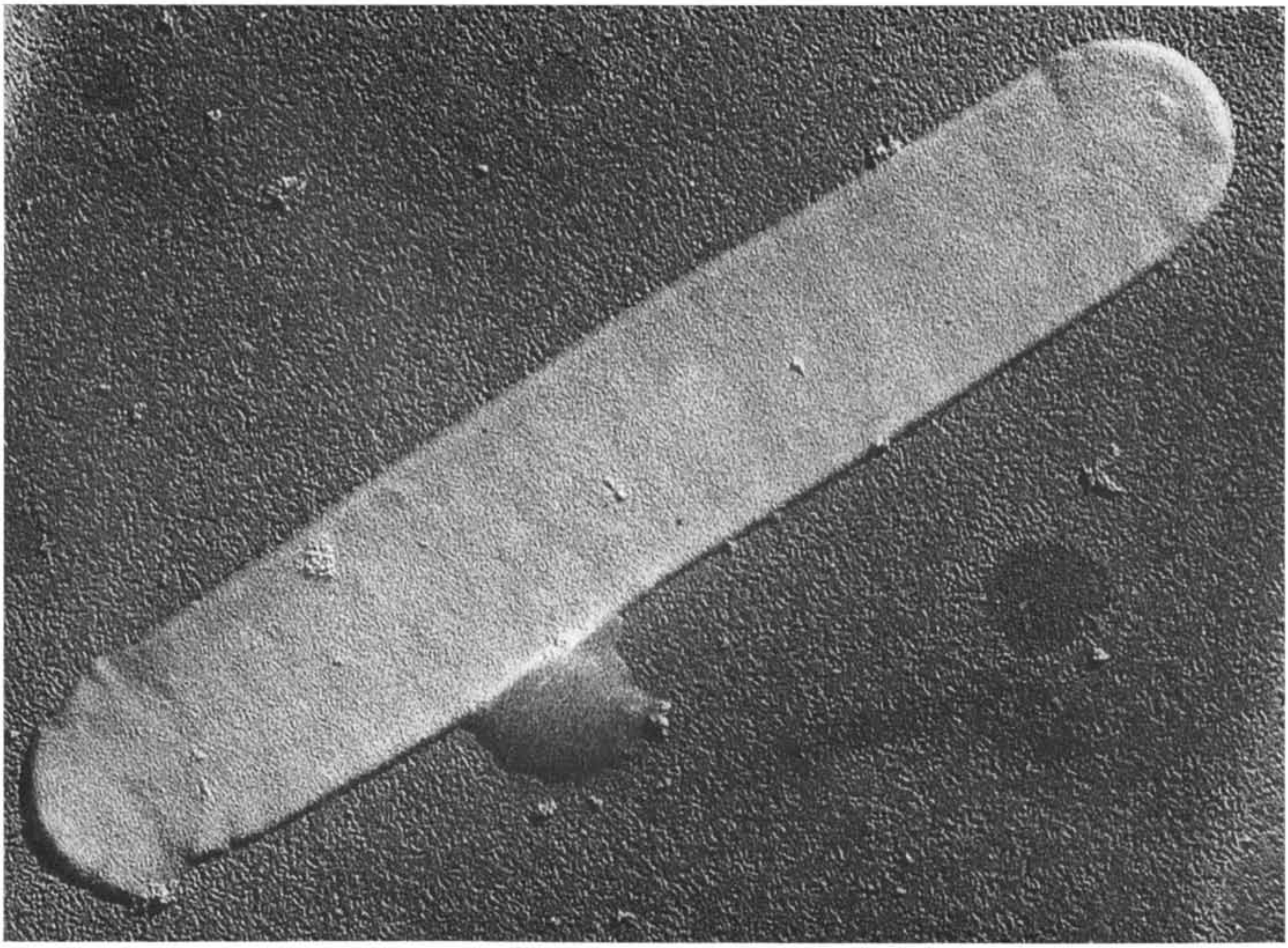
ked cell have been investigated in order to learn the composition of the cell wall and the process by which bacteria synthesize the wall material. Thanks to these and other studies that I shall discuss, it is now possible to understand the selective action that makes penicillin such an effective antibacterial agent.

The foundations for the investigation of the bacterial cell wall were laid by Milton R. J. Salton at the University of Cambridge in the early 1950's, when he succeeded in isolating cell walls and examining them in the electron microscope. At a large magnification the isolated walls look like empty bags or deflated balloons that have been spread out on a table [*see illustrations on these two pages*]. Salton found that, as one might have expected, the cell walls had the same shapes as the bacteria they had formerly housed. The cell walls of cocci are round and the walls of bacilli are elongated.

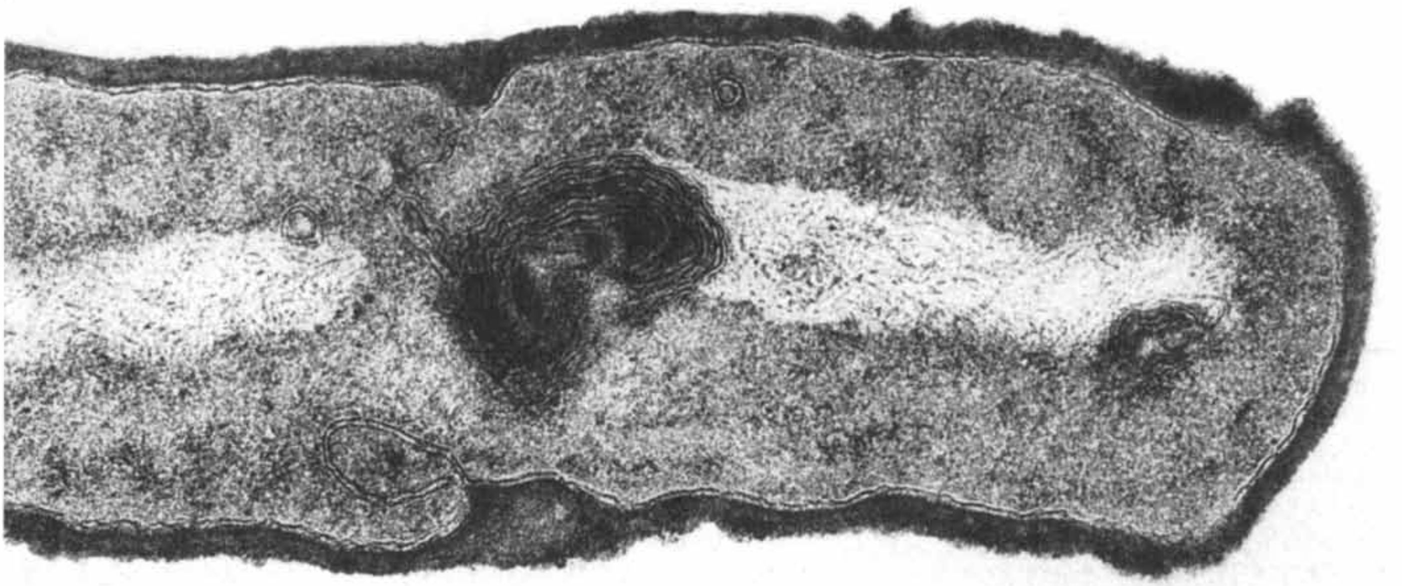
Although the investigation of these structures has flourished during the past decade, before that time progress was slow. The main difficulty was the dimensions of bacteria. Most bacterial cells are between .5 and one micron wide and between one and five microns long. (A micron is a thousandth of a millimeter.) The investigation of such tiny cells was impeded not only by technical difficulties but also by the widely held premise that cells of such small dimensions must be structureless.

The work that has elucidated the fine structure of bacteria came about as the result both of a radical change in the conception of the living cell and the development of new techniques for its study. An essential tool in investigating bacteria is the electron microscope, whose resolving power is more than 100 times that of the optical microscope. Another important method is paper chromatography, which enables one to examine the chemical composition of cell-wall material and conduct experiments on its structure even when only minute quantities of the material are available.

It may appear to be contradictory that whereas bacteria are killed by agents that disrupt their cell walls, the microorganisms can be viable when the cell wall is removed. To clarify this apparent contradiction, let us compare the behavior of bacteria with the behavior of animal cells under certain conditions. Animal cells such as red blood corpuscles will remain intact in a solution that has about the same concentration of salt as the concentration inside the cell (an isotonic solution). On the other hand, if red blood corpuscles are placed in a hypotonic solution (distilled water, for instance) whose osmotic pressure is lower than the pressure of the cell contents, water will enter the cells in accordance with the elementary principles of osmosis. In a short time the corpuscles swell up, and eventually they burst. If the corpuscles are suspended in a hypertonic solution, so that the osmotic pressure is higher than the pressure inside the cell, the corpuscles shrivel up to an unrecog-



ELONGATED CELL WALL retains the shape of the rodlike bacterium *Bacillus licheniformis* from which it was taken. In this electron micrograph and the one on opposite page, both of which were made by the author, the cell walls are enlarged 53,000 diameters.



SECTIONAL VIEW of *Bacillus subtilis* shows the cell wall as a dark layer around the edge of the cell. Lining the cell wall is the thin layer of the plasma membrane. Various subcellular particles are visible in the cytoplasm of the bacillus. The bacillus is seen in longitudinal section in this electron micrograph, which was made by Elizabeth H. Leduc, now at Brown University, and Philippe Granboulan at the Institut de Recherches Scientifiques sur le Cancer. The bacillus is enlarged approximately 80,000 diameters.

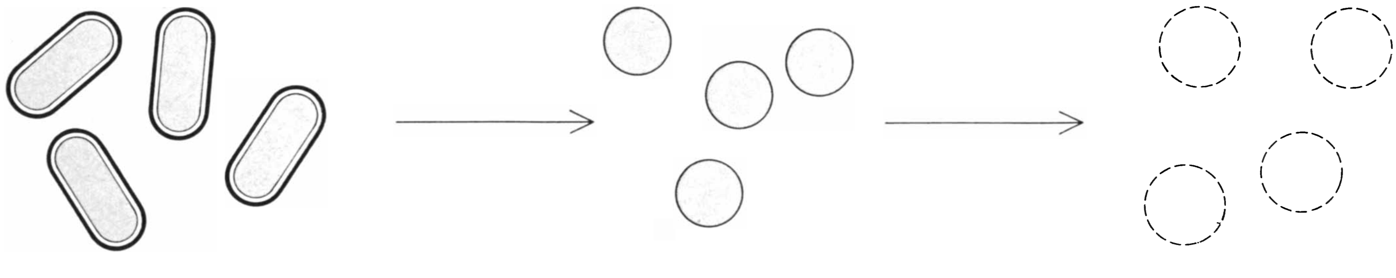
nizable shape as liquid flows out of them.

In contrast to this behavior, bacteria do not change in their outward appearance when they are in a hypotonic or hypertonic solution. This is because of the tough and inflexible cell wall, whose shape and volume are nearly unchangeable. In bacteria, as in animal cells, the plasma membrane has the property of selective permeability and thus performs the function of "pumping" solutes from the environment into the cell. Indeed, the membrane is so efficient at concentrating metabolites that the osmotic pressure inside the cell can reach 20 atmospheres (300 pounds per square inch). The plasma membrane by itself cannot withstand such pressure; it remains intact only because it transmits the pressure to the cell wall. Hence if the wall of a bacterium is damaged or removed, the membrane bursts.

Weakening or destroying the bacterial cell wall by treating it with lysozyme (or inhibiting the wall's synthesis by means of substances such as penicillin) kills bacteria by causing them to burst. A bacterium that lacks a cell wall will survive, however, if its plasma membrane is preserved intact, which can be done by keeping the microorganism in an isotonic solution. Accordingly one method of preparing the naked protoplasts is to treat bacteria with lysozyme when they are in an isotonic solution. (A relatively concentrated solution of sucrose is used.)

It is interesting that although bacteria have a variety of shapes, their protoplasts are always spherical. The reason is that the weak, flexible plasma membrane assumes the spherical shape of maximum stability. As long as protoplasts remain in an isotonic solution, they take up oxygen and eliminate carbon dioxide, conduct biosynthesis and under special circumstances will even reproduce. In the form of protoplasts, bacteria with flagella retain these whiplike appendages. The flagella do not, however, propel the protoplasts as they do the bacteria, because the solid fulcrum the firm wall structure affords is lacking. Protoplasts from which the cell wall has been entirely removed (some wall-stripping agents do not do a complete job) are not attacked by bacteriophages, the viruses that parasitize bacteria.

If the osmotic pressure of a solution in which protoplasts are suspended is re-



CELL WALLS ARE REMOVED to expose protoplasts (viable naked cells) by treating bacteria with penicillin or with the enzyme lysozyme, which lyses, or dissolves, the wall substance. During the process the bacteria must be kept in a solution that balances the osmotic pressure across the plasma membrane. Bacteria without a wall assume a spherical shape. Plasma membranes of bacteria are prepared by reducing the osmotic pressure of the solution. The protoplasts then swell and burst, releasing their contents.

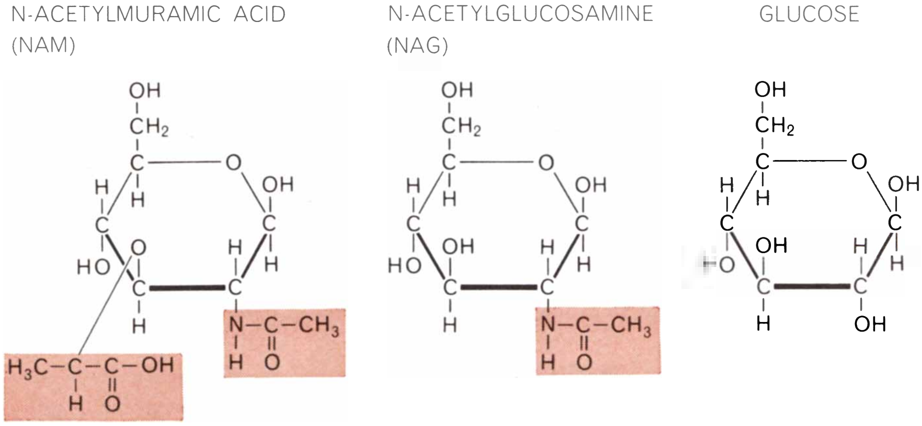
duced, the cells burst and their contents escape, leaving the plasma membrane an empty sac or in fragments. This is the basis of a technique that is used to prepare bacterial plasma membranes, which are now under study in many laboratories.

In investigating the cell wall of bacteria two basic approaches can be followed. In one the wall is studied as part of the intact cell. Thus the examination of very thin slices of bacterium in the electron microscope reveals that the thickness of the cell wall is usually between 15 and 20 millimicrons, which is about 1 percent of the overall thickness of an average bacterial cell. The wall appears to envelop the cell completely; it is also possible to observe changes in the wall during cell division.

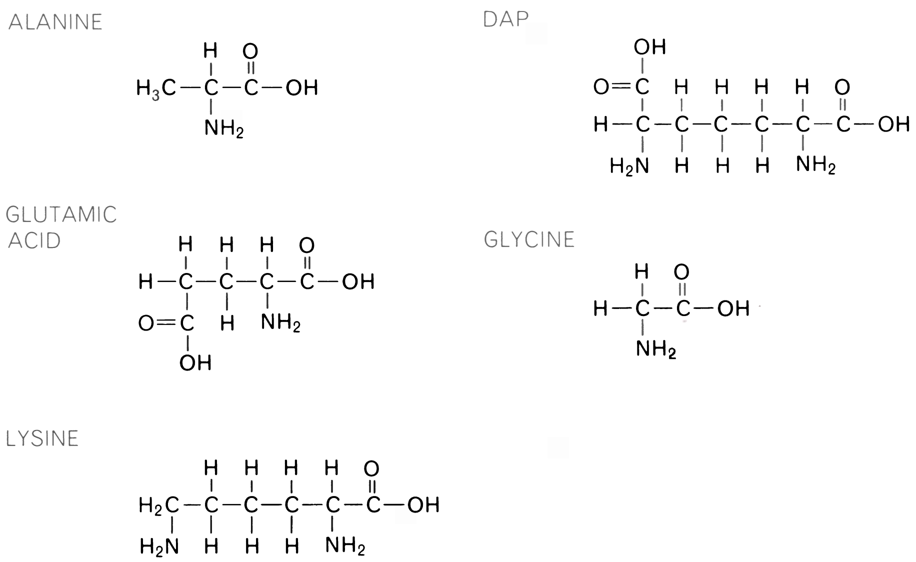
The second approach to studying cell walls is to isolate them from bacteria, as one must do in order to analyze their chemical composition. A simple and effective method for the preparation of cell walls is to shake a thick suspension of bacteria and water together with tiny glass beads. The cells are punctured, their contents pour out into the water and the cell walls, which are insoluble, can be readily separated from the denser glass beads and the water-soluble contents of the bacteria. After several washings a white precipitate is obtained that consists solely of cell walls, as can be shown by examination under the electron microscope.

Early investigators were surprised to find that the bacterial wall accounts for 20 to 30 percent of the cell's dry weight. Although the wall is much smaller in volume than the cell cytoplasm, it is mostly solid material whereas the cytoplasm is a relatively dilute solution.

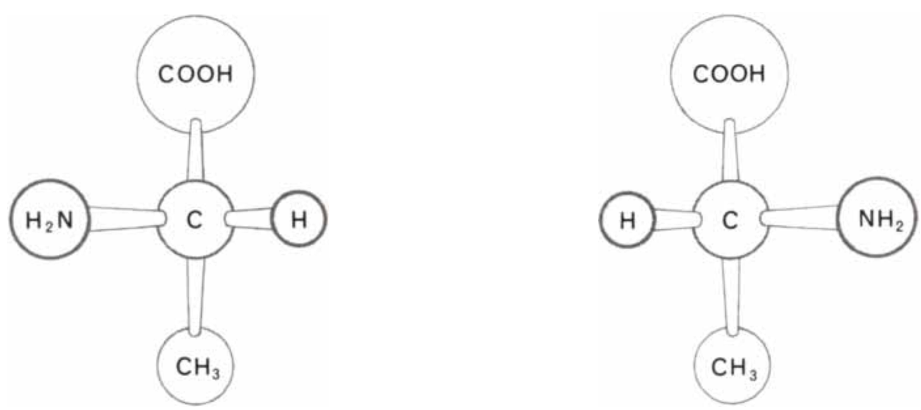
The chemical composition of the cell wall was first analyzed by Salton. His analyses indicated that the wall substance includes almost all the kinds of material that are found in living cells, with the exception of the nucleic acids. He found sugars linked in chains (polysaccharides), amino acids linked in the long chains of proteins and the shorter ones of peptides, and also lipids (fats). As more bacteria were examined, however, it became clear that all cell walls have a few common components: they are two simple sugars and three or four amino acids. These form the "basal structure" of the wall. In the instances where large amounts of other substances were found, it was shown that they came from substances linked to the wall, such as the substances that form the gummy or slimy capsule encasing many bacteria. Treat-



SACCHARIDE MOLECULES indicate (*color*) where the amino sugars N-acetylmuramic acid (NAM) and N-acetylglucosamine (NAG) differ from glucose. NAM and NAG are components of the glycopeptide that forms the foundation in cell walls of many bacteria. Cellulose, the structural material in plant cell walls, is composed of linked glucose units.



AMINO ACID MOLECULES are the other components of the glycopeptide that gives the cell wall its shape. Alanine and glutamic acid have a configuration different from the one they have in other natural materials (*see illustration below*). In cell walls of many bacteria, lysine is replaced by diaminopimelic acid (DAP). DAP is peculiar to the cell wall.



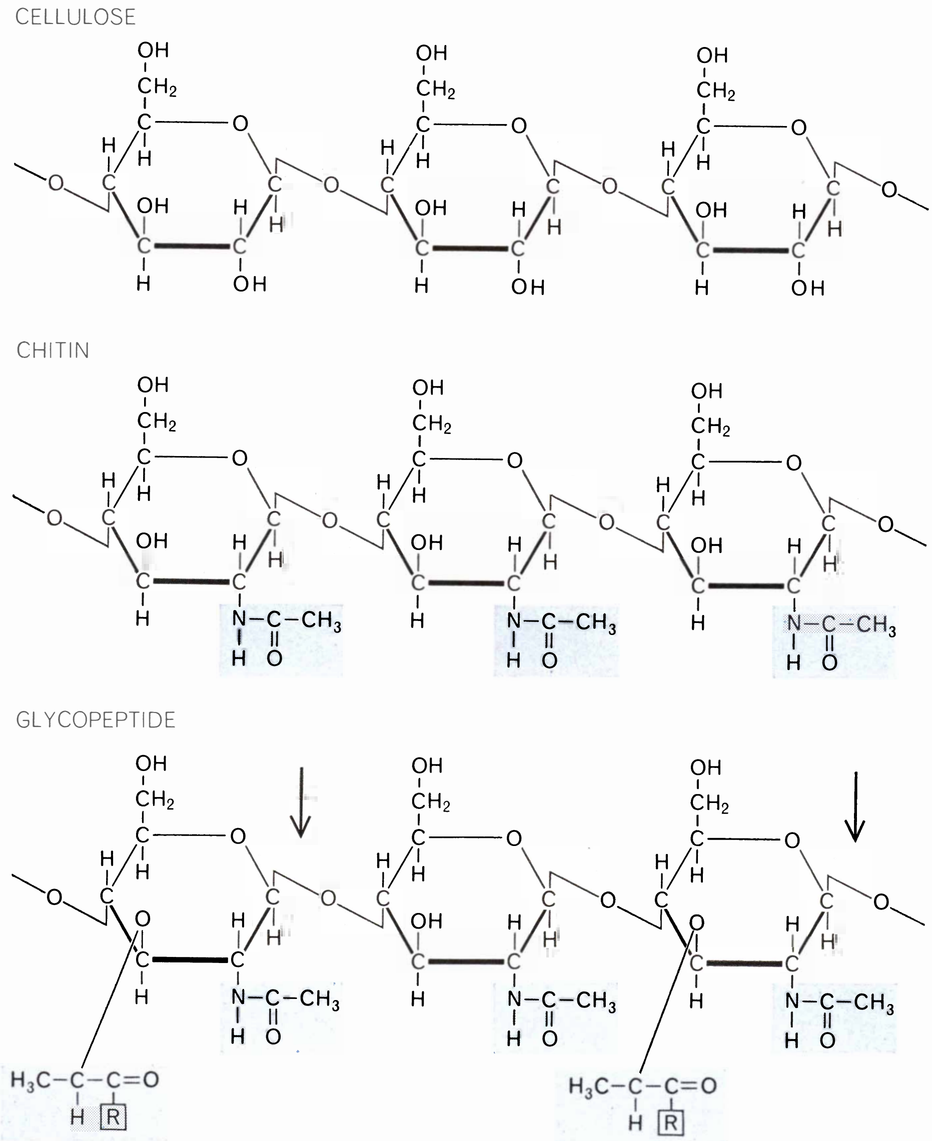
TWO CONFIGURATIONS OF ALANINE are found (in equal amounts) in the glycopeptide of the cell wall. When in solution, one configuration, or stereoisomer, designated *L*-alanine (*left*) rotates plane-polarized light in one direction; its mirror image, *D*-alanine (*right*), rotates polarized light in the opposite direction. *L*-amino acids are normally found in natural materials. Only *D*-glutamic acid appears in cell-wall glycopeptide.

ment with the appropriate solvents (for example salt solutions or organic liquids) was found to remove these substances, leaving an insoluble material that, when it was examined in the electron microscope, still retained the characteristic wall shape. It is therefore this material that provides the cell wall's rigid foundation.

When this material is decomposed by prolonged heating in acid solution, one obtains its constituent saccharides and amino acids. In some bacteria the cell wall is composed almost exclusively of these components. The two sugars are simple ones related to glucose. One is glucosamine, an amino sugar (so named because an amino group—NH_2—is attached to the sugar molecule). Glucosamine is a common constituent of natural polymers. For instance, chitin, the principal structural material of the external skeleton of insects, which among natural polymers is probably second only to cellulose in abundance, is made up solely of glucosamine units. This amino sugar is also found in animal connective tissues and in many protein-carbohydrate compounds. It is usually in the form of N-acetylglucosamine (NAG), and it is in this form in the bacterial cell wall as well.

The other saccharide of the bacterial cell wall is a lactic acid derivative of glucosamine. It was named muramic acid (from *murus,* the Latin word for wall). Muramic acid has been found only in bacteria and microorganisms that resemble bacteria, such as the blue-green algae. Like glucosamine, it is usually in the form of the N-acetyl derivative.

Only a limited number of the 20 amino acids that form protein are found in the cell-wall material. In the walls of many bacteria the amino acids are glutamic acid, glycine, lysine and alanine. Two of the amino acids, however, are found in an "unnatural" configuration, that is, certain of the atoms or groups of atoms in their molecules are arranged differently from the way they are in the amino acids of other natural substances. This configuration, which is designated dextro (*D*), is a mirror image of the "normal" configuration, levo (*L*). Glutamic acid appears as a *D*-stereoisomer in bacterial walls whereas lysine has the usual *L* configuration. Alanine in the cell wall is found as a *D*-stereoisomer and also as an *L* one [*see bottom illustration on preceding page*]. In many bacteria there is no lysine in the cell wall; instead the wall contains diaminopimelic acid, whose structure resembles that of lysine. Diaminopimelic acid is peculiar to the bacterial cell wall; it is not found in any protein.



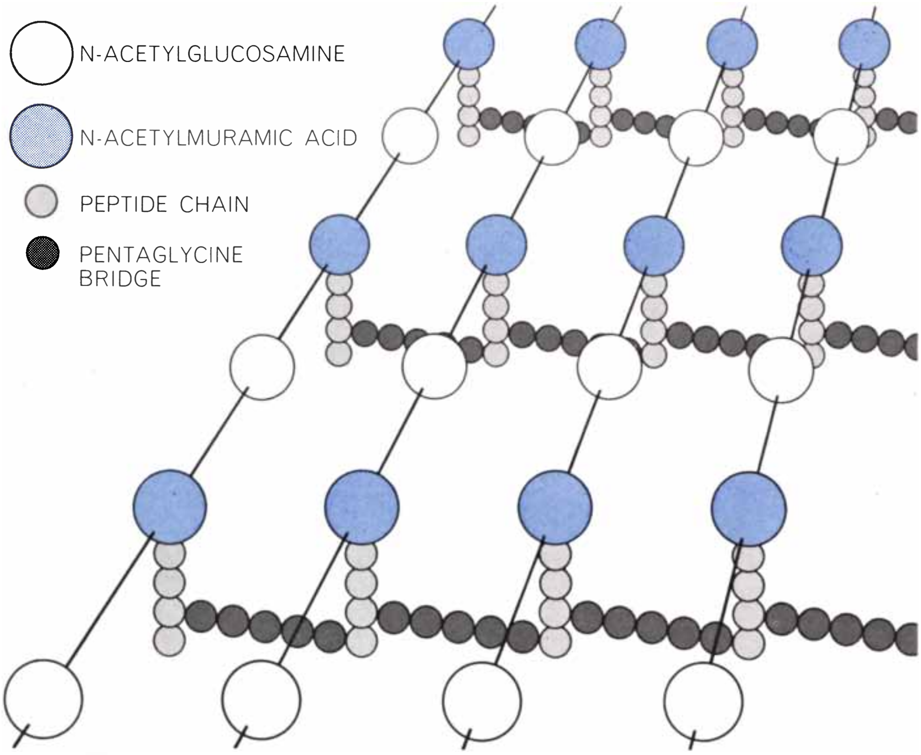
STRUCTURAL POLYSACCHARIDES in plant cell walls (*top*), the external skeleton of insects (*middle*) and bacterial cell walls (*bottom*) are similar. The manner in which the chitin and cell-wall polysaccharides differ from cellulose is indicated in color. The polysaccharide of bacterial walls consists of alternating units of NAM and NAG. By cleaving bonds between these units lysozyme dissolves the cell wall. *R* stands for an OH group or a peptide.

How are the basic constituents of cell-wall material linked to form its rigid structure? In answering this question lysozyme proved a particularly valuable tool. The enzyme was discovered by Sir Alexander Fleming in 1922, six years before his discovery of penicillin. Fleming observed that tears, saliva, nasal mucus and other secretions of the body are capable of dissolving certain bacteria, and he attributed this activity to a cell-lysing enzyme (which he accordingly named lysozyme). He hoped that lysozyme might be useful in fighting pathogenic bacteria. This hope, however, has never been realized.

Lysozyme is also found abundantly in the white of hen's eggs, and it was from this source that lysozyme was isolated and crystallized by other investigators. Fleming found that the bacterium most susceptible to dissolution by lysozyme is *Micrococcus lysodeikticus.* (*Lysodeikticus* means "lysis meter.") This bacterium is still widely used in investigations of lysozyme and enzymes that resemble it. If a tear or a drop of egg white is added to a suspension of *M. lysodeikticus,* in only a minute or so one can see with the unaided eye the turbid suspension clear up. Microscopic examination shows that the cells have simply disappeared.

Until Salton had investigated this phenomenon it was not clear exactly what lysozyme did to the cells, although some information on its action had been gathered by Karl Meyer at Columbia University and by other workers. Salton showed that lysozyme dissolves the cell wall by cleaving the chemical bonds between its amino sugar subunits.

In investigating the composition of cell walls dissolved by lysozyme, Salton discovered a two-sugar substance composed of acetylglucosamine and acetylmuramic acid. The detailed structure of this disaccharide was worked out in 1963 by Roger W. Jeanloz, Harold M. Flowers and myself in the Laboratory for Carbohydrate Research at the Massachusetts General Hospital. Other investigations have served to clarify the cell wall's architecture, notably those by Jack L. Strominger of the University of Wisconsin School of Medicine, by Jean Marie Ghuysen of the University of Liège, by Howard J. Rogers and H. R. Perkins of the National Institute for Medical Research in London and also those by my colleagues and myself at the Weizmann Institute of Science in Israel. A glycopeptide that appears to represent the fundamental repeating unit of most bacterial cell walls was recently isolated and characterized in our laboratory by David Mirelman.



STRUCTURE OF CELL-WALL GLYCOPEPTIDE is represented diagrammatically. Attached to the polysaccharide chains are chains of amino acid units (peptides). The peptides, linked to one another by pentaglycine bridges, cross-link the polysaccharide chains. By inhibiting cross-linking, penicillin prevents cell-wall formation in growing bacteria.

These investigations have led to the conclusion that the walls of bacteria are made up of two types of polymer, one composed of saccharide subunits and one of amino acid subunits. The saccharide portion of the wall consists of long chains of alternating units of acetylglucosamine and acetylmuramic acid, linked by bridges that include an oxygen atom (glycosidic linkages). This polysaccharide closely resembles the cellulose of plant cell walls and the chitin of insects [*see illustration on opposite page*].

The cell wall of a bacterium ought to be insoluble by virtue of its polysaccharide alone, as the walls of plants and the external skeletons of insects are. In the bacterial wall, however, there is an additional factor that contributes to the insolubility and also to the strength and toughness of the material. This factor is provided by peptides, the short chains made up of amino acids. The peptide chains, which are cross-linked to one another, are attached to the polysaccharide chains, so that they serve to join them and form a three-dimensional network [*see illustration on this page*]. The cross-linking of polymers is well known as a means of achieving toughness and mechanical strength in synthetic materials.

The amino acids of the cell wall are linked by peptide bonds (HN–CO), but they are not susceptible to digestion by enzymes, such as trypsin or pepsin, that act to split such bonds (proteolytic enzymes). This resistance may well be related to the unusual *D* configuration of the wall components glutamic acid and alanine. Most proteolytic enzymes are unable to split peptide bonds between *D*-amino acids, and it may be that bacteria are naturally protected from lysis by these enzymes. To be sure, the cell-wall peptides are not totally resistant to all enzymes. If this were so, the world would be full of the cell walls of dead bacteria.

The three-dimensional network of the cell wall can be conceived of in a general way as a gigantic bag-shaped molecule. Such a structure belongs to the general class of glycopeptides; the wall probably is a glycopeptide with a molecular weight of tens of billions. Penicillin, as I have noted, prevents this three-dimensional structure from forming. At what point in the synthesis of the wall glycopeptide does penicillin act?

Fleming himself tried to solve the problem of penicillin's mechanism of action, and the problem has occupied many other workers, particularly during the 1940's, when penicillin came into wide use as a drug. The key to the problem was discovered in 1949 by James T. Park, who is now at the Tufts University Medical School. Park found that when staphylococci are incubated for several hours in a medium containing penicillin, there is an accumulation of substances that at the time were unknown. The detailed structure of these substances was revealed several years later by Park and by Strominger. They were shown to have a resemblance to the glycopeptide of the cell wall, but they had a low molecular weight. There was also present in these substances in combined form a compound that plays an important role in the biosynthesis of polysaccharides, namely uridine diphosphate.

In 1957 Park and Strominger jointly put forward a hypothesis to account for these findings. The substances associated with uridine diphosphate that accumulate under the influence of penicillin were identified as intermediates in cell-wall synthesis; they result from interference with the synthetic process. This hypothesis explained the well-known fact that penicillin kills only multiplying cells: only at the time of reproduction do bacteria need to synthesize new cell-wall material. It is noteworthy that shortly before Park and Strominger published the results of their work, Joshua Lederberg, who was then at the University of Wisconsin, concluded, on the basis of other evidence, that penicillin kills bacteria by inhibiting the synthesis of their walls.

The hypothesis that the cell wall is penicillin's site of action explained the great susceptibility of bacteria to this drug, which is not toxic to animals. (Only a few micrograms of penicillin are needed to kill staphylococci, but humans are usually not affected by doses 10 million times larger.) This response is to be expected, since penicillin interferes with the synthesis of a structure that is vital for bacteria but is not even present in animals.

During the past decade Park and Strominger's hypothesis has been verified experimentally. The details of the biosynthesis of the intermediate substances and the ways these small water-soluble molecules are converted into the gigantic insoluble glycopeptide of the cell wall have been clarified. Today it is possible to synthesize the uridine diphosphate intermediates from the amino sugars and amino acids of the cell wall with the aid of about 12 specific enzymes that have been extracted from bacteria.

The synthesis of intermediates is only the first step in biosynthesis of the cell wall, and penicillin does not interfere with the process at this stage. In the next stage the uridine-linked intermediate is polymerized together with uridine-linked acetylglucosamine to form the polysaccharide backbone with the aid of enzyme bound to the plasma membrane and a special cofactor (a phosphate derivative of a polyisoprenoid alcohol). Penicillin does not influence this process either. Other antibiotics such as vancomycin and bacitracin do, however, inhibit synthesis at this stage. Quite recently Park and Strominger independently discovered that penicillin inhibits the last stage in synthesis of the cell-wall glycopeptide. This is the synthetic step in which adjacent polysaccharide chains are linked by reaction between their peptide side chains.

Thus on a molecular level the two great discoveries made by Fleming, lysozyme and penicillin, have been joined. Both substances interact with the cell-wall glycopeptide, although at different sites. The investigation of penicillin and lysozyme has not, however, come to an end. Penicillin's mode of action is being studied in further detail in the search for information that might be useful in combating resistant bacteria, for example through the synthesis of new "tailor-made" antibacterial drugs. Recently there has been an upsurge of interest in lysozyme as the first enzyme whose three-dimensional structure has been precisely determined, so that its properties are understood in atomic detail. It is believed that lysozyme, which we too are studying in terms of its detailed effect on the bacterial cell wall, may offer the key to understanding the secrets of enzyme action.

Right: Fabry-Perot interferometer pattern in krypton-ion laser beam

looked for oil. Now they seem interested.

scare away fish, porpoises or anything else.

What's more, it has a snorkel. This allows burned gases to escape to the surface. So the water stays clean.

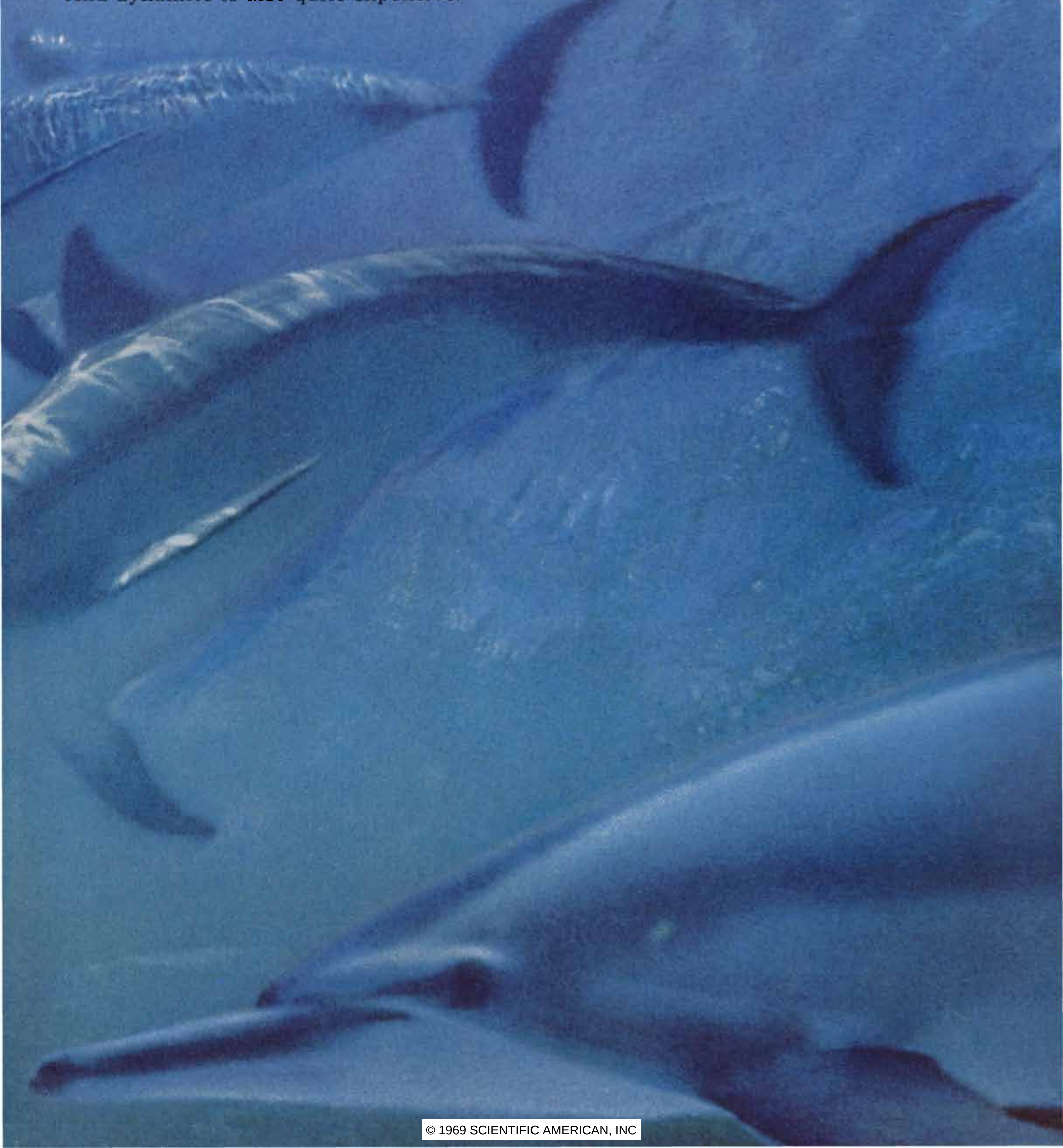
But fishermen aren't the only people to cheer.

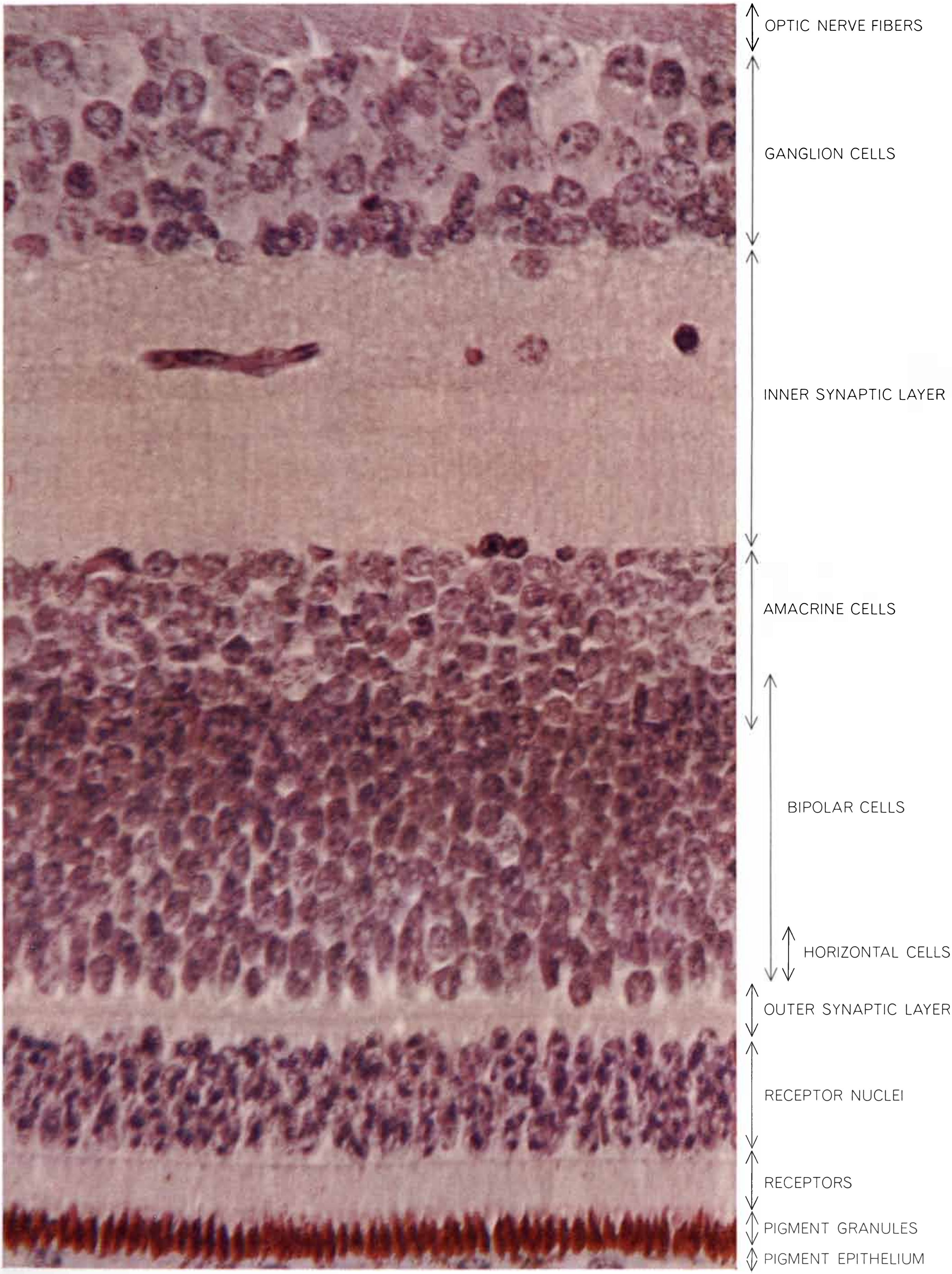
Dynamite is often tricky stuff to handle. The popper is completely safe. Exploration crews have one less danger to contend with.

And dynamite is also quite expensive. Fifteen dollars a shot. The popper costs a penny a pop and gives a better seismic picture in the bargain. At the rate the oil industry is exploring, it could literally save millions.

Good news for people. Great news for fish. Quite an invention.

Standard Oil Company (New Jersey)





RETINA of the ground squirrel is enlarged 800 diameters in a photomicrograph made by John E. Dowling of the Johns Hopkins University School of Medicine from a section prepared by Richard L. Sidman of the Harvard Medical School. Light striking the retina passes back (*down in the micrograph*) through the cell layers and is absorbed by visual pigments in the receptors. Depending on the pattern of retinal synapses, the resulting nerve activity excites or inhibits horizontal, bipolar and amacrine cells and ultimately the ganglion cells. The output of the ganglion cells constitutes all the information that is conducted to the brain along the optic nerve.

Retinal Processing of Visual Images

Information is processed within the eye, and in some species it is processed to a remarkable extent. In frogs and ground squirrels the retina's integrative capacity rivals that of the cortex in primates

by Charles R. Michael

In the eye of vertebrate animals an image of the external world is focused on the retina by the cornea and the lens. The light is absorbed by the visual pigments of the retinal receptor cells, the electrical activity of which varies with the quantity of light they receive. The conversion of light into electrical activity is not the only function of the retina, however. The retina is more than just the biological equivalent of a photographic emulsion. The transformation of the visual image into nerve impulses traveling along the optic nerve calls for a considerable amount of processing. Activity in the optic nerve is not related simply to the intensity of illumination falling on each retinal receptor but rather to specific aspects of the visual image, and some aspects are emphasized at the expense of others. The information transmitted to the brain is related not so much to patterns of light and dark as to such properties as contrast at borders, the movement of an object or its color.

It is now clear that the degree of retinal transformation varies among species. Curiously, the degree of transformation does not parallel the evolutionary development of the vertebrates. For example, the retina of primates (monkeys, apes and man) is simpler in terms of both anatomy and physiology than the retina of the frog. On the other hand, some mammals, such as the rabbit and the ground squirrel, have retinas that are almost as complex as the frog's. In each species there is a close correlation between the anatomy and the physiology of the retina. Furthermore, there appears to be a direct relation between the complexity of an animal's retina and the development of the visual centers of its brain.

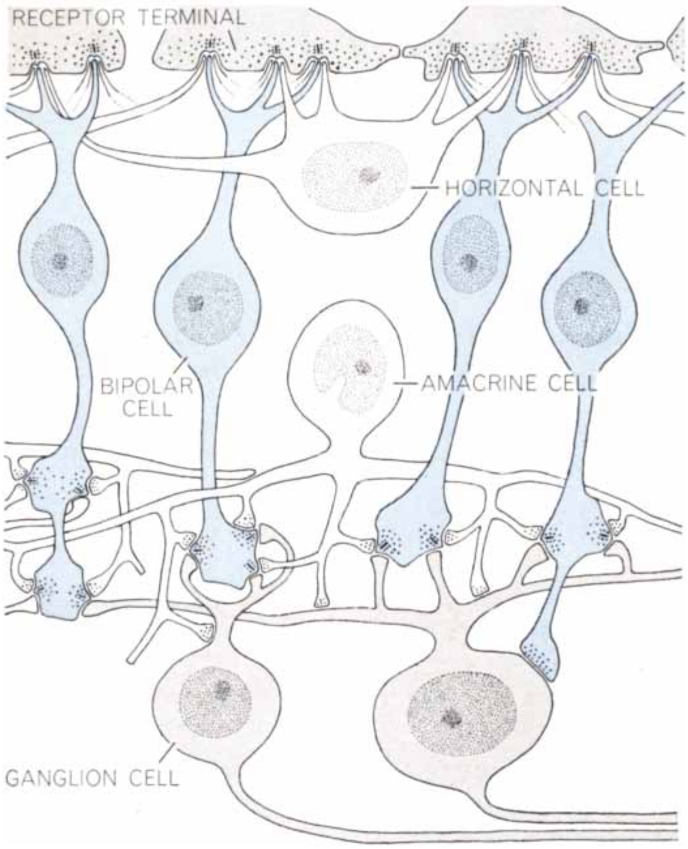
A brief description of the structure and interactions of neurons, or nerve cells, is necessary for a clear understanding of the retina's organization and operation. A number of fine processes called dendrites radiate from the cell body of each neuron [*see illustration below*]. In addition there usually is a single long process—an axon—that extends some distance from the cell body. Messages, in the form of brief electrical nerve impulses that vary in frequency but not in amplitude, travel from the cell body along the axon to its endings, which come in contact with the dendrites or the cell body of another neuron at junctions known as synapses. Information is transmitted from one neuron to another at the synapses, usually by the release of a chemical substance from tiny vesicles, or sacs, in the axon endings. The release of the chemical is initiated by the arrival of a nerve impulse.

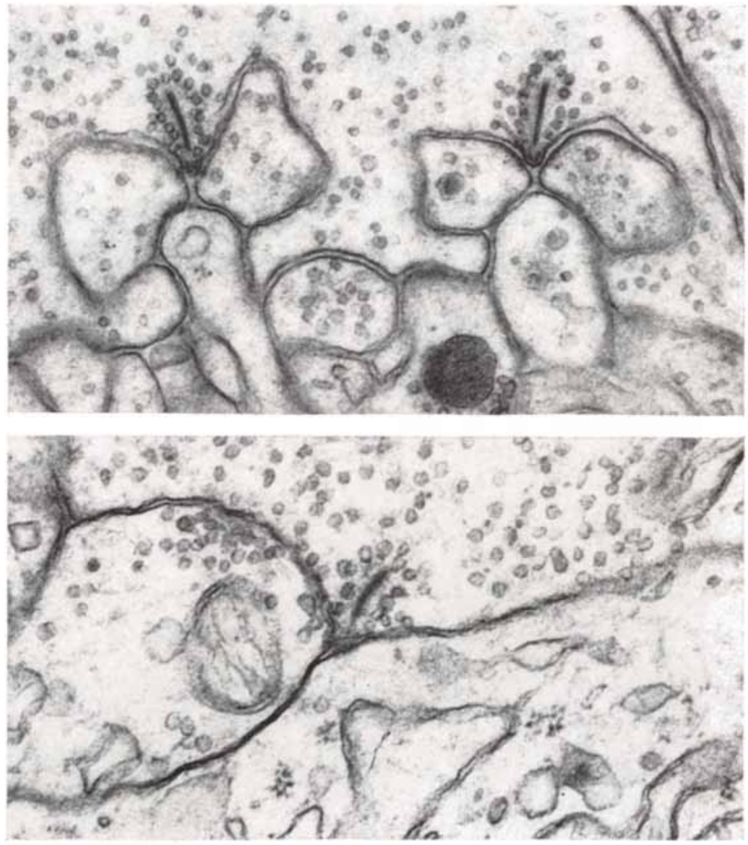
There are two basic types of chemical synapse. In one type the substance diffusing from the axon has an excitatory effect on the dendrite or cell body beyond the synapse and makes it more likely that the postsynaptic cell will discharge. In the other type the chemical has an inhibitory effect on the postsynaptic process and renders the cell less likely to discharge. The interplay of the excitatory and the inhibitory synaptic activity impinging on a single cell strongly influences its pattern of discharge.

In the vertebrate retina the cell bodies of the neurons are arrayed in three distinct layers [*see illustration on opposite page*]. The outermost layer (the one farthest from the lens of the eye) consists of the receptor cells containing the light-absorbing visual pigments. The next layer includes the bipolar cells (which conduct messages from the receptors to the cells in the third layer) and the horizontal and amacrine cells, which appear to be involved in the lateral transmission of information. The third layer contains the ganglion cells, whose axons form the optic nerve, the sole output of the retina. In between the three layers of cell bodies are two synaptic layers in which the different cell processes come in close contact. One might think a system containing only two layers of synapses and five types of cell could not accomplish much in terms of the analysis of the retinal image. The richness of the synaptic connections in the retina, however, makes possible a variety of integrative mechanisms.

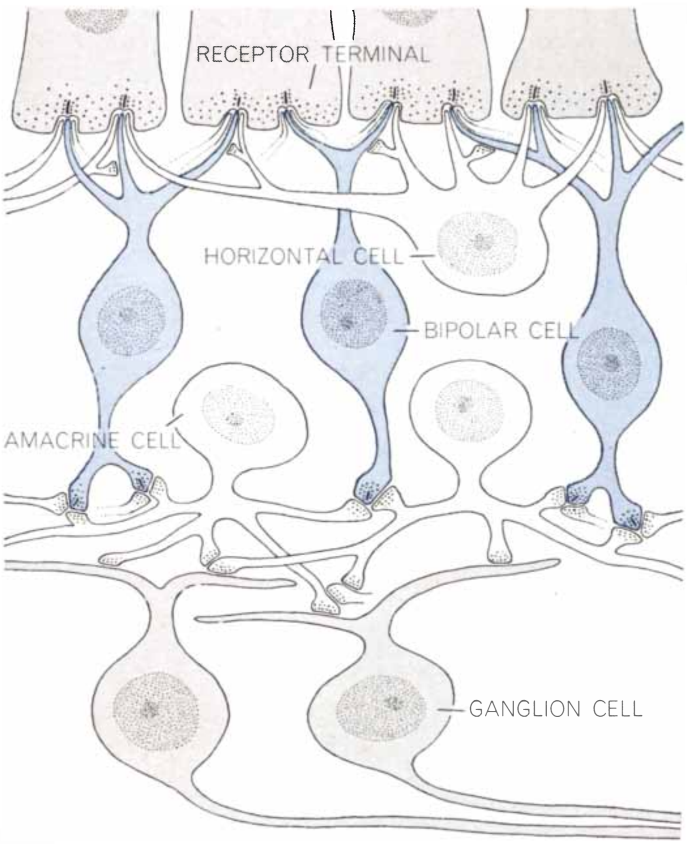
John E. Dowling of the Wilmer Ophthalmological Institute of the Johns Hopkins University School of Medicine has

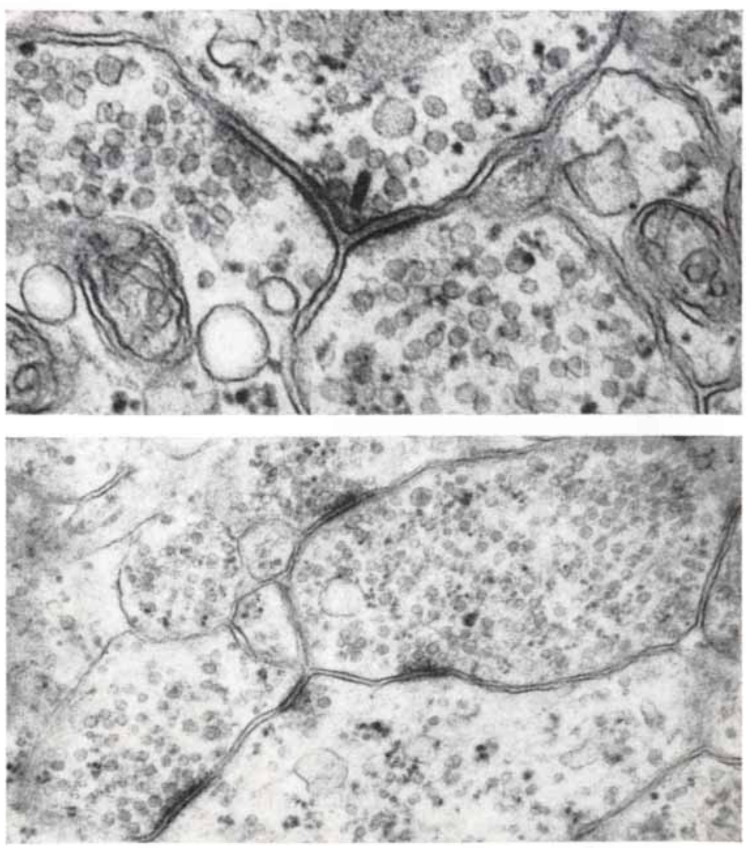
INFORMATION is transmitted from an axon ending of one nerve cell to the cell body or dendrite of another by a chemical transmitter substance that diffuses across the synaptic gap. Impulses from an excitatory cell (*color*) tend to make the cell beyond the synapse (*gray*) fire. Impulses from inhibitory endings (*black*) make it less likely that the cell will fire.



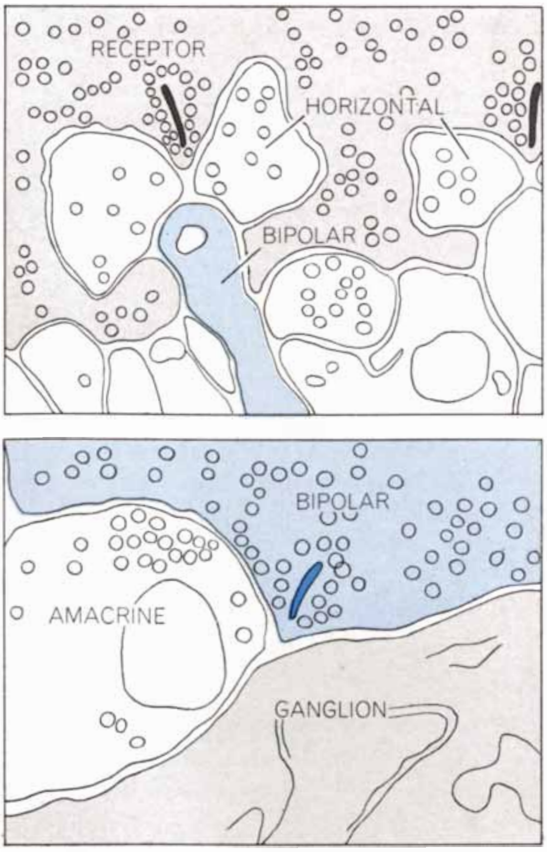


PRIMATE RETINA'S synaptic organization is diagrammed (*left*) on the basis of electron micrographs made by Dowling, two of which are reproduced (*middle*) and mapped (*right*). Two "ribbon" synapses in the base of a receptor in a monkey's retina are enlarged 45,000 diameters (*top*); at each of them a bipolar-cell dendrite and two horizontal-cell processes make contact. The small spheroidal objects are sacs containing transmitter substances. An axon ending of a bipolar cell in a human retina, enlarged 35,000

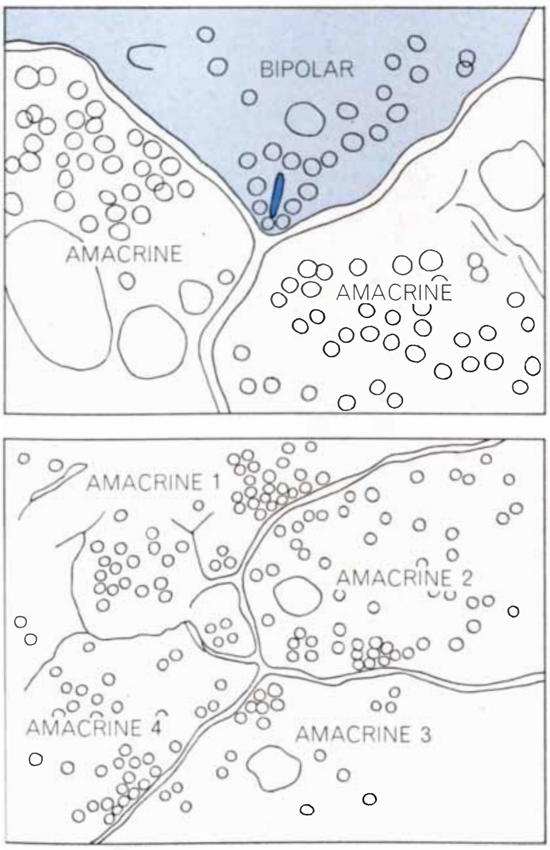




FROG RETINA'S synaptic contacts are illustrated. In the two electron micrographs a bipolar-cell axon (enlarged 60,000 diameters) synapses with two amacrine-cell processes (*top*), and four amacrine cells (enlarged 30,000 diameters) synapse serially with one another (*bottom*). In the frog's retina horizontal cells not only connect receptors but also synapse on bipolar-cell processes.



diameters (*bottom*), synapses with processes from an amacrine cell and a ganglion cell. In the primate retina the signal from a receptor is conducted directly to a ganglion cell.



Signals from receptors are conducted not directly to ganglion cells but rather to amacrine cells and from them to ganglion cells.

carried out a detailed electron-microscope study of the synaptic organization of the retina [*see illustrations on these two pages*]. In the outer synaptic layer of all the retinas he has studied the terminals in the bases of the receptors form synapses with bipolar-cell dendrites and horizontal-cell processes. The horizontal cells connect neighboring receptors; the bipolar cells send information to the inner synaptic layer. In the retinas of the frog, the pigeon and the rabbit there are additional connections: horizontal-cell processes also form synapses with other horizontal cells and with bipolar-cell dendrites.

In the inner synaptic layer of the primate retina each bipolar terminal forms synapses with two processes, a ganglion-cell dendrite and an amacrine-cell process. The tangential processes of the amacrine cells extend as much as one millimeter along the inner synaptic layer and are most likely involved in the lateral transmission of information across the retina. In the inner synaptic layer of the frog's retina the bipolar terminals make contact only with amacrine cells, which in turn form synapses with ganglion cells; the frog's ganglion cells are therefore primarily influenced by amacrine rather than by bipolar cells. In fact, in the frog's retina anywhere from one to five amacrine cells may be interposed between a given bipolar cell and the ganglion cell with which it is associated. Through these serially arranged amacrine cells there is the possibility of considerable neural interaction in the inner synaptic layer of the frog.

It appears that it is primarily the pattern of organization in the two synaptic layers that distinguishes the retinas of different species. How is it that the retina of primates is simpler than that of the frog, an animal much lower on the evolutionary scale, and that the frog and the pigeon, which are widely separated in terms of overall development, have remarkably similar retinas? As we shall see, the synaptic complexity of these retinas is reflected in their analytical capacity.

By some unknown mechanism the absorption of light produces an electrical response in the receptors that is transmitted to the bipolar cells. These neurons in turn transmit information to the retinal ganglion cells, whose axons form the optic nerve. Since the optic nerve is the only connection between the retina and the brain, the information it carries represents the total integrative capacity of the retina. It would be ideal if one could study the electrical activity of each of the five types of neuron in the retina and thus learn the function of each and how they interact with one another. Unfortunately it is difficult to record the electrical activity of any individual neurons in the retina other than the ganglion cells. Most investigators have therefore studied ganglion cells or their axons, the individual fibers of the optic nerve. This type of study enables one to determine the overall analytical powers of a retina, and in some cases to deduce the individual steps of the processing.

A given retinal ganglion cell receives information from a rather small population of receptor cells. The area covered by these receptors is called the receptive field of that ganglion cell. In other words, the receptive field of a cell in the visual system is the area of the retina that, when stimulated, influences the electrical activity of the cell in either an excitatory or an inhibitory manner. In an experiment a microelectrode is inserted into the retina or the optic nerve of an anesthetized animal until the electrical activity of a single ganglion cell or optic nerve fiber is recorded. The eye is presented with a series of test stimuli, projected directly onto the retina or onto a white screen the animal is facing, while the microelectrode is simultaneously advanced through the optic nerve or the retina. Often it is necessary to try a large variety of stimuli before finding the one that will evoke the strongest response from a cell. The search may take several hours, but in all cases it is eventually possible to map a cell's receptive field and define precisely the type of stimulus to which it responds.

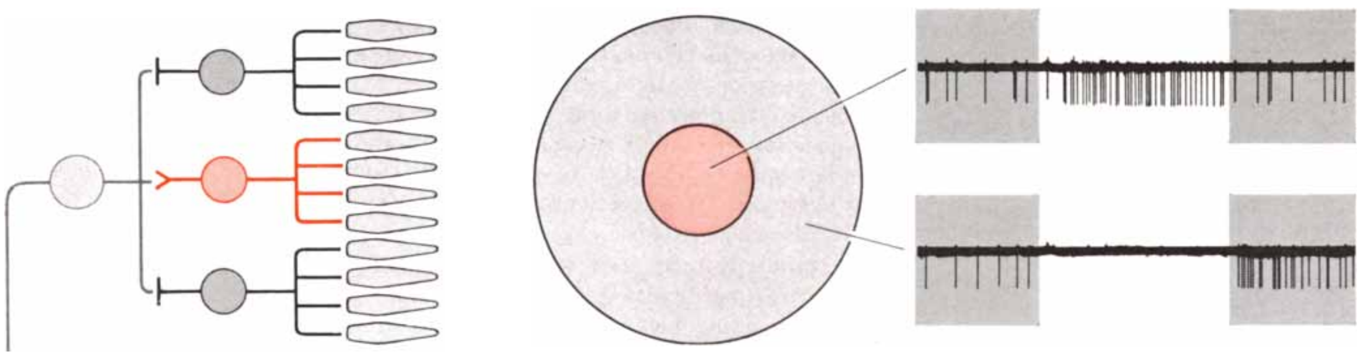
In 1938 H. K. Hartline, working at the University of Pennsylvania, studied the receptive fields of the frog's ganglion cells and for the first time succeeded in mapping the receptive fields of cells in a visual system. (For such pioneering investigations Hartline received a Nobel prize in 1967.) In 1953 Stephen W. Kuffler, then at the Wilmer Institute, found that the receptive fields of the cat's retinal ganglion cells were organized in a concentric manner, with a circular central area surrounded by a ring-shaped outer zone. In some instances a spot of light in the central region excited a cell (an "on" response), whereas light falling on the surround inhibited any spontaneous discharge and a burst of impulses followed when the illumination ceased (an "off" response). In other cells the situation was reversed: illumination of the center produced an "off" response, and stimulation of the surround an "on" response. Stimuli that simultaneously covered both the center and the surround had little effect on a cell's discharge. What each of these ganglion cells was doing, in other words, was comparing the illumination of the center of its receptive field with that of the surround. Ganglion cells with this type of receptive field have been found in the retinas of every vertebrate that has been studied.

Several years later Jerome Y. Lettvin and his colleagues at the Massachusetts Institute of Technology decided to reexamine the receptive fields of ganglion cells in the retina of the frog. They found that the frog's retina is much more complex than the cat's. It appears to have at least five classes of ganglion cells, including some that respond only to convex edges or only to changes in contrast. For example, the convex-edge detectors respond to the positive curvature of an edge that is darker than the background. Straight edges are poor stimuli, but any perceptible convexity or projecting angle evokes a discharge; in general, the greater the curvature of the edge, the larger the response.

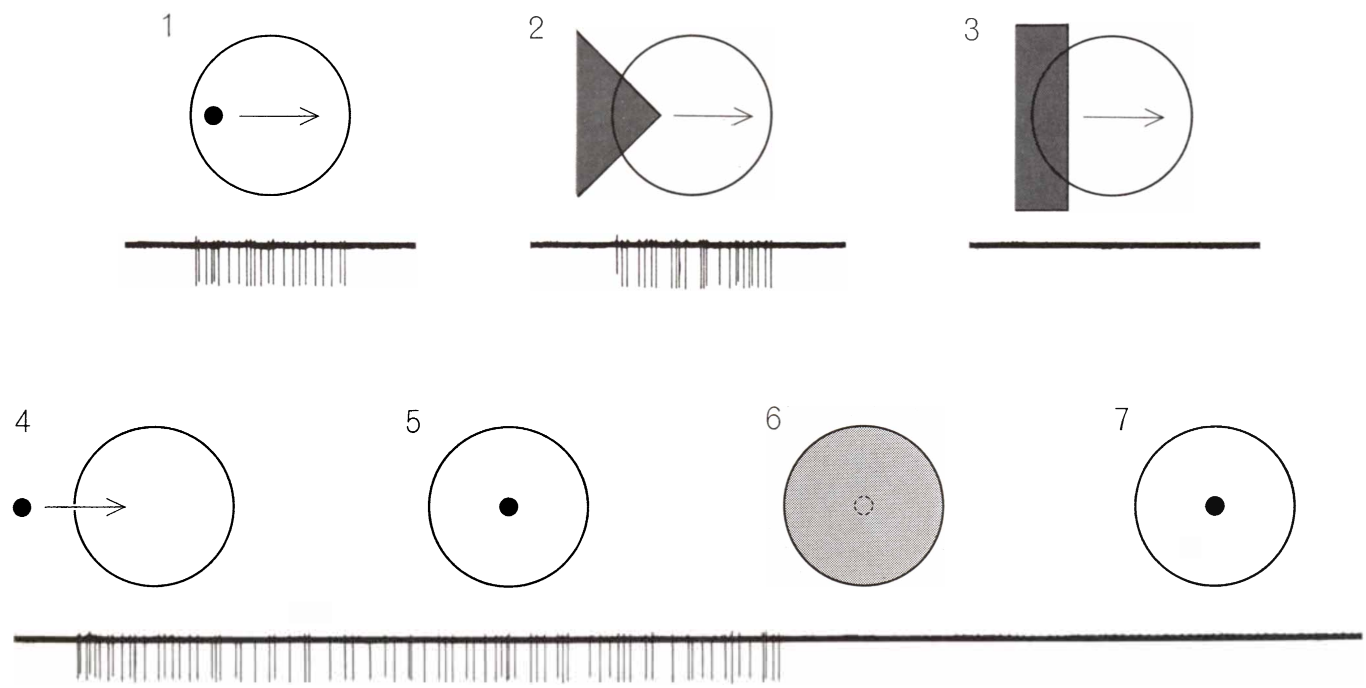
These cells respond to moving stimuli as well as to those that are stationary within the receptive field. The response to a stationary dark spot lasts for many minutes, but it ceases immediately when the background light is turned off and does not appear again when it is turned on. Similarly, when a stimulus is brought into the receptive field in total darkness and the background light is then turned on, there is no response. Apparently an additional requirement for the discharge of these cells is that the object be "seen" during its movement into the field.

The frog is primarily interested in catching flying insects, and so most of its ganglion cells, including the convex-edge detectors, are organized to respond to small moving objects. Cells with such sophisticated discriminatory properties have never been seen in the cat's retina. The complexity of the ganglion cells' behavior in the frog may be related to the extensive serial synapses among amacrine cells interposed between the bipolar axons and the ganglion-cell dendrites.

For the past 10 years David H. Hubel and Torsten N. Wiesel of the Harvard Medical School have been studying the receptive fields of cells in the visual system of cats and monkeys [see "The Visual Cortex of the Brain," by David H. Hubel; SCIENTIFIC AMERICAN, No-



CONTRAST-SENSITIVE ganglion cells in the cat's retina have fields with a concentric organization. The oscilloscope records (*right*) show that a spot of light in the center of the receptive field (*middle*) of this "on"-center ganglion cell excites the cell; stimulation of the surround inhibits it. (The responses would be reversed if this were an "off"-center cell.) Presumably there are two types of bipolar cell, excitatory (*color*) and inhibitory (*black*), that collect information from receptors in the two parts of the field (*left*).



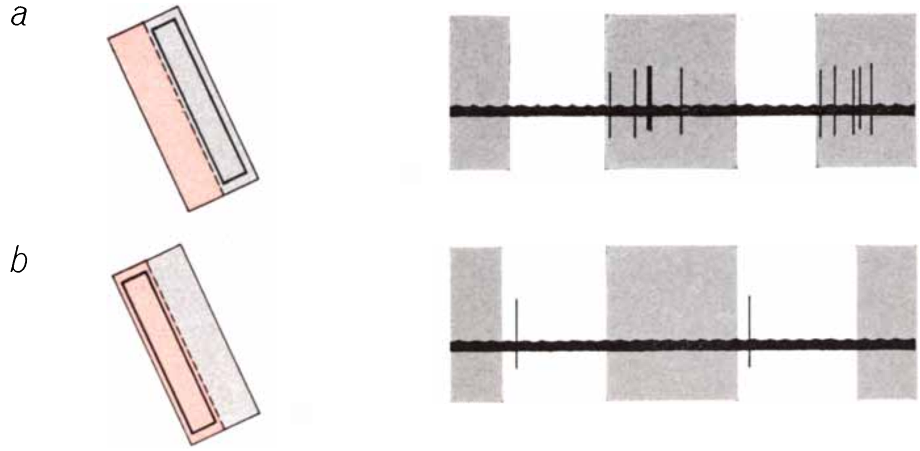
CONVEX-EDGE DETECTORS in the frog's retina respond to a moving stimulus that has a positive curvature (*1*) or contains an angle (*2*) but not to a moving straight edge (*3*). The response to an object entering the field (*4*) continues when the object stops within the field (*5*). The response ceases when the background light goes off (*6*) and does not recur if the light goes on again (*7*).

vember, 1963]. In the course of their investigations farther along the visual pathway they have found that the receptive fields of neurons in the visual cortex of the brain are organized so that the cells are most sensitive to line stimuli, such as white or black bars or straight edges separating light areas from dark ones. In all cases the size, shape, position and orientation of the stimulus is highly critical for an optimum response.

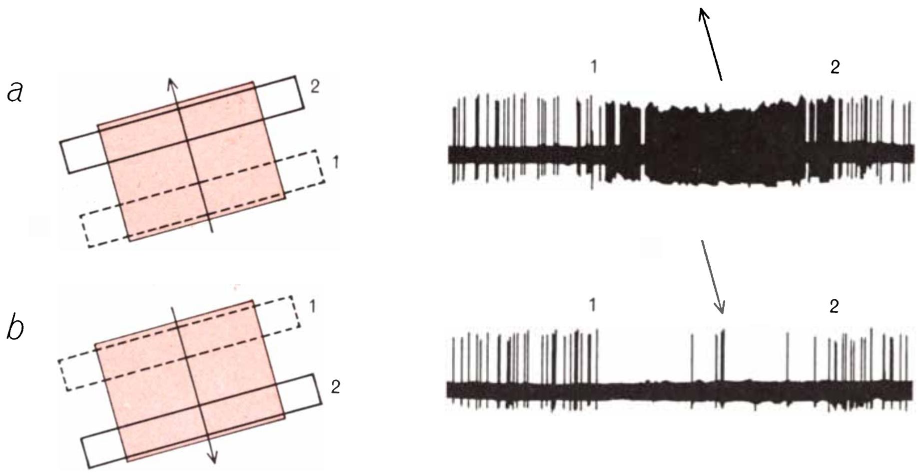
So far Hubel and Wiesel have identified three major classes of form-sensitive cortical cells [*see illustrations at right*]. The first, called simple cells, have receptive fields that can be mapped with stationary stimuli. The fields are subdivided into excitatory and inhibitory regions separated by boundaries that are straight and parallel. The neurons next highest in order, the complex cells, have receptive fields that cannot be mapped into "on" and "off" regions and are best studied with moving stimuli. Unlike the simple cells, the complex ones respond with sustained firing to movement throughout their receptive fields, and the response is usually directionally selective.

The highest order of cortical neurons studied, the hypercomplex cells, are most effectively activated by a properly oriented line stimulus that is limited in its length at one end or both ends. The receptive fields consist of a central orientation-sensitive "activation" area flanked on one side or on opposite sides by orientation-sensitive "antagonistic" regions. The hypercomplex cells respond only to moving stimuli, again usually in a directionally selective manner. Cells with receptive fields of these three types occur only in the cortex of the cat and the monkey, not in the retina. Moreover, of these three types of cortical cell only the hypercomplex ones have functional properties that approach in sophistication the retinal ganglion cells of the frog.

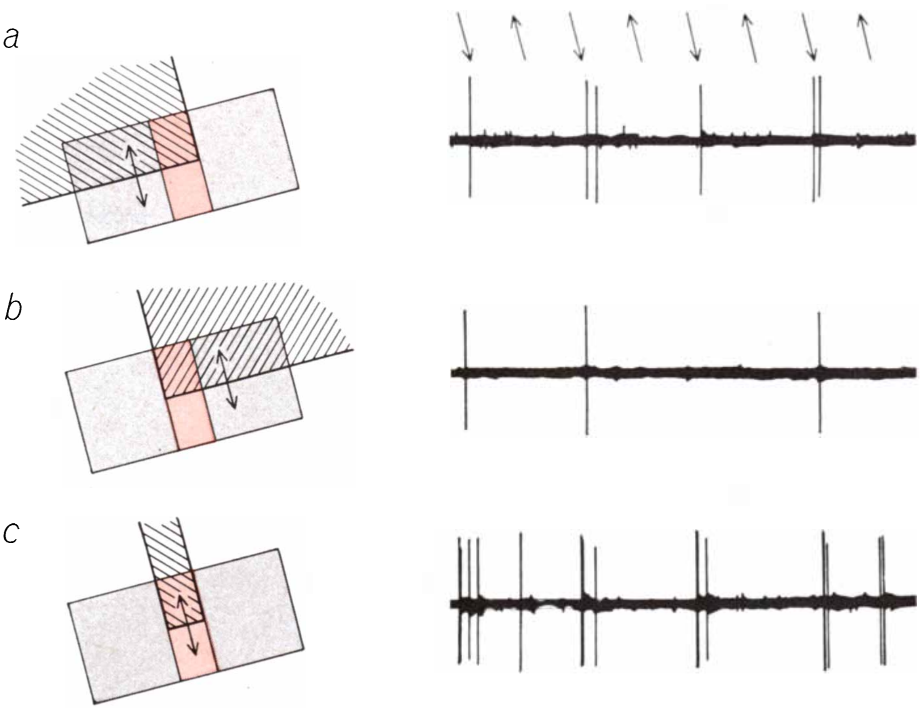
From the work of Kuffler, Lettvin, Hubel and Wiesel one might have concluded that it is only in lower animals such as frogs that the visual image is analyzed to a significant extent in the retina, and that cells with complicated response properties and receptive fields are found only at the cortical level in the mammalian visual system. Recent investigations—by Horace B. Barlow and William R. Levick at the University of California at Berkeley on the rabbit's retina and by me at Harvard University and Johns Hopkins on the retina of the ground squirrel—make it clear that such a conclusion is not justified. In certain mammals complex analysis of sensory information does occur in the retina, be-



SIMPLE CELL in the cat's visual cortex has a field with excitatory (*color*) and inhibitory regions separated by straight, parallel boundaries. This one gives an "off" response to a slit stimulus in one region (*a*) and a small "on" response to a stimulus in the other region (*b*).



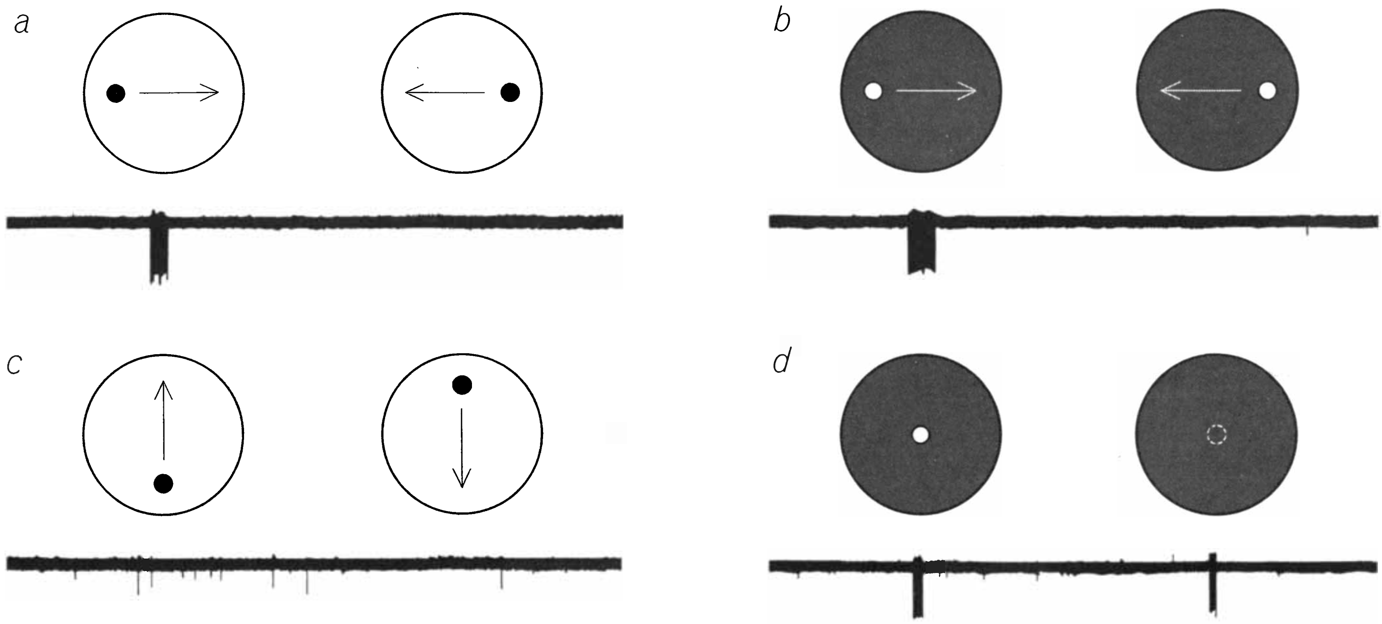
COMPLEX CELL in the cat's cortex responds continuously to a properly oriented stimulus moving across its entire field. This spontaneously active cell responds vigorously to movement in one direction (*a*) and is largely inhibited by movement in the other direction (*b*).



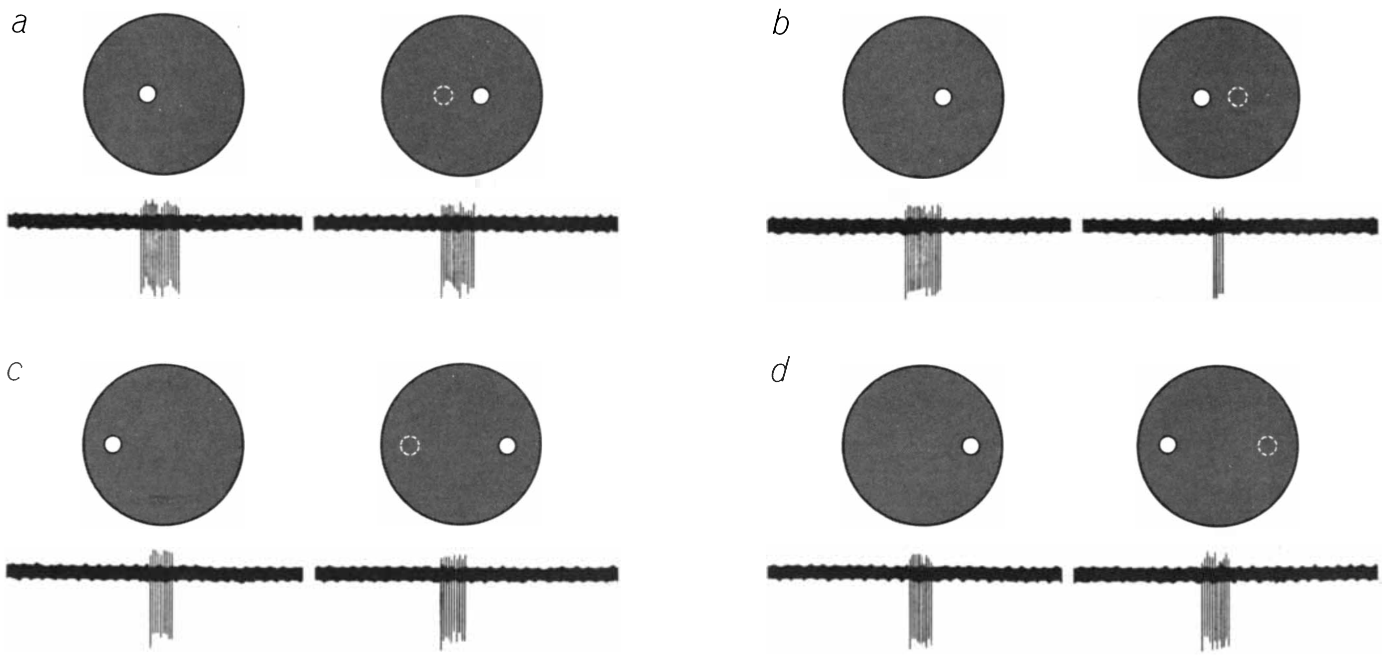
HYPERCOMPLEX CELL has a field with a central activation region (*color*) and antagonistic flanks (*gray*). It responds best to stimuli that are limited in length. Here the longer stimuli affect both kinds of region (*a*, *b*), the most limited one only the activation area (*c*).

fore the neural activity moves on to the higher nervous centers. Some mammalian retinas, in fact, appear to be capable of a complexity of neural integration that in the cat and the monkey is attained only in the visual cortex.

We find that the retina of the rabbit and that of the ground squirrel (*Citellus mexicanus*) contain many types of ganglion cell, each specifically sensitive to a particular aspect of the stimulus such as color, convex edges or oriented lines. The most thoroughly investigated of these cells are the directionally selective neurons found in both animals. They are vigorously excited by a stimulus moving in one direction (the "preferred" direction) across their receptive fields and are inhibited by motion in the reverse direction (the "null" direction). The directionally selective response is independent of the velocity of movement of the stimulus, its shape, the contrast between it and the background and the level of the background illumination [*see upper illustration below*]. Smaller stimuli are more effective than larger ones, indicating that a powerful antagonistic region surrounds the center of the receptive field. The activity of these cells would seem to provide a basis for discriminating the direction of motion of small objects in the animal's visual field.



DIRECTIONALLY SELECTIVE ganglion cells in the ground squirrel's retina respond to movement in one direction but not in the opposite direction (*a*). A change in contrast makes no difference (*b*). Movement at a right angle does not produce a clear response (*c*). A stationary spot evokes a brief discharge when the light goes on and another discharge when the light goes off (*d*).

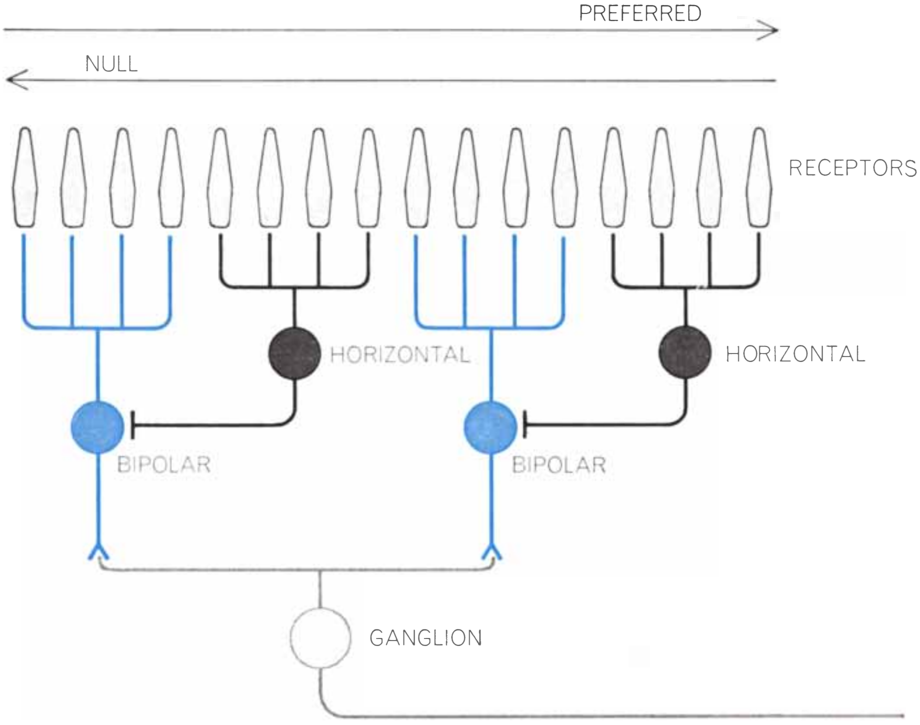


SEQUENCE-DISCRIMINATION is the basis of directional selectivity. When two spots close together are flashed sequentially in the preferred direction, there is a good "on-off" response to each flash (*a*). (In this illustration only "on" responses are shown.) When they are flashed in the opposite direction, the response to the second flash is much weakened (*b*), apparently because of inhibition from the first flash. When the two spots are farther apart, however, the sequence of illumination makes no difference (*c, d*).

We have established that this directional selectivity is accomplished primarily by an inhibitory mechanism. The most direct evidence for inhibition was the cessation of the discharge of spontaneously active units during null movements. Most of the directionally sensitive ganglion cells are not spontaneously active, however. For such "quiet" cells a light spot anywhere in the field center produced a short burst of impulses when it was turned on and another when it was turned off; if the same spot was moved in the null direction, it produced no such response—even though the movement of its leading and trailing edges should be equivalent to the turning on and off of a stationary spot. Apparently a wave of inhibition precedes the null-moving stimulus, preventing or counteracting an excitatory response that would occur if the spot were stationary.

By working with two independent stationary stimuli instead of one moving stimulus we learned more about the inhibitory mechanism and its spatial extent. When two small white spots were positioned next to each other on the directional axis, each spot by itself produced the expected "on-off" response [*see bottom illustration on opposite page*]. When the spots were flashed sequentially in the preferred direction, the response to the second spot was as large as or larger than the response to the first one. When they were flashed sequentially in the null direction, however, only the first spot produced a strong "on-off" discharge; the second response was weak or absent. Apparently any potential response to the second spot was partially or completely inhibited by the first flash. It must therefore be the sequence of changes in the illumination of points along the directional axis that determines the response to a moving stimulus.

The next step was to move the two white spots away from each other. When the separation was small, there was a clear indication of inhibition for the null sequence of illumination. When the separation reached 20 minutes of arc, however, the second response was as strong as the first regardless of the sequence of illumination. This showed that the complete mechanism for discriminating the sequence of excitation is contained within an area extending about 15 minutes of arc along the directional axis, a distance corresponding to about 30 microns (30 thousandths of a millimeter) on the retina. Since the diameter of the field centers ranged between 30 and 60 minutes of arc, the mechanism for directional selectivity clearly does not require movement over the entire center in order to operate effectively.



MECHANISM for directional selectivity is suggested. Each bipolar cell is connected to two groups of receptors—to one directly and to the other by way of an inhibitory horizontal cell. A stimulus moving to the right (preferred direction) excites the bipolar cells, which in turn excite the ganglion cell. A stimulus moving to the left (null direction), however, first excites the horizontal cells, inhibiting any subsequent response from the bipolar cells.

Barlow and Levick proposed a mechanism to explain the directional selectivity of these cells, and their conclusions were confirmed and extended by my own work on the ground squirrel's retina. The results from both laboratories suggest that a directionally selective ganglion cell must be excited by a group of sequence-discriminating subunits that share the same preferred direction of motion. This must be the case because the experiments with two spots showed that sequence discrimination involved distances considerably smaller than the size of the ganglion cell's field center. The directionally selective mechanism must therefore be located at an earlier stage than the retinal ganglion cells, and it seems likely that the bipolar cells are the subunits.

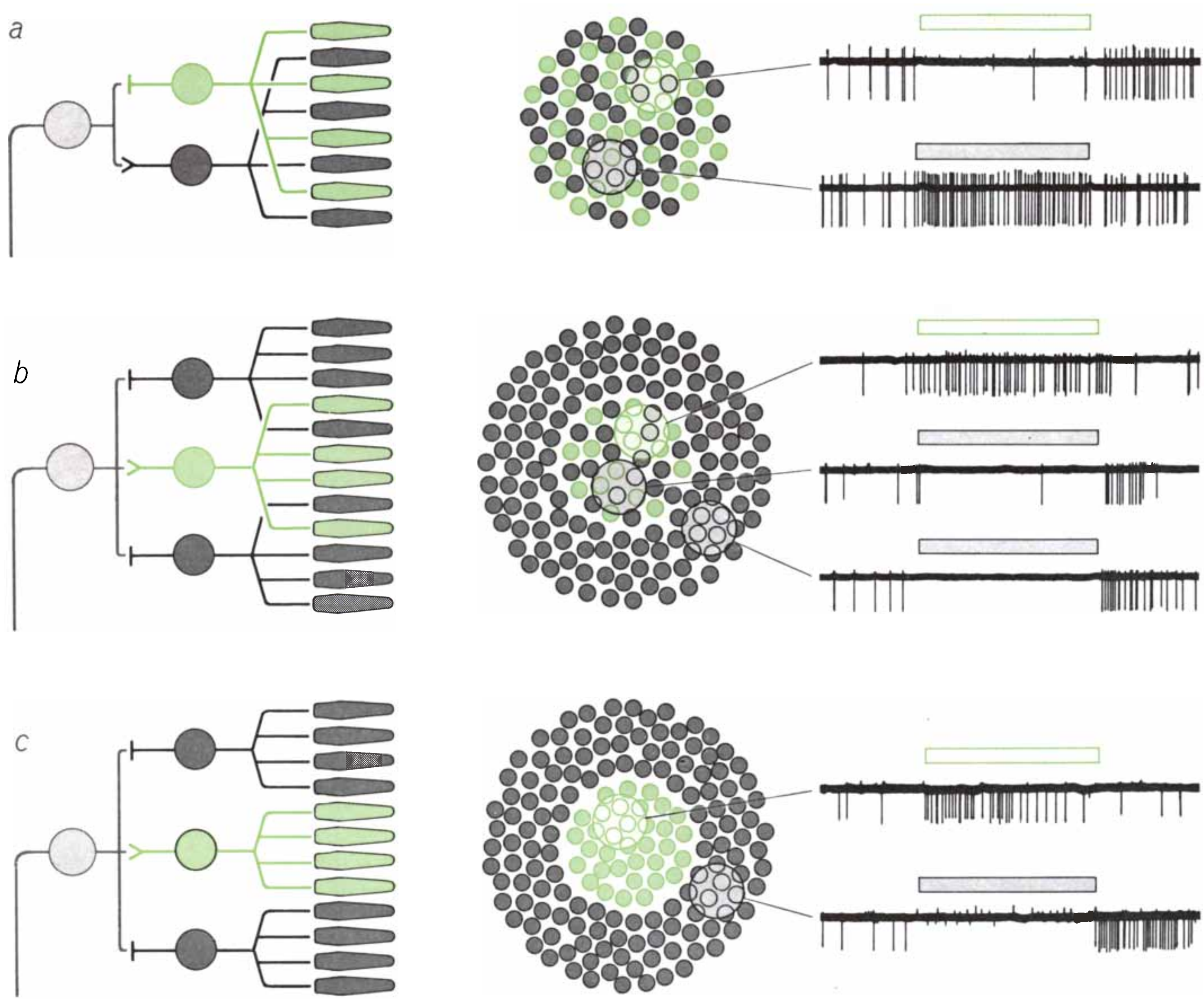
Suppose a given bipolar cell is connected to two groups of receptors, to one set directly and to the other by way of an interneuron, probably a horizontal cell [*see illustration above*]. The receptors have an excitatory effect on the horizontal or bipolar cell with which they are in contact, but the horizontal cell makes an inhibitory synapse with the bipolar cell. The sequence of excitation of the two populations of receptors will determine the response of the bipolar cell. A stimulus moving in the preferred direction will first excite the bipolar cell through the directly connected receptors. Although the horizontal cell will subsequently be activated, its inhibitory effect will be too late to prevent the bipolar cell's excitatory response. A spot moving in the null direction, on the other hand, will first stimulate the receptors connected to the horizontal cell, thereby inhibiting the bipolar-cell activity that would otherwise be excited by the directly connected receptors. Thus the bipolar cells distinguish between the null and the preferred sequences of excitation of the two neighboring receptor populations with which they are associated. A ganglion cell receives excitatory inputs from a number of these sequence-discriminating bipolar cells and therefore is itself excited by preferred motion. Since any spontaneous discharges by ganglion cells are inhibited by null movement, such spontaneous activity is probably produced by a constant excitatory bombardment from the bipolar cells. Any null movement inhibits the bipolar cells, and so the spontaneous activity of the ganglion cell ceases.

This proposed mechanism needs further study, but so far it is supported by all the physiological experiments performed independently in Barlow's laboratory and in my own. Moreover, the theory's requirement of connections between horizontal and bipolar cells receives anatomical confirmation from Dowling's discovery of horizontal-cell processes in the rabbit's retina that synapse on the dendrites and cell bodies of the bipolar cells. The lateral extent of these processes is in the same range as the dimensions of the subunit systems, measured physiologically. To be sure, these are preliminary microscopic observations, but the organization of the rabbit's outer synaptic layer does seem to support the proposed mechanism for directional selectivity.

Let us now turn to another aspect of the visual image, the perception of color. It is surely one of the most fascinating sensory capacities man possesses, and he shares it with few other animals. Among the mammals only man and some of the Old World monkeys have complete color vision as we know it; some New World monkeys, the tree shrew and the ground squirrel have partial color vision. Any animal that does see color must have two or more visual pigments in its retina. These pigments are contained in the receptors called cones. (The other photoreceptor cells of vertebrates, the rods, function in dim illumination and their visual pigment is not involved in color perception.) Since the ground squirrel's retina contains only cones, it is not surprising that many of its ganglion cells code and relay color information.

The ground squirrel appears to have two cone visual pigments, one that absorbs maximally in the green region of the spectrum and another that is most sensitive in the blue. The ganglion cells concerned with color coding are "opponent color" cells. They are either excited by green light and inhibited by blue or excited by blue light and inhibited by green. It seems probable that a given ganglion cell receives information from two classes of bipolar cells, one connected only with cones containing the green-sensitive pigment and the other only with cones containing the blue-sensitive pigment. Presumably one type of bipolar cell excites the ganglion cell and the other inhibits it. As one would expect, these ganglion cells are poorly responsive to white light, which contains all wavelengths and therefore stimulates both the excitatory and the inhibitory inputs.

A series of experiments revealed that

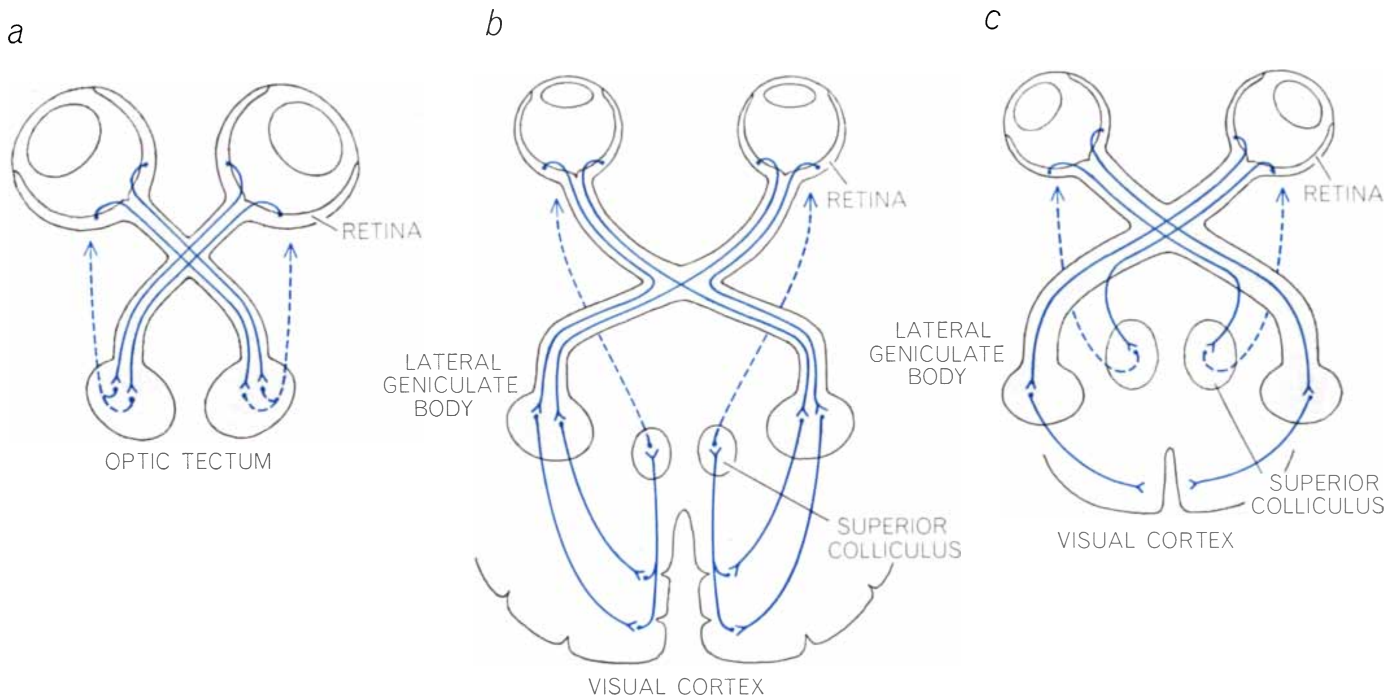


GROUND SQUIRREL'S RETINA seems to have two cone pigments, one more sensitive to green light and the other to blue (*shown here as gray*). Three types of color-coded ganglion cell (*left*) have been identified: some with receptive fields (*middle*) in which two cone populations overlap completely (*a*), some in which they are partially segregated (*b*) and some in which they are completely segregated (*c*). Probably each ganglion cell receives information from some bipolar cells connected to green-sensitive cones and others connected to blue-sensitive cones. The bipolar cells have opposite effects: one excites a ganglion cell and the other inhibits it.

the receptive fields of the ground squirrel's opponent-color cells are divided into several classes [*see illustration on opposite page*]. In many cases the field seemed not to be organized into a center and a surround but instead gave opponent-color responses throughout its extent; apparently the green-sensitive and the blue-sensitive cones feeding into these cells had identical spatial distributions. Another class of cells had a field center and a surround; only the center received inputs from green-sensitive cones, whereas both the center and the surround were influenced by blue-sensitive cones. The third group also had a center-surround organization, but here the center was driven only by green-sensitive cones and the surround only by blue-sensitive ones; in this last type of field there was complete spatial separation of the two color systems.

The color-coded responses of ganglion cells were first studied in the goldfish by Edward F. MacNichol, Jr., of Johns Hopkins and Henry G. Wagner and Myron L. Wolbarsht of the Naval Medical Research Institute [see "Three-Pigment Color Vision," by Edward F. MacNichol, Jr.; SCIENTIFIC AMERICAN, December, 1964]. Recently Hubel and Wiesel have mapped the receptive fields of several types of opponent-color cells in the monkey's lateral geniculate nucleus, the neural way station between the retina and the visual cortex. In all the animals studied the receptive fields of most of the color-coded cells are organized in such a way that they can deal with both color and contrast information. In other words, there are opponent-color and opponent-spatial mechanisms influencing the activity of a single cell. This means that the optimum stimulus must be specified not only in terms of color but also in size and shape.

It appears to be a general rule that the retinal processing of information involves a comparison by a ganglion cell of the signals from two sets of receptors. What the contrast-sensitive units in the cat are doing is comparing the information received from receptors in the field center with information from other receptors located in the surround. The directionally selective cells in the rabbit's and the ground squirrel's retina are collecting data from subunits sensitive to the sequence in which two separate sets of receptors are illuminated. Finally, the opponent-color units in the ground squirrel are comparing the excitatory and inhibitory signals from two populations of cones that have different spectral sensitivities and often different spatial distributions. For each type of cell there is



OPTIC NERVE FIBERS have different destinations in different species. The frog and the pigeon have no cortex, and almost all the fibers project to the optic tectum (*a*). In the cat and primates almost all the fibers go to the lateral geniculate nucleus, where signals are relayed to the well-developed visual cortex (*b*). The ground squirrel may be a special intermediate case. Some fibers (the more sophisticated, directionally selective ones) go to the superior colliculus; the remainder go to the lateral geniculate, which projects to the cortex (*c*). From the colliculus (or tectum) signals travel to the muscles controlling eye movement (*broken arrows*).

an antagonistic interaction of the excitatory and inhibitory effects of two groups of receptors, and so a generalized stimulus is far less effective than one that is quite specific in contrast, movement or color.

One can see, then, that there are two principal types of visual system. The first is typified in the frog, the rabbit and the ground squirrel. (The work of Humberto R. Maturana in Chile on the pigeon's retina indicates that it too belongs in this group.) The individual ganglion cells of these animals are usually highly specialized in terms of stimulus requirements, and such fundamental variables as edges, color, contrast, orientation and directional movement are processed intensively within the retina. The second type of visual system is the one found in cats, monkeys and presumably man. Here the ganglion cells at the retinal level are concerned only with the simultaneous contrast between the centers and the surrounds of their receptive fields, and in some cases with color information. The aspects of edge detection, orientation and directional selectivity are dealt with only later in the visual cortex, and there in a most detailed and precise manner.

Why should some animals process visual information so intensively within the retina whereas others put off this integration until farther along the visual pathway? One major factor may be the presence or absence of a visual cortex and, if it is present, its level of development. The frog and the pigeon, for instance, have no visual cortex; almost all their optic nerve fibers go to the optic tectum. The cat and the monkey have a highly developed cortex; almost all their optic nerve fibers go to the lateral geniculate nucleus, whose neurons in turn project their axons to the visual cortex. The ground squirrel has a visual cortex, but it is one that lacks the extensive convoluted surface characteristic of the cat's and the primate's cortex and presumably has not developed functionally to the same degree as it has in the higher mammals. And, as one might have predicted, in the ground squirrel about half of the optic nerve fibers project to the lateral geniculate nucleus and the rest go to the superior colliculus, the mammalian analogue of the optic tectum [*see illustration above*].

The ground squirrel, then, represents an interesting intermediate situation. It has some highly specialized retinal ganglion cells, the directionally selective neurons. These, I have found, project to the superior colliculus just as the sophisticated neurons of the frog's and the pigeon's retina go to the analogous optic tectum. On the other hand, the ground squirrel's retina also contains some simpler ganglion cells, the contrast-sensitive and opponent-color neurons. As in the cat and primates, these cells project to the lateral geniculate nucleus, where the information is relayed to the visual cortex. It appears that, regardless of the presence or absence of a visual cortex or of its degree of development, highly specialized retinal ganglion cells always project to the superior colliculus (or the optic tectum). Since the superior colliculus is associated with eye movements, it is not surprising that the information on directional movement is sent there. Nor is it surprising that the contrast and color information goes to the cortex, which is involved in the conscious perception of the visual image.

This parceling out of information occurs in a different way in the cat and the primate, whose retinas are simpler. In these animals one of the major outputs of the visual cortex is to the superior colliculus, perhaps providing a route for information related to the voluntary control of eye movements. This suggests a functional unity amid anatomical diversity. The colliculus has not lost its importance with the extensive development of the cortex in higher mammals; rather, its relative position in the visual system has simply been shifted.

RECENT FINDINGS

RESEARCH LABORATORIES

Ford

Lasers in Surface Research

Ford Motor Company scientists have developed a new method to measure the mobility of surface atoms. Special chemical etching and annealing techniques corrugate the surface of a solid sample so it resembles an old-fashioned washboard. When this sample is heated, surface atoms migrate from the hills to the valleys making the surface smoother. The atomic mobility can be determined directly from quantitative measurements of the rate of change of surface topography.

But the problem that confronted Ford scientists was how to measure the extent of decay in the corrugations while the sample remained in an ultra-high vacuum system (Fig. 1.). A vacuum environment is necessary because surface atoms are extremely reactive and

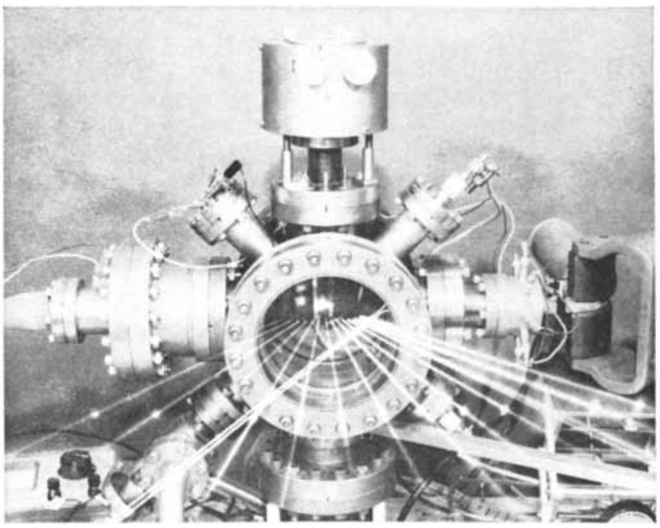


Figure 1. LEED System showing actual laser diffraction pattern.

their mobility is greatly influenced by absorbed gases. With the discovery that the "surface washboard" diffracts laser light like a reflection optical grating, the problem was solved (Fig. 2.). A modulation in the diffracted intensities occurs because of the sinusoidally-shaped surface, and this enables the amplitude of the corrugations to be measured accurately.

Performing these experiments under ultra-high vacuum conditions allows the investigator to exploit

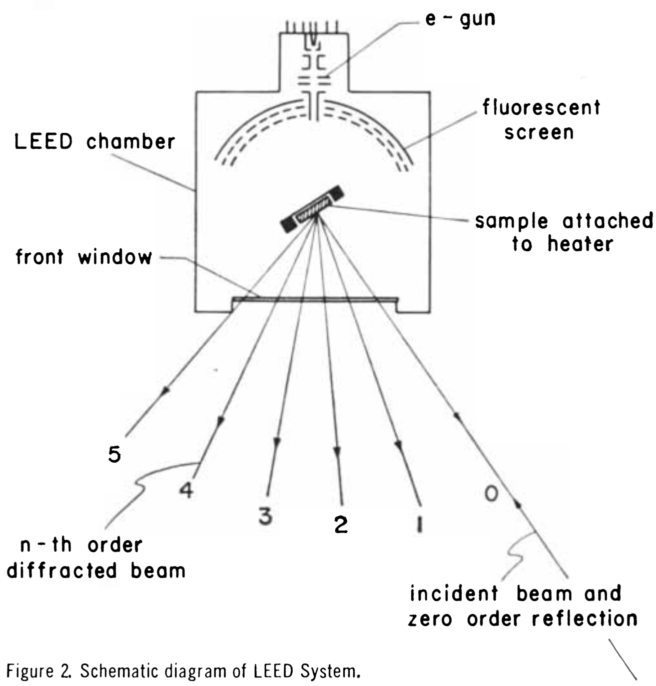


Figure 2. Schematic diagram of LEED System.

other modern surface techniques—such as Low Energy Electron Diffraction (LEED) and Auger Electron Spectroscopy. (AES) can be employed in conjunction with the laser diffraction method to probe the chemical composition of a surface while LEED can be used to obtain the atomic arrangements on the outermost surface layer.

This multi-pronged attack is probing the fundamental factors underlying the complex nature of atomic processes on solid surfaces. Processes important to catalysis, corrosion, adhesion, thin film technology, and other surface technology.

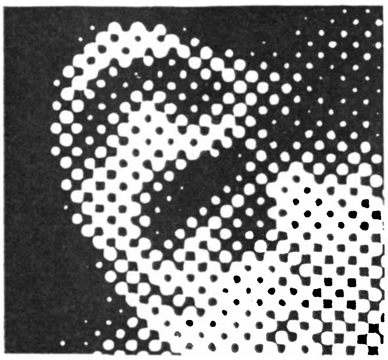
PROBING DEEPER FOR BETTER IDEAS

Ford

A Measure of Progress

Noise pollution—a problem or a solution

The human ear is a marvelous device—billion-to-one dynamic range, time resolving ability of a few microseconds, pitch discrimination of less than one-half percent. But as a measuring instrument the ear falls far short of scientific necessity: it's completely uncalibrated. Either it has its off days, or it differs markedly from person to person. Yet the ear has been around so long that most scientific instruments for measuring sound are calibrated *somehow or other* in terms of the ear.



There's not much Hewlett-Packard can do about the physiology of sound—or noise pollution—but we have spent some time bringing more definition to the phenomenon. Because, if a scientist, engineer, physiologist or acoustician wants to do something with sound, he needs a measuring tool far more precise and trustworthy than the ear.

Now the scientist can have his choice of three such tools from Hewlett-Packard, depending on how much he wants to know and what he wants to do with the information. Each measures sound pressure across the audio spectrum. Each registers the loudness in decibel units (or other units if the ear's involved). And each will register sound continuously, at a single instant, at a peak, or average it over a short period.

The simplest of these tools is the 8052A Impulse Sound Level Meter at $670. It measures the gross sound energy in an environment that is usually well defined—like machine noises in a factory, or the tick of a clock in a car. Its readings can be weighted A, B, C and D for low, middle and high frequencies and an annoyance factor—to reflect roughly the response of an ear. A companion instrument will break the sound up into octave-bands if you need to distinguish the loudness in specific frequency bands.

A more sophisticated instrument, calibrated to match the human ear, automatically displays on an oscilloscope the loudness over the total audio spectrum from 45 Hz to 14 kHz. It breaks sounds up into 20 bands and weights the loudness in each band according to the Zwicker formula, which allows for the frequency sensitivity and masking effects of the ear. The 8051A Loudness Analyzer, at $5500, is an analytical tool for use in investigations where the ear has been standard—such as gear testing—or where human comfort is paramount.

The ultimate instrument—disregarding systems with a computer—is the 8054A Real Time Audio Spectrum Analyzer. At $8950, it can afford 24 channels of 1/3rd octave frequency bands and all the electronic interfaces to feed into analog or digital data processing instruments. It measures loudness in absolute, unweighted units so that you can manipulate the data to fit whatever mode of analysis you like. It is particularly useful in real-time analyses of aircraft flying over, submarines floating past, impact effects on architecture and a host of industrial noises and vibrations.

If you'd like to know more about these varied techniques for surpassing the human ear's critical capacity, ask for Application Note 100, "Acoustics Handbook."

Lightening the Load for Chemists

One of the true tests of any instrument's merit is how unobtrusively it does its job. Amateur photography, for example, is enjoying a popularity boom simply because camera makers have put the user first. Today it's unprecedentedly easy to produce a photograph of nearly professional quality. Just aim, focus and *click*. No fuss, no bother.

Usability. That's the word for it. An instrument should do its job without befuddling the user, without creating more problems than there were to start with. And this principle holds especially when you extend electronic instrumentation into the chemical laboratory. Understandably, chemists would like to make their measurements without having to go back to school for an electronics degree.

We agree. That's why Hewlett-Packard chemists have put themselves in other chemists' places —trying to anticipate as fully as possible the problems they face.

Take Gas Chromatography—the separation of a compound into its component parts for analytical purposes. Gas chromatographers not only want to know what components exist, but also in what quantities—and they want to find out quickly, simply and accurately. A perennial problem has been how best to measure the area under a GC curve to gain this quantitative information. Now, HP has an Integrator that virtually lets the chemist forget electronics and get on with the analysis. The HP 3370A Integrator provides, for the first time, a completely *pushbutton* method for getting accurate quantitative GC data.

How? First, the chief analyst tells the instrument how to assess the chromatographic curve—what up slope to expect, what down slope, etc. He sets up these characteristics on special cards that plug into the instrument. After that, anyone in the lab can simply squirt a sample into the gas chromatograph, start the analysis, and as the chromatograph plots its curve, the integrator measures the area, generating quantitative data. This electronic shortcut costs the lab only an extra $4500 and cuts calculation time significantly while saving many a grey hair. The data can also be digitally printed out for computer processing.

If you know a gas chromatographer who's still struggling with a slide rule, perhaps he'd enjoy reading Bulletin 3370A. Tell us his name and we'll mail it out immediately.

Making the Stork's job easier

Childbirth is incontestably the most dangerous time in a little tyke's life. During labor, tremendous demands are made on his system while he is still dependent on the mother for nourishment and oxygen.

Early cardiotocology has shown a correlation exists between labor activity and fetal heartbeat frequency. A decrease in fetal heartbeat frequency during uterine contractions, for example, is not abnormal. Similarly, it's been found that a constant heartbeat during labor may very definitely be abnormal; the fetal heart may not be adjusting to varying loads.

In the search for better and more reliable means of detecting critical conditions which may threaten the infant, people have tried a variety of approaches. Some have listened to fetal heartbeats with a stethoscope or traced pitifully weak fetal ECG's through electrodes taped to the mother's abdomen.

A more definitive picture of the relationship between mother and child before and during birth is now available to physicians. The Hewlett-Packard 8020A Cardiotocograph monitors the baby's heartbeat and the uterine muscle contractions simultaneously through an external transducer placed on the mother's abdomen. Computer-like circuits in the 8020A filter out interfering noises and make allowances for undetected beats. The resultant frequencies of heartbeat and muscular contraction are interrelated and displayed together on a single chart, in real-time fashion.

Where once a varying heartbeat caused alarm and consternation, doctors can now determine immediately if that variation is, in fact, normal. And, conversely, if a steady heartbeat is abnormal. The cost of the complete system including transducer and recorder: $3750. We don't expect you to buy one for yourself, but you might want to mention it to your obstetrician. We have a number of publications on Fetal Monitoring available for the asking. Just write us. Hewlett-Packard, 1502 Page Mill Road, Palo Alto, California 94304; Europe: 1217 Meyrin-Geneva, Switzerland.

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MATHEMATICAL GAMES

The rambling random walk and its gambling equivalent

by Martin Gardner

He calmly rode on, leaving it to his horse's discretion to go which way it pleased, firmly believing that in this consisted the very essence of adventures.
—Don Quixote

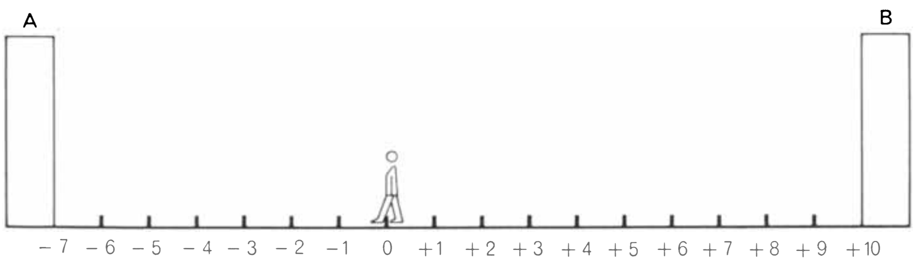
The compulsive drifter who wanders aimlessly from town to town may indeed be neurotic, and yet even the sanest person needs moderate amounts of random behavior. A refreshing form of such behavior is traveling a random path. Surely the popularity of the great picaresque novels such as *Don Quixote* is due partly to the reader's vicarious pleasure in the unexpectedness of events that such haphazard paths provide.

Jorge Luis Borges, in his essay "A New Refutation of Time," describes a random walk through the streets of Barracas: "I tried to attain a maximum latitude of probabilities in order not to fatigue my expectation with the necessary foresight of any one of them." G. K. Chesterton's second honeymoon, as he describes it in his autobiography, was a random "journey into the void." He and his wife boarded a passing omnibus, left it when they came to a railway station, took the first train and at the end of the line left the train to stroll at random along country roads until they finally reached an inn, where they stayed.

Mathematicians insist on analyzing anything analyzable. The random walk is no exception and (mathematically speaking) is as adventurous as the wanderings of the man of La Mancha. Indeed, it is a major branch of the study of Markov chains, which in turn is one of the hottest aspects of modern probability theory because of its increasing application in science.

A Markov chain (named for the Russian mathematician A. A. Markov, who first investigated them) is a system of discrete "states" in which the transition from any state to any other is a fixed probability that is unaffected by the system's past history. One of the simplest examples of such a chain is the random walk along the line segment shown in the illustration below. Each interval on the line is a unit step. A man begins the walk at spot 0. He flips a coin to decide the direction of each step: heads he goes right, tails he goes left. In mathematical terminology his "transition probability" from one mark to the next is 1/2. Since he is just as likely to step to the left as to the right, the walk is called "symmetric." Vertical bars *A* and *B*, at −7 and +10, are "absorbing barriers." This means that if the man steps against either barrier, it "absorbs" him and the walk ends.

A novel feature of this walk is its isomorphism with an ancient betting problem called "gambler's ruin." Player *A* starts with $7, *B* with $10. They repeatedly flip a coin. For each head *B* gives *A* $1 and for each tail *A* gives *B* $1. The game ends when either player is "ruined," or runs out of money. It is easy to see the correspondence between this game's progress and the random walker's movements. At any moment *A*'s capital in dollars is represented by the walker's distance from barrier *A*, *B*'s capital by the walker's distance from barrier *B*. If the first two tosses are heads, the walker moves two steps to the right; in the betting interpretation, *A* has increased his capital from $7 to $9, whereas *B* has gone from $10 to $8. If the walker hits barrier *A*, it corresponds to *A*'s ruin. If he hits barrier *B*, it corresponds to *B*'s ruin.

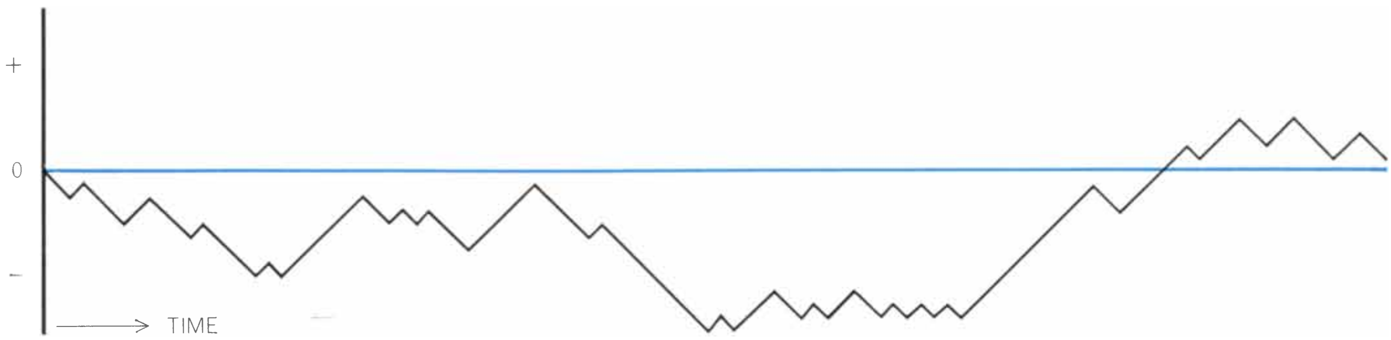


One-dimensional random walk with absorbing barriers

All kinds of probability questions have identical answers in both interpretations. Some are easy to solve, some are extremely difficult. One of the easiest is: What is the probability of each player's winning? This is the same as asking for the probability that the walk will end at one barrier or the other. It is not hard to prove that the probability of each man's winning is given by his original capital divided by the total number of dollars held by both players. *A*'s probability of winning is 7/17, *B*'s is 10/17. In random-walk terms the probability that the walk ends at barrier *B* is 7/17, at barrier *A* 10/17 [for a simple proof of this, based on a stretched rubber band, see "Brownian Motion and Potential Theory," by Reuben Hersh and Richard J. Griego; SCIENTIFIC AMERICAN, March].

The two probabilities must add to 1 (certainty), meaning that if the walk or game continues long enough, it is sure to end. What happens if one barrier, say *B*, is removed, allowing the line to stretch rightward to infinity? Then, if the walk continues long enough, it is certain to end at barrier *A*. In the betting interpretation, if *A* plays against an opponent with an infinite supply of dollars, eventually *A* is sure to be ruined. This is bad news for the compulsive gambler: even if all his wagers are at fair odds, he is playing against an "opponent" (the gambling world) with virtually unlimited capital, making his eventual ruin almost certain.

Another type of easy calculation is the probability that the walker, starting at a certain spot, will reach another given spot (or return to his starting point) after a specified number of steps. Odd and even parity is involved, so that in half the cases the answer is 0 (impossible). For instance, the walker cannot go from 0 to an even-numbered spot in an odd number of steps or to any odd-numbered spot in an even number of steps. What is the probability that he will walk from 0 to +1 in exactly three steps? It is the same as the probability that three coin tosses will show, in any order, two heads and one tail. Since this happens three times in the eight equally probable outcomes, the answer is 3/8. (The situation can be complicated by replacing either or both absorbing barriers by a "reflecting barrier" halfway between two marks.



Symmetric random walk based on the first 101 digits of pi

When the walker hits such a barrier, he bounces back to the mark he has just left. In the betting interpretation this happens when a ruined gambler is given \$1 so that he can stay in the game. If both barriers are reflecting, of course, the walk never ends.)

Another simple calculation, although one that is harder to prove, is the expected number of tosses before the walker, on the line with two absorbing barriers, is absorbed. "Expected number" is the average in the long run of repeated repetitions of the walk. The answer is the product of the distances of the two barriers from the starting spot. In this case, $7 \times 10 = 70$. The "typical" walk lasts for 70 steps; the typical game ends with one player ruined after 70 coin tosses. This is considerably longer than most people would guess. It means that in a fair betting game between two players, each starting with \$100, the average game will last for 10,000 bets. Even more counterintuitive: If one man starts with \$1 and the other with \$500, the average game will last for 500 bets. In the random walk, if the man begins one step from one barrier and 500 steps from the other, his average walk before being absorbed is 500 steps!

A more difficult problem is to determine the expected (average) distance from 0 after n steps. For one step it is 1, for two steps it is also 1 (the four equally possible distances are 0, 0, 2, 2), for three steps it is 1½, and so on. As n approaches infinity the limit for the expected distance (which may be on either side of 0) is $\sqrt{2n/\pi}$, or about $.8\sqrt{n}$ for large n, as Frederick Mosteller and his coauthors point out in their book *Probability and Statistics* (Addison-Wesley, 1961), page 14.

The hardest to believe of all aspects of the one-dimensional walk emerges when we consider a walk starting on a line with no barriers and ask how often the walker is likely to change sides. Because of the walk's symmetry one expects that in a long walk the man should spend about half of his time on each side of the starting spot. Exactly the opposite is true. Regardless of how long he walks, the most probable number of changes from one side to the other is 0, the next most probable is 1, followed by 2, 3 and so on!

William Feller, in a famous chapter on "Fluctuations in Coin Tossing and Random Walks" (in his classic *An Introduction to Probability Theory and Its Applications,* Vol. I, Chapter III), has this to say: "If a modern educator or psychologist were to describe the long-run case histories of individual coin-tossing games, he would classify the majority of coins as maladjusted. If many coins are tossed n times each, a surprisingly large proportion of them will leave one player in the lead almost all the time; and in very few cases will the lead change sides and fluctuate in the manner that is generally expected of a well-behaved coin." In a mere 20 tosses the probability that each player will lead 10 times is .06+, the least likely outcome. The probability that the loser will *never* be in the lead is .35+.

If a coin is tossed once a second for a year, Feller calculates, in one out of 20 repetitions of this experiment the winning player can be expected to lead for more than 364 days and 10 hours! "Few people will believe," he writes, "that a perfect coin will produce preposterous sequences in which no change of lead occurs for millions of trials in succession, and yet this is what a good coin will do rather regularly."

The illustration above is a graph of a typical random walk along the infinite vertical line at the left, with time represented by movement to the right. Instead of flipping a coin or using a table of random numbers the walk is based on the digits of pi to 100 decimals. (Since the decimals of pi have passed all randomness tests, they provide a convenient source of random digits.) Each even digit is a step up, each odd digit a step down. After 101 steps the walker has been above the line only 17 times, about 17 percent of the total. He has crossed the starting spot only once. The graph is also typical in showing how returns to 0 or close to 0 come in waves that tend to increase in length at a rate about equal to the square root of the time. Similar graphs based on simulations of 10,000 coin tosses appear in Feller's book.

We can complicate matters by allowing transition probabilities to vary from 1/2 and by allowing steps longer than one unit. Consider the following curious paradox first called to my attention (in betting terms) by Enn Norak, a Canadian mathematician. A walker starts 100 steps to the right of 0 on a line that has no barriers [*see illustration at top of next page*]. Instead of a coin a packet of 10 playing cards—five red and five black—is used as a randomizer. The cards are shuffled and spread face down and any card is selected. After its color is noted it is discarded. If it is red, the walker steps to the right; if black, he steps to the left. This continues until all 10 cards have been taken. (The transition probability varies with each step. It is 1/2 only when there is an equal mixture of red and black cards before the draw.) The walk differs also from walks discussed above in that before each card is noted the walker chooses the length (which need not be integral) of his next step.

Assume that the walker adopts the following halving strategy in choosing step lengths. After each card is noted he takes a step (left or right) equal to exactly half of his distance from 0. His first step is $100/2 = 50$ units. If the card is red, he goes to the 150 mark. His next step will then be $150/2 = 75$. If the first card drawn is black, he goes left to the 50 mark, and so his next step will be $50/2 = 25$. He continues in this manner until the 10th card is noted. Will he then be to the right or to the left of the 100 mark where he began the walk?

The answer is that he is sure to be to the left. This may not be very surprising, but it is surely astonishing that, regardless of the order in which the cards are drawn, he will end the walk at exactly

Paradox based on a random walk along a line without barriers

the same spot! It is about 76 units left of where he started. The precise distance is given by the following formula,

$$a - \left[a\left(\frac{3}{4}\right)^n\right],$$

where a is the starting spot and n the number of red (or black) cards in the packet. When a is 100 and n is 5, as in the present example, the formula gives 76.26953125 as the distance he has moved to the left when the walk ends.

Let us translate this into Norak's betting game. A man starts with \$100. Wins and losses are decided by a shuffled packet of five red and five black cards, from which cards are drawn and discarded. (This is equivalent to flipping a coin 10 times, provided that the coin happens to show an equal number of heads and tails. Using cards guarantees this equality.) The man wins on red and loses on black. Each time he bets half of his capital. It is hard to believe, but at the end of every such game he will have lost exactly \$76.26953125. This amount increases as n increases. If n is 26, as it is if a standard deck of 52 cards is used, he will lose more than \$99.90. His loss, however, will always be less than \$100.

Instead of betting half of his capital each time, he can bet a fixed fraction. Let the fraction be $1/k$, where k is any positive real number. The smaller this fraction is, the less he will have lost by the end of the game; the larger the fraction, the more he will have lost. If it equals 1, he is certain to lose everything. In this more general case the amount lost is

$$a - \left[a\left(1 - \frac{1}{k^2}\right)^n\right].$$

The formula can be generalized further by allowing an unequal mixture of red and black cards, but this gets too complicated to explore here.

Now consider an amusing problem suggested by Norak and based on a variation of the game just described. It can be given as a random walk problem but I shall give only its betting equivalent. The game is the same as before except that the *opponent* of the man who starts with \$100 is allowed to name the size of each bet. Call the opponent Smith and assume that he has enough capital to be able to pay any loss. A standard deck of 52 playing cards is used. Before each card is drawn and discarded Smith bets exactly half the capital then owned by the *other* man, the player who begins with \$100. After the last card is noted will Smith have lost or gained? In either case, is the loss or gain always the same and, if so, what is its formula? If you have understood the discussion to this point, you should be able to answer these questions almost immediately.

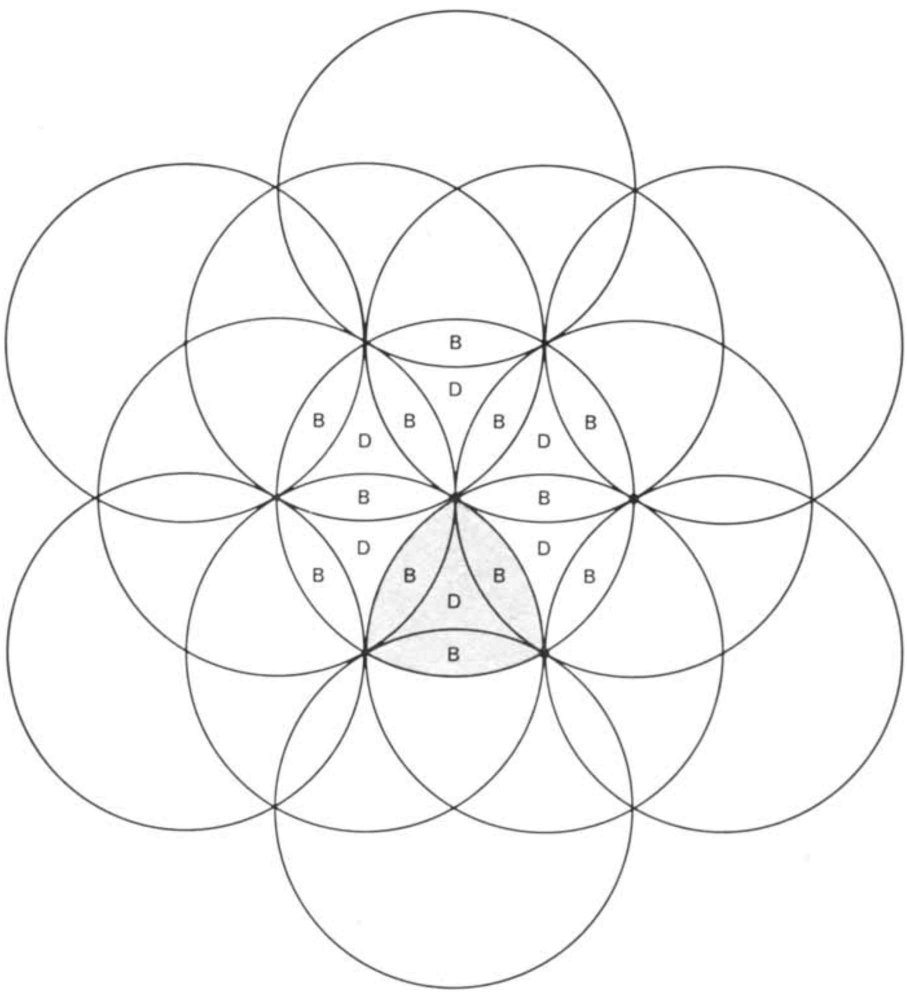
The staggering topic of random walks will be concluded next month with a consideration of some random walks on the plane and in space, and on lattices such as checkerboards and the edges of regular solids.

The answers to the short problems presented in this space last month follow.

1. If a circular table seats an even number of people, equally spaced, with place cards marking their spots, no matter how they seat themselves it is always possible to rotate the table until two or more are seated correctly. There are two initial situations to be considered:

(a) No person sits correctly. The easy proof is based on what mathematicians call the "pigeonhole principle": If n objects are placed in $n - 1$ pigeonholes, at least one hole must contain two objects. If the table seats 24 people, the number given last month, and if every person is incorrectly seated, it clearly is possible to bring each person opposite his card by a suitable rotation of the table. There are 24 people but only 23 remaining positions for the table. Therefore at least two people must be simultaneously opposite their cards at one of the new positions. This proof applies regardless of whether the number of seats is odd or even.

(b) One person sits correctly. Assume that it is *not* possible to rotate the table to a position at which at least two people are correctly seated. For this to apply, the initial position must be such that no two people are displaced clockwise from their place cards by the same number of seats. In our example 24 are



Solution to intersecting-circles problem

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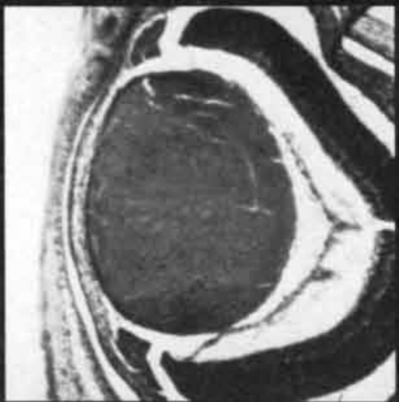

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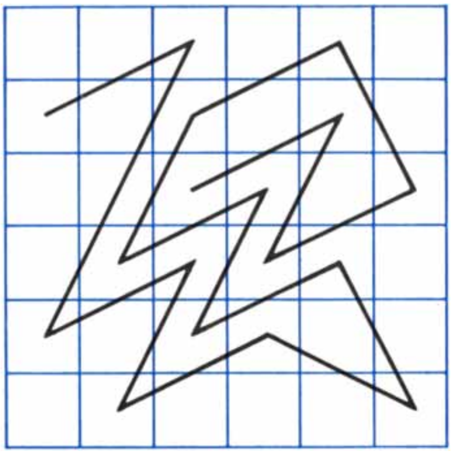


Knight's tour on order-6 board

seated, only one of them correctly. If two of the others are, say, seven chairs clockwise from their cards, obviously the table can be rotated to bring both of them simultaneously to their correct spots. Therefore, assuming that it is impossible to bring at least two people to their correct spots, one person must be displaced one chair clockwise, another displaced two chairs, another three chairs, and so on up to a 23rd person who is displaced 23 chairs. It can be shown (I know of no way to compress the proof to a reasonable length) that such a series of displacements is impossible without at least two people sitting in the same chair. This contradicts the original assumption, forcing us to conclude once again that a rotation of the table can always bring two or more people to correct positions. Here the proof applies only to cases where the number of seats is even.

2. How can White, using only his knights, win a game of "single check" chess in five or fewer moves?

The opening move must be N (knight) to QB3. Since this threatens several different ways of checking in two moves, Black is forced to advance a pawn that will allow his king to move. If he advances the queen's pawn, N–N5 forces the black king to Q2, then N–KB3 leads to a check on White's fourth move. If Black moves his king-bishop pawn, N–N5 leads to a check on the third move. Black must therefore advance his king's pawn. If he advances it two squares, N–Q5 prevents the black king from moving and White wins on his third move. Black's only good response, therefore, is P–K3.

White's second move is N–K4. Black is forced to advance his king to K2. White's third move, N–KB3, can be met in many ways but none prevents a check on or before White's fifth move. If Black tries such moves as P–Q3, P–KB3, Q–K1, P–Q4, P–QB4 or N–KB3, White responds N–Q4 and wins on his next move. If Black tries P–K4, P–QB4 or N–QB3, White's N–KR4 wins on his next move.

Early this year William H. Mills discovered that White could also check in five by opening N–QR3. Black must advance his king's pawn one or two squares. N–N5 forces Black's king to K2. White's third move, P–K4, is followed by White's Q–B3 or Q–R5, depending on Black's third move, and leads to a check on White's fifth move.

Two other opening moves leading to five-move checks have since been found by Mills and Georg Soules, another mathematician at the Institute for Defense Analyses in Princeton. They are P–K3 and P–K4. Against most of Black's replies Q–N4 leads to a three-move check. If Black's second move is N–KR3 or P–KR4, Q–B3 leads to a check in four. If Black's second move is P–K3, White moves Q–R5. Black must respond P–KN3. Then Q–K5 does the trick. (Black's Q–K2 is met by Q takes QBP; B–K2 is met by Q–N7; N–K2 is met by Q–B6.) If Black's second move is N–KB3, White's N–QR3 forces Black to advance his king's pawn one or two squares, then N–N5 forces Black to advance his king, and Q–B3 leads to a check on the next move.

It seems unlikely that there is a strategy by which White could be sure of winning in fewer than five moves, although as far as I know this has not yet been proved.

3. To determine the target word in Anatol W. Holt's word game, label the six probe words as follows:

	Even		*Odd*
*E*1	DAY	*O*1	SAY
*E*2	MAY	*O*2	DUE
*E*3	BUY	*O*3	TEN

*E*1 and *E*2 show that the target word's first letter is not D or M, otherwise the parity (odd or even) would not be the same for both words. *E*1 and *O*1 show that the target word's first letter is either D or S, otherwise the parity could not be different for the two words. The first letter cannot be D and therefore must be S.

Since S is the first letter, *E*2 and *E*3 are wrong in their first letters. Both end in Y, therefore the second letter of the target word cannot be A or U, otherwise *E*2 and *E*3 could not have the same parity. Knowing that U is not the second letter and D not the first, *O*2 shows that E is the third letter. Knowing that the target word begins with S and ends with E, *O*3 shows that E is the second letter. The target word is SEE.

4. Three intersecting circles, each passing through the centers of the other two, can be repeated on the plane to form the wallpaper pattern shown in the bottom illustration on page 120. Each circle is made up of six delta-shaped figures (*D*) and 12 "bananas" (*B*). One-fourth of a circle's area must therefore equal the sum of one and a half deltas plus three bananas. The area common to three mutually intersecting circles (*shown shaded in the illustration*) consists of three bananas and one delta, and therefore it is smaller than one-fourth of a circle by an amount equal to half a delta. Computation shows that the mutual overlap is a little more than .22 of the circle's area.

5. Each cube must bear a 0, 1 and 2. This leaves only six faces for the remaining seven digits, but fortunately the same face can be used for 6 and 9, depending on how the cube is turned. The picture shows 3, 4, 5 on the right cube, and therefore its hidden faces must be 0, 1 and 2. On the left cube one can see 1 and 2, and so its hidden faces must be 0, 6 or 9, 7 and 8.

6. The illustration on this page shows the unique solution, discovered by Donald E. Knuth's computer program, to a maximum-length uncrossed knight's tour on the 6-by-6 square board.

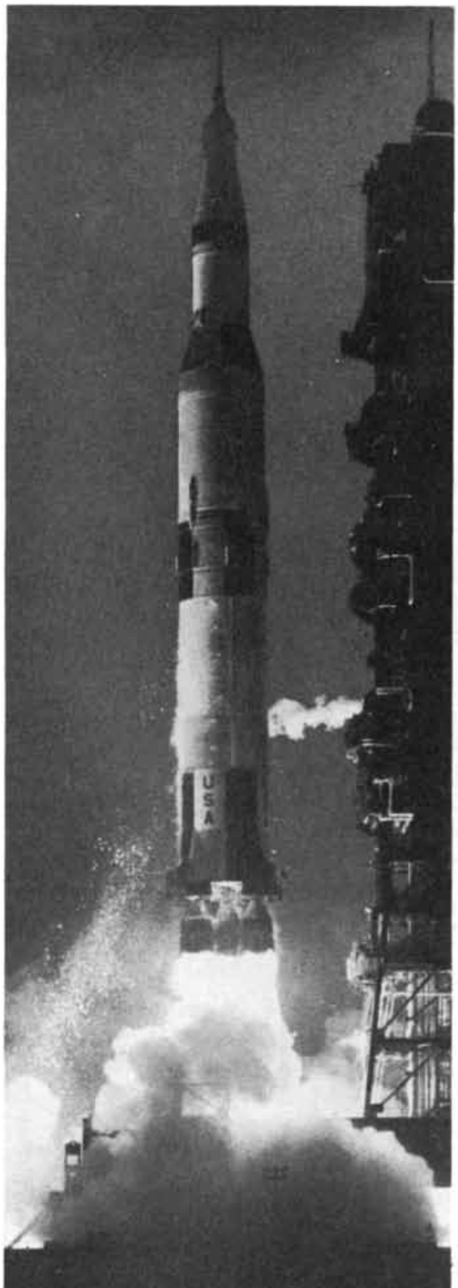
7. It was stated that if counters are drawn according to a certain procedure from a bag containing an unknown mixture of white and black counters, there is a fixed probability that the last counter will be black. If this is true, it must apply equally to each color. Therefore the probability is 1/2.

Although this answers the problem as posed, there remains the task of proving that the probability is indeed fixed. This can be done by induction, starting with two marbles and then going to three, four and so on, or it can be done directly. Unfortunately both proofs are too long to give, so that I content myself with referring the interested reader to "A Sampling Process," by B. E. Oakley and R. L. Perry, in *The Mathematical Gazette* for February, 1965, pages 42–44, where a direct proof is given. The problem generalizes to any number of colors. If the bag initially contains any mixture of counters of n colors, the sampling procedure ensures that the probability of the last counter's being a given color is $1/n$.

8. The answers to the 10 quickies are as follows:

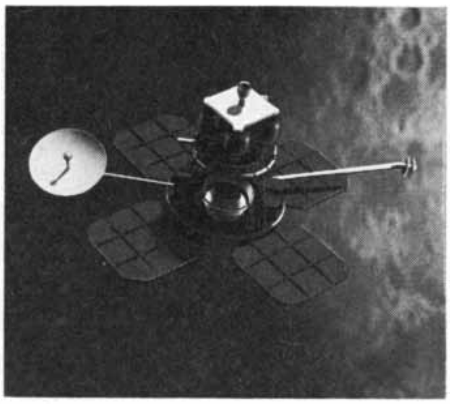
(1) Start the seven- and 11-minute hourglasses when the egg is dropped

Reliability... a matter of record at Boeing.



Right across the spectrum of Boeing activities—from jetliners and military aircraft to missiles, from spacecraft and hydrofoil vessels to defense systems—Boeing products combine the benefits of advanced design, structural integrity and massive testing.

LUNAR ORBITER. Designed and built by Boeing for NASA, Lunar Orbiter flew five spectacularly successful moon photo missions to scout landing sites for America's Apollo astronauts. Orbiter's record: Five flights. Five flawless performances.



SATURN 5. NASA's Apollo/Saturn 5 flights, including the recent Apollo 9 mission, start with the firing of the Boeing-built first-stage booster. Largest in the U.S., it produces 7.5 million pounds of thrust. Boeing is also integration and evaluation contractor, and performs systems engineering and launch support for NASA on the entire Saturn 5 system. Record to date: Four flights. Four successes.

TUCUMCARI, the U.S. Navy's first hydrofoil gunboat, was designed and built by Boeing. Water-jet propelled and incorporating an advanced foil system, it can "fly" at better than 40 knots and is highly maneuverable, even in heavy weather. In operation since fall, 1967, Tucumcari has "flown" the equivalent of San Francisco-Tokyo and return, and has achieved a near perfect score on schedule reliability.

MINUTEMAN III's first launch was a complete success. So was Minuteman II's. Minuteman I's was one of the most successful first flights in U.S. missile history. Successful Minuteman launches to date: More than 200. As weapon system integrator, Boeing assembles, tests, installs and delivers the complete missile system to the U.S. Air Force.

BOEING

into the boiling water. When the sand stops running in the seven-glass, turn it over. When the sand stops in the 11-glass, turn the seven-glass again. When the sand stops again in the seven-glass, 15 minutes will have elapsed.

(2) Each tire is used 4/5 of the total time. Therefore each tire has been used for 4/5 of 5,000 miles, or 4,000 miles.

(3) Whatever the color of the first card cut, this card cannot be the top card of the second cut. The second cut selects a card randomly from 51 cards of which 25 are the same color as the first card, and therefore the probability of the two cards' matching in color is 25/51, a bit less than 1/2.

(4) One hundred and twenty-one is a perfect square in a number system with any base that is a positive integer.

(5) The illustration below shows how six equal line segments can form eight equilateral triangles. There are six small triangles and two large ones.

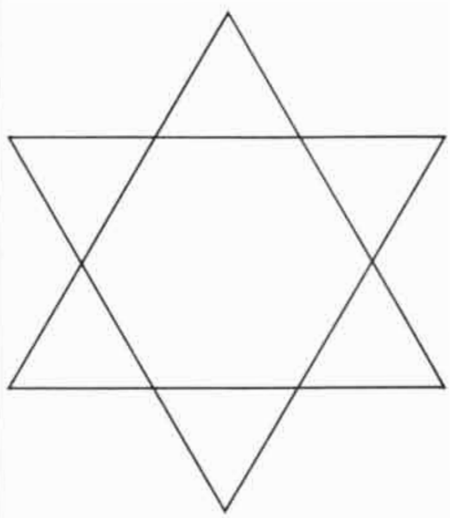
(6) Any angle can be bisected with a compass and straightedge. By repeated bisections we can divide any angle into 2, 4, 8, 16, . . . equal parts. If any number in this series is a multiple of 3, then repeated bisection obviously would allow trisection of the angle with compass and straightedge. Since this has been proved impossible, no number in the doubling series is evenly divisible by 3.

(7) The farmer has 60 horses. Calling a cow a horse doesn't make it a horse.

(8) "He spoke from 22 to 2 to 2:22 to 2,222 people."

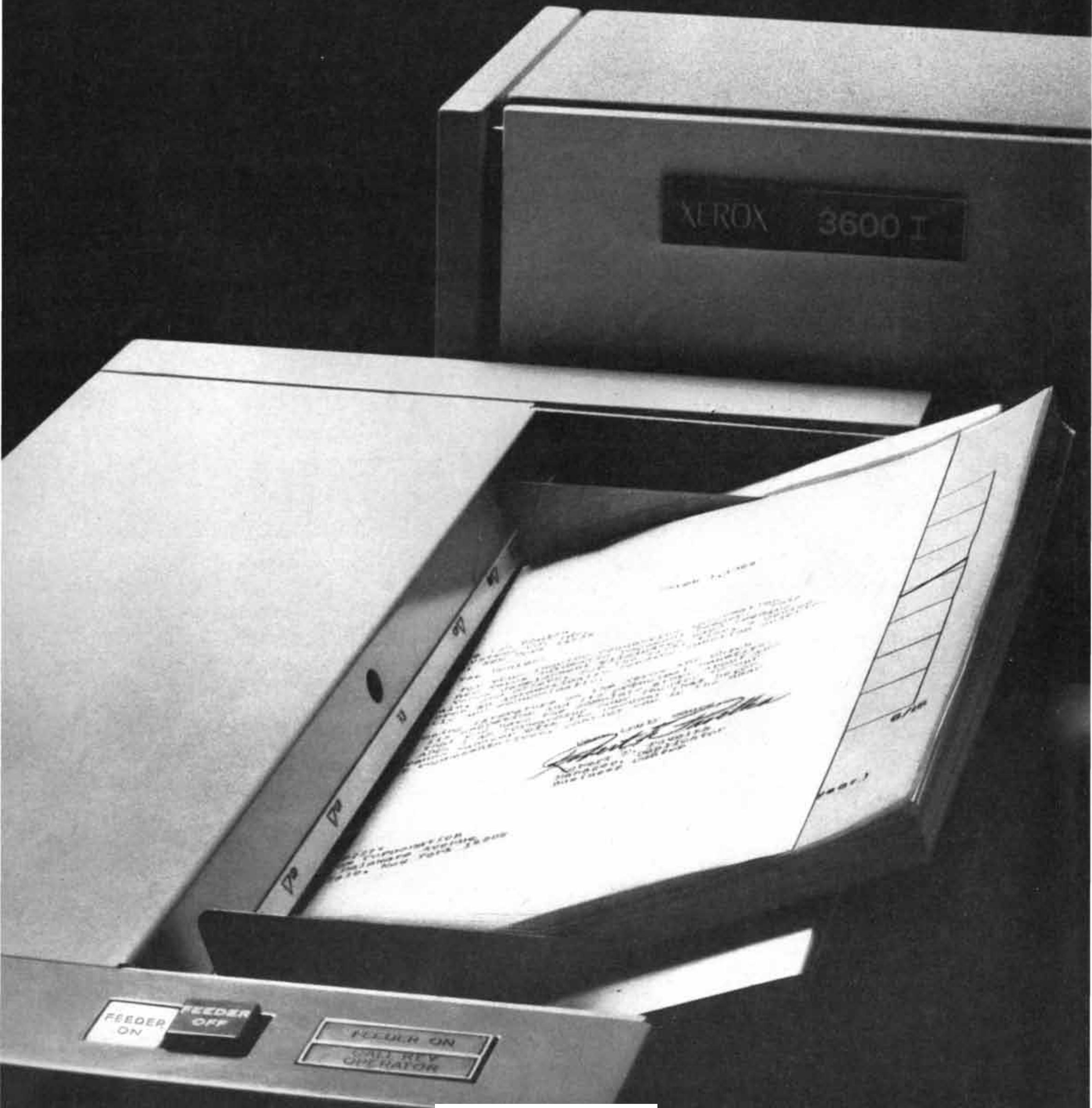
(9) The Greek lived 79 years. There was no year 0.

(10) Ask the woman "Are you an alternator?" twice. Two noes prove she is a truther, two yeses prove she is a liar, and a yes-no or no-yes response proves she is an alternator.



Six lines make eight triangles

Xerox introduces a way to do



THE AMATEUR SCIENTIST

How to blow soap bubbles that last for months or even years

Conducted by C. L. Stong

About two months ago I blew a big soap bubble inside a glass jug and put the jug on a bookshelf. The bubble is still there, iridescent and shimmering. It may last for years.

Since then I have blown other bubbles that lacked the protection of a glass cover. They have survived for a few minutes or even a few hours, depending on such conditions as drafts and the amount of dust in the air. In any case the bubbles have lasted long enough for experimentation. For example, I have made bubbles into inexpensive instruments that measured the viscosity of gases, determined the surface tension of fluids or served as ultrasensitive manometers for measuring atmospheric pressure. Other bubbles have been blown to demonstrate simple geometric propositions and to solve mathematical equations related to electrical circuits and optical lenses. Mostly, however, I have been blowing bubbles for fun: spheres up to two feet in diameter, small bubbles blown inside larger ones, "weightless" bubbles that float in containers of heavy gases, configurations of adjoining bubbles that resemble the lattice structure of crystals, and so on.

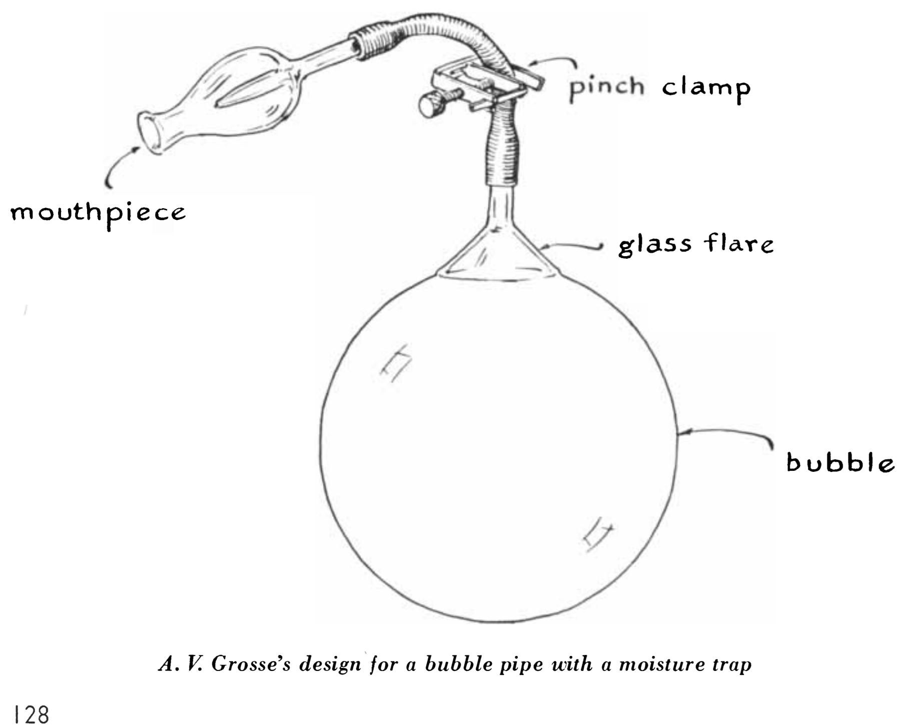
It all began early last winter when I visited A. V. Grosse, president of the Research Institute of Temple University in Philadelphia. Much of Grosse's career has been devoted to nuclear research and the investigation of high temperatures. For this reason I was scarcely prepared, on entering his office, to see a huge display of soap bubbles. They were on tables and bookshelves, and one bubble, suitably protected, even served as a paperweight. Since the career of most bubble blowers ends at about the age of 10, I wondered why soap bubbles continued to interest the administrator of a prominent research establishment. In answering that question Grosse not only revived my own interest in bubbles but also agreed to share his enthusiasm with readers of this department. He writes:

"During a pleasant discussion several years ago with my former colleague Willard F. Libby we concluded that as members of the older generation of atomic scientists we might well spend part of our spare time devising simple new experiments for the entertainment and education of the younger generation. The discussion eventually led me to the investigation of soap bubbles. This field of experimentation seemed appropriate because soap bubbles are inexpensive and very pretty and present many unanswered questions. I set up a small bench in my basement at home and have been blowing bubbles ever since. So many new facts and phenomena turned up that until now I have neglected my original objective of passing my findings along to amateurs.

"A soap bubble behaves somewhat like an inflated rubber balloon. The skin of the bubble is stressed, because of surface tension, and like stretched rubber it compresses the air trapped inside. As soon as the bubble is blown the compressed air begins to make its way through the permeable skin. The bubble shrinks. Eventually the bubble collapses to a flat film stretched across the blowpipe. I call this interval—the time required for the bubble to shrink to a flat film—the natural life-span of the bubble.

"My first bubbles all died in infancy. Few lasted more than a minute. They were blown with much the same kind of soap that Isaac Newton used for his classic bubble experiments. I turned to the literature and found that a much better soap was described more than a century ago by the blind Belgian physicist Joseph A. F. Plateau, who laid the foundations of our present knowledge of soap bubbles. Bubbles blown with Plateau's solution will last for several minutes in an ordinary room and for several hours with proper protection.

"Amateurs can make this solution with materials that are available from dealers in chemical supplies. To 40 ounces of distilled water add one ounce of chemically pure sodium oleate. Sodium oleate comes as a white powder that floats for a time on water. Do not mix the powder



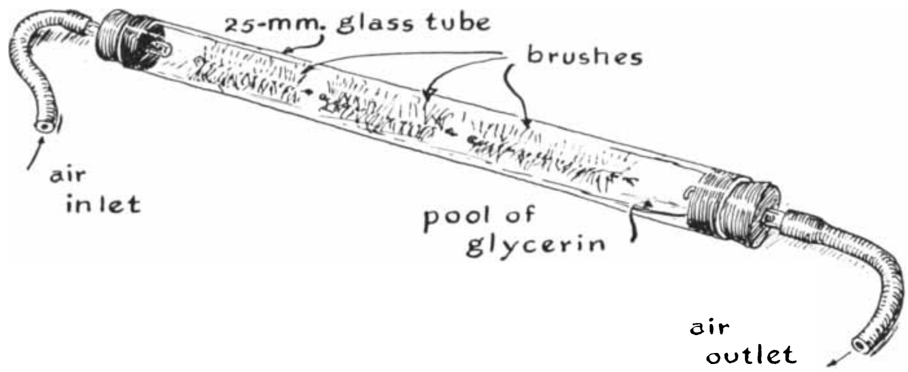
A. V. Grosse's design for a bubble pipe with a moisture trap in the water; put the powder on the water and let the container stand in a dark place for 24 hours. The powder will then have dissolved. Add 10 ounces of U.S.P. glycerin and mix the solution thoroughly by pouring the fluid slowly into a clean container and back again several times. Store the mixture in darkness for about a week. Then siphon off the clear fluid below the scum. Add two drops of household ammonia to the clear fluid, stir the solution gently to mix the ingredients and bottle it for use.

"Small bubbles blown from this solution to a radius of four or five centimeters usually last for two or three minutes in ordinary room air. About 10 years ago the Canadian chemist A. L. Kuehner described a solution that makes more durable bubbles. He first purified oleic acid by a painstaking procedure and then by the addition of bromine converted it into 9,10-dibromostearic acid. When this acid is carefully neutralized with sodium hydroxide and mixed with glycerin, it forms bubbles that will last for months if they are protected by an enclosure.

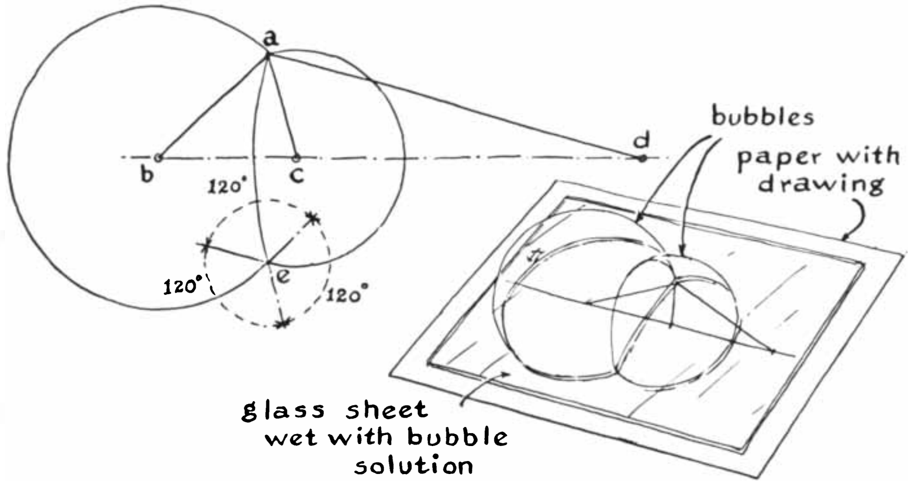
"Having experimented with Kuehner's solution, I decided to take advantage of recent developments in polymer chemistry in the hope of compounding a solution of even greater interest. The result is what I call a 'double bubble' solution: two solutions that are mixed just before use. Bubbles can be blown with either solution, hence the name 'double bubble.' Large bubbles blown with the mixture have lasted for three years so far and are likely to last for many more. From the rate at which one bubble is shrinking I estimate a natural life of more than 20 years.

"One of the two solutions consists essentially of Kuehner's dibromostereate soap. The other one is a solution of polyvinyl alcohol, water and glycerin. Bromine is an extremely hazardous substance before it has reacted with the acid, and compounding these mixtures calls for controls that are not available in the home. For these reasons amateurs should not attempt to make double-bubble solution. It can be bought from the Techno Scientific Supply Company, Inc., P.O. Box 191, Baldwin, N.Y. 11510. The solution costs $4 a pint, a quantity sufficient to blow thousands of bubbles.

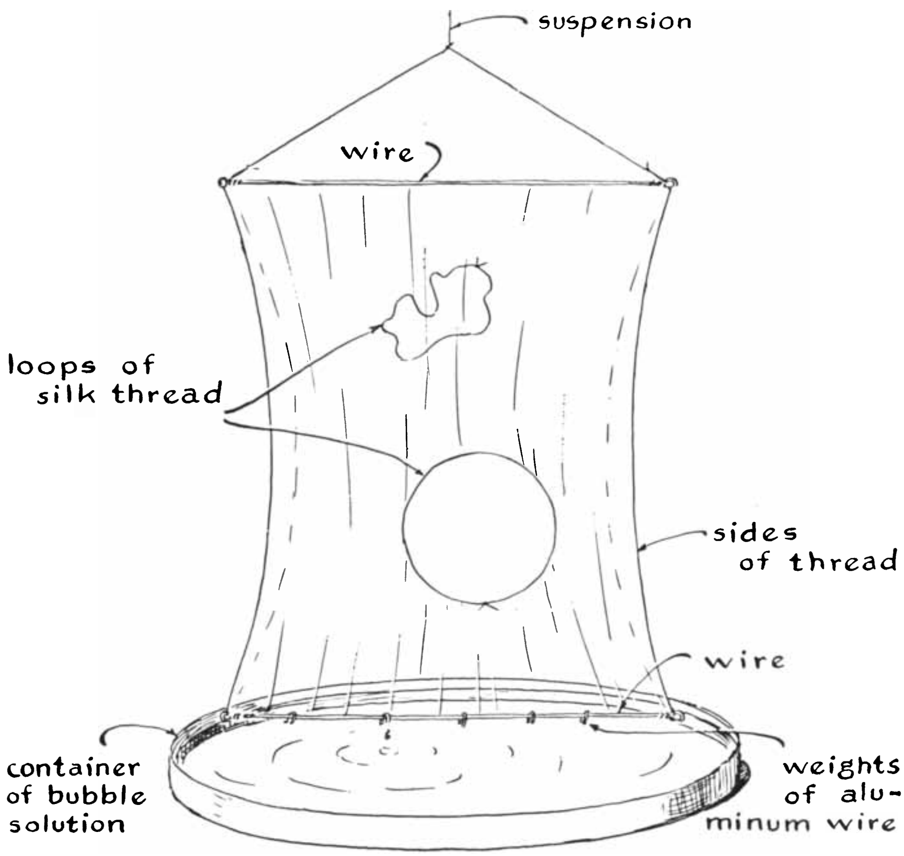
"Bubbles can be blown with almost any pipe. As was pointed out by the English experimenter C. V. Boys, however, moisture from the breath tends to condense inside the pipe and drain into the soap film, where it dilutes the solution and hence reduces the life of the



Filter for cleaning air



Geometry of adjoining bubbles



Method of demonstrating surface tension bubble. Pipes that are blown by mouth should have a trap of some kind to catch the exhaled moisture [*see illustration on page 128*]. The carbon dioxide in the breath may also be harmful to the bubble. Therefore it is best to do the blowing with compressed air. Small compressors of the kind used for supplying air to aquariums are ideal for blowing bubbles. The rate at which the bubbles are blown can be adjusted by placing a pinch clamp on the tubing that leads from the compressor. To blow big bubbles it is advisable to interrupt the blowing periodically.

"Dust is the archenemy of bubbles, particularly dust that contains crystals of salt. It is interesting to set up a bubble in one corner of a room filled with clean air and with a perfume atomizer inject a puff of brine into the air at the opposite corner. Microscopic crystals of salt from the evaporated mist will make their way across the room; within a minute or two they will break the bubble! For this reason I blow my bubbles with 'glycair,' which is air that has been filtered through glycerin. An adequate filter can be made by cutting the bristle sections from four to six test-tube brushes and inserting them into a glass tube they fit snugly. The tube is closed at the ends by perforated rubber stoppers [*see top illustration on preceding page*]. An ounce or so of glycerin is placed inside the tube, which is kept in the horizontal position. The bristles are moistened with glycerin periodically by rotating the tube.

"Big bubbles require more solution than small ones. A relation also exists between the ultimate size to which a bubble can be blown and the diameter of the blowpipe from which it is blown, since the bubble is held only by the surface tension between the solution and the rim of the pipe. Bubbles up to about 10 centimeters in diameter can be blown with a pipe one centimeter in diameter, but I prefer a ratio of about five to one. Bubbles that are intended to last their full natural life must be blown inside a protective enclosure, preferably one with a spherical shape, such as a Florence flask.

"I first wash the container carefully, put about 10 milliliters of bubble solution in it and flush it with glycair for a few minutes to remove as much dust as possible. A blowpipe is pushed into a perforated stopper that fits the neck of the container. I dip the lower end of the pipe into soap solution, insert it in the container and blow the bubble. The stopper is pressed firmly into the neck of the container and the free end of the blowpipe is sealed by a stopper.

"Bubbles made in this way may break after a short time because of dust trapped in the container. The bubble traps the dirt, however, and purifies the air of the flask. Therefore, without opening the flask to the dusty air outside, I push the blowpipe through its supporting stopper down into the solution inside the container, slide it back up and blow another bubble. The second or third bubble should last for its natural lifetime. The container is stored on a mat of foam rubber for protection against mechanical shock. The diameter of each bubble is measured at weekly intervals and the shrinkage is plotted against time. From these data I estimate the ultimate life.

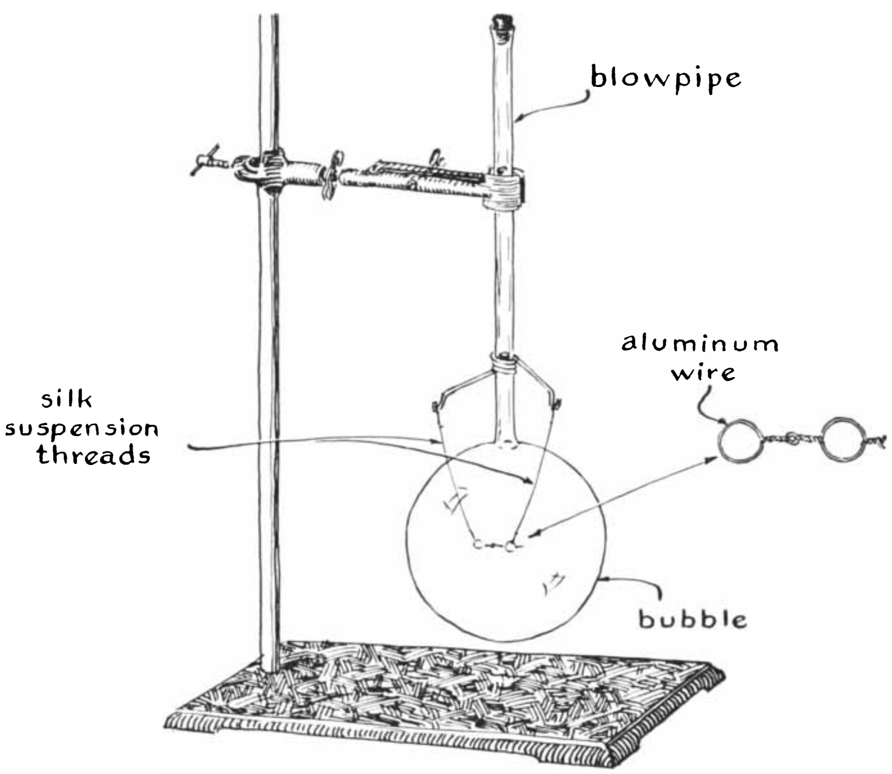
"Bubbles can be blown inside one another by several methods. An easy way is to blow a small bubble, about the size of an orange, and put it on the rim of a paper cup that has been moistened with bubble solution. Detach the blowpipe from the bubble by turning the pipe at a right angle to the film and lifting it gently. The film will close and peel away from the pipe.

"Immerse the end of the pipe in bubble solution to a depth of a few centimeters and push it into the top of the bubble. It will penetrate the bubble without breaking the film. As you blow the inner bubble the outer one will expand in proportion. Detach the inner bubble by pulling the pipe upward, abruptly but not violently. This is a knack that comes with practice.

"Concentric bubbles can also be blown by means of coaxial pipes telescoped together and supported by spacers of rubber or plastic. Place a soap film across the end of the outermost pipe and blow the outer bubble. Slide the next smallest pipe, with a film, into its supporting pipe axially and blow the second bubble, which enlarges the first one. Additional bubbles can be blown. I have had triple bubbles, with beautiful colors, that have lasted for more than a year.

"Foams are also easy to make. Tie a bag of terry cloth around the end of a blowpipe, soak the cloth in bubble solution and blow. The walls between adjacent bubbles make interesting geometric patterns. To observe the walls clearly, blow foam between two sheets of window glass, spaced about an inch apart, that have been moistened with bubble solution.

"The air pressure inside a bubble increases as the bubble shrinks. For this reason the wall that is shared by two adjoining bubbles, as in foam, always curves toward the larger of the two bubbles by an amount that can be predicted by simple geometry. For example, make a dot on a sheet of paper. From the dot draw three straight lines spaced at angles of 60 degrees. Then draw a straight line that intersects the three lines. Place the point of a compass at each of these



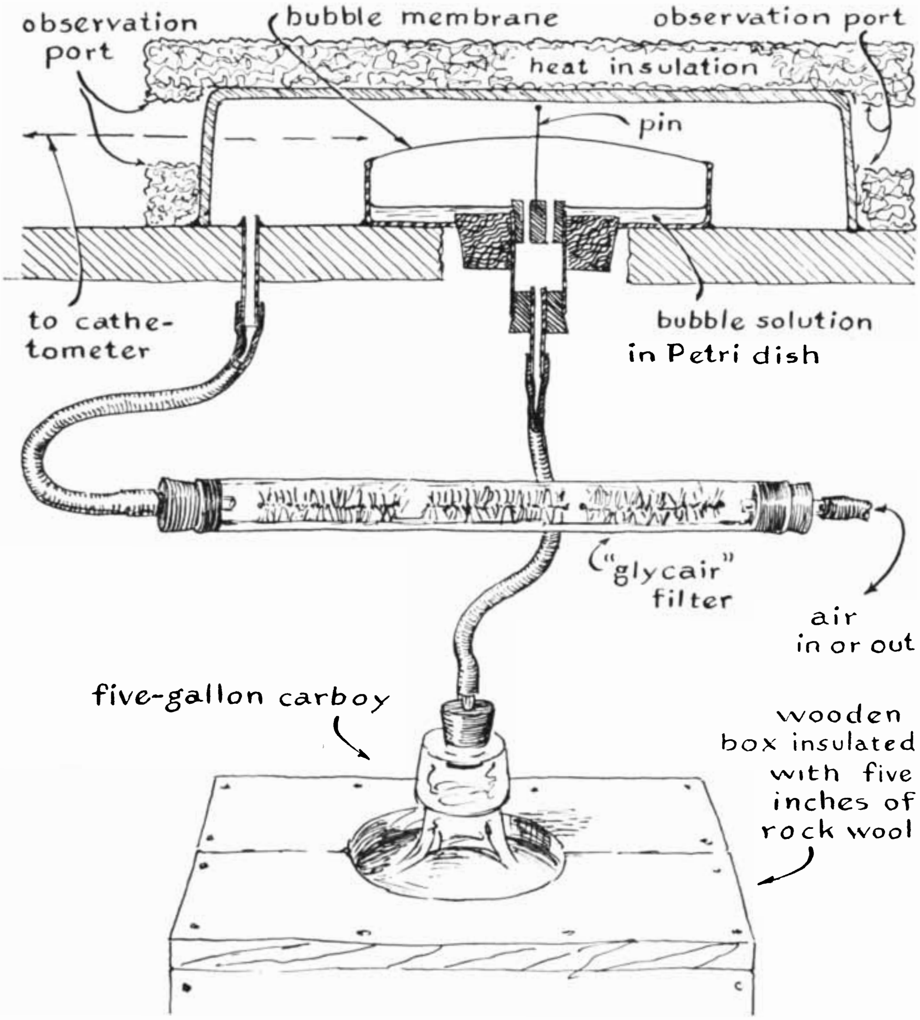
Fixture for making a small hole in a bubble intersections successively and, with the dot as the radius, draw three circles. The two smaller circles mark the boundary that would be formed if two bubbles of this size were placed in contact with each other. The smaller circles intersect the largest circle at two points. The arc of the largest circle included between these two points marks the position of the wall that would be shared by the adjoining bubbles.

"This theory was worked out by Plateau. You can prove it by experiment. Place a diagram so drawn under a sheet of window glass moistened with bubble solution. Blow a pair of hemispherical bubbles against the glass, about the size of the two smaller circles. Detach the blowpipe from each bubble and with the end of the pipe center the bubbles over the circles. The size of the bubbles can be adjusted by adding air or letting air escape through a small blowpipe, such as a soda straw. When you have matched the size of the bubbles to the diagram, you will find that the curvature of the shared wall conforms to the geometric prediction [*see middle illustration on page 129*]. This combination of bubbles can be used to find the total resistance of an electrical circuit consisting of parallel resistors and to predict the distance at which a scene will come to focus behind a lens of known focal length.

"Observe also that any three walls of the bubbles make equal angles of 120 degrees at the point where they come together. This must be so because the surface tension of the three soap films is equal: all three films exert pull on the point where they meet. They balance only when the three pulls are exerted in mutually opposing directions.

"To prove that surface tension acts uniformly in all directions, cut two wires about 10 centimeters long, bend small loops at the ends and tie the mating pairs of loops together with silk threads about 10 centimeters long. The resulting structure is a rectangle with ends of wire and sides of thread [*see bottom illustration on page 129*]. Attach a bridle thread to one of the wires and dip the assembly in bubble solution. When you pull it out of the solution, a soap film will cling between the wires and the threads. The film will have straight ends and curved sides. If the sides curve inward excessively, hang wire weights to the bottom member.

"Tie a length of silk thread into a loop, dip the loop in bubble solution and toss it onto the film. Touch the film inside the loop with a point of dry paper. The film will break, and surface tension



A manometer making use of a film of soap

outside the loop will snap the thread into a perfect circle. The circle is the only possible shape the loop can assume when it is pulled outward by a uniform radial force.

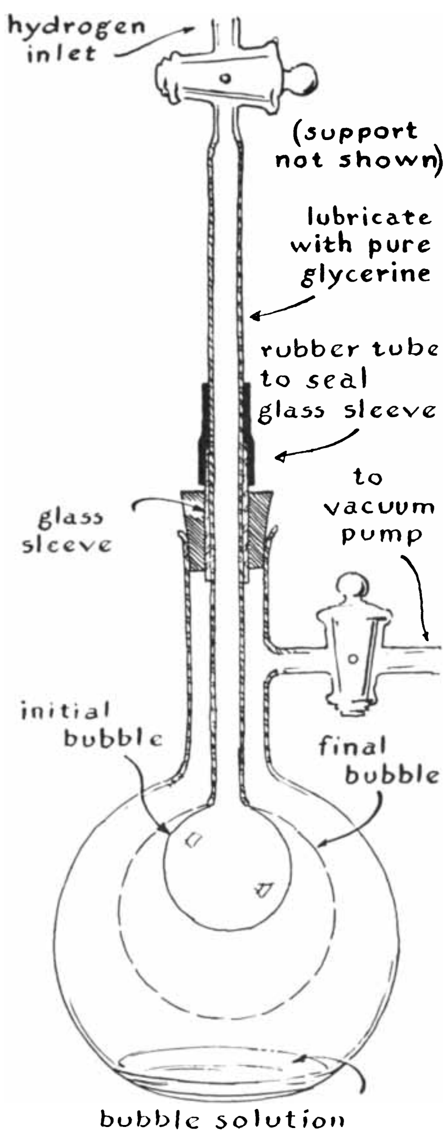
"As mentioned, surface tension compresses the gas inside a bubble. If you punch a small hole in the bubble, air will flow out. The bubble will collapse at a rate that increases with the size of the hole and with the surface tension and decreases with the density of the gas. To make a bubble deflate slowly twist a length of fine wire into a row of three small loops that lie in a common plane. With silk thread tied to the end loops, dip the assembly in bubble solution and suspend the wire against the bubble [*see illustration on opposite page*]. To let the air out, puncture the soap film in the middle loop with a splinter of dry wood.

"I recently devised a similar experiment that amateurs can use for measuring the surface tension of soap film or the viscosity of a gas if either quantity is known. If both quantities are known, the experimenter can accurately predict in advance of the experiment how long it will take the bubble to deflate from any size to any smaller size. All you need for the experiment is bubble solution, a slender blowpipe, a fixture to support the pipe, a small aquarium and a watch with a second hand.

"Blow the bubble, plug the blowpipe with a stopper and measure the diameter of the bubble. Remove the stopper. Time the interval during which the bubble shrinks. Measure the diameter of the shrunken bubble. With these data and the known dimensions of the blowpipe you can easily determine the quantities of interest.

"My blowpipe is 29 centimeters long with an inner radius of .183 centimeter. (It is a length of four-millimeter glass tubing.) The ends were pushed into perforated rubber stoppers and the stoppers were in turn pushed into three-centimeter lengths of 10-millimeter glass tubing. These large glass nipples at the ends prevent bubble solution from entering the bore of the small tube. Either nipple will also accept a stopper for plugging one end of the blowpipe. The dimensions are not critical. Any slender tube of about this size will work. It is essential, however, to determine the actual dimensions as accurately as possible. The length can be measured with a ruler. To find the radius fill a portion of the slender tube with mercury and measure the length of the filled portion in centimeters. Transfer the metal to a container and determine its net weight in grams. Divide the weight of the metal by 42.55 times the length of the column. The square root of this quotient is equal to the radius of the tube in centimeters. For example, a 10-centimeter length of my tube holds 14.2 grams of mercury. Therefore its radius is $(14.2 \div 42.55 \times 10)^{1/2} = (.0333)^{1/2}$, or .183, centimeter.

"I blow the bubble inside a small aquarium of the type used for keeping tropical fish. (Any large glass beaker or battery jar will do.) The aquarium is covered with a sheet of transparent plastic that has two narrow slots along the middle that lead almost to the hole in the cover through which the blowpipe is inserted; the slots are thus on a straight



Hydrogen-bubble apparatus

line through the center. Through the slot I suspend two small plumb bobs made with a silk thread and a penny. To measure the diameter of the bubble I slide each plumb bob toward the bubble until the thread is within .5 millimeter of the soap film, as judged by eye. This brackets the bubble and gives its diameter within one millimeter.

"The experimental procedure is simple. Blow a bubble of any diameter. Remove the air hose from the blowpipe, plug the pipe and measure the radius of the bubble. Remove the stopper from the blowpipe and time the interval during which the bubble shrinks. Insert the stopper and measure the smaller radius.

"It turns out that the time of efflux varies as the fourth power of the radius of the bubble. Raise each radius to the fourth power (multiply it by itself four times). Subtract the smaller figure from the larger one. Assume, for example, that you let the bubble contract from a radius of two centimeters to a flat film across the end of the blowpipe. The figure would be $(2 \times 2 \times 2 \times 2) - 0 = 16$. If the bubble had contracted from a radius of 20 centimeters to one of 18 centimeters, the corresponding figures would be $(20 \times 20 \times 20 \times 20) - (18 \times 18 \times 18 \times 18) = 55{,}024$.

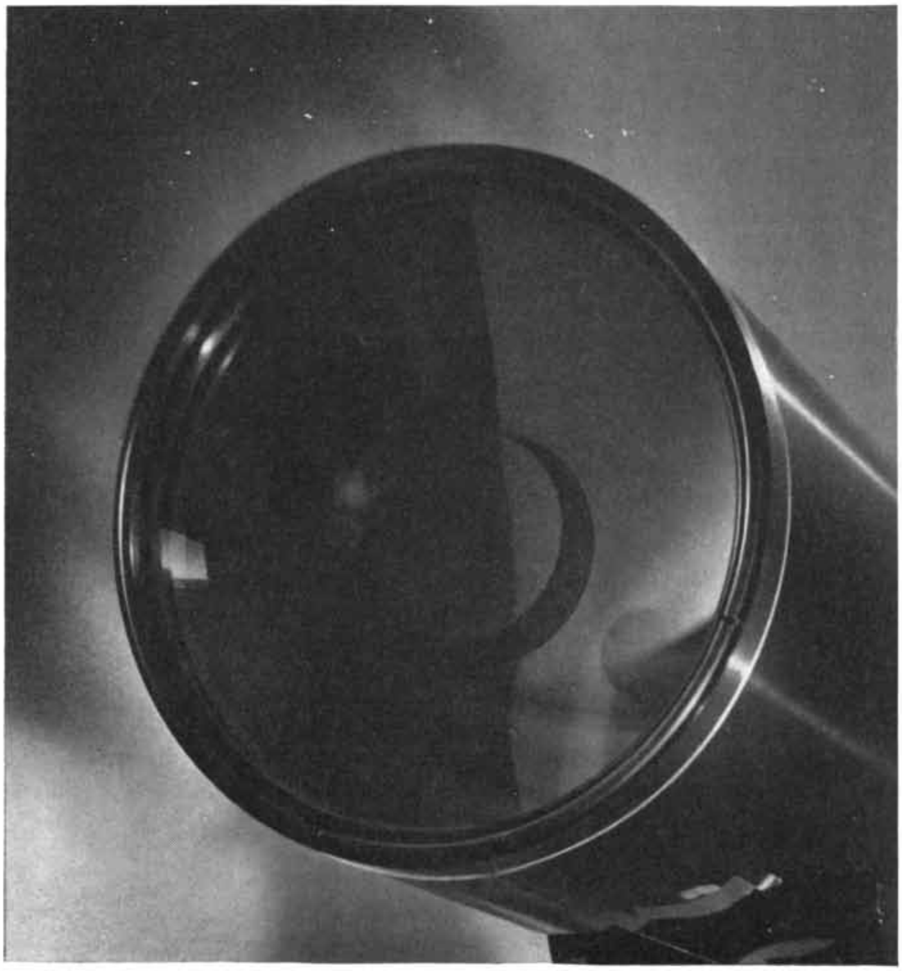
"Assume that you want to determine the surface tension in a soap bubble that contracts from a radius of two centimeters to a flat film in 4.94 seconds. The next consideration is viscosity, which is measured in units of poises; olive oil at room temperature has a viscosity of about one poise. The viscosity of air at 20 degrees Celsius is 1.83×10^{-4}, or .000183, poise. The surface tension of the two-centimeter bubble is equal to twice the length of the blowpipe, multiplied by the viscosity of the air and the fourth power of the radius as determined above, divided by the product of the time in seconds multiplied by the fourth power of the radius of the blowpipe. The example works out as follows: $2 \times 29 \times 1.83 \times 10^{-4} \times 16 \div 4.94 \times 11.31 \times 10^{-4} = 30.4$ dynes per centimeter. (A force of one dyne is about equal to the weight of a hungry mosquito.) Both the surface tension and the viscosity of the air are now known, so that the efflux time can be predicted. With the same blowpipe, how long would a bubble take to shrink from a diameter of 40 centimeters to one of 36 centimeters? The difference in the fourth power of the radii is 55,024. To compute the efflux time, multiply twice the length of the blowpipe by the viscosity of the air and divide the product by the surface tension multiplied by the fourth power of the radius of the blowpipe. The resulting quotient is a constant: $2 \times 29 \times 1.83 \times 10^{-4} \div 30.4 \times 11.31 \times 10^{-4} = .309$. Multiply the difference in the fourth power of the radii by the constant to get the time in seconds. In this example, $55{,}024 \times .309 = 17{,}002$ seconds, or about 4.7 hours.

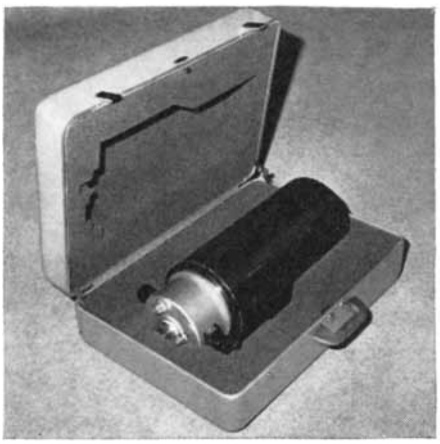
"Assume that the surface tension of the bubble is known and you want to determine the viscosity of a gas, such as hydrogen. Blow the bubble with hydrogen and proceed as above. Experiment would reveal that the efflux time needed for a hydrogen-filled bubble to shrink from a radius of 20 centimeters to 18 centimeters is about 8,100 seconds. The viscosity of the gas is equal to the product of the surface tension, the fourth power of the radius of the blowpipe and the difference of the fourth power of the radii divided by twice the length of the blowpipe multiplied by the efflux time in seconds: $30.4 \times 11.31 \times 10^{-4} \times 8{,}100 \div 2 \times 29 \times 55{,}024 = 8.76 \times 10^{-5}$ poise. I find it interesting to blow bubbles with different gases, such as a variety of Freons, and determine their viscosity by this procedure.

"A more ambitious project involves the construction of a useful manometer in which a nearly flat soap film functions as the sensing element. The instrument is capable of indicating directly changes in air pressure of less than a millionth of an atmosphere. Cut a circular hole, 45 millimeters in diameter, through the bottom of a plastic Petri dish to take a No. 10 rubber stopper. Perforate the stopper axially to accommodate a sleeve of 20-millimeter glass tubing four centimeters long. Push the sleeve through the stopper from the smaller end until it is flush with the top, and insert the assembly into the Petri dish from the top. Plug the top of the sleeve with a No. 2 rubber stopper perforated by two holes and plug the bottom by a similar stopper that has one central hole.

"The assembly rests on a tabletop, preferably one that is covered with hard, smooth plastic. Drill a hole in the table to take the glass sleeve and couple the sleeve to a five-gallon carboy under the table [*see illustration on preceding page*]. The carboy must be well insulated against heat, preferably by a covering of rock wool 12 centimeters thick.

"Place about 10 milliliters of bubble solution in the Petri dish and blow a soap film across the edge of the dish. Insert a roundheaded pin through the film and into the doubly perforated No. 2 stopper. Drill a second hole in the tabletop near the Petri dish to admit a snugly fitting glass sleeve and couple





the lower end of the sleeve to a glycair filter. Invert a cake plate over the Petri dish and insulate it with at least five centimeters of rock wool. Make two holes in the rock wool insulation for observing the relative distance between the pinhead and the soap film. As the barometric pressure changes, the soap film will move up or down in relation to the pinhead. You can observe the changes through a small telescope. I constructed the device to demonstrate one of many possible applications of soap films. The details of construction are obviously amenable to modification, as is the method of reading the instrument.

"In conclusion, I invite both amateurs and experts to help me solve a fascinating puzzle that turned up during a recent experiment. I wondered how a bubble would behave if it were blown with hydrogen in an atmosphere of hydrogen at low pressure. I blew the bubble in a round-bottomed flask that had a side arm and stopcock connected to an air pump. The blowpipe was inserted through a glass sleeve in a perforated stopper that fit the flask, and the telescoping joint between the blowpipe and the sleeve was sealed with a thin rubber tube [*see illustration on page 132*]. Bubble solution was placed in the bottom of the flask. The flask was exhausted to the limit of the air pump, flushed with hydrogen twice and again evacuated. The pump was shut off. Hydrogen was admitted to the flask until a manometer in the system indicated a pressure of 40 torr. The blowpipe was lowered into the bubble solution and withdrawn, and hydrogen was admitted to blow a bubble with a radius of about two centimeters.

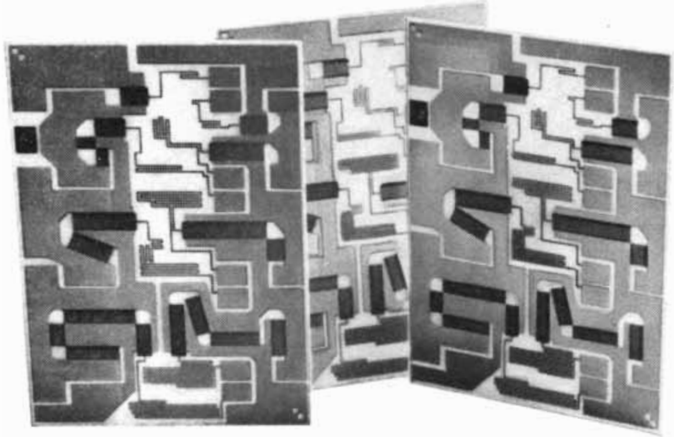
"Next I shut off the hydrogen supply, intending to observe the rate at which the diffusion of hydrogen through the soap film caused the bubble to shrink. To my amazement the bubble began to expand! Within about four hours it doubled in size. Thereafter it slowly shrank to a flat film as expected. I then blew the flat film into another bubble. The cycle was repeated.

"The experiment has been performed with other apparatus and under other conditions but always with the same result. The bubble expands without apparent cause! None of the obvious explanations is satisfactory. My stopcocks do not leak, the vacuum is held constant for weeks and the apparatus is trustworthy in other respects. I can only conclude that much remains to be learned about soap bubbles, and I urge amateurs to join me in the fun of solving the puzzle."

Western Electric
MANUFACTURING & SUPPLY UNIT OF THE BELL SYSTEM
AN EQUAL OPPORTUNITY EMPLOYER

The squares in question are the ceramic bases for the thin-film integrated circuits made at Western Electric's Allentown Works. The plates from which these bases are made have to be scored so they can be separated quickly and easily into bases of appropriate size.

Until, recently, this created two problems. First, each different scored shape (and there are many) required a separate, expensive die. Second, this scoring had to be performed before the ceramic was fired. And since ceramic shrinks when it's fired, some lines which started out straight became crooked, ruining the scored pattern.



We decided that scoring the plates with a laser might prove effective. A serious challenge in this area involved the control of the laser beam itself. Precise control over the powerful beam—getting it to cut only a fraction of the way through the ceramic plates, for instance (and the *correct* fraction at that)—had not been achieved by any other manufacturer up to that time, to the best of our knowledge.

By using a digital control console to control the laser, we were able to control the pattern it cut with great precision. A pre-punched tape was fed into this console. This, in turn, controlled the path taken by the movable base holding the plate under the beam, while the laser itself remained stationary. This device is faster and more flexible than manual control; since tapes are used instead of dies, the cutting shapes can be changed in seconds.

Because the laser cuts tiny holes part way through the ceramic, our "squares," if you'll pardon a play on words, are made out of "circles."

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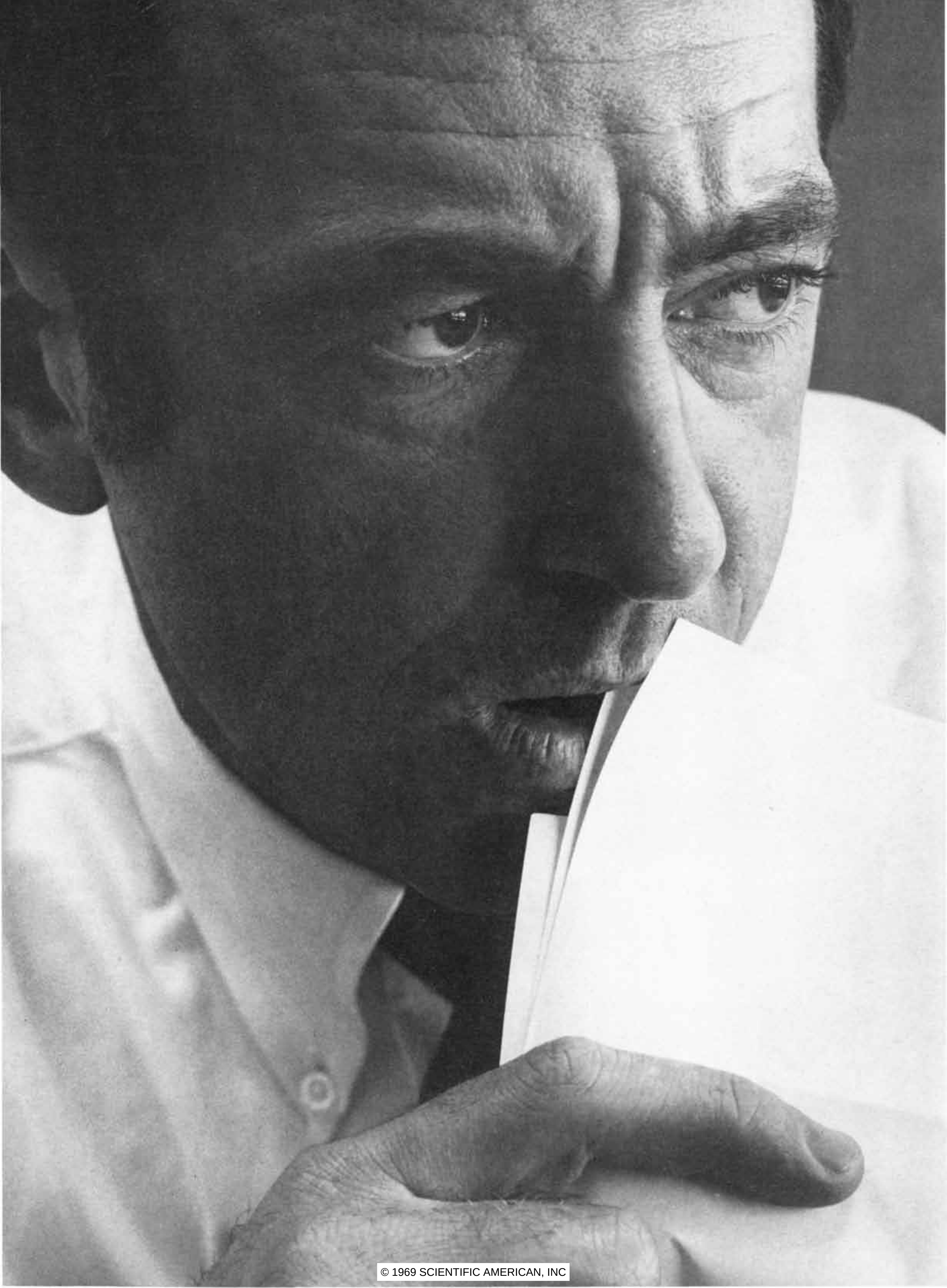

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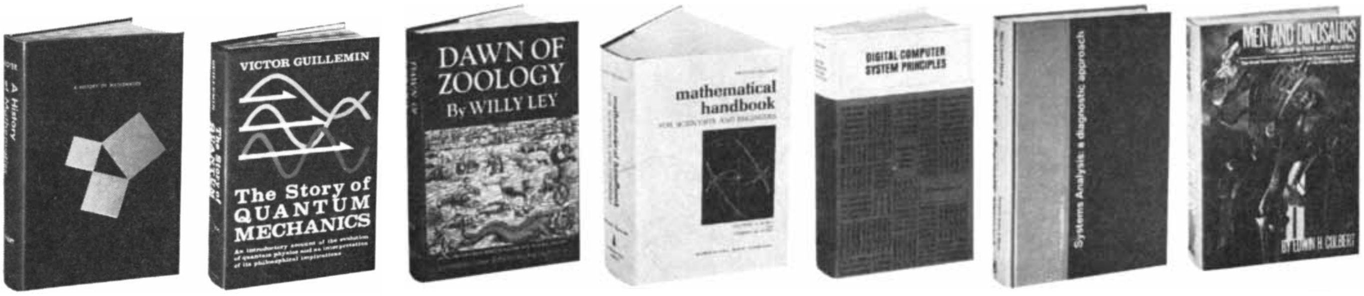

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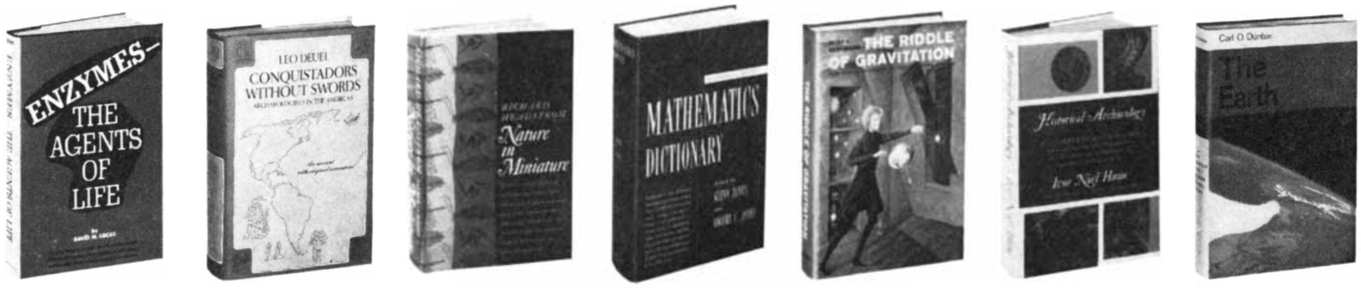

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BOOKS

Spencer Klaw's "The New Brahmins" and the current crisis of U.S. science

by Dorothy Zinberg and Paul Doty

The New Brahmins: Scientific Life in America, by Spencer Klaw. William Morrow & Company, Inc. ($6.50).

In recent times and particularly in the past decade we have come to accept change as the most characteristic feature of our society. This change has been pervasive, clearly visible year by year and rather orderly in that the rate of change, if not our accommodation to it, has been reasonably steady and predictable. The source of change is generally identified as being science, or the scientific community. This, of course, is an oversimplification. Science is primarily the unending search for understanding the physical world; change is a result of how the wider community exploits the new understanding. The wider community begins with the applied researcher and extends outward to engineers, technologists, managers, investors and manufacturers to Congress, the Administration, the vast Federal agencies and ultimately to the consumer and the taxpaying voter. Science nonetheless remains the source, and not unexpectedly it mimics the change it spawns by its own exponential growth.

The interactions of the scientific community with government, industry or society in general have been the subject of numerous studies and reports, most often the work of scientists. The interior of the community, although occasionally explored by social scientists, has been studied largely from a particular vantage point such as the sociology of career choice or the psychology of occupations. Perhaps it is the rapid growth of the scientific community in the past decade that has discouraged a comprehensive study of its internal and external relationships: the scene has changed by the time data have been collected and analyzed. In any event, we have had no exhaustive examination of the current scientific scene from the sociological point of view. Thus when a journalist presents his impression of scientific life in America, it merits attention by both sociologists and natural scientists; hence this collaborative review by a sociologist (Zinberg) and a chemist (Doty).

The New Brahmins is Spencer Klaw's account of his explorations among tribes of natural scientists located predominantly in clusters on the East and West coasts of the U.S. In an attempt to capture the essence of an entire subculture, to place it and its influence in the larger culture, to identify its political and class structure, its values, its language, its rituals and the methods it employs to ensure the continuity of the species, he has spent four years interviewing scientists, visiting universities and industries, reading scientific publications and attending lectures. In addition he has assimilated the research findings of social scientists and has used their insights as a framework for his own observations and impressions. As a result he has managed to "convey a sense of what it is like to be a scientist in America in a time when science has become a form of established religion, and scientists its priests and ministers." Although the metaphor could be developed by likening Klaw's four years among the natives, notebook in hand, to Bronislaw Malinowski's sojourn in the Trobriand Islands, the approach is actually closer to what John Gunther does in his "inside" books.

Yet Klaw's book is better than that, perhaps because the subject is a small subculture (100,000 Ph.D.'s and 200,000 others of professional standing), not a continent, and his focus is limited to the practice of science, not its substance. Klaw came to know the terrain well enough so that the few interviews he reproduces from his sample of 125 are nicely to the point. A couple of dozen slightly disguised biographical vignettes enliven the book and convey rather well the kind of people one meets in science. The result is a fairly detailed picture of American science in the mid-1960's. In addition to recording the usual features that are familiar to scientists, Klaw has tried to explore the values, mores and status concerns of the entire community, not just the men at the top. He prefers description and nuance to argument and the imposition of ideas.

This subjective technique is the strength and the weakness of the book. It serves breadth and vividness, but it does not give the reader the deeper view necessary for any comprehension of the complexities of this powerful institution. Nonetheless, the facts and numerous quotations speak for themselves, and generally they ring true. Inevitably, with the emphasis on catching an image at a moment of time, the book is short on the past and the future—on perspective. Yet it may be one of the best impressions we shall have of what will almost surely come to be known as the most explosive period of the scientific enterprise. Before developing this point, let us look at some of the details.

In his first chapter Klaw examines the sociological base of the scientific Ph.D., his position in the graduate school and the relevance of his postdoctoral appointment to his future career. This chapter sets the tone for the rest of the book. Klaw notes the comparatively low socioeconomic origins of Ph.D.'s and indicates the significance of science as a channel for social mobility. Right here readers may begin to experience a dual response to the book. On the one hand they will sense the accuracy of his contention. On the other they will miss the data concerning the origins of this social phenomenon that might enable them to consider such matters as the consequences of increasing affluence for the recruitment of scientists.

For example, Klaw's argument that the more diverse student bodies at richer colleges are producing more scientists-in-the-making does not hold when data from Harvard and other leading universities are considered. Indeed, since 1957 the number of students intending scientific careers on entering Harvard has fallen off. Using older data, Klaw argues the opposite. As an extreme case, in the six-year period beginning in 1961 bachelor's degrees in science at Yale fell from 26 percent of all bachelor's degrees to 10 percent. Klaw's next argument—"A scientist can seldom rise above his academic origins"—is that the choice of graduate school is crucial for success. The only support provided for this contention are the observations that more than half of the Ph.D.'s in science are awarded by 30 institutions, and that half of the National Science Foundation Fellows, free to select their institution, go to only four. (It is actually five; for some reason the Massachusetts Institute of Technology, which is in second place, was omitted.)

Such data are not convincing, yet it turns out that Klaw is right. A check of the membership list of the National Academy of Sciences (if one accepts election to that body as a measure of success) shows that of the 105 members under 51 nearly half received their doctorate at one of three institutions. This raises questions: Why is it so? Do students destined to be first-class scientists flock to a few centers? Or do these few centers alone hold the secret of converting good students into first-class scientists? Are the brilliant men with wrong credentials destined to failure in gaining recognition? Are we to accept the few as being the wellspring of the brightest? Is this the natural order of the subculture? Can this order be changed? Should it be changed? Such questions are stimulated by Klaw's book but are not asked in it.

Klaw's consideration of the graduate student shows a keen perception of his special problems. Unlike the budding doctor or lawyer, the graduate student in science must decide how much the interests and style of the professor to whom he apprentices himself will count and how much they will influence him. Klaw appreciates the spurts and pauses on the way to the Ph.D., the disappointment that many must endure on realizing that experiment rather than theory must be their goal, the benefits of collaboration and the dangers of exploitation, the joys of the first discovery and the plight of those who in spite of excellent grades never rise above their initial bafflement in research. Still, Klaw's assessment of graduate training in America is on the whole disappointing. He concedes that at its best it is unsurpassed anywhere in the world, but he holds that the most serious thing wrong is that the student is too often treated as a peon. Although this undoubtedly does not help to produce independent and creative minds, it is more likely that our most serious shortcoming is in the poor scientific and intellectual quality of a small but significant fraction of the system, both professors and students, and that this fraction is growing more rapidly than the rest.

The chapter closes with a look at the postdoctoral experience. For the majority this has now become the last stop on the way to becoming a professional. With training behind and responsibility for others still ahead, the postdoctoral years are often the freest a scientist will have. For many it is exhilarating; it is a period when they can test their strength and find themselves. On balance Klaw gives a proper appreciation of a most important, although noninstitutionalized, class of scientific workers, one that is vital to the basic research done at universities and that is so often overlooked. Again, however, Klaw fails to provide the rigorous examination of those elements in this period that produce the true Brahmins.

It is in this way that the book proceeds to examine the scientific life. The narrative continues on to pure science, the good professional life, the price of affluence, the styles of big science, the research institutes, applied research, industrial research, "movers and shakers," an assessment and finally an appendix: "Why Social Scientists Don't Fit In." The emphasis is not on organization but rather on what various members of the community do, how they feel about their work and what their motivation and their sense of accomplishment or disappointment is. Klaw shows that there are several elites: those who are given great freedom to work at what interests them, those who move from this experience to administer large laboratories or universities or industries, those who seek to shape the community or the nation or international relations by involvement on the Washington scene. He does not neglect any group. We see those whose work is dreary and repetitious, those whose first discovery has not been followed by a second, those who have not found administration creative, those who are caught in the lower reaches of a hierarchy whose purpose they either do not perceive or do not share and those who find delight or at least a sense of well-being in lesser jobs well done.

The diverse and throbbing community Klaw pictures seems to be in a steady state of growth and unaware of any really vital threat to its continued development. Such can hardly be the case. In the interval since the material for the book was collected American science has been put in a soul-searching mood by the sudden leveling of research and development budgets and by the haunting concern that the beneficial changes science promises are not being delivered.

Consider first the demographic aspects of the scientific community. Although the Ph.D.'s in science are not a majority, they do form the bulk of the upper echelons, as well as most of the independent investigators and leaders of research teams. Hence the character of the community is basically expressed by their numbers and quality. Since 1960 the rate of production of Ph.D.'s has been increasing at a steady 10.5 percent per year. This means a doubling of the rate every seven years. The fertility of this span far exceeds that of any previous period, even the years immediately after World War II. For many reasons such an increase in the "birthrate" of Ph.D.'s cannot be sustained. If it were continued and adjusted for the larger age groups coming through, we would by 1990 be producing in one year as many doctorates as existed in the entire community in 1965. The more telling arguments, however, are those involving resources, both human and financial.

The strain of the present situation on the more intellectually gifted young adults is indicated by the fact that one out of every 31 white males in their late twenties is now obtaining a doctoral degree of some kind (Ph.D., M.D. and so on). Of these young doctoral candidates nearly a quarter are in science (not including mathematics and engineering). One might think that, since science is so demanding and competitive, this group was selected from a large undergraduate pool. Such is not the case. The pool of bachelors in science is only about three times larger than the doctorates produced from it (when allowance is made for those going into medicine).

Thus either in terms of the fraction of the population taking the doctoral route or in terms of the college graduates prepared to undertake doctoral study, the human resources are already stretched thin. Yet the exponential increase in the number of Ph.D.'s goes on. If the present growth in the rate of Ph.D. production is maintained, lower standards will have to be accepted and new ways of stimulating undergraduate concentration in science will have to be discovered and applied. (It appears that the increase is now being reduced by the drafting of graduate students, but in time it will resume.)

As for financial resources, the requirements for continuing this rate of growth can be estimated by recognizing that during the past decade the growth has

been sustained primarily by the injection into the university system (in terms of research grants, training grants, fellowships and construction funds) of an extra $130,000 for each Ph.D. produced in excess of the number produced the year before. With the annual increase estimated at 850 for the current year, this calls for an increase of $100 million in Federal funds going to the university science departments this year and proportionately more in future years. In actuality there is no increase but a slight decrease.

We see, therefore, that all the forces that have been so balanced as to produce a steady rate of growth in recent decades are in disarray. Although the crisis has been greatly intensified by the abruptness of the leveling of Federal support, a radical readjustment in the coming decade is inevitable unless several unlikely changes occur. At a minimum these would seem to be (1) a solution to the many problems that keep women and nonwhite males out of the doctoral world (their likelihood of obtaining a doctorate is only about 10 percent that of the white males), (2) a continuously lowering standard for the Ph.D., (3) an increase in those concentrating in science in college and (4) a stable growth of Federal investment in university science of at least 13 percent per year (allowing for an average of 2.5 percent inflation). Before concluding that these changes are impossible, or only partially attainable even if they are judged to be desirable, it is necessary to make some assessment of the morale and satisfaction with work inside the community, and to inquire of the society its attitude on the return it believes it is getting on its investment, both human and economic. This matter is treated in the closing pages of Klaw's book.

Let us consider the social return first. A recent critique of the National Institutes of Health (the "Ruina report") states that "the most crucial single problem to be faced at NIH is the scarcity of individuals in the biomedical area with the technical background, experience and temperament needed to assume the responsibilities of program management. The biomedical administrator or manager, at present, lacks status in the eyes of his peers."

Klaw comments: "A scientist may argue that this is all too bad, but that putting science to practical use is not his job. Even from a purely selfish standpoint, however, this makes little sense. Basic researchers in the United States are supported largely by tax money, and the taxpayers' representatives have been taught by scientists themselves that basic research is not really useless—that it differs from applied research mainly in that it doesn't pay off quite so quickly. In the long run, the patrons of basic research will judge it by its utility....

"The trouble with applied research in the United States is not only, as I have suggested, that able scientists tend to turn their noses up at it. The main trouble is that the conditions under which applied scientists have to work in government and industry are often frustrating and sometimes degrading. If science is to be used more efficiently, ways must be found of preserving in large-scale applied research some of the autonomy and free cooperation that characterize basic research."

The diagnosis has merit: the system is out of balance. The psychological incentives and sense of participation are largely in basic science; the world's work gets short shrift. Klaw's frame of reference is nonetheless too narrow. To detach the scientific community from society and inquire of the balance of payments is a useful approximation, but if it is carried too far it presents a false dilemma. Klaw falls into this trap with an outburst that is at odds with the rest of the book. "The expectations that were aroused in 1945, when it appeared that if scientists could invent an atom bomb they could invent anything, have not been realized. New products... have, to be sure, flowed in a generous stream from the springs of scientific knowledge.... But science has done little or nothing to mitigate hunger, poverty, inequality, ignorance, or even improve the quality of housing, urban transportation, and medical services."

Science in this larger sense, which includes technology and the management and funding of the scientific enterprise, is not simply a specially skilled unit of the labor force retained by the society. Rather, it is a highly coordinated system of ideas, techniques and patterns of action that is an integral part of society—indeed permeates the society. For more than a century this system has been consumed with carrying out a broad mandate to understand the natural world and exploit that understanding for expressed needs, whether these be relief from the ravages of disease or the production of superior weapons. The operation of the system has transformed the environment: capricious nature has been controlled.

This conquest of the earth is nearly over; the frontier has moved to the moon and the planets. Yet here on the earth we are besieged by new problems of our own making, problems often arising from the unforeseen consequences of using science and technology for a much more limited purpose. The social function of science now lies in a new direction: to help in creating a truly hospitable human environment on this planet to replace the jerry-built one the younger generations are inheriting from an age when science and technology were asked to do quite different things. To move in these new directions requires new instruments. The free market and government planning as we know it are not enough. Most of all a keen social interest is needed, one quite different from the tone of alienation and disenchantment of much current social criticism, which mistakes the vehicle for the driver. If the driver neither decides where he wants to go nor tends to the driving, it is unseemly to blame the car for a rough trip to an unwanted destination.

If we return now to the human situation within the scientific community, we are struck by the similarity between the personal problems scientists face in their work and those confronting others throughout the society. Again one cannot detach this community from the larger culture.

Nowhere is this more striking than in Klaw's interviews about science as work, that is, the career or job aspect of the scientific life. The hierarchical organization of scientists can be likened to a pyramid, but it is more accurate to describe it as a pyramidal iceberg with only the top tenth of its bulk visible. This visible section—the Nobel prize winners, the President's scientific advisers, the active members of the National Academy, the inventors of new electronic devices and those who are involved in the development or control of nuclear weaponry—are the men who are the collective public image of science. It is they who are Klaw's new Brahmins. As in most fields, however, only a few make it to the top. What happens to the other nine-tenths is not often written about, yet it is they who make up the work force of American science—industrial, governmental and academic. The outsider looking at scientists may see them as a homogeneous elite, but the majority of those inside do not recognize themselves as Brahmins.

As Klaw presents his findings, the attitudes toward success vary to some degree with the expectations of the individual. A student whose doctoral-thesis experiment failed sees himself as doomed to a life in industry. Yet another scientist who has not attempted to go to graduate school works his way up through the very same organization, to the same position the failing Ph.D. took for want of anything better, and sees his promotion as a sign of success. Now that more than 50 percent of American youth are attending college, everyone's expectations about the possibility of "surfacing" have been lifted. For the majority of the workers in the broadest stratum of the pyramid (now increasingly filled by college graduates) their work will bear little resemblance to the excitement of science as depicted by college professors, appealing research-and-development advertisements, industrial-personnel scouts and the ever visible tip of the iceberg.

Although jobs may be upgraded by title, their content becomes apparent all too quickly. For some a shift into management is the answer. For others the response is a feeling of having been betrayed by the system that promised a career but produced a job. It is the discrepancy between the expectation and the reality that heightens the disillusionment.

As social science is beginning to demonstrate, the real recruitment of scientists begins in school, not college. Students may shift out of science in large numbers in college but they rarely shift in. As the high schools must provide sufficient stimulus to would-be scientists to prepare them for the college science curriculum, so must the college serve as a relevant link to postcollege opportunities.

Because of the rapid accumulation of knowledge and the resulting change in industrial research and production, the colleges must cope with the problem of obsolescence in the science curriculums. A recent study of science graduates in Britain indicated that they make use of roughly 15 percent of what they learned in college. The figure is probably higher in the U.S. because of less rigorous academic requirements, but it does serve as a warning. If the college is to fulfill its function of providing an education for those other than an emergent elite, it must somehow make the curriculum relevant to the situation its graduates will face. This is not an easy task.

The challenge now is to concern ourselves with the quality of work, not the quantity. Several companies affluent and inventive enough to do so have begun to experiment with new career patterns for scientists in their organizations, by changing task groups, by continuous education and by increased participation in company decisions. These companies, however, are clearly not in the majority. In most places one finds a growing unease about life, not at the top but in the middle. Science students who are not headed for graduate school but who know they can find a job somewhere are beginning to question their future. An undergraduate recently interviewed about his prospects in chemistry said that he was beginning to change his mind and would probably shift to economics because it was "too much of a slog in college to end up as a drone."

The curtailment of funds for the support of academic research has suddenly reduced the number of openings in good universities for this year's doctorates. For a promising M.I.T. physicist to have to choose between a third-rate university job with little opportunity for research and a second-rate job in industry is understandingly frustrating. It is hardly surprising if he joins in a research stoppage for a day's discussion of the misuse of science.

These dissatisfactions, which Klaw picked up a few years ago and which are now more evident, run parallel to the increasingly frequent use of science as a scapegoat. The rash of physical assaults on computers illustrates this distemper. It is clear that dissatisfactions are running wide and deep both inside and outside the community of the new Brahmins.

It is interesting that Klaw, in attempting to portray the scientific community as an established elite, chose the metaphor of organized religion to convey his impression of institutional solidity and permanence. Consider what is happening within the religious establishment at the moment: the clergy find themselves torn by conflicting views on the role of authority, on the war in Vietnam, on the relevance of their church to society, on church-state relations, on civil disobedience and on the modern role of the church. With a little modification this list becomes the issues that disturb many scientists.

For the new Brahmins, as for the clergy, this turmoil and self-questioning are probably a prelude to a new relationship with society. If this new relationship is successful, there will be much new work to do. Many of the present discomforts and frustrations will disappear. The number of scientists will again increase, and their support will multiply. Society may even get the new, hospitable environment it wants, and then perhaps find itself dissatisfied with what it has got. So the cycle may continue. Among the Brahmins, however, there will be some for whom the pursuit of science itself is sufficient. They will not be dismayed by the inner turmoil or the outer upheavals. This is what they expect and what they need. As Klaw reminds us, in the scripture according to Jacques Monod there is this passage: "In science, self-satisfaction is death. Unquietness, anxiety, dissatisfaction, and torment, those are what nourish science. Without fundamental anxiety, there is no fundamental research."

Shorter Reviews

by Philip Morrison

UNIFORMITY AND SIMPLICITY: A SYMPOSIUM ON THE PRINCIPLE OF THE UNIFORMITY OF NATURE, edited by Claude C. Albritton, Jr. The Geological Society of America ($4.50). THE HISTORY OF THE EARTH'S CRUST: A SYMPOSIUM, edited by Robert A. Phinney. Princeton University Press ($13.50). The astronomers of the 18th century placed man within space. Even the distant galaxies were interpreted correctly by Immanuel Kant. Putting man into time, however, was the task of the 19th century, when geologists began to perceive the true span of the earth's history. Four authors—a geologist, a historian of science, a paleontologist and a philosopher—address this topic in the first of these two books, a rather too costly but very interesting paperback. They approach in their different ways the question of that overarching but somewhat mystical principle of uniformity that governed the rise of modern geology. It is plain that the principle is not literal: the earth and the sun must wear out and run down, if physics is not wholly in error.

The mighty thermodynamicist Lord Kelvin, with his magisterial manner, his long equations and his long beard, demanded that his not very quantitative adversaries set *some* limit on geologic time. The field men and the evolutionists, from Lyell and Darwin on, knew from the data that the time was long, far longer than Kelvin's energy sources would allow. Their great principle amounts in hindsight only to this: the sum of geologic change is patently large. Still, the observed rates of change are painfully slow. Either the elapsed time is very long or the rates of our epoch are hopelessly misleading. It was learned step by step that although rates must and do differ (there are more glaciers during ice ages), the possible differences in rate seem small compared with the vast ratio between the Biblical time scale and the geologic one.

This insight was the implicit basis for the principle of uniform change, which

American Mail Line's *Washington Mail* built by Todd, Los Angeles

was never logically admissible and yet informed a century of triumphs. Norman D. Newell makes a strong case for the rapid extinction of animal forms at certain periods, but even this special circumstance seems to imply nothing different from what we can see in recent times. It was the American geologist T. C. Chamberlin who seems to have led the way to reconciling physics and geology, by breaking through Kelvin's (and Helmholtz') limit of 20 million years with the observation that the theory "takes no cognizance of latent and occluded energies of an atomic or an ultra-atomic nature." He wrote in 1899, only three years after Becquerel had found his fogged photographic plate.

The second book, an updated report of a symposium held late in 1966, ornamented by two striking magnetic maps in color, is devoted to the geologists' second victory over an immature geophysics. Nearly a score of papers set out the impressive evidence for the change of geography over the span of geologic time—the long-denied formation of the modern oceans by the worldwide wanderings of the continents. Only three of the papers fail to present strong evidence for continental drift. They are all paleontological. It is plainly dangerous to conclude from the presence of coal-forming swamps that the climate was warm; coal is being formed today in northern Greenland. Even so, the main climatic indicators such as fossil desert soils or tropical trees tend to bear out the drift, just as the jigsaw-puzzle fit of continental shapes and rock types do.

The story of sea-floor spreading is also told here—the stuff pouring out of the seismically active submarine ridges to solidify in stripes of differing magnetic polarity, neatly arranged in perfect symmetry and well ordered by radioactive dating. It is compelling to see the magnetic directions on the sea floor near Iceland fit so well the magnetic-reversal time scale deduced from profiles taken in the South Pacific! The rich and satisfying order in these studies seems all but final.

One misses some remarks about the purely technical problem of position-finding at sea implied by these maps. Even the summaries drawn here show positions meaningful at resolutions of a couple of kilometers; the original data were 10 times better than that. Doppler tracking of satellites is to be thanked for these elegant results, today and in the future.

The kinematics of continental drift now appear plain; its dynamics are still in doubt. Hot crystals do creep, however, under a prolonged small stress. The huge blocks in the earth's crust rub together, starting earthquakes whose direction of first motion confirms the expected direction of flow and exhibits the nature of the offsets in the submarine ridges. California is sliding oceanward an inch a year; someday soon, between lasers and radio interferometry, we shall be able to see it move. Someday we shall also know what is pushing or pulling it.

ALVAN CLARK & SONS: ARTISTS IN OPTICS, by Deborah Jean Warner. Smithsonian Institution Press ($1.75). When Dom Pedro, the urbane emperor of Brazil, came to the U.S. for the Centennial Exposition, he visited Cambridge, Mass. There he sought to meet only three people: Henry Wadsworth Longfellow, Louis Agassiz and Alvan Clark. Clark was the head of the Yankee instrument-making firm that gained America preeminence in large telescope lenses, a preeminence that was carried over to mirrors by the energy of George Ellery Hale and that has been maintained since 1873. The Lick Observatory in California, the Yerkes in Wisconsin and the Pulkovo in Russia each used a big Clark lens. His shop was prepared to start on a 60-inch, and no one has yet beaten the 40-inch they made, which is still working well at Yerkes.

Alvan Clark was an engraver, a miniature-painter and an amateur gunmaker and sharpshooter. When the great comet of 1843 stirred excitement, his son, then a student at Phillips Andover, melted down the broken dinner bell to make a metal mirror. Father too was beguiled by the new craft. The business began a few years later, and for 50 or 60 years Alvan and his two sons, with half a dozen workmen in a riverbank shop in Cambridge, furnished the finest lenses in the world (and many accessory instruments) to observatories in Europe and all over the U.S. Their work was conservative, conventional, not much concerned with new designs. They chiefly made big Fraunhofer doublets. It was painstaking care, patient local correction and the artist's integrity with which they worked French and British optical glass that enabled them to lead the world in big lenses.

One anecdote must stand for the many told so well in this small book. The University of Mississippi built a replica of the Pulkovo Observatory and ordered from the Clarks the world's biggest lens, a 19-inch objective. The Clarks moved to a larger shop to make the lens, the diameter of which they finally set at 18½ inches. The work was finished late


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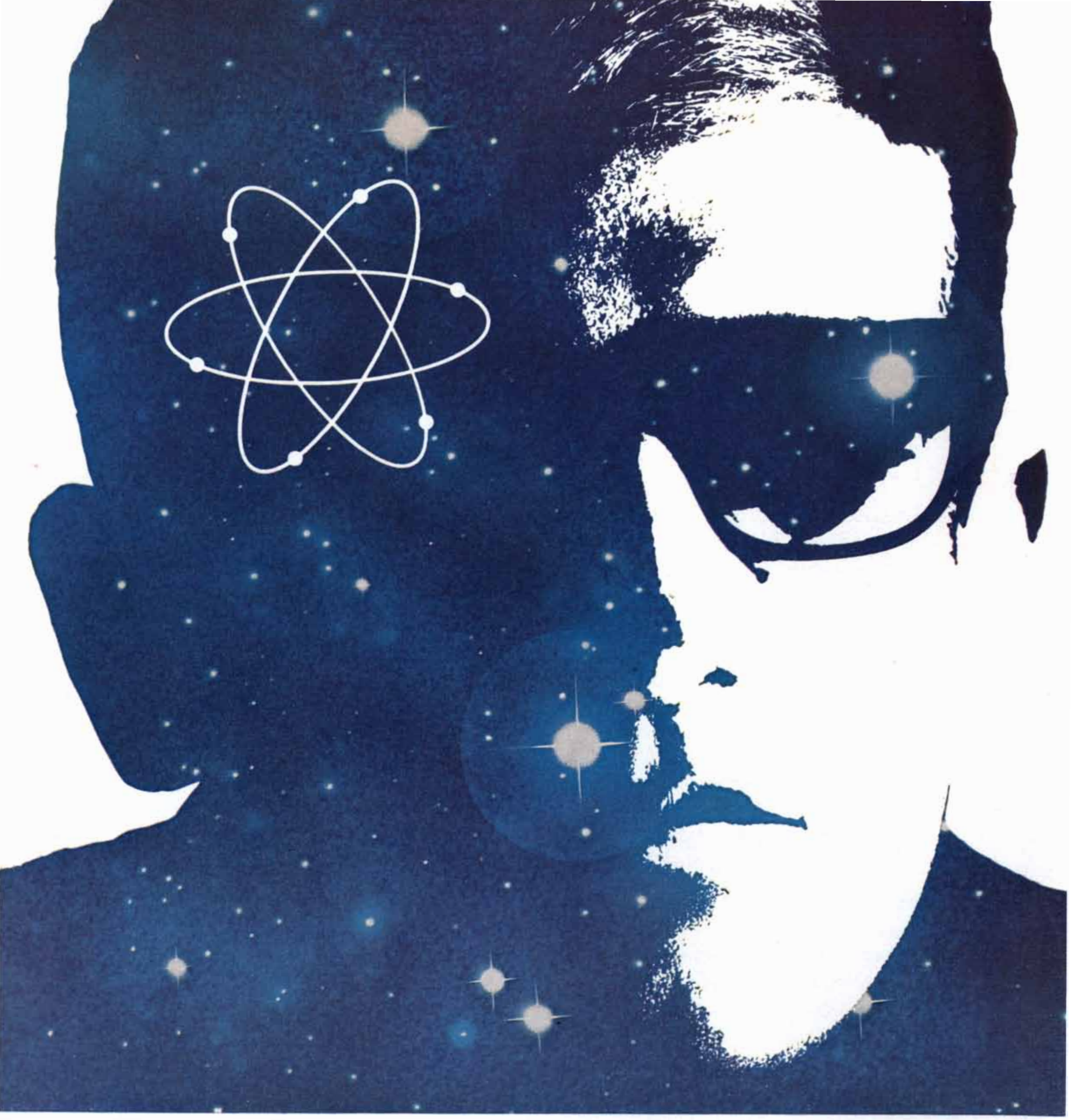

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A quality company of Ling-Temco-Vought, Inc. **LTV** in 1861, but by then Mississippi and Massachusetts were at war. The Clarks tested the lens on stars from a pier on their own grounds. They were watching to see how early the light from Sirius could be perceived around the corner of a building before the star itself came into view; thus did they discover in 1862 the famous dense companion of Sirius. Their lenses and prisms were used to compile the great Draper catalogue of spectra; their clock drive at Harvard helped to make the first successful celestial photographs.

The refractors they foresaw as the great telescopes of the future have been all but superseded, but the Clark workmanship remains a monument. "For the final rub, Alvan Clark could find no sufficiently soft cloth, and so he used his bare thumbs!" Under this punishing regime his thumbs burst open late in life; the Puritan view of a contemporary astronomer, Maria Mitchell of Nantucket, was that "into every superior work the martyrdom must come."

NOBLE-GAS CHEMISTRY, by John H. Holloway. Methuen & Co. Ltd. ($6.75). In late summer of 1962 it became clear to chemists that the noble, or inert, gases in actuality had a normal stable chemistry. Discovered in Britain and first elaborated at the Argonne National Laboratory in the U.S., compounds of xenon and fluorine were made. The author of this attractive, brief and interesting book was then beginning work in Birmingham on his Ph.D. thesis in inorganic chemistry, which led him to prepare xenon compounds. Since then he has been caught up in this energetic field of work, which has in so few years justified his sober remark that "the broad features of the chemistry of the noble gases are now fairly well established."

The text has three distinct parts. First there is a useful, but hardly novel, review of the discovery and properties of the noble gases themselves. Then he discusses the older, weakly bound kind of chemistry long known for the noble gases: the existence of short-lived molecules and ions including these atoms, marginally capable of isolation and known only from the spectroscopy of discharge tubes and in the mass spectrometer. All the gases that are heavier than helium, for example, are theoretically expected to form two-atom molecules at room temperature and pressure on the order of 1 percent concentration; it seems that such neutral diatomic argon and xenon molecules have even been detected. X-ray work in the postwar years revealed that a long-known class of compounds named clathrates (after the Latin word meaning protected by a grating) consisted of a crystalline lattice of a "host" substance (an organic crystal or an unusual form of ice) holding in its cavities "guest" molecules such as sulfur dioxide, argon and xenon. The noble-gas cages made by ice were discovered, if not recognized, as soon as the inert elements were known. Clathrates are now used to store the noble gases, particularly their radioactive isotopes.

The real, strongly bound chemistry of noble gases occupies better than half of the book, with detail extending from the history of this young science through the theoretical arguments behind it to the methods of preparation and the management of the hazards of the art. The compounds of the heavier noble gases are not challenges to chemical theory, however forgotten the possibilities were. Linus Pauling predicted several of the most important compounds quite accurately in 1933. Don M. Yost and Albert L. Kaye tried that same year to make xenon and fluorine react in a spark, with no success. The method they chose does work; the small quantity of xenon available and the crudeness of fluorine technology at the time seems to have hidden the result. Holloway comments: "Yost seems to have been particularly unlucky."

Now we have the main results. Only krypton, xenon and radon form stable compounds. In these the noble-gas atoms are always bound either to fluorine or to oxygen. Most of the work is done with xenon; krypton is so light that it forms few bonds and radon is so radioactive that it can be studied only in minute quantities. But xenon compounds abound. They are all potential explosives, because they react easily with water to form the white, transparent crystals of xenon trioxide (XeO_3). This stuff is set off by rubbing, pressing or gentle heating; it detonates with a blue flash and the violence of TNT. A convincing sketch of a nickel container blown asunder by 200 milligrams of solid XeO_3 adds emphasis to the text.

The material in this book is not only interesting but also occasionally surprising. Consider the class of compounds called perxenates. An example is sodium perxenate (Na_4XeO_6), which at room temperature is an entirely stable, not very soluble colorless crystal. The perxenates are the most powerful solid oxidizing agents we have. They are rivals to fluorine gas, and can rapidly oxidize water to oxygen. One imagines a conscientious editor of science fiction some years back striking out as being too whimsical a sentence suggesting that rocket engines might use a compound of xenon!

THE CP PUZZLE: STRANGE DECAYS OF THE NEUTRAL KAON, by P. K. Kabir. Academic Press ($6). Everyone with an interest in science that dates back at least to Sputnik days can recall the excitement with which the world learned about the work of T. D. Lee and C. N. Yang. They had foreseen that nature does not treat every physical system and a model made in its mirror image equally. Before a year was out the late Lev Landau had generalized on the matter a bit: even if right and left were distinct, it might still be that the distinction depended on knowing positive charge from negative. The overall mirror, which reflects right into left and particle into antiparticle, might remain indiscernible in nature. Then the beta decay of anticobalt would have a handedness exactly inverse to the handedness observed in the decay of real cobalt. This elegant view persisted until 1964, when a remarkable experiment at Princeton challenged the symmetry of the Landau mirror (called the CP mirror for charge and parity).

The Princeton experiment was a sharper look at a phenomenon even more remarkable than beta decay. It is the decay of the neutral kaon, or *K* particle, which is different from the decay of any other particle. First note that the neutral kaon and its antiparticle are not identical. They are opposites in the quantity called strangeness, which governs the interaction with neutrons and protons. But strangeness (unlike, say, electric charge, to which it is in a way analogous) does not remain strictly constant in nature. The neutral kaon, and the antikaon as well, both slowly decay into two neutral pions, or into a positive-negative pion pair. We know of no way to tell the kaon and antikaon products apart.

The result of the existence of two indistinguishable modes of decay is an interference phenomenon, just as the two alternative slits by which an electron can indistinguishably reach a detector give rise to an interference phenomenon. The kaon we observe, then, is neither the pure neutral kaon nor the antikaon but a superposition of the two. This philosophically startling notion is a firm prediction of quantum mechanics, and it leads to an anomalous decay of the experimental kaon, a decay that is nonexponential and changes its nature as time goes on. Over a short time span the neutral kaon decays mainly into two pions; after the particle beam has moved a few centimeters the remaining kaons decay chiefly into three pions. It is even possible to regenerate the two-pion decay by allowing collisions along the way, all according to the well-tested theory. The Princeton experimenters showed, however, that the distinction is only approximate; once in a great while even the well-traveled neutral kaons can still decay into a pion pair.

This book is a careful treatment of the puzzle. It is not for the general reader; it assumes a good knowledge of the mathematical formalism of one-particle quantum theory in the style of P. A. M. Dirac, although not of the full many-particle field theory. It considers all the ways out of the problem, which revolve around the need to drop the Landau mirror theorem, so that the neutral kaon and its antiparticle are no longer to be represented by distinct states that behave in precisely the opposite manner in the CP mirror but rather by some mixture. No other conclusion seems possible.

It is unfortunate that the book can refer only in a footnote to an important result obtained in the summer of 1967: that the long-lived neutral kaon component decays into negative pion and positive muon more often, by a couple of parts in a thousand, than into the CP-mirrored pair (a negative muon and a positive pion). This is a much clearer basis for claiming CP violation than the subtler two- and three-pion decay experiments, on which the exposition focuses. The entire treatment is nonetheless clear and complete; it will be valuable for students who want to enter this difficult and deep field of investigation, and for workers in other fields who want a clear account of the results in simple quantum-mechanical language.

ECOLOGY OF PARASITES, by N. A. Croll. Harvard University Press ($3.25). In the 100-odd pages of this little book a London zoologist has written a lively beginning account for students and general readers. The startling engineering ingenuity of the host-parasite relationship best appears in specific examples, and they are here in plenty. Unlike the usual text on the subject, this work does not present the parasites by zoological class. Instead it discusses the generalities of parasitism: a sensible heuristic definition, the range of parasitism, the transmission schemes, the effects on hosts, the path of evolution and so on.

An almost moral conclusion is implied by most descriptions of the commonly degenerate state of the adult parasite.

Photograph: Sigurgeir Jónasson, from SURTSEY, The Viking Press.

In 1963 the island of Surtsey was born of a volcanic eruption in the Atlantic submarine ridge south of Iceland.

One parasitic adult crustacean is hardly more than a "bizarre, extravagantly developed egg sac," quite unidentifiable as to family. It was finally learned that its tentacled free-living larva was quite similar to the larva of many nonparasitic relatives. There is typically such a "staggered division of labor" during the various life stages of the parasite; viewed over the entire cycle of its life the organism is in no way degenerate. It is a successful, adaptive, independent form.

The reactions of the hosts are most varied: the oyster forms a pearl around not only a grain of sand but also the larva of a fluke. A shore crab parasitized by one kind of barnacle suffers so severe a hormonal disturbance that it stops molting. Its unrenewed carapace gradually becomes covered with weeds and other barnacles. Sometimes the disturbance goes so far as to turn an infested male into a female. Again, a larval worm matures inside a bee host. The larva must return to water at maturity in order to burst out of the host's body, mate and lay eggs. It is reported that "an infected bee flying over a pool . . . about six feet over it [dived] straight into the water. Immediately on impact the gordian worm burst out and swam into the water, the maimed bee being left to die." The mechanism is obscure; one would like statistics.

Parasites must of course avoid overkill. Too many guests living off a single host means disease and is generally not efficient. ("The parasite must live off interest and not capital.") Certain nematode worms found in the gut of the sheep and of the rat demonstrate the phenomenon of self-cure. The larva burrows deep into the stomach lining, inducing by irritation a secretion of histamine in the host's bloodstream. The histamine is taken in by the adult worms clamped to the gut, where they feed directly on the flowing blood. Enough of the agent causes the adults to release their hold. Thus a second infection by larvae does not add worms but rather replaces the old adults by new ones. No sheep or rat can pick up too many of these worms at once. Parasitism is full of such feedback loops, at once the fruit of long evolution and the evidence of it.

AROUND THE WORLD: A VIEW FROM SPACE. Rand McNally & Company ($4.95). The Government Printing Office gave us the first album of color photographs from the Gemini orbital flights (reviewed here in January, 1968). Now we have a commercial version, with 96 pictures in excellent offset color repro-

NEVER MIND OUR OPINION after all, we're prejudiced BUT read these new quotes from two road tests of the Rover 2000 TC

On why we don't need a yearly model change:

"The design of the TC is such that even in today's fast changing automotive world, the appearance of the Rover will never grow old."[1] "Few excuses need to be made for its performance, roadability, or accommodation when comparing it to other sedans in the same class but of more recent design."[2]

On Rover engineering:

"This is a car which does everything just right and to say that the Rover 2000 TC is a perfect piece of automotive engineering is certainly not exaggerating."[3]

On the Rover "ride":

"Springing is soft, and the result is a very plush ride with less harshness than any car short of a large American sedan."[4] "Radial tires have been standard on 2000's from the outset"[5] "and the suspension has been tuned to these radial ply tires in such a manner that"[6] "their usual effects on ride harshness have been completely tuned out."[7]

On manoeuverability and spunk:

"The TC also has very high cornering power for a sedan."[8] "We had occasion to come up against a few sports cars in town, and no doubt their drivers were somewhat amazed when this sedan managed to leave them during cornering manoeuvres. It is a very satisfying feeling to have a luxurious sedan which can give you adequate acceleration and then perform like a true GT when it comes to roaring through corners, along super highways or over country roads."[9]

On the engine:

"The engine does run flexibly and without temperament, starting quickly on its manual choke and having no carburetion flat spots or low-speed bucking to spoil everyday city-suburban driving."[10] "The car's highway performance is superb and cruising at 90 mph is an effortless job for the engine."[11]

On shifting and braking:

"The all synchromesh gear box makes shifting a delightful experience and the throws are quick and accurate."[12] "The gearbox itself is quiet and infallibly synchronized and its ratios are appropriate for the car and engine. The shift lever, which has a trigger release for getting into reverse, is in just the right place."[13] "The brakes are familiar Girling solid discs all around with plenty of swept area and *two* vacuum boosters."[14]

On getting into the Rover for the first time:

"When you first sit in the TC it brings out a certain excitement."[15] "In the 2000's interior, the car's individuality is as clear as in the handling and ride. There's a definite English feeling about the surroundings, with proper leather ...used as you would expect."[16]

On instrumentation:

"Control switches are easy to reach and there is no mystery as to what they are as each one is clearly marked."[17] "The steering wheel is adjustable up-and-down about 1½ in. but not fore-and-aft; a widely adjustable backrest, however, takes care of all adjustable needs."[18] "Standard equipment for our market is an intriguing gadget known as Icelert."[19] "This flashes on and off when the temperature goes below the 36 degree mark and stays on when the temperature reaches the freezing point."[20]

On fresh air and heating:

"Most notable is the heating and ventilation system, which in spite of much catching-up by other manufacturers over the past five years is still the best we've experienced in a British car. Especially notable are the dash vents smack in front of the driver and passenger."[21]

On creature comforts:

"Another touch, one we'd applaud in *any* car, is the pair of drop-down bins under each side of the dash that serve as storage space and as the best knee protection in a crash that we've seen."[22] "The seats themselves, both front and back, fit like a glove providing maximum comfort."[23]

On visibility:

"The view out over the sloping hood is outstanding, little fender-cap lights defining the front corners, and to the sides and rear vision is also more than acceptable."[24]

On buying a Rover:

The price we're quoting these days for the car that brought forth all this unsolicited enthusiasm is $4,198. Write: British Leyland Motors Inc., 600 Willow Tree Road, Leonia, New Jersey 07605. Or, better still, see your Rover dealer. He'll do his best to make you happy—and you can quote *us* on that.

Road and Track: 2,4,5,7,8,10,13,14, 16,18,19,21,22,24
Canadian Track & Traffic: 1,3,6,9,11,12, 15,17,20,23

BRITISH LEYLAND ROVER

duction. This one shows the same world, our white-blue-green-red home, in many of the same photographs. The volume is cheaper and smaller; it does not give the data for the pictures, but it does present an outline of each photographic field, carefully drawn on a color photograph of a relief globe. It is on the whole a less technical work and a better one for schools. The great deltas from the Colorado to the Yangtze, the great ranges from the Andes to the Hindu Kush, the great deserts from the Kalahari to the Atacama of Chile are all present.

Man's work shows here and there; the checkered pattern of the irrigated fields of the Imperial Valley is the clearest evidence in the book that we live on this lovely planet. "Nature's lacy patterns on the South Pacific surface," the text says, "are the numberless and mainly nameless coral reefs.... We see here Bikini Atoll...one of the most beautiful to be found. In 1946 two atomic bombs were exploded here." In 1954 a 15-megaton thermonuclear shot was fired too, and the mile-wide bite taken out of the reef still seems plain. The adjoining photograph shows the carelessly thrown loop of Rongelap Atoll, whose people suffered the fallout from that same shot.

The Shell: Five Hundred Million Years of Inspired Design, by Hugh and Marguerite Stix and R. Tucker Abbott. Photographs by H. Landshoff. Harry N. Abrams, Inc. ($25). The devoted collectors, the learned conchologist and the talented photographer who share the credit for this beautiful book have powerful silent partners: the unnamed Japanese craftsmen who designed, printed and bound it. There are some 200 illustrations, 82 in full color and tipped in by hand. They display the desirable marine shells of the world, some larger than life. Each species has its capsule description, and the book is gracefully introduced with an account of the role of the shell in human imagination since the time of Tyre and before. Here is the shell in art, in architecture, in modern industrial iconography. There is a quite unfamiliar painting by Odilon Redon of the birth of Venus, not out of a scallop but stunningly out of an enfolding shell. A white fluted whorl called the noble wentletrap, enlarged four times in a brilliant black-and-white print, will stand for the entire tasteful collection, aimed at the eye and the imagination alike. It is too bad that not one diagram or measurement is given to place before the reader the elegant mathematics of the shell, so essential to its deepest beauty.

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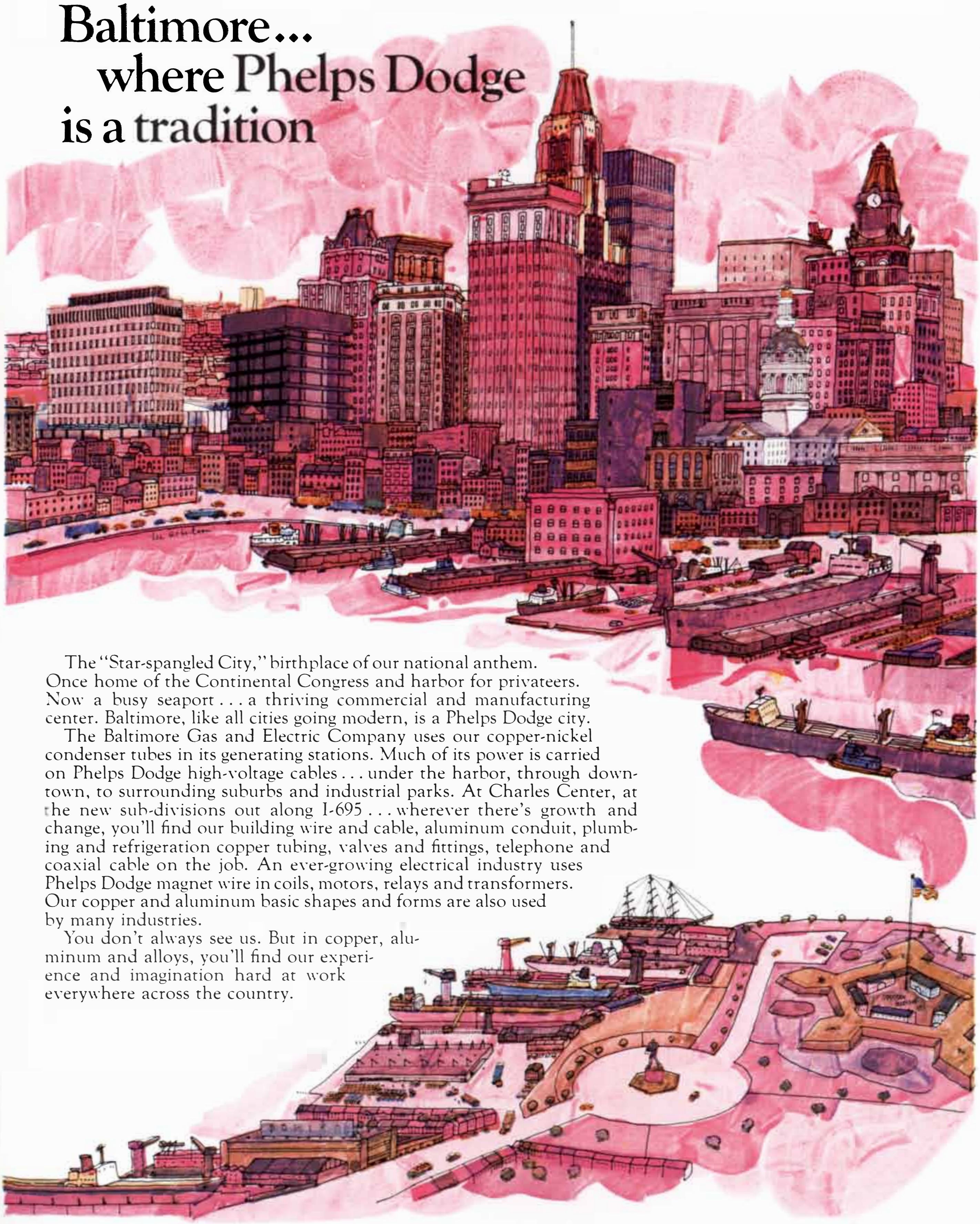

The "Star-spangled City," birthplace of our national anthem. Once home of the Continental Congress and harbor for privateers. Now a busy seaport . . . a thriving commercial and manufacturing center. Baltimore, like all cities going modern, is a Phelps Dodge city.

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You don't always see us. But in copper, aluminum and alloys, you'll find our experience and imagination hard at work everywhere across the country.


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But what we look forward to now is seeing you someday without a stitch on.
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