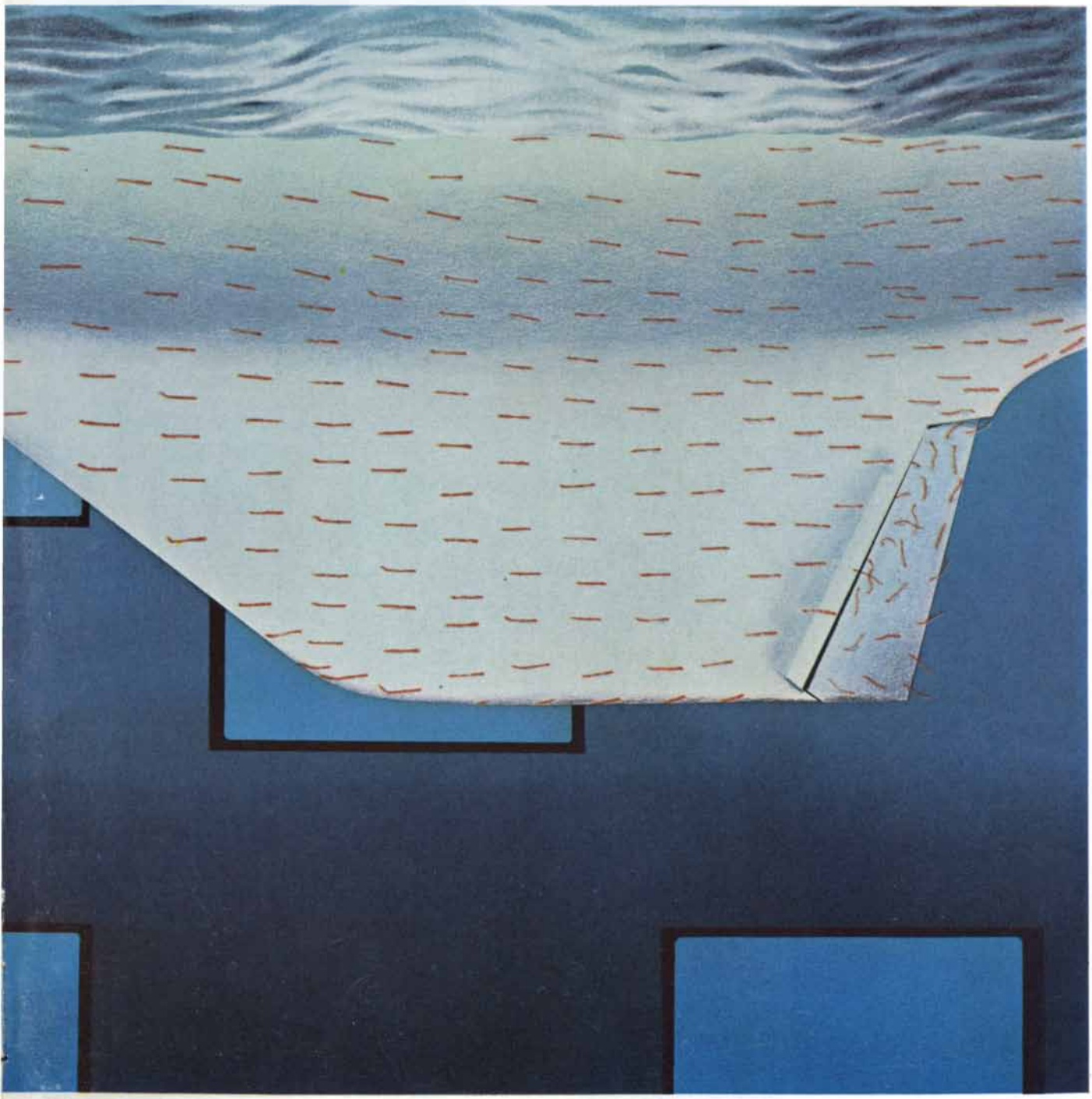
SCIENTIFIC AMERICAN



SAILING YACHT IN TANK

SIXTY CENTS

August 1966

Heat...cold...light...darkness...old enemies meet new defenses

A normally friendly environment can be decidedly hostile under certain conditions. Through M&T chemistry, there are defenses against a number of such situations.

Take high temperature. For melting steel, it's good. For ladle lining, it's bad. Causes failure. But not nearly so fast when linings are M&T zircon.

Freezing cold is good for preserving food. Bad for warm bodies and water pipes. By amazingly fast catalytic action, M&T organotin chemicals puff up urethane plastics into an insulating foam suitable for clothing interliners or pipe coverings.

Man couldn't survive without light. Clear vinyl plastics can't live *with* it (at least the ultra-violet part of it) unless stabilized. Nothing yet developed protects rigid vinyls against degradation from light and heat better than M&T organotin chemicals.

Darkness is good for sleeping. Not for seeing. When visibility is vital, as with instrument panels, electroluminescence is the answer. M&T tin chemicals are a key to this "cold light" that consumes little power.

In other ways and in other fields, M&T contributes to man's protection. Write M&T Chemicals Inc., General Offices, Rahway, N.J.... or M&T Products of Canada Ltd., Hamilton, Ont.

M&T Chemicals Inc.

Now aerospace designers can calculate fracture toughness of aluminum with new Alcoa data

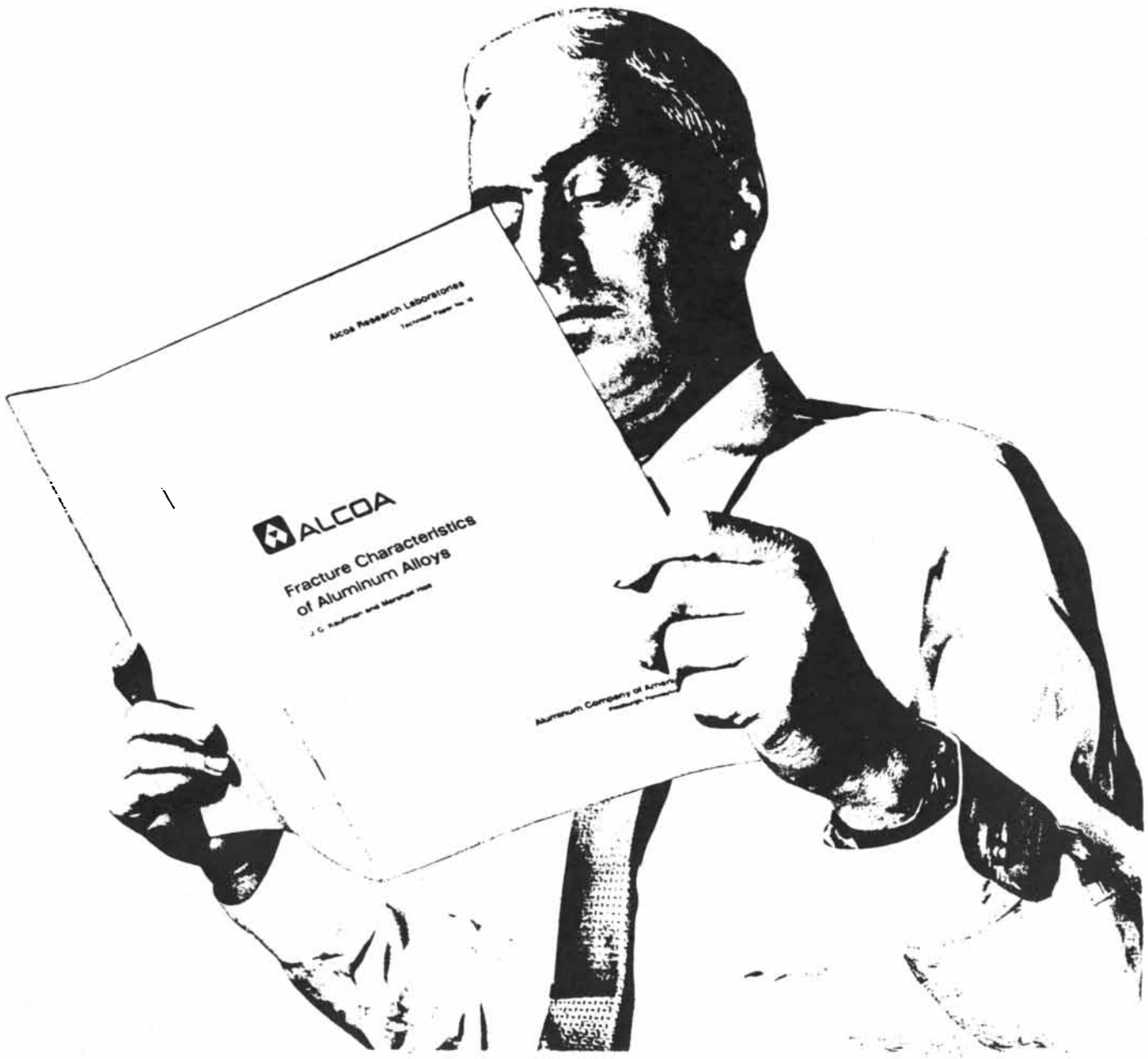
Consider a piece of high-strength aluminum alloy in elastic tension. What happens if a small shell fragment goes through it, or a fatigue crack appears? Whatever the cause, either a rapid fracture results, or it doesn't. The trick is to design aircraft and rockets that can sustain such damage, without designing in unnecessary weight—a difficult task with only qualitative information.

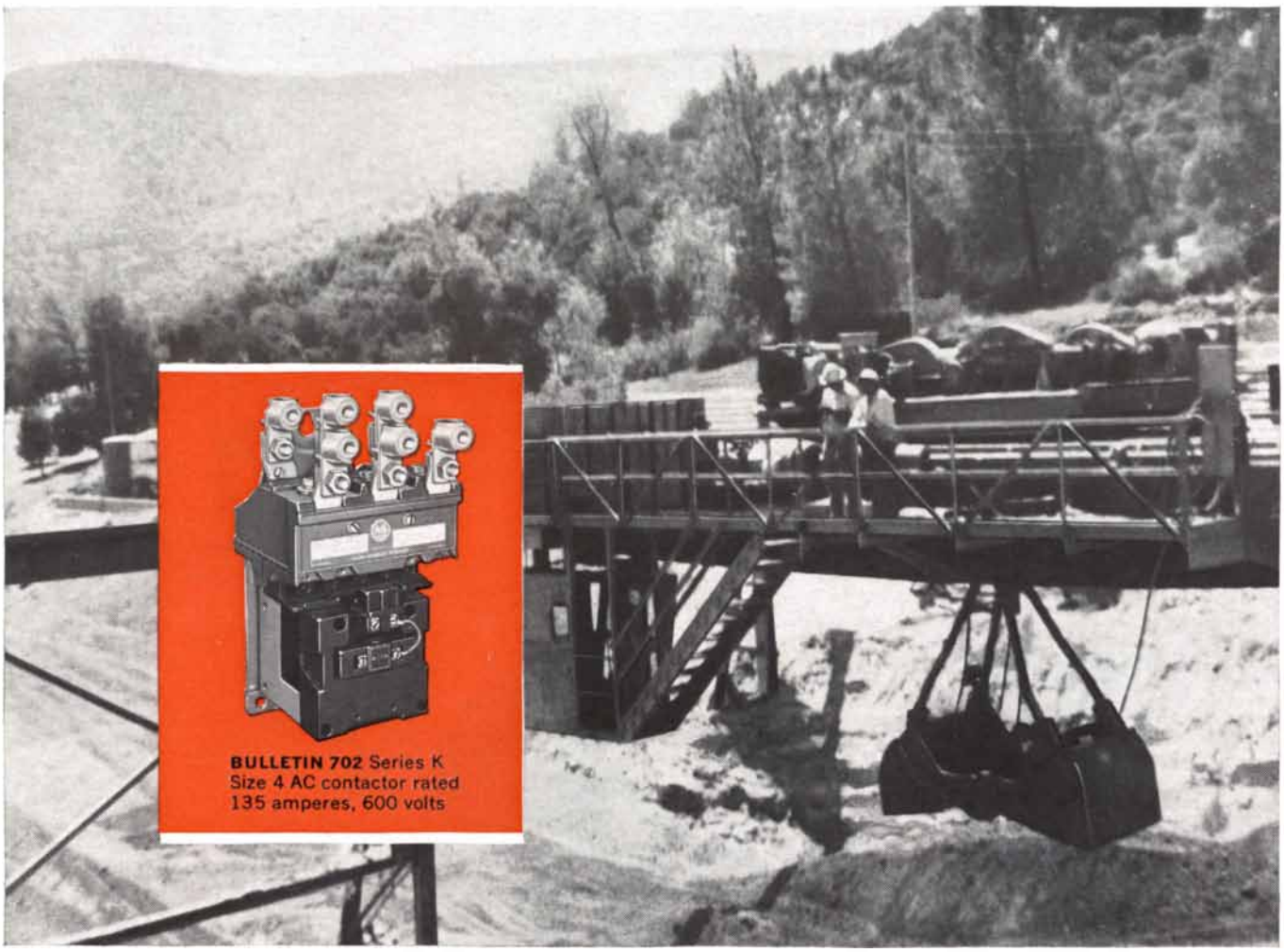
Now Alcoa Research Laboratories is providing engineers and designers with never-before-available quantitative data. Tables, graphs and procedures for calculating the fracture toughness of aluminum alloys are now available, along with criteria for selecting toughest alloys and tempers—the distillation of years of testing. Alcoa's new 48-page book evaluates 124 combinations of configuration, alloy and temper.

If you are working on light, high-strength structures, you should find this information useful. Write to Aluminum Company of America, 901-H Alcoa Building, Pittsburgh, Pa. 15219. Ask for Alcoa Research Laboratories' Technical Paper No. 18, *Fracture Characteristics of Aluminum Alloys* by J. G. Kaufman and Marshall Holt.

Change for the better with Alcoa® Aluminum

ALCOA





It is difficult to believe Allen-Bradley Series K controls can be so trouble free!

Here's an unusually demanding application for motor control, which, over the years, has taken its toll of equipment. This particular unit is the accelerating contactor for a bucket crane at a cement plant. There's frequent operation — several times a minute — round-the-clock duty, and extreme atmospheric contamination from cement dust.

What was the history of performance for the previous equipment? Several different makes were tried, and none lasted more than three months without a major overhaul. Then, an Allen-Bradley Bulletin 702 Series K contactor was put on the job, and here's how it compared with the other controls. At the end of the usual three months of service—when the best of other contactors had needed extensive maintenance—the Series K contactor was still operating like new. This round-the-clock operation continued for six months . . . nine months . . . a year . . . and still no maintenance! At the end of two years, and many millions of operations, the Series K contactor was giving the same dependable performance as the day it was installed—not even the contacts had been changed.

While this performance may be unusual for this type and size of equipment, it's not unusual at all for the Series K controls. They are regularly establishing records for long life and trouble free operation that would have been considered impossible only a few years ago.

Would you like to know more about the advantages built into all Series K controls that mean "extra value" in your day-to-day operations? If so, please contact your local Allen-Bradley appointed distributor—he's factory trained to give you full details on such Series K features as the simple solenoid design, weld-resistant contacts, pressure molded coil, and cushioned magnet, to name a few. Allen-Bradley Co., 1204 S. Third Street, Milwaukee, Wisconsin 53204. Export Office: 630 Third Avenue, New York, New York, U.S.A. 10017.

A-B QUALITY

ALLEN-BRADLEY

Member of NEMA

QUALITY MOTOR CONTROL

865-2B

Established 1845 **SCIENTIFIC AMERICAN** August 1966 Volume 215 Number 2

ARTICLES

DEPARTMENTS

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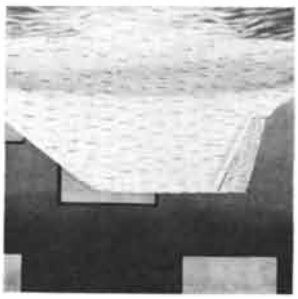

THE COVER

The painting on the cover shows the hull of the *Antiope*, a sailing yacht of the International 5.5-Meter Class, undergoing tests in the flow-observation channel of the U.S. Navy's David Taylor Model Basin near Washington (see "The Study of Sailing Yachts," page 60). Normally the basin is used for testing scale models of naval vessels; the experiments with the *Antiope* were the first with a full-scale sailing yacht and provided a basis for comparing the performance of the yacht with that of scale models. In a flow tank the hull remains stationary while water is propelled past it; observers can watch from below the hull's waterline by means of viewing ports, some of which are visible in the painting. The *Antiope*'s hull was painted white on one side so that it would show up clearly in photographs. Strips of nylon yarn were attached to the hull as flow indicators. The painting depicts a test in which the rudder has been turned sharply. The flow indicators on the rudder show a pronounced stalling effect as a result.

THE ILLUSTRATIONS

Cover painting by Jerome Kühl

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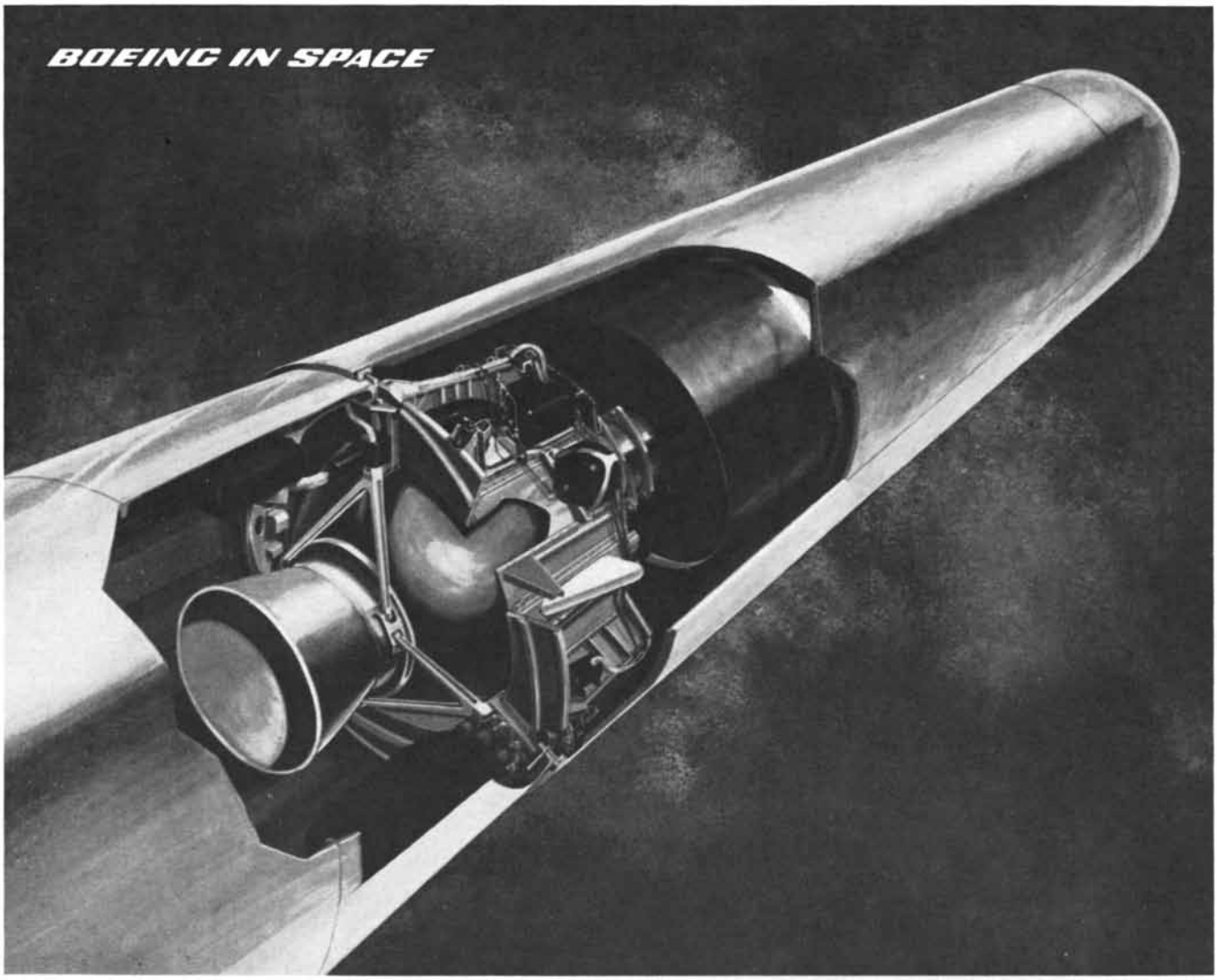
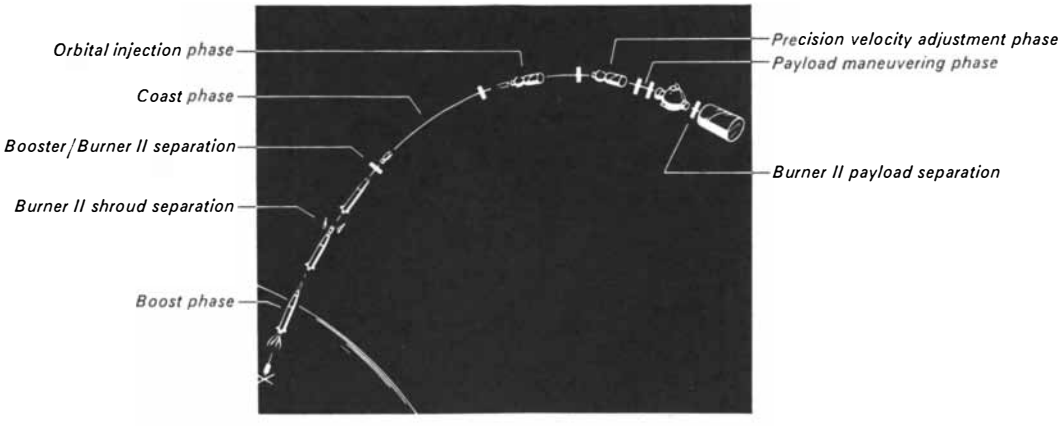


New Burner II is the first solid-fuel upper stage with full control and guidance capability developed for general space applications. Designed and built by Boeing for the U.S. Air Force Space Systems Division, Burner II will provide the final "kick" for placing small-to-medium payloads into precise orbits. It will be able to push its payload to the exact speeds required for specific earth-orbit or earth-escape missions. By filling the payload gap between the small Scout launch vehicle and the more complex liquid upper stages, Burner II can effectively lower launch costs.

Designed specifically as the second stage on the Thor booster, versatile Burner II can be used as the upper stage on the complete range of standard launch vehicles, from Thor through Titan III. **BOEING SPACE DIVISION**

Burner II



LETTERS

Sirs:

Readers of the article "River Meanders," by Luna B. Leopold and W. B. Langbein [SCIENTIFIC AMERICAN, June], might be interested to know that on January 7, 1926, a lecture was delivered to the Prussian Academy entitled "The Cause of the Formation of Meanders in the Courses of Rivers and of the So-called Baer's Law." This address was published in *Die Naturwissenschaften*, Volume 14. The author was Albert Einstein.

R. J. GREET

Mellon Institute
Pittsburgh, Pa.

Sirs:

Robert P. Ambroggi's article "Water under the Sahara" [SCIENTIFIC AMERICAN, May] is a much needed appeal for intelligent regional groundwater management. It is also an exciting look into the future potential of groundwater as a factor in the world's economic development.

Dr. Ambroggi's article caused great excitement here because it confirms in general some interesting observations made by aerial photography. For example, in the map on pages 22 and 23 the arrow and the "embayment" in the 100 contour in the United Arab Republic coincides with major solution features in limestones leading northward. It appears in this area that the Nile may lose some of its water to underground streams, apparently streams of some size because one particular sinkhole is more than 1,000 feet in diameter.

Similarly, a zone of vegetation that is extremely sparse but can nevertheless be seen in high-altitude photography delineates the Chad Basin trend as it passes into the Mediterranean from the southwestern corner of the U.A.R.

The loss of water into the sea should be emphasized and made a target for recovery. We have recently determined that certain narrow-spectral-band aerial film will distinguish freshwater springs offshore from the surrounding salt water. Attention to this would quickly lead to specific onshore sites designed to capture major groundwater flow of relatively high velocity. Specifically, this would be of benefit in Tunis, the U.A.R., Iran, Iraq, Libya and other countries in the Mediterranean basin. Elsewhere—in Spain, Hawaii and virtually all limestone and volcanic formations—it could also help. In the Canary Islands, for example, we estimate that at least 90 percent of the rainfall becomes groundwater, and that nearly all of it passes out to sea unused in an area that is dependent on water to maintain its economy.

DONALD J. BELCHER

Director
Center for Aerial Photographic Studies
Cornell University
Ithaca, N.Y.

ERRATUM

In the caption for the illustration on page 20 of the article "The Detection of Underground Explosions" (SCIENTIFIC AMERICAN, July) it is stated: "The explosion created a temporary cavity (*white dot*) 19.8 meters in diameter." The radius of the cavity is indicated not by the white dot but by the larger broken circle around it.

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If after all this time you still don't know what a Uniroyal is, we (the U.S. Rubber Co.) ought to be shot. Uniroyal is the new world-wide trademark of the U.S. Rubber Co. and it also replaces the dozens of different names and trademarks we've been using in 150 countries.

But—what's wrong with the good old-fashioned name of U.S. Rubber?

The answer is—we have neither been old-fashioned nor exclusively U.S. nor exclusively rubber for a very long time. Just look at some of the exciting non-rubber products we make:

Royalex,® a thermoplastic for auto and truck bodies which is not only harder to dent than steel but, if dented, pops back as good as new under heat. Sexy Eskiloos® boots for the ladies, and Keds,® the famous line of soft, colorful family shoes that are as easy to look at as they are to wear. Wet suits for aquanauts. Polycrest,® our new olefin fiber, that's more stain resistant than any other kind of carpet fiber alive. Alanap,® a smart weed killer for weeds that are too smart for other weed killers. SBR, a synthetic rubber (from which we make our Rain Tires™ and Tiger Paws ™) that's tougher, safer and longer-lasting than natural rubber.

Now you can see why we had to change our company's trademark—we needed a new trademark to better suit our derring-do. But we're never going to forget our forebear, the U.S. Rubber Company. Never! In fact, some of us here would feel a great deal better in our hearts if our new world trademark read, "Uniroyal, son of U.S. Rubber."

UNIROYAL
U.S. RUBBER

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

AUGUST, 1916: "The duration of the European war, the most stupendous conflict of nations the world has ever witnessed, is about to extend from the second into the third year of strife. The war is not yet ended, and the end is not yet in sight, but every indication points to a growing superiority of the Entente over the Teuton in men and all-important guns. The perspective of two years, combined with the mathematical probabilities of the future, lead to a constantly expressed opinion by military observers that the decisive battle of the war will not be told in history as marking the close of the war; it will be known as the Battle of the Marne, when the German plan to eliminate France at once failed signally."

"The present war has given new life to the enterprise of building a railway tunnel beneath the English Channel between Dover and Calais. Had the tunnel been in existence in 1914, the problem of conveying troops and supplies to the Continent would have been greatly simplified, and the burden laid upon the British navy in keeping open a channel ferry would have been lightened. There are growing indications that one of the first engineering works to be undertaken at the conclusion of peace will be the driving of this tunnel through the underlying chalk formation which exists in an unbroken stratum between the French and English coasts at this point."

"The flight of Antoine Marchal, an aviator in the French army, is unique in many ways. First of all, he captured the world's record for a non-stop flight by flying 807 miles, from Nancy to Chelm, in Russian Poland, by way of Berlin. His mount was a special weight-carrying Nieuport monoplane. Second, in passing over the German capital he released large numbers of proclamations, which, it is perhaps needless to state, were far more influential than if he had dropped explosive bombs, resulting in great loss of life in the crowded city. His capture when within 60 miles of the Russian lines must have been a great blow to the aviator, who after landing to change two of the spark plugs of the engine discovered two more plugs that needed changing. It was while changing the latter that he was captured by Austrian soldiers."

"A recent paper by M. Baldet discusses the helical filaments observed by M. Quénisset and himself in the tail of Morehouse's comet. He was struck by the resemblance in form between these filaments and the trajectories of cathode rays under the influence of a magnetic field. He was thus led to believe that the rarefied gases of the comet's tail were the seat of cathodic discharges influenced by a magnetic field, and he undertook to determine the intensity of this field, as deduced from the curvature of the filaments, according to a well-known formula. The intensity of the field as determined is very small, something like a hundred-millionth of that of the earth's magnetic field."

Scientific American.

AUGUST, 1866: "After four trials, involving an expense of not less than $3,000,000, the great work of successfully laying a submarine telegraph between Europe and America is accomplished, and on July 29th the New York dailies were by its means furnished with news from central Europe only 30 hours old. The cable of 1858 indisputably worked, but in an unsatisfactory manner and only for a short time. There is hope that this present line will prove to be a permanent service. If perseverance and determination ever deserved success, it is in this instance. The news will be a cause of rejoicing among all enlightened and intelligent people."

"The published scale of prices of the Atlantic Telegraph Company shows that for a message of 20 words, including date and address of sender, the sum of £20 will be charged—which is equal to $150 American money at the present rate of gold. Further than that all figures must be written out, and they will be charged as words. Messages in cipher will be double the above rates. Vast amounts of money have been invested and sunk in laying the cable, and its permanency is at least uncertain, but it does not seem to us judicious to attempt to get *all* the money back this summer. There are not many journals or firms that can afford to have regular messages of any length, and under the circumstances the news transmitted would be scanty and indefinite. Heavy rates defeat the end and aim of such enterprises, which are to be a popular medium for the transaction of business. The cable, however, is not indispensable; steamships cross in nine days—from land to land in much less time—and except in cases of great urgency the capacity of the line will not be taxed to its utmost, unless the tariff of charges be considerably reduced. Doubtless the competition of the Collins Overland Telegraph will have a healthy effect and aid materially in lowering the price."

"The East Indian budget, just laid before the British Parliament by Lord Cranborne, presents some curious facts relating to the opium trade as a source of revenue. The gross revenue of the Government for the years 1864–5 amounted to £47,041,000, showing a small surplus beyond expenditures, owing to the unexpected receipts from the customs tax on opium. In this item there is a large gain over the previous year, which yielded £7,361,000, the increase being £1,277,000. These amounts are paid wholly by the Chinese, by whom the drug is consumed."

"The National Academy of Sciences has just held a session of five days at Northampton, Mass. A large number of the most distinguished scientists of the country were in attendance, and the proceedings were of a most satisfactory character to those attending. Speaking of the labors of the Academy, the reporter for the *Tribune* says that 'Professor Bache, the President, was in such intimate relations with the Government and Mr. Lincoln set so high a value upon his services that a Cabinet meeting was held in his office every week during the war. It was Professor Bache who made the Academy especially valuable to the Government. By his vast labors during the war Professor Bache was entirely broken down and for the last year has been utterly unable to work. It is to be most ardently hoped that he may soon recover and resume his great usefulness to the country and to science. Of the immediate usefulness of the Academy to the country there is sufficient evidence in the fact that the annual report shows that the Government has referred to the Academy for reports on a wide range of subjects.' "

Report from

BELL LABORATORIES

Superfluidity and superconductivity: a common origin

In 1962 B. D. Josephson of Cambridge University suggested that if a voltage were maintained between two pieces of superconductor joined by a thin dielectric layer, the matter waves in each piece of the superconductor would oscillate coherently, at frequencies differing by an amount proportional to the voltage between them.

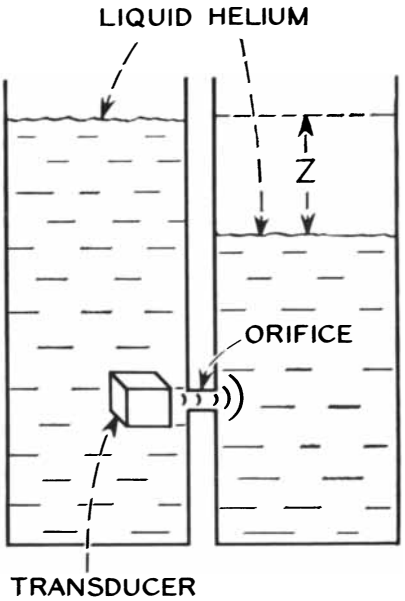
This led P. W. Anderson and P. L. Richards at Bell Telephone Laboratories to reason as follows: if, as many scientists believe, superfluidity has the same matter-wave origin as superconductivity, it should be possible to perform an analogous superfluidity experiment. In this case, oscillation would take place at ultrasonic frequencies and would be proportional to the difference in height of two columns of superfluid, joined by a tiny orifice (see diagram and graph). Their success with these experiments strongly confirms the similarity between the two phenomena.

Theory predicts that the matter waves in each column are coherent (in phase) but that the wave frequency in one column differs from that in the other by an amount proportional to the height difference. The difference frequency is evidenced by an alternating flow through the orifice, superimposed on the overall steady flow from the high to the low column.

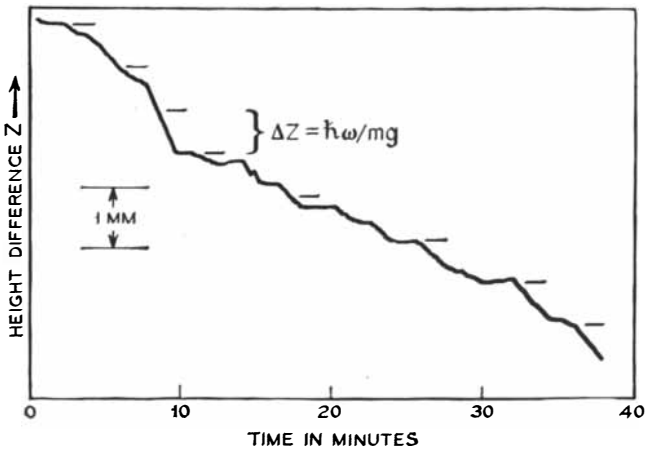
Anderson and Richards detect this alternating flow by locating a small transducer near the orifice and operating it at constant frequency. As the liquid levels gradually equalize, the height-determined difference frequency successively equals a number of simple multiples of the transducer frequency. At each of these points, the steady flow is strongly affected or may even cease briefly.

Bell Telephone Laboratories
Research and Development Unit of the Bell System

P. W. Anderson, left, and P. L. Richards with apparatus used in superfluidity experiment.



Height difference between two columns of superfluid helium is analogous to voltage difference between superconductors. A superfluid would normally flow smoothly and rapidly through the 15-micron diameter orifice. In the Anderson-Richards experiment, however, flow proceeded in steps (illustration below).



The two columns of superfluid helium begin at different heights (ordinate of graph). When the ultrasonic oscillator (69.3 KHz) is turned on, the two heights equalize in steps, as shown. The explanation is that the frequency of matter waves within superfluid helium changes with changing difference in heights of the two columns. Changing frequency results in a series of matter frequencies that are integral multiples and submultiples of the frequency of the ultrasonic waves impressed on the orifice. As a result, helium is periodically impeded as it flows from the high- to low-level column. The results are summarized by the quantum rule shown on the graph where Z is the height difference, $\hbar$ is Planck's constant over 2π, ω is frequency, m is the mass of the helium atom, and g is the gravitational acceleration.

THE AUTHORS

SCOTT McVAY ("The Last of the Great Whales") is assistant to the president of Princeton University. Following his graduation from Princeton in 1955 he worked for three years in Berlin as a civilian with Army Intelligence. Then he spent nearly five years as recording secretary of Princeton University and two years as assistant to the director of the Communication Research Institute in Miami. McVay was an English major in college and became interested in whales as a result of reading *Moby Dick*. He has spent much time in reading, correspondence and research on the subject; he writes that what troubles him most is "the prospect that the whales, possessing the largest brains on earth and gloriously unique in the scheme of living things, will be gone from the earth before man may be able to understand them."

RAYMOND BOWERS ("A Solid-State Source of Microwaves") is temporarily with the U.S. Office of Science and Technology while on leave of absence from Cornell University, where he is professor of physics. Born in London, he received his undergraduate degree from the University of London in 1948 and a doctorate in physics from the University of Oxford in 1951. Soon thereafter he took up research at the University of Chicago. In 1953 he joined the Westinghouse Research Laboratories and in 1960 he went to Cornell. Bowers has worked on several aspects of low-temperature physics and solid-state physics, including studies of liquid helium, semiconductors and metals. His current research interest is the study of plasma effects in solids; he was the author of an article on that subject in the November 1963 issue of SCIENTIFIC AMERICAN.

GEOFFREY BURBIDGE ("The Origin of Cosmic Rays") is professor of physics at the University of California at San Diego. His principal field is astrophysics, to which he turned from meson physics when he met and married an astronomer who was working at the University of London Observatory; Geoffrey and E. Margaret Burbidge have since often worked as a team. He received a doctorate from the University of London in 1951 and joined the Harvard College Observatory, while his wife became a fellow at the University of Chicago's Yerkes Observatory at Williams Bay, Wis. In 1953 they returned to England, where he worked in the Cavendish Laboratory of the University of Cambridge. After they came back to the U.S. in 1955 Burbidge successively held appointments at the Mount Wilson and Palomar Observatories and the University of Chicago before taking his present position.

DAVID M. SPAIN ("Atherosclerosis") is director of the department of pathology at the Brookdale Hospital Center in Brooklyn, N.Y. Among the positions he has held since receiving his medical degree from the University of Maryland School of Medicine in 1936 are assistant and associate professor of pathology at the Columbia University College of Physicians and Surgeons from 1943 to 1960, clinical professor of pathology at the Downstate Medical Center of the State University of New York since 1960, director of the pathology department in the chest diseases division of Bellevue Hospital in New York City and director of the department of laboratories and research of Westchester County in New York. He writes that he "became aware of the magnitude of the problem of atherosclerosis, particularly in younger individuals," in 1949 during his work in Westchester County, when his responsibilities included examining all sudden deaths in the county.

HALSEY C. HERRESHOFF and J. N. NEWMAN ("The Study of Sailing Yachts") both do research in naval architecture and each became interested in the subject largely as a result of a childhood spent sailing on the New England coast. Herreshoff, who represents the third generation of a family that is well known for the design and construction of yachts, received his undergraduate training at the Webb Institute of Naval Architecture and obtained a master's degree at the Massachusetts Institute of Technology. He is in charge of the yacht-research program at M.I.T. Newman, who studied naval architecture as an undergraduate at M.I.T. and received a doctorate in theoretical hydromechanics there, also studied hydrodynamics at the University of Cambridge. Since 1959 he has been at the U.S. Navy's David Taylor Model Basin near Washington.

R. G. EDWARDS ("Mammalian Eggs in the Laboratory") is a research fellow in the physiological laboratory at the University of Cambridge. After graduation from the University College of North Wales he obtained a Ph.D. at the University of Edinburgh, where he began research on embryological and endocrinological genetics in mammals. He left Edinburgh in 1957 to work for a year at the California Institute of Technology, spent five years at the National Institute for Medical Research in London and went to the University of Cambridge in 1963. At intervals he has also worked at the University of Glasgow and at Johns Hopkins University. This summer he is carrying on his research activities at the University of North Carolina School of Medicine.

DANIEL E. BERLYNE ("Conflict and Arousal") is professor of psychology at the University of Toronto. Born in England, he took bachelor's and master's degrees at the University of Cambridge and a doctorate in experimental psychology at Yale University. Since 1948, when he began teaching and research, he has been associated with the University of St. Andrews, Brooklyn College, the University of Aberdeen, the University of California at Berkeley, the National Institute of Mental Health and Boston University. He went to the University of Toronto in 1962. Berlyne's principal research interests are motivation and the theory of behavior.

LAWRENCE BADASH ("How the 'Newer Alchemy' Was Received") is assistant professor of history at the University of California at Santa Barbara. He took an undergraduate degree in physics at the Rensselaer Polytechnic Institute in 1956, spent three years as a Navy flier and then went to Yale University, where he received a doctorate in the history of science in 1964. He taught at Yale for a year and spent the next academic year on leave from the university as a postdoctoral fellow in Cambridge, England, where he examined the large collection of Lord Rutherford's papers and interviewed many of the physicist's former students. He also examined the manuscripts left by other early workers in the field of radioactivity. He plans to write a history of the development of radioactivity based on these studies.

FRANK A. BEACH, who in this issue reviews *Human Sexual Response*, by William H. Masters and Virginia E. Johnson, is professor of psychology at the University of California at Berkeley.

How do you measure the "wiggle" in a blast-off?

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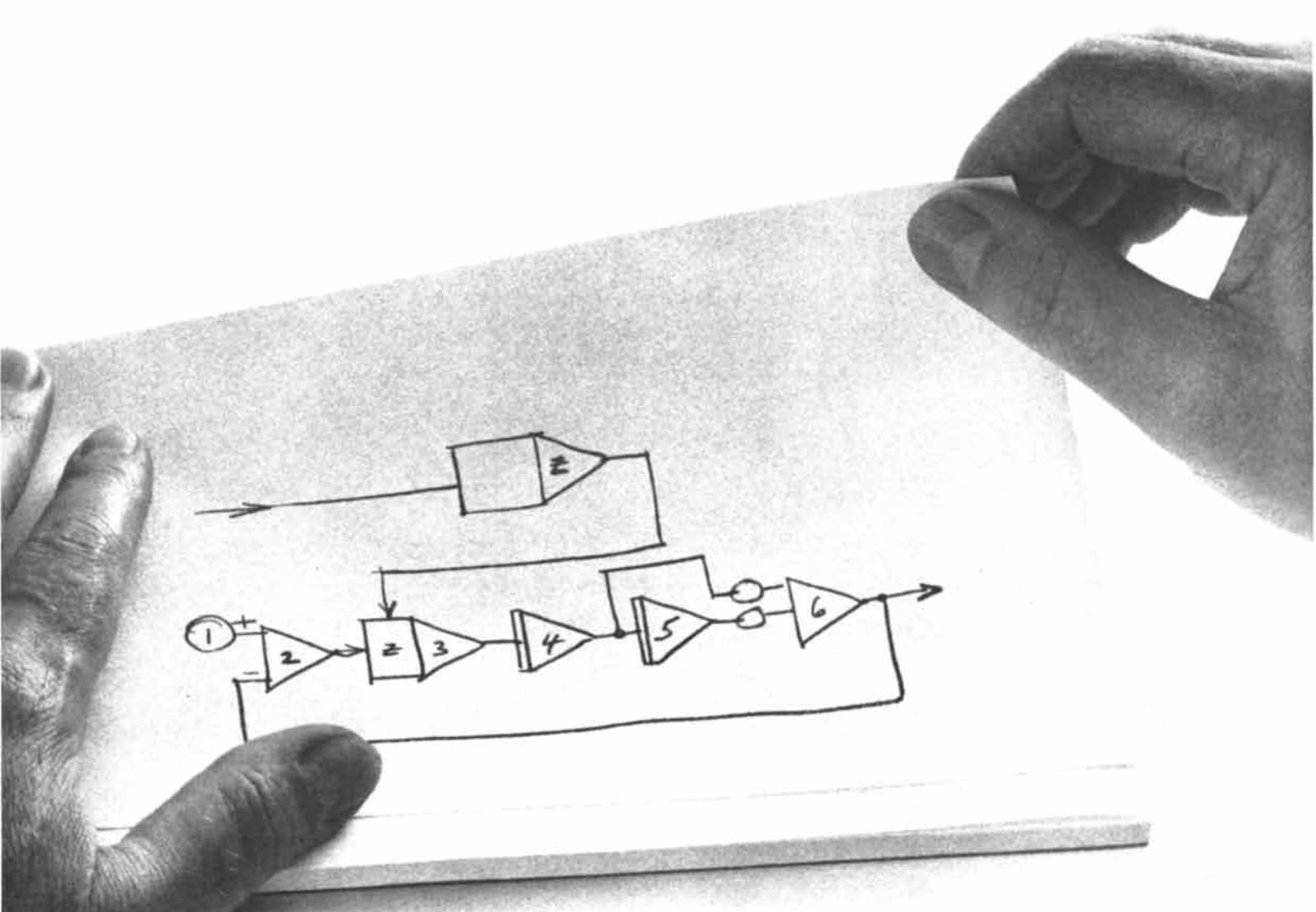

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The Last of the Great Whales

After bringing two species of great whales in the Antarctic to the verge of extinction and badly overhunting two others, the whaling industry is now endangering the last abundant species in the world

by Scott McVay

The order Cetacea—the whales—consists of more than 100 species. The 12 largest either were in the past or are now commercially important to man. At one time their oil was valued as a lamp fuel and a high-grade lubricant. Today most whale oil is made into margarine and soap, some whale meat is eaten and the rest of the animal is utilized as feed for domestic animals and fertilizer. Whale hunting is profitable, and as a result a majority of the 12 commercially hunted species have been all but exterminated. In the 18th and 19th centuries the whaling vessels of a dozen nations sailed all the oceans in pursuit of five species of whales. In that period four of the five were hunted almost to the point of extinction; the complete disappearance of these whales during the age of sail was probably prevented only by a slump in the demand for whale oil late in the 19th century. With the age of steam another seven species (which were unsuitable as quarry in the previous era) became the hunted. These species are now also in danger of extinction. It is the purpose of this article to trace the circumstances that have allowed this sorry episode to be repeated in so short a time.

The ultimate fate of the great whales has been a question for more than a century. Herman Melville included such a query among the observations that make his *Moby Dick* an encyclopedia of whales and whaling: "Owing to the almost omniscient look-outs at the mastheads of the whale-ships, now penetrating even through Behring's straits, and into the remotest secret drawers and lockers of the world; and the thousand harpoons and lances darting along all the continental coasts; the moot point is, whether Leviathan can long endure so wide a chase, and so remorseless a havoc; whether he must not at last be exterminated from the waters." Melville's conclusion was that Leviathan could endure. This was not unreasonable at the time (1851), when whalers pursued whales in open boats and killed them with lances. The five species of whales that were hunted then included only one from the suborder Odontoceti, or toothed whales; this was the sperm whale (*Physeter catodon*). The other four were baleen whales, of the suborder Mysticeti. These were the bowhead (*Balaena mysticetus*), the two right whales (*Eubalaena glacialis* and *E. australis*) and a lesser cousin, the gray whale (*Eschrichtius glaucus*). All five were hunted because they do not swim too fast to be overtaken by oarsmen and because they float when they are dead.

The bowhead whale and the right whales suffered near extinction. Very few of these once abundant animals have been seen in the past decade. In May, 1963, for example, the Norwegian ship *Rossfjord* was steaming west of the Russian island Novaya Zemlya when a whale with "jaws [that] were extremely curved" was sighted. The event was duly noted in the *Norwegian Whaling Gazette* with the observation that the whale—clearly a right whale—belonged to "a species that the crew had not previously seen."

Today all four of these baleen whales (the gray, the bowhead and both right whales) are nominally protected by international agreement, although three right whales that were sighted in the Antarctic in the early 1960's were promptly killed and processed. Perhaps because of its gregarious way of life, the gray whale has managed a slow recovery from the pressure of hunting. An estimated 6,000 gray whales now migrate annually from the Arctic Ocean to their breeding grounds off the coast of Lower California [see "The Return of the Gray Whale," by Raymond M. Gilmore; SCIENTIFIC AMERICAN, January, 1955]. No one knows today how many (or how few) bowhead and right whales are still alive.

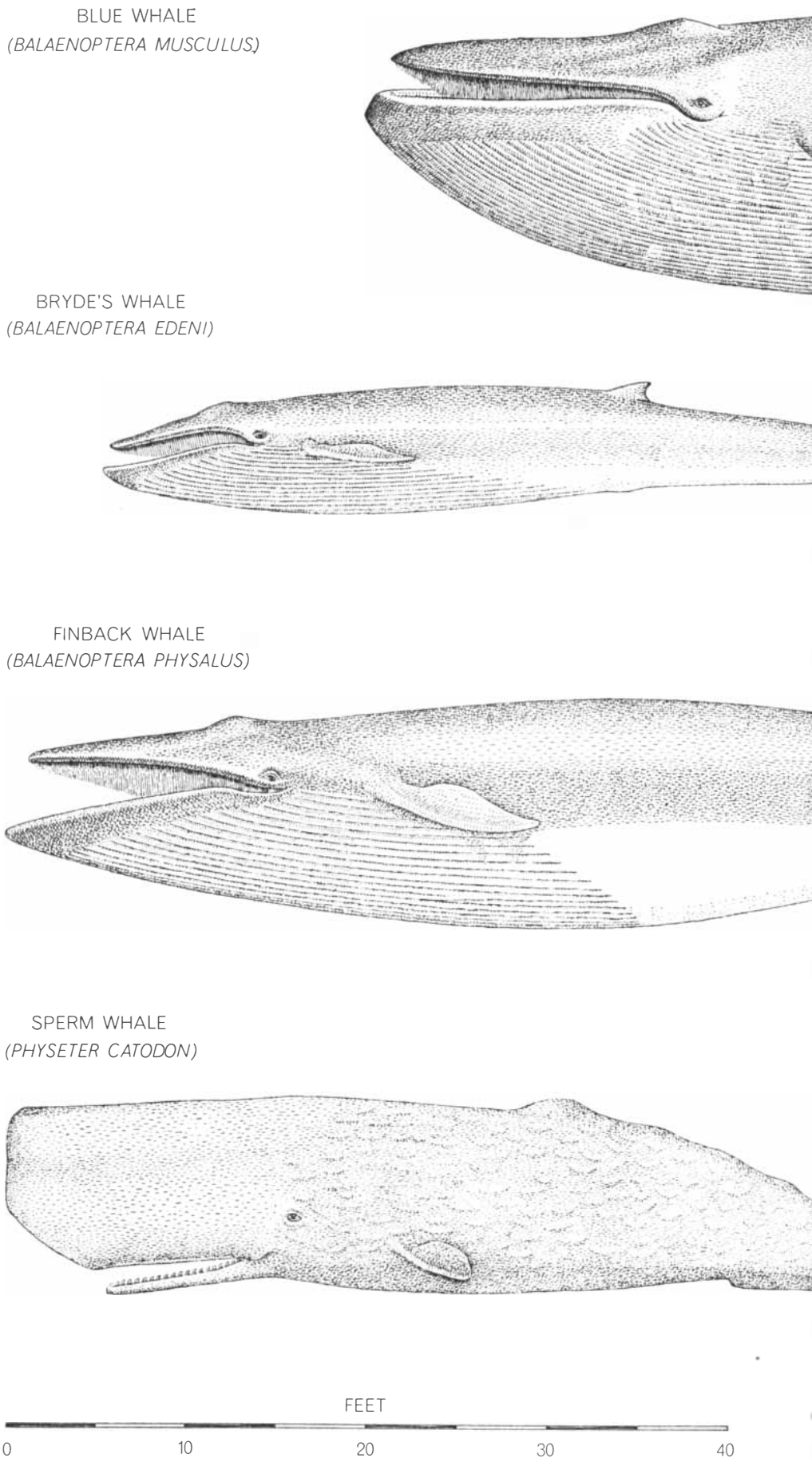
Of the eight great whales that are the quarry of modern whaling fleets, seven belong to the suborder of baleen whales and six of these to the genus *Balaenoptera* [*see illustration on next two pages*]. The largest of the six is the largest animal known to evolutionary history: the blue whale (*Balaenoptera musculus*). Weighing as much as 25 elephants and attaining a length of as much as 85 feet, this is the true Levi-

athan. It was known to Melville, who remarked that blue whales (he called them sulfur-bottoms) are seldom seen except in the remoter southern seas and are never chased because they can "run away with rope-walks of line." The modern catcher ship, armed with cannon-launched explosive harpoons, proved to be the blue whale's nemesis. Over the past 60 years antarctic waters have yielded more than 325,000 blue whales, with an aggregate weight in excess of 26 million tons [see "The Blue Whale," by Johan T. Ruud; SCIENTIFIC AMERICAN, December, 1956]. Even though the blue whale is now a rare animal, many of the statistics concerning baleen whales caught in the Antarctic continue to be reckoned in terms of "blue-whale units," as are the whaling nations' annual antarctic quotas.

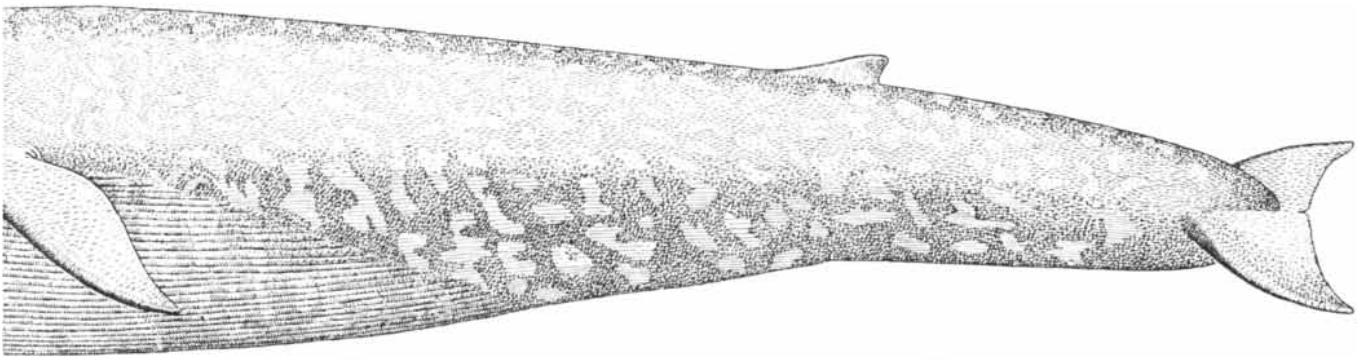
Five other baleen whales of commercial significance are the finback whale (*Balaenoptera physalus*), the sei whale (*B. borealis*) and three smaller whales: Bryde's whale (*B. edeni*) and the two minke whales (*B. acutorostrata* and *B. bonaerensis*). The finback averages little more than 65 feet in length and yields only 10 tons of oil, compared with the blue whale's 20 tons. Accordingly in terms of blue-whale units it takes two finbacks to equal one blue. The sei is slighter, averaging 55 feet in length. It is comparatively blubber-poor and meat-rich; six sei whales equal one blue-whale unit. Bryde's whale and the minkes, the first averaging 45 feet and the other two 30 feet, are not separately identified in whaling statistics. When taken, they are probably counted as sei whales; they will receive no further mention here.

The remaining baleen whale to be taken commercially is the small but oil-rich humpback whale (*Megaptera novaeangliae*). This animal is shorter than the sei, averaging about 45 feet, but it is so stocky that it yields some eight tons of oil. Two and a half humpbacks thus equal one blue-whale unit. The humpback has evidently never existed in large enough numbers to constitute a major whaling resource. Nonetheless, until recently some 1,000 humpbacks were taken each year.

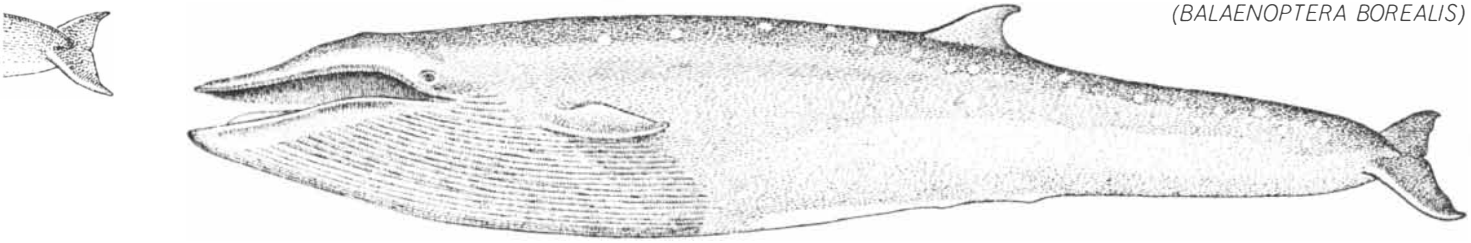
The eighth and last whale that is hunted today, surprisingly enough, is one that somehow escaped the near extermination that was the lot of the gray, bowhead and right whales in the days of sail. This is the sperm whale, which dives deep to hunt for squid along the ocean floor (its deepest-known dive is about 3,500 feet) and can remain sub-



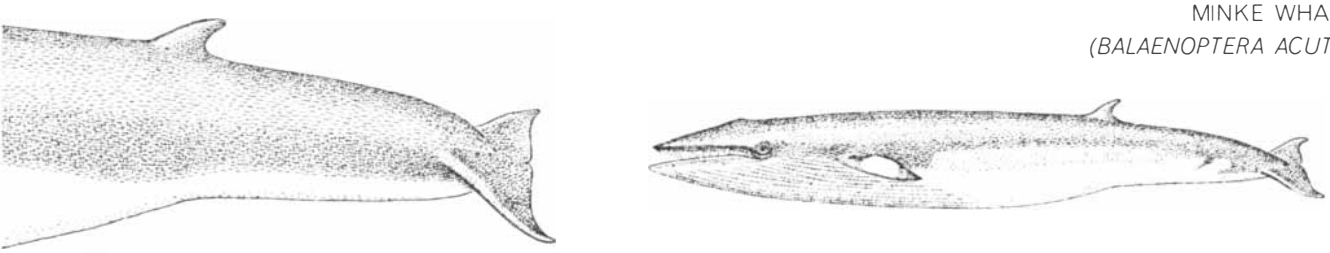
WHALERS' QUARRY TODAY consists mainly of animals of the baleen suborder; six of the seven species are illustrated above. The blue whale, the world's largest animal, is on the verge of extinction, as is the oil-rich humpback. The finback is seriously overhunted and the same fate is befalling the sei whale. Kills of Bryde's whale and two minke whale



SEI WHALE
(BALAENOPTERA BOREALIS)

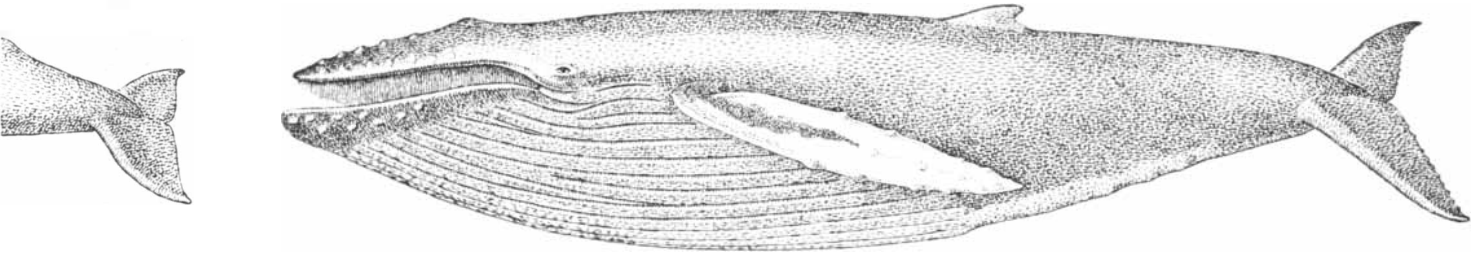


MINKE WHALE
(BALAENOPTERA ACUTOROSTRATA)



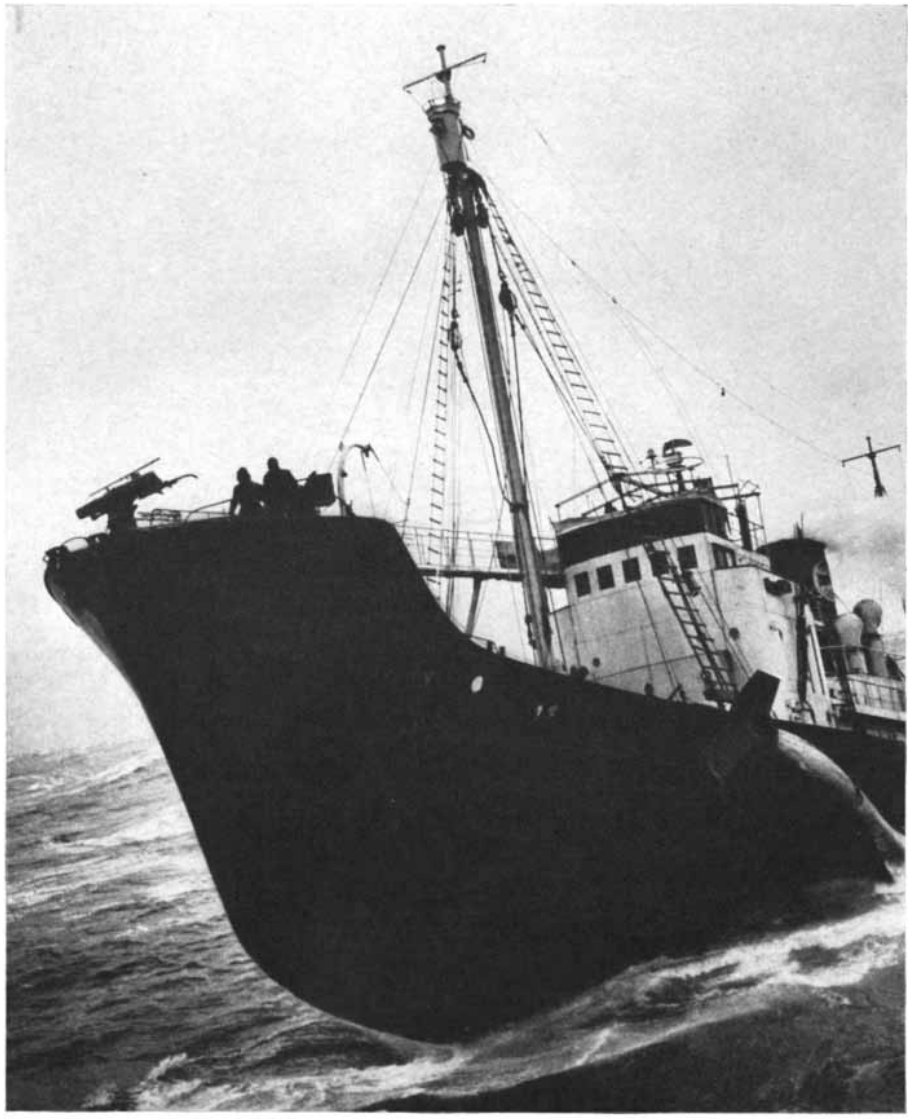
WHITE WHALE
(DELPHINAPTERUS LEUCAS)

NARWHAL
(MONODON MONOCEROS)



HUMPBACK WHALE
(MEGAPTERA NOVAEANGLIAE)

species (one of which is not illustrated) are not reported by name in the whaling statistics; they are probably counted as sei. As a result their present numbers are unknown. The toothed suborder of whales includes such familiar animals as the porpoises, the dolphins, the grampus, pothead and the true and false killer whales. Three of the toothed whales are illustrated. Only the largest, the sperm whale, is commercially valued and endangered by overhunting, although the narwhal and white whale are hunted occasionally.



CATCHER VESSEL pitches in a heavy antarctic swell. The stubby device seen silhouetted on the bow platform is the cannon that fires harpoons loaded with explosives. A dead whale, probably a finback, has had its flukes bobbed and is chained by its tail to the ship's side.

merged as long as 90 minutes. The sperm's huge square head contains the largest brain in the animal kingdom: it weighs more than 20 pounds. Sperm whales roam the mid-latitude oceans in groups that whalers call pods, including bulls, cows and calves. Once a year the mature bulls leave the pack and travel to antarctic waters for the summer months. As a result the whaling fleets have an opportunity to kill sperm bulls in the Antarctic and bulls and cows alike during the voyage to and from the fishery.

As the population of baleen whales in antarctic waters has dwindled, the whaling fleets have begun to spend more time in the North Pacific, where the primary quarry is the sperm whale. Every year since 1962 the industry has killed more sperm whales than whales of any other single species; the peak catch (in 1964) was more than 29,000. Sperm whales are not counted in terms of blue-whale units, and as yet there is no limit on the number that may be taken in any year. The only limitation is on the minimum size of sperm cow that may be killed. The bowhead and the right whales, on the other hand, are supposedly protected everywhere in the world, as are the humpback and the blue whales throughout the Pacific and the humpback south of the Equator around the world.

Before World War II whaling was a *laissez faire* enterprise. Then in the postwar epoch of international cooperation 17 interested nations entered into a convention designed to regulate the whaling industry. In December, 1946, the International Whaling Commission was established as an executive body to oversee the conservation and sensible utilization of the world's whale resources. The participating nations in the Western Hemisphere were Argentina, Brazil, Canada, Mexico, Panama and the U.S., although only Argentina and Panama were then active in the industry. (Both have since abandoned whaling.) Among the nations of Europe, Denmark, France, Britain, the Netherlands, Norway and the U.S.S.R. were signatories. So were Iceland, South Africa, Australia, New Zealand and Japan. At that time five nations operated factory ships and catcher fleets; today only Japan, Norway and the U.S.S.R. are major whaling nations. The Netherlands and Britain have abandoned their fleets, although the British continue their shore-based antarctic whaling enterprise (which is now conducted jointly with the Japanese) on the subantarctic island of South Georgia.

Since its activation in the fall of 1948 the International Whaling Commission has been charged with such tasks as protecting overexploited whale species, setting minimum-size limits below which various species may not be taken, setting maximum annual catch quotas for the antarctic fishery and designating areas closed to hunting. Although each commissioner is in principle responsible for his nation's observance of the commission's regulations, the commission itself unfortunately has neither inspection nor enforcement powers; any member nation can repudiate or simply ignore the commission's actions. Nonmember nations, of course, are equally unrestricted in their whaling activities. It calls for little political insight to forecast that recommendations made by the nonwhaling members of such a body will be ignored by the whaling members. What comes as a surprise is the fact that both the whaling and the nonwhaling nations on the commission were unresponsive to the significance of the whaling statistics that were presented to them each year during the 1950's.

In the years after World War II the waters of the Antarctic constituted the world's last great whaling ground. Record catches such as the one of 1930–1931 were never repeated, but up to 1950–1951 the whalers killed some 7,000 blue whales each season. The commission's annual quota for the antarctic fishery was 16,000 blue-whale units; the catch of finbacks (at the rate of two for each blue) helped to fulfill the quota. During this period about 18,000 finbacks were killed each season [*see bottom illustration on page 18*].

As the 1950's progressed, however, an ominous trend was evident. The blue whales were becoming scarce. The blue-whale kill, which totaled only about 5,000 in 1951–1952, fell below 2,000 in 1955–1956 and was down to 1,200 by 1958–1959. To counterbalance the declining catch of blues, the whalers pursued the finbacks more vigorously. By the end of the 1950's, 25,000 or more finbacks were being taken each season. Those familiar with patterns of predation could see that the blue whales were being fished out and were in need of immediate full protection. The finbacks in turn probably could not survive another decade like the preceding one, during which some 240,000 animals had been subtracted from the stock.

By 1960, in spite of continued indifference on the part of the whaling nations, the commission finally decided to undertake some fact-finding. A special three-man committee was assigned the task of assessing the antarctic whale populations, even though an expert as well-regarded as the Dutch cetologist E. J. Slijper declared that the danger of their extinction was "surely remote." The committee was also to recommend any actions necessary to maintain the fishery as a continuing resource. It was agreed that, to avoid bias, the three men should be neither citizens of any nation active in antarctic whaling nor experts on whales. Three specialists in the field of population dynamics were chosen: K. Radway Allen of New Zealand, Douglas G. Chapman of the U.S. and Sidney J. Holt. Although Holt is a British subject, he has the status of an international civil servant by virtue of his employment with the Food and Agriculture Organization of the United Nations. The three men were asked to report their findings to the commission at its annual meeting in 1963.

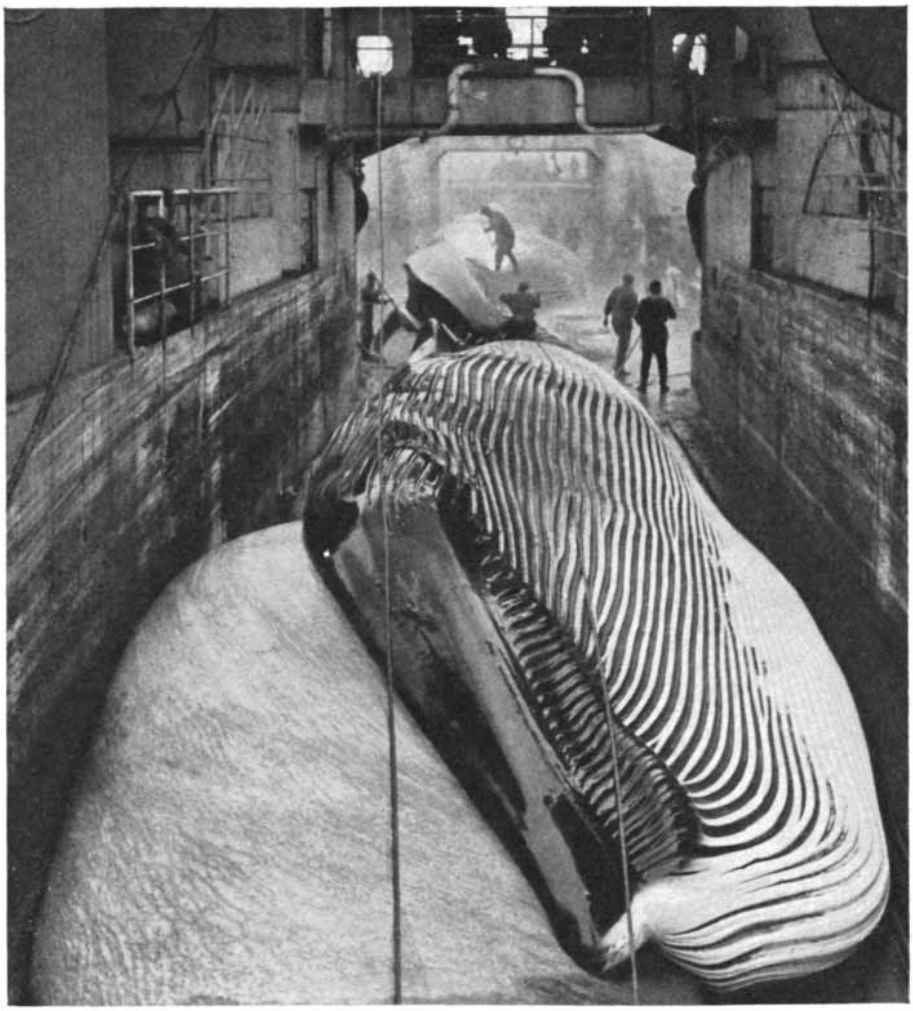
As the special committee set about its three-year job, the world's whaling fleets continued to kill whales indiscriminately in the antarctic fishery. For the first season following the appointment of the committee the International Whaling Commission failed to set any quota for the antarctic catch. The whaling industry took more than 16,000 units that season, as well as some 4,500 nonquota sperm whales. Within the 16,000 units the catch consisted of 1,740 blue whales (510 more than the previous season) and 27,374 finbacks (a record number for kills of that species). The industry also took 4,310 sei whales, 718 humpbacks and even two protected right whales that surfaced within range of the gunners.

During the second year of the committee's work the whaling industry did less well in the antarctic fishery. Once again the commission set no quota; the industry only managed to process 15,229 units. A few more sei and sperm whales were killed than during the previous season and another right whale was illegally shot. Among the whales that counted most—the blues and the finbacks—a larger number were immature and the numbers of both were diminishing.

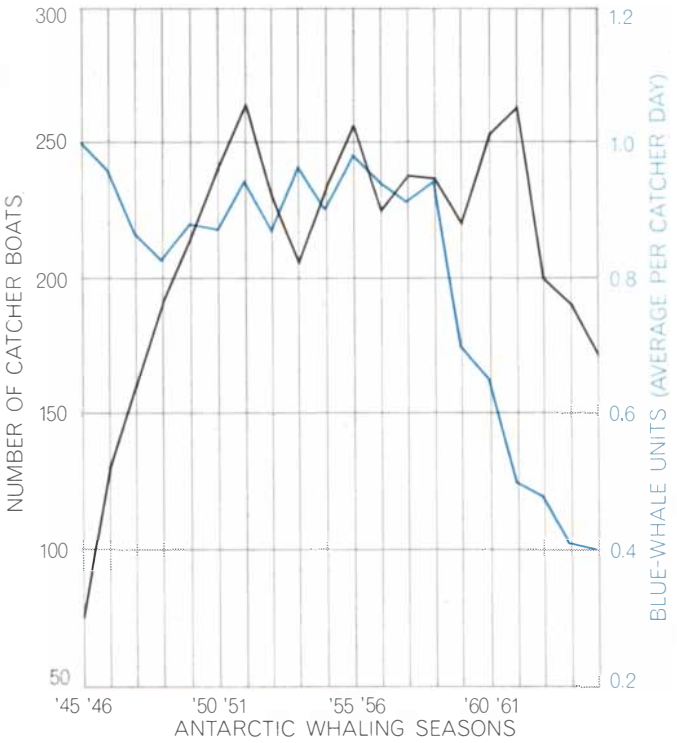
The final season before the committee's report was due (1962–1963) produced a similar record. The commission set a quota of 15,000 blue-whale units. There was a modest increase in the sei and sperm kill but a sharp decline in blue and finback kills. For the first time since World War II the kill of blues fell below 1,000.

In July, 1963, the commission met in London and the special committee presented its report. The committee stated that in the antarctic fishery both the blue whale and the humpback were in serious danger of extermination. It was estimated that no more than 1,950 blue whales—possibly as few as 650—still survived in antarctic waters. The committee also noted that overfishing had reduced the stock of finbacks to approximately 40,000, far below the population level required for a maximum yield. It was recommended that the taking of blues and humpbacks be immediately prohibited and that the annual kill of finbacks be limited to 5,000 or fewer. Elimination of the blue-whale-unit system of accounting and substitution of separate quotas for each whale species was also strongly recommended.

Finally the committee's three members gave the whaling industry a prediction with a clear practical meaning. They forecast that, if unrestricted whaling were permitted in the 1963–1964 season, the industry would not be able

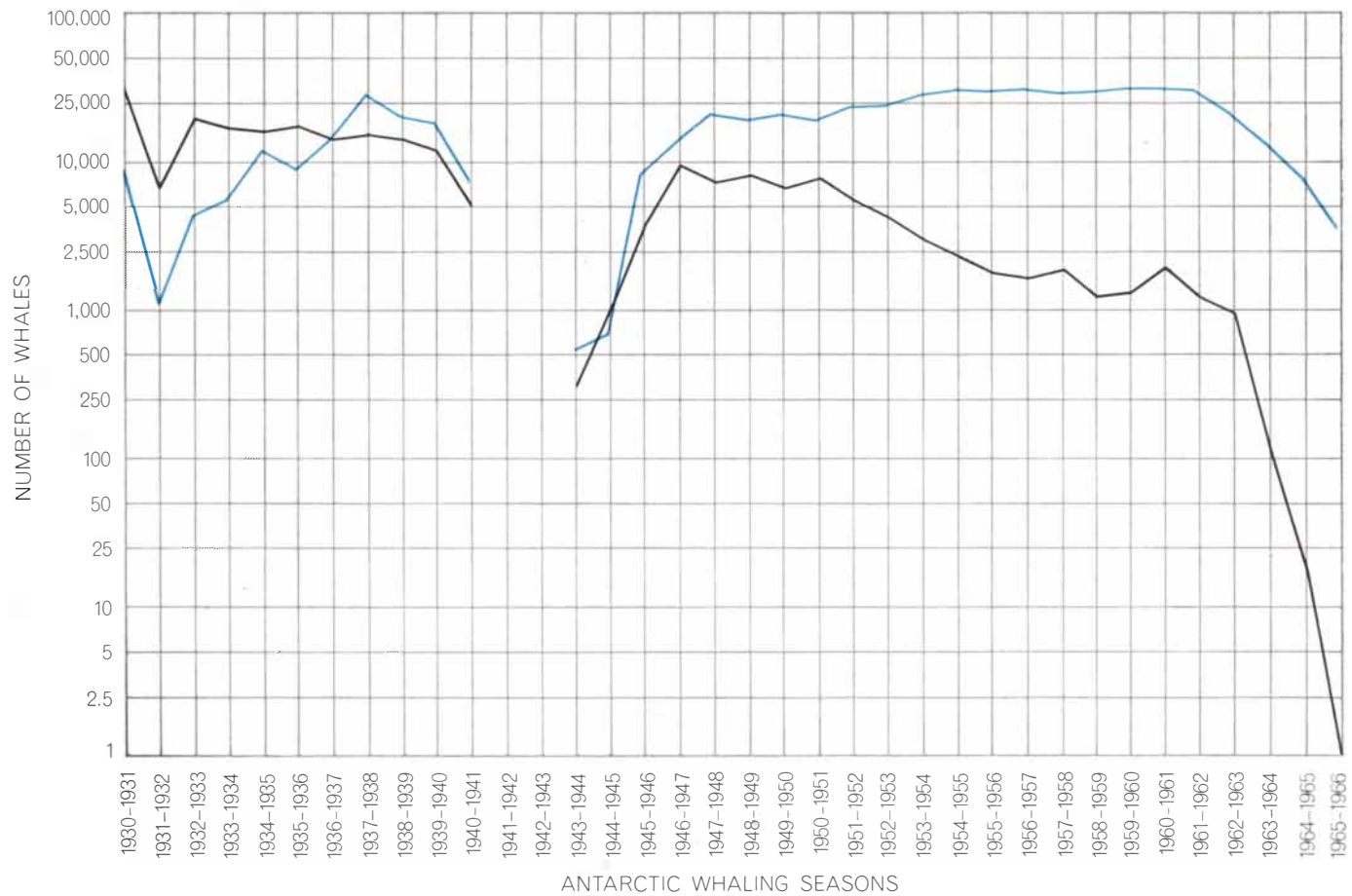


BLUE WHALE is winched from the sea up the stern ramp of a factory ship. Its tongue is grotesquely expanded by the action of air that was pumped into the corpse to keep it afloat. On the flensing deck (*rear*) another blue whale is having its blubber stripped for trying out.



PRODUCTIVITY of the antarctic fishery began a sharp decline in the late 1950's (*color*). The decline, measured in terms of the catch per catcher-day, continued unchecked into the early 1960's although the number of catcher vessels (*black*) remained well above 200.

NINE-SEASON RECORD of the average length of blue whales killed in the Antarctic shows a decline that began in the 1959–1960 season. The average mature female is 77 feet long and a mature male 74 feet. Evidently recent catches have included immature whales.



RISE AND FALL in the numbers of blue and finback whales that have been killed in the Antarctic during the past 36 years shows a correlation between the steadily diminishing blue-whale catch during the 1950's and an increase in the catch of finbacks (*color*). Just as the blue-whale stock dwindled away under the pressure of overhunting, the finback stock is now showing a severe decline.

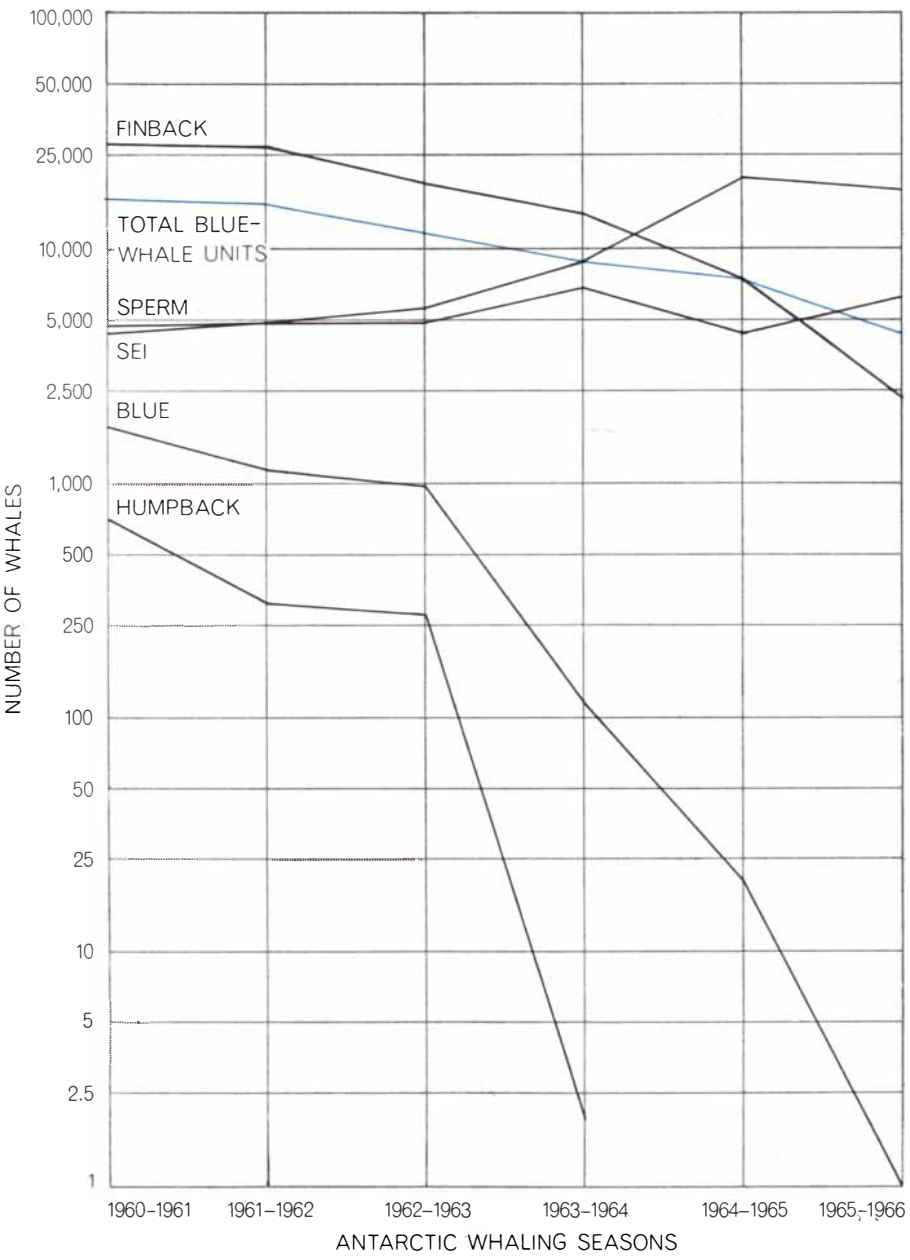
to harvest more than 8,500 blue-whale units and would slaughter 14,000 finbacks—nearly three times the recommended number—in the process.

The prediction was disregarded. The commission voted a 1963–1964 quota of 10,000 blue-whale units for the antarctic fishery on a motion by the Japanese commissioner that was seconded by the Russian commissioner. In view of the committee's predicted maximum catch this was in effect no quota at all.

As for the committee's other findings, the commission failed to act on some and was lukewarm toward others. In the case of the now economically insignificant humpback the commission could afford to be forthright; that whale was declared protected anywhere in the world south of the Equator. In the case of the blue whale a partial sanctuary was established in all waters south of 40 degrees south latitude except some 3.3 million square miles from 40 to 55 degrees south latitude and from the Greenwich meridian to 80 degrees east longitude. Japanese whalers had taken some 700 small blue whales in this zone during the 1962–1963 season; they considered it too good a hunting ground to be put out of bounds. The suggested elimination of the blue-whale unit and the establishment of species quotas were ignored. The commission added a fourth man (John A. Gulland of Great Britain) to the special committee and asked that a further report be presented in 1964. At that time it was intended to set the antarctic quota at a level in line with the committee's findings.

In 1963 a few members of the commission may have viewed with skepticism the ability of the three committee members to make accurate forecasts of a phenomenon as full of variables and unknowns as the effects of harvesting the antarctic whale stock. If so, the results of the 1963–1964 season settled their doubts. Sixteen factory ships and their catcher fleets worked the fishery; the industry's statistics, weighing such factors as the number of days each catcher was able to spend in hunting, showed that the total effort of the catchers was 91 percent of that during the season of 1962–1963. The number of blue whales killed, however, was the lowest of any season in the industry's history: a mere 112. The committee had predicted a total catch of 8,500 blue-whale units; the fleet managed to process 8,429 units. The committee had predicted that 14,000 finbacks would be killed; the finback toll came to 13,870. The committee's forecasts thus proved to be highly accurate.

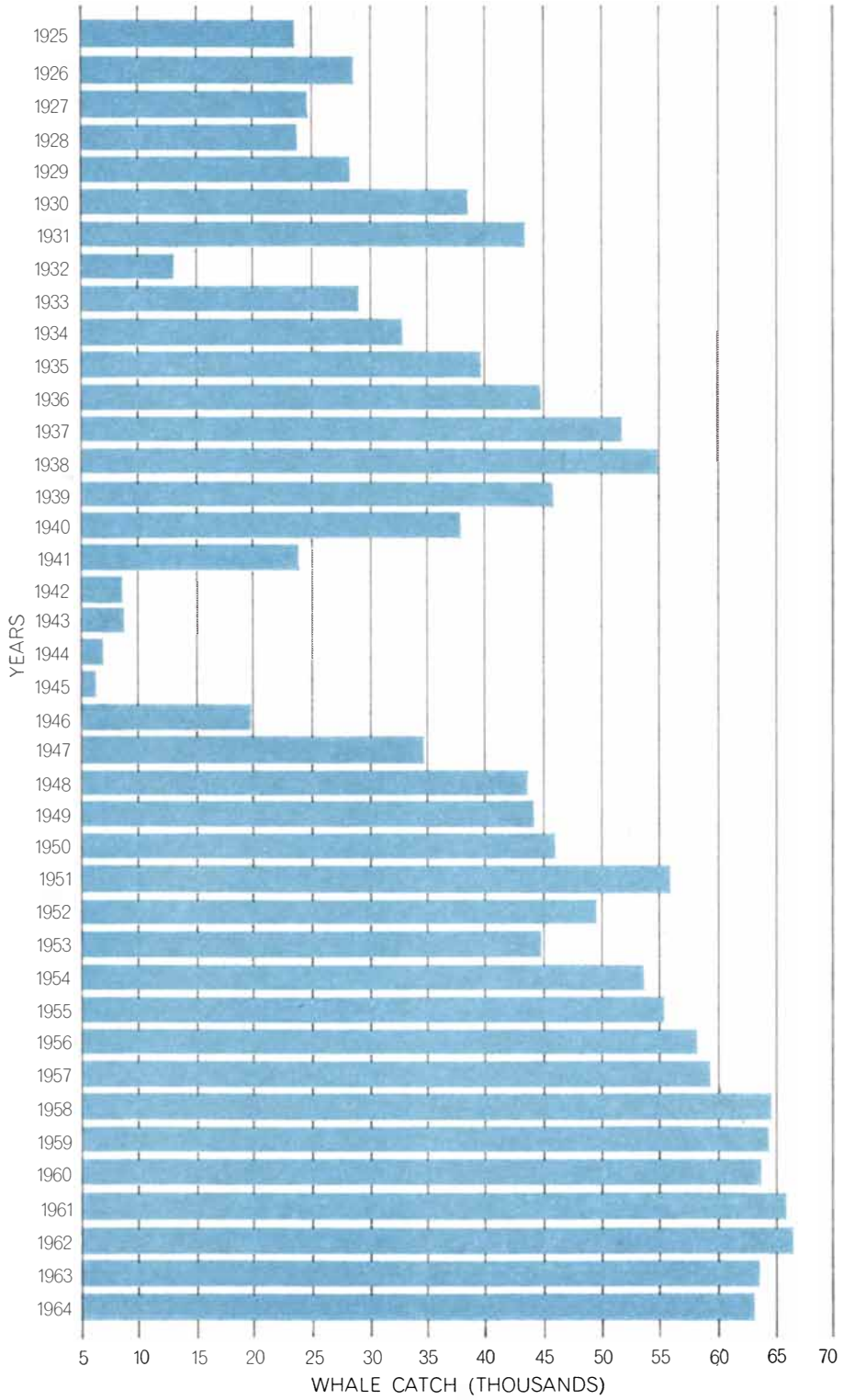
At the commission's 1964 meeting the enlarged committee added the sei whale, formerly the least prized of any in the antarctic fishery, to the list of the overhunted. The committee pointed out that the total sei population had probably never exceeded 60,000, yet more than 20,000 sei had been killed in the course of the four previous seasons. With a whale stock of reasonable size it is a rule of thumb that 10 to 15 percent of the population can be harvested annually without causing a decline. With the expectation that more and more sei whales would be killed each season as the finback population thinned out, the committee anticipated sei kills above the sustainable level in the immediate future. In line with the commission's declared intention of setting quotas according to the committee's findings, it was proposed that the antarctic quota be drastically reduced in three annual steps. A limit of 4,000 units was sought for the 1964–1965 season, a limit of 3,000 units for 1965–1966 and one of 2,000 units for 1966–1967. This degree of restraint, the population experts declared, was necessary merely to hold the number of whales in the Antarctic at the present level. They once more ap-



CATCH RECORDS for five species of whales killed in the Antarctic during the past six seasons show that increasing catches of sperm and sei whales have failed to counterbalance the decline in the fishery's productivity. The yield, calculated in blue-whale units (*color*), has dropped from 16,375 units in 1960–1961 to one-quarter of that amount in 1965–1966.

pealed—once more unsuccessfully—for the establishment of species quotas in place of the blue-whale-unit system.

Finally, a new gloomy statistic came before the commission: in 1963, for the first time since modern whaling had begun in the Antarctic, the larger part of the world catch had been taken in other waters. The most heavily fished area had been the North Pacific; most of the whales taken there had been sperm, which continued to be free of quota restrictions. The committee pointed out that this diversion of the industry's effort from the dwindling antarctic whale resource to the North Pacific could have ominous consequences for the sperm-whale stock.



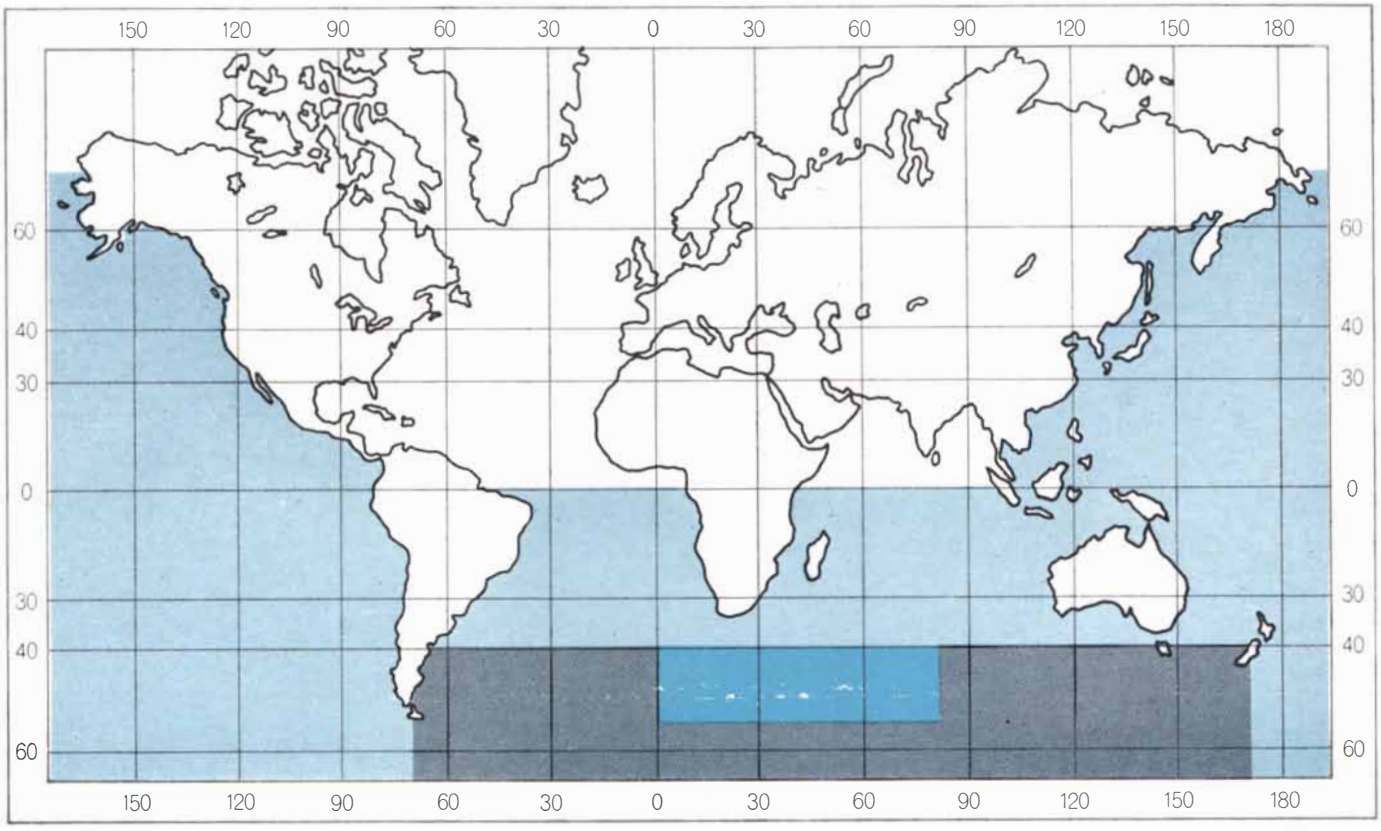
WORLDWIDE WHALE CATCH during the 40-year period through 1964 exceeded 1.6 million animals. The increase in numbers of whales taken from the 1950's on reflects the antarctic fishery's growing dependence first on finbacks in lieu of blue whales and next on sei whales in lieu of finbacks. From 1963 on the antarctic fishery has provided less than half of the world's whale catch. Figures are from Norway's Bureau of International Whaling Statistics.

The proposal for a reduced antarctic quota came to a vote in the commission. Japan, the U.S.S.R., Norway and the Netherlands all voted against it; in spite of the commission's declared intent to give substance to the committee's findings, the 1964 meeting adjourned with no commission quota set for the next antarctic season. The four whaling nations subsequently agreed in private that they would limit themselves to 8,000 blue-whale units in the 1964–1965 season, a figure twice the one recommended by the committee.

The 1964–1965 season was disastrous. The industry processed only 7,052 units, more than 10 percent short of its self-established quota. Only 20 blue whales were killed. The finback kill, declining for the fourth successive year, was 7,308 animals, or only a quarter of the 1960–1961 peak. As the committee had anticipated, the industry made up the difference by overkilling sei whales —almost 20,000 of them. In spite of this slaughter and a fairly large nonquota sperm-whale catch, the antarctic fishery for a second year supplied the industry with fewer whales than were taken in other waters.

For the first time since the beginning of the crisis the International Whaling Commission convened a special meeting. At this meeting (in May, 1965) the commission established a quota for the 1965–1966 antarctic season that reflected, at least in part, the committee's concern. The catch, even the whaling nations agreed, should not exceed 4,500 blue-whale units. At the regular June meeting that followed, the reduced quota was approved, and the commission agreed on a plan for further successive reductions of the antarctic fishery's quotas in the seasons to come.

The commission also attempted a first step toward partial protection of the world's sperm-whale stock. Up to that time the only restriction governing sperm kills was that cows less than 38 feet in length should not be taken. In 1964 the worldwide sperm catch had risen to a high of more than 29,000. The fleets en route to and from the Antarctic had killed 4,316 sperm whales. Once they were in the antarctic fishery they had taken 4,211 more; most of the rest had been killed in the North Pacific. In the hope of protecting sperm cows in Temperate Zone waters the commission ordered a worldwide hunting ban in the area between



REFUGE AREAS within which designated species of whales are safe from hunting by member nations of the International Whaling Commission have been expanded in recent years. The nearly extinct bowhead and right whales enjoy worldwide protection. The blue and humpback whales are protected throughout the Pacific. The humpback is also protected south of the Equator elsewhere in the world, but the blue whale's protection elsewhere is limited to a zone south of 40 degrees south latitude (*gray area*). Even within this zone of protection 3.3 million square miles of ocean were kept open for blue-whale hunting at the request of Japan until a year ago.

40 degrees north latitude and 40 degrees south latitude. All three whaling nations, however, objected to the commission's order; the ban has simply been ignored. The worldwide sperm catch in 1965 was somewhat lower than in 1964: future catch records will reveal whether or not this drop reflects overkilling.

The imperative need for a reduced antarctic quota was demonstrated clearly enough by the results of the 1965–1966 season. With a quota of 4,500 blue-whale units the antarctic fleets could process only 4,089 units. The finback kill reached a new low, less than 10 percent of the 1960–1961 peak; in spite of protection, one blue whale and one humpback were taken. Again it was the sei whales that bore the brunt of the slaughter, and even their numbers were less than in the previous season. The conclusion was inescapable: The antarctic fishery, with its seasonal yield down to less than 100,000 tons of oil, was no longer economically significant.

Can the antarctic whale fishery ever be restored? Even with the progressively reduced quotas now envisioned it may take 100 years before this resource recovers to the level of the middle 1950's. Recovery to the levels before World War II, which depended almost exclusively on the blue whale, is improbable. This giant mammal—one of the most remarkable ever to appear on the earth—has probably been reduced in numbers below the level that allows a species to survive; its worldwide population today may well be less than 1,000. Certainly there are 594 fewer blue whales this year than last. Whaling from land stations in Peru and Chile—two nations that are not parties to the international convention—accounted for 449 of these casualties in 1965.

The crucial question today does not concern the antarctic fishery but rather the future of all whaling. Continued overhunting of the finback whale can be expected to do to that species what has already been done to the blue whale. Last year, in addition to the antarctic season's kill of 2,314 finbacks, roughly 4,500 more of these animals were taken in other waters. Throughout the world's oceans today the only great whale that survives in economically significant numbers is the sperm. Yet a measure of the industry's lack of concern for its dwindling resources may be gained from recent efforts to establish quotas in the North Pacific, where the absence of quotas or restrictions allows hunting all year long. In spite of efforts by Canada and the U.S. the two whaling nations with fleets in the North Pacific—the U.S.S.R. and Japan—could not even agree to restrict the finback kill, let alone that of either sei or sperm.

Each of two past eras of whaling has virtually eradicated its own most highly prized whale species. The bowhead whale and the right whales are monuments to man's thoughtlessness in the days of sail. The blue whale and humpback—and possibly the finback and sei as well—are monuments to an industry's lack of foresight in the days of steam. The whaling nations today face a third and almost certainly a final decision. If essentially unrestricted whaling continues, the only surviving stock of any economic importance—the sperm whale, of whose numbers more than 250,000 have been killed in the past 12 years—is doomed to become a monument to international folly. Only sharply reduced annual harvests and protective regulations that are both enforceable and enforced offer the possibility that the last of the great whales will survive.

A Solid-State Source of Microwaves

A tiny crystal of gallium arsenide can be made to emit microwaves simply by applying a steady voltage across it. This phenomenon, known as the Gunn effect, may revolutionize microwave technology

by Raymond Bowers

Solid-state physics has been a generous benefactor to the technology of electronics. The transistor is the prime example; in less than two decades this simple solid-state device has replaced the bulkier vacuum tube in a multitude of applications in radio-frequency electronics (in the range between 10^5 and 10^8 cycles per second). It now appears that another important contribution is about to be made to very-high-frequency electronics (near 10^{10} cycles per second). The new device is a solid-state source of microwave radiation; it consists of nothing more than a tiny crystal of gallium arsenide, which can be made to emit microwaves simply by applying a steady voltage across it. At its present stage of development this device is already as efficient at producing microwaves as some low-power models of the klystron vacuum tube. The gallium arsenide source is much simpler than the klystron, however, and would be much cheaper to fabricate on a large scale.

Microwave power is currently used in all aircraft radars and in the long-distance transmission of telephone conversations and television programs. Because the frequency of microwaves is much higher than that of broadcast-band radio waves, the capacity of microwaves to transmit information is much greater. The comparatively expensive klystron tube, with its perishable filaments, vacuum requirements and bulk, dominates microwave technology at present, just as the ordinary vacuum tube dominated radio technology before 1955. The arrival of a cheaper, more efficient source of microwave power can be expected to bring changes in microwave technology no less sweeping than those produced in radio technology by the advent of the transistor. Microwaves may then break out of their present province of sophisticated industrial and military uses and enter the much wider realm of everyday applications. The particular device described in this article, which is only one of several possible solid-state microwave generators, seems especially promising in this respect.

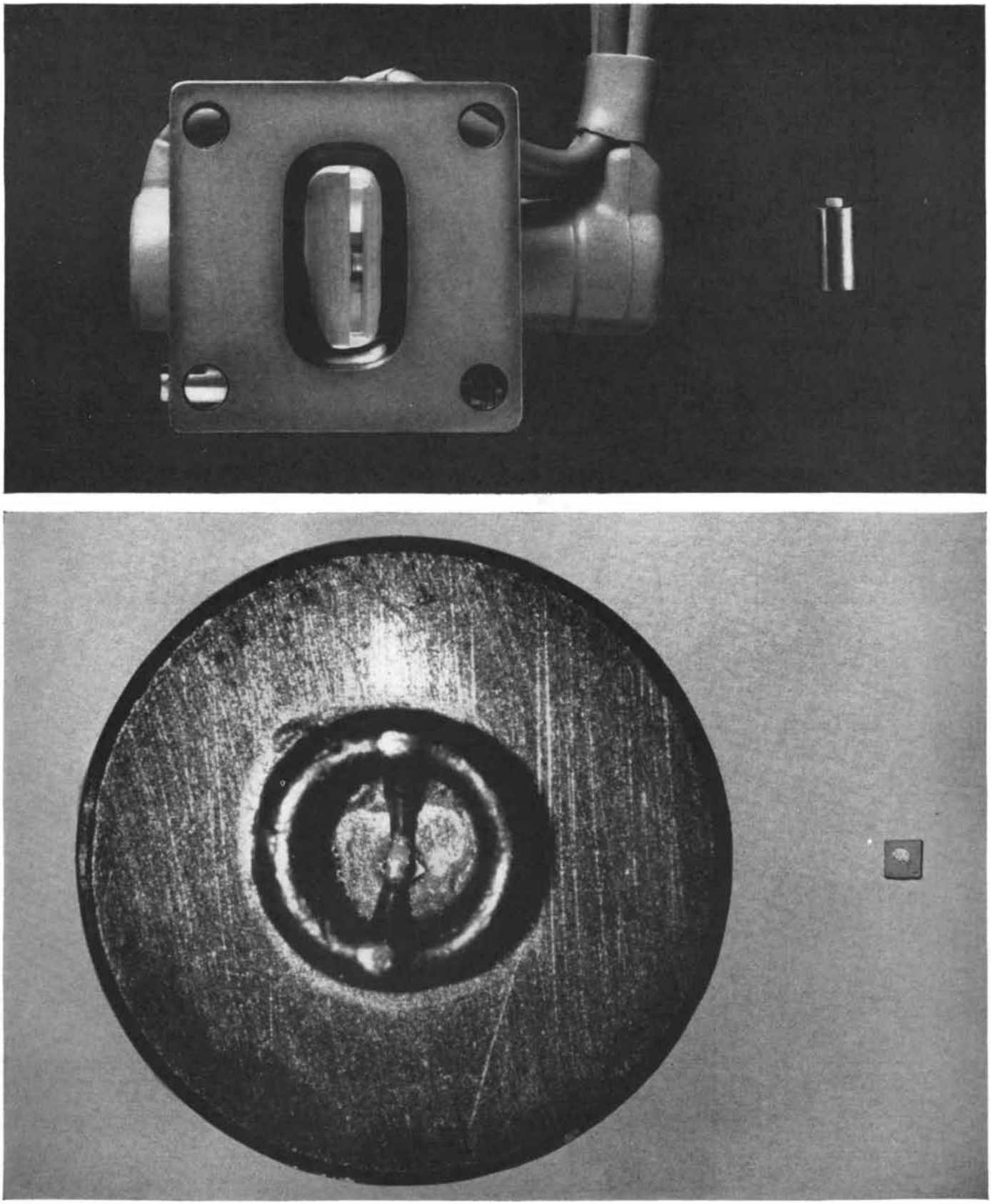
The gallium arsenide microwave source was not invented in the course of improving existing high-frequency devices. It is the product of basic research on the behavior of electrons in solids, and although applications are always close at hand in solid-state research, the early work leading to this discovery had little to do with microwaves. In the early stages of the development of the new source experiment and theory proceeded quite independently, providing an interesting example not only of the unpredictable manner in which solid-state physics delivers its benefits but also of the frequently tortuous path between discovery and explanation. I shall relate this development from the point of view of an informed onlooker. I have made no direct contributions to the findings reported in this article. I do, however, work in a closely related area of electronic effects in solids (plasmas of electrons in solids), and I have followed the microwave developments with great interest and admiration.

The discovery that microwaves could be generated by applying a steady voltage across a crystal of gallium arsenide was made in 1963 by J. B. Gunn at the Watson Research Center of the International Business Machines Corporation. The discovery was quite unexpected. At the time Gunn was studying what is called the "hot-electron problem" in semiconductors (substances intermediate in conductivity between metals and insulators). This problem is concerned with the mechanism by which electrons in a semiconducting crystal give up the energy they acquire from an electric field to the lattice of atoms through which they move.

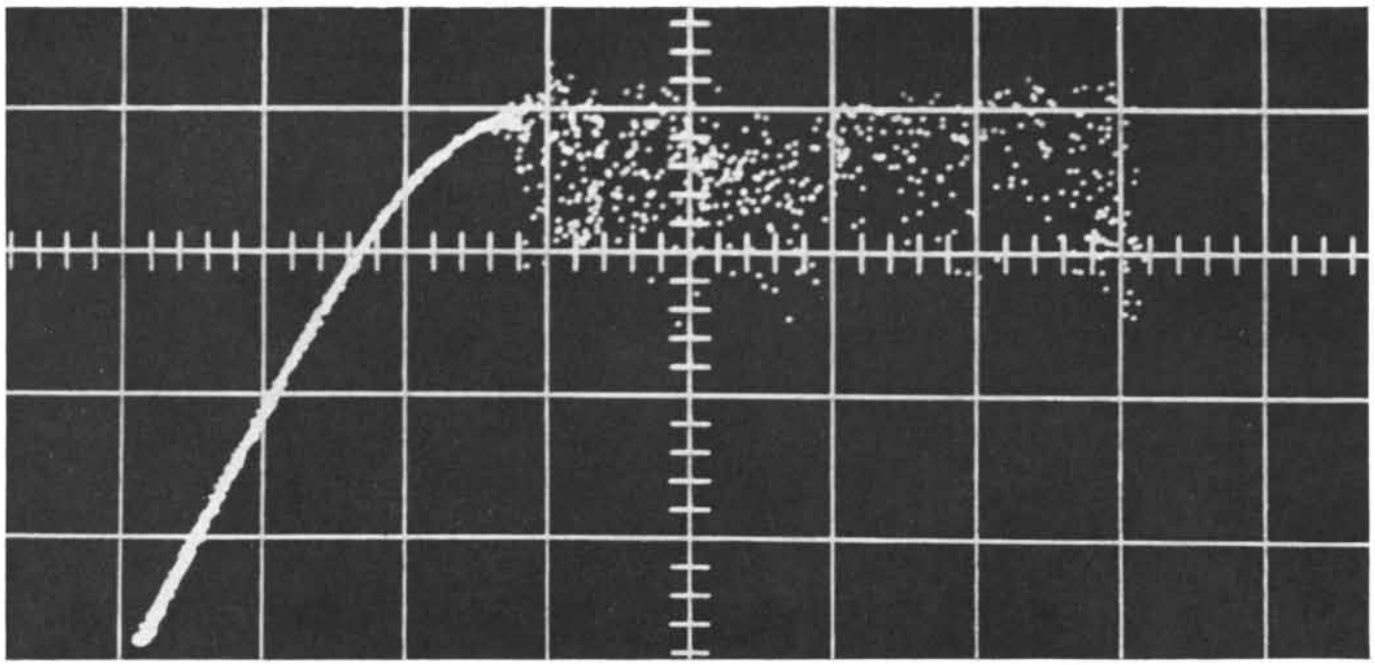
The mobile electrons that are the carriers of an electric current in a solid have a wide range of velocities and hence a wide range of thermal energies associated with their motion. The effect of applying an electric field to the solid is to accelerate all the electrons, and if it were not for the effect of collisions with the atoms, the electrons would increase their energy indefinitely in the electric field. It is easy for the electrons to yield energy to the atoms of the solid, and in most conductors the extra energy the electrons can gain from the electric field is very small compared with their random thermal energy. This small increase in the energy and hence the velocity of the electrons in the presence of an electric field is nevertheless quite important—it results in an electric current. When such a situation prevails, the current will be proportional to the electric field; this proportionality is the familiar Ohm's law, and most conductors obey it.

There are some semiconductors, however, in which it is possible to apply a large enough electric field for the electron-drift energy to become appreciable compared with the thermal energy. The entire distribution of electron energies then becomes distorted as the electrons gain large amounts of energy from the electric field. These higher-energy electrons are sometimes referred to as "hot" electrons. In this situation the electric current is no longer proportional to the electric field, and Ohm's law is no longer valid.

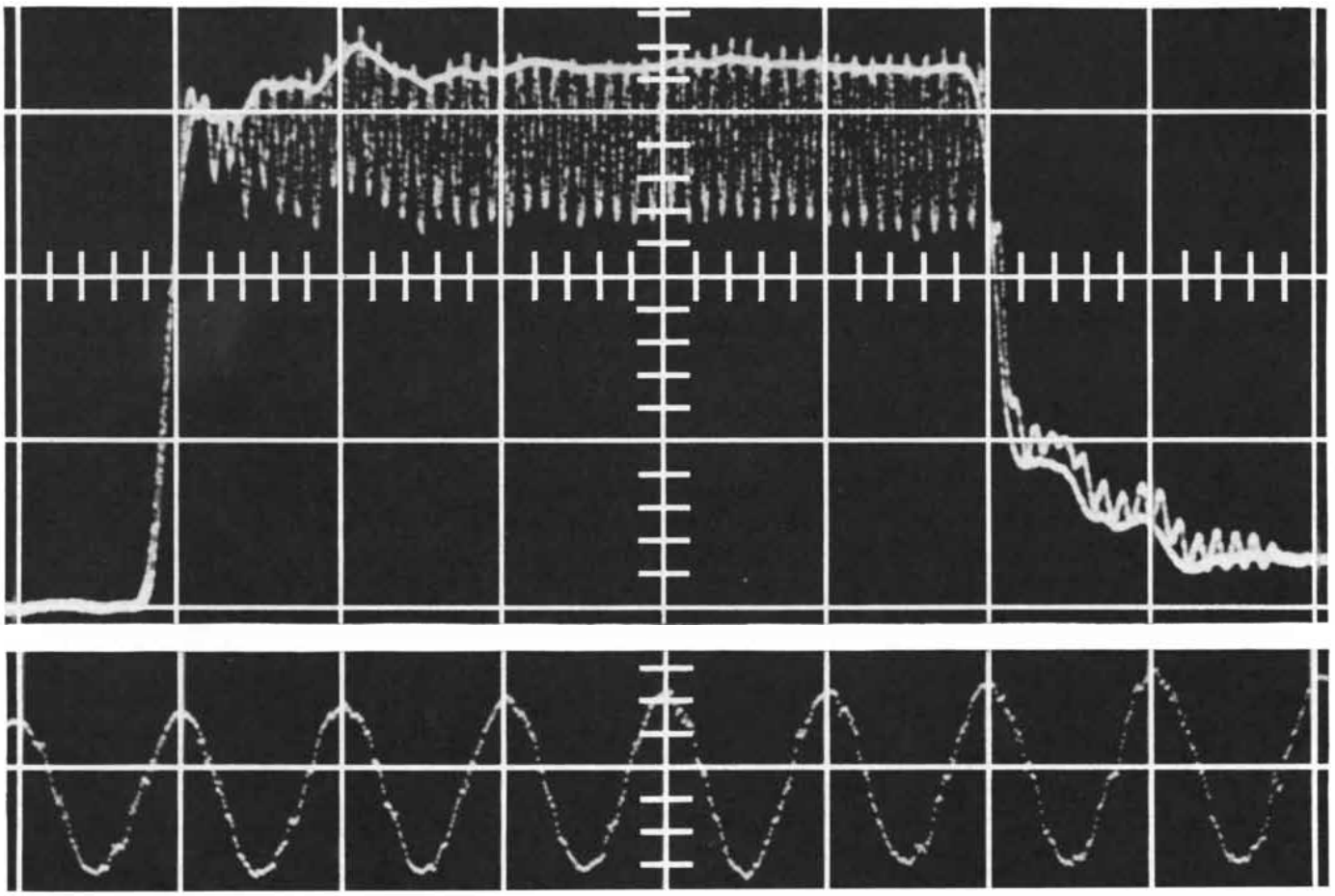
It is this phenomenon that Gunn was investigating at the time of his dis-



TWO MICROWAVE GENERATORS are compared here. At top left is a low-power klystron vacuum tube, manufactured by Varian Associates. It is capable of producing microwave power continuously in the range between 80 and 200 milliwatts. The microwaves are emitted through the window at the center, which is normally attached to a wave guide. At top right is a cylindrical copper mounting for a Gunn oscillator, a tiny crystal of gallium arsenide that can be made to emit microwaves simply by applying a steady voltage across it. The end of the mounting that holds the crystal is shown greatly enlarged at bottom left, and alongside it to the right is a small, square crystal of gallium arsenide. The Gunn device is capable of generating microwaves continuously in roughly the same power range as the klystron tube. The klystron is about an inch and a half across, the mounting for the Gunn device about a half-inch long and the gallium arsenide crystal about a hundredth of an inch across. Besides being smaller, the advantages of the Gunn device are that it is cheaper to fabricate and requires no vacuum, no filaments and has a simpler power supply. The photographs were made in the laboratory of J. B. Gunn at the Watson Research Center of the International Business Machines Corporation.



GUNN EFFECT was first observed in a sample of *n*-type gallium arsenide by means of an oscilloscope trace similar to the one shown here. The curve is a mathematical plot of the current passing through the sample (*ordinate*) as a function of the voltage applied to the sample (*abscissa*) with the time held constant. At low voltages Gunn found, as expected, that the current is proportional to the voltage (the familiar Ohm's law). When he applied increasingly higher voltages, however, deviations from Ohm's law began to appear. As he pushed the voltage well into the region where Ohm's law was breaking down, the system abruptly became unstable at a certain "threshold" voltage, and current fluctuated wildly for a fixed voltage. Scattered dots represent many individual measurements.



FREQUENCY OF CURRENT INSTABILITY in a sample of *n*-type gallium arsenide is revealed in these two oscilloscope traces, which show the variation of current (*ordinate*) as a function of time (*abscissa*) with voltage held constant. The photograph at top is a double exposure, showing the current wave form both when the applied voltage is just less than the threshold value (*smooth solid curve*) and when the applied voltage is just greater than the threshold value (*rapidly oscillating curve*). The time scale in the expanded view (*bottom*) of this particular oscillation is approximately .2 nanosecond (billionth of a second) per division. The frequency of the oscillation generated in this sample is on the order of 10^9 to 10^{10} cycles per second, or within the microwave range.

covery. He was studying hot electrons in the semiconducting compound gallium arsenide and was measuring the deviation from Ohm's law in this crystal at high electric fields. As in the case of the common semiconducting elements germanium and silicon, the addition of trace impurities to gallium arsenide can produce either *n*-type material, in which negative charge carriers (electrons) predominate, or *p*-type material, in which positive charge carriers (electron "holes") predominate.

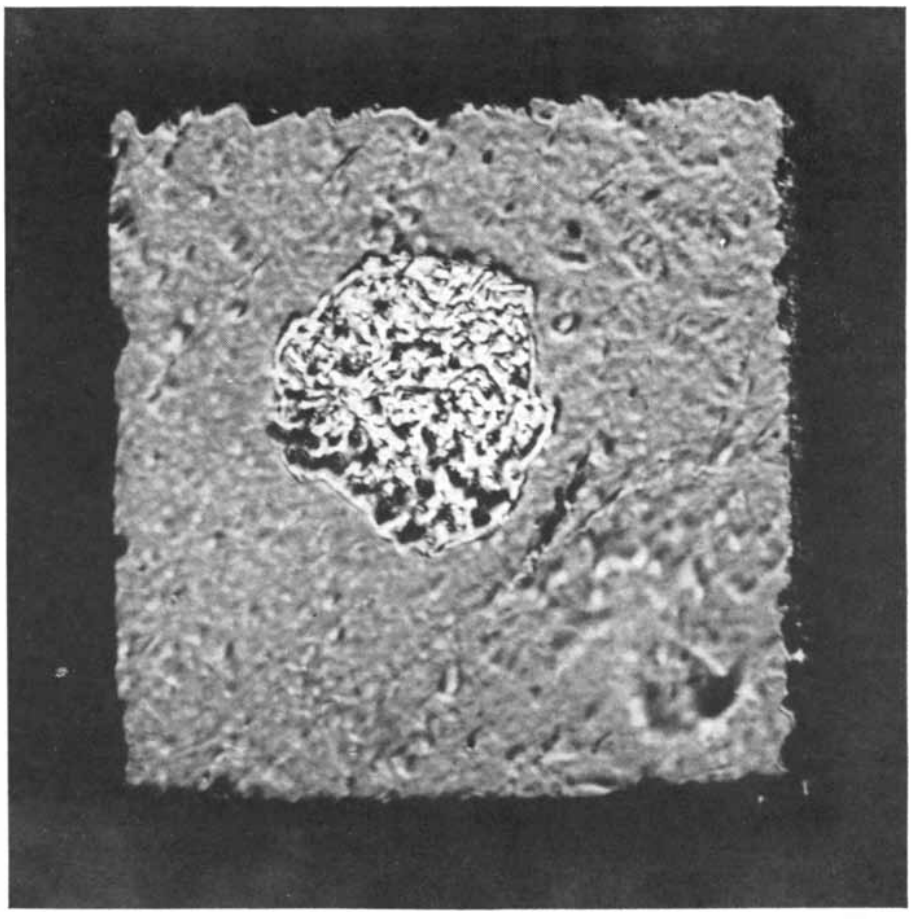
Gunn was particularly interested in measuring the relation between current and voltage in *n*-type gallium arsenide. For low voltage he found, as would be expected, that the current is proportional to the voltage; when he applied increasingly higher voltages, deviations from Ohm's law began to appear [*see top illustration on opposite page*]. In principle this is a straightforward direct-current measurement, involving a steady voltage and a steady current. In practice the dissipation of heat becomes too large at the higher voltages, and to avoid destroying the specimen it is necessary to use pulse methods: keeping the electric field on for a very short time, typically for 10^{-8} second, and repeating the pulse approximately 60 times per second, giving the crystal time to dissipate the heat.

Gunn's discovery came as he pushed the voltage well into the region where Ohm's law was breaking down. At a certain voltage the system became unstable—the current fluctuated wildly for a fixed voltage. In some samples the fluctuations had the character of random noise but contained components with frequencies of the order of 10^9 to 10^{10} cycles per second. In other samples (those smaller than about half a millimeter between electrodes) the instability appeared as a steady oscillation of current whose frequency was near 10^9 cycles per second.

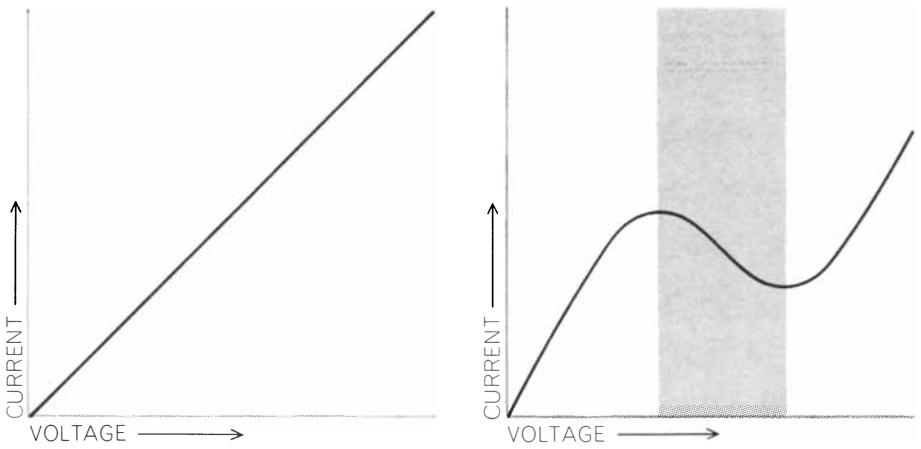
Having established that the effect was not a spurious phenomenon connected with the external circuit, Gunn began the task of determining the dependence of the oscillation on a number of variables. He found that in short samples giving a coherent oscillation the frequency of the oscillation was inversely proportional to the length of the sample. He determined that the inverse of the observed frequency was roughly equal to the time it takes an electron to go from one end of the sample to the other at the voltages being applied. This was a most important clue in linking the phenomenon directly to electrons traveling across the sample from one electrode to the other. He also found that the critical voltage necessary to induce oscillation varied with the length of the specimen; the threshold voltage was roughly proportional to the length of the specimen. The voltage divided by the length of the specimen is the electric field in the specimen, and Gunn's observations therefore suggested that the effect appears at a definite electric field but not at a definite voltage or at a definite electric current, since both the voltage and the current varied from sample to sample.

In a further series of experiments Gunn varied the electrical contacts used on the specimen; he placed the sample in a magnetic field; he changed the temperature; he altered the cross section and the surface condition of the specimen. He established that neither the contacts nor the state of the surface had any major effect, and that he was dealing with a phenomenon determined by a bulk property of gallium arsenide rather than a surface or a contact phenomenon. Magnetic fields had no effect on the oscillation, whereas changes in temperature produced small changes in threshold voltage and frequency. By changing the cross section of the sample he could study the phenomenon with a wide range of electric currents passing through the sample. He verified again that the onset of the oscillation was determined by a critical electric field no matter how much current was passing through the sample.

Gunn also found that on changing the voltage back and forth between the unstable region and the stable one the oscillations would switch on or off very rapidly, perhaps in less than 10^{-9} second. He tried various semiconductor materials. Germanium and silicon did not oscillate, but *n*-type indium phosphide did. Indium phosphide is a compound semiconductor whose electronic structure is closely similar to that of gallium arsenide, indicating that electronic structure is an important factor in causing the oscillation. Although the emission from *n*-type gallium arsenide was observed in many samples, Gunn was not able to excite the oscillation in *p*-type gallium arsenide. All these ob-



GALLIUM ARSENIDE CRYSTAL is enlarged about 400 diameters in this photomicrograph. The round spot on the crystal is a metal contact area to which one of the two electrodes is applied. The metal was evaporated onto the crystal, where it forms a thin film.



CONCEPTS of positive and negative electrical resistance are illustrated in these two graphs. A normal conductor of electricity has a positive resistance in the sense that the current passing through it increases with increasing applied voltage (*left*). In some systems it is possible to have a situation in which the current first increases with increasing voltage but then decreases with increasing voltage (*right*). Increasing the voltage still further finally results in the current's rising again. The region in which the current is decreasing as the voltage is increased is called a region of negative *differential* resistance, since it is only the slope of the current-voltage curve that changes sign. This characteristic causes the system to oscillate.

servations proved to be of great importance in deciding among the many possible explanations of the Gunn effect. These properties provided an almost unique "signature" that could only be matched to a single mechanism.

Gunn compared this signature with the one expected from a number of possible causes. He first examined the "pinch effect" as a possible explanation. This effect can arise when a large current is passed through a medium containing mobile positive and negative charges; it can occur either in a gas or in the charge carriers of a solid. If the current is large enough, the magnetic field associated with the large current (the self-magnetic field, as it is called) can become large enough to squeeze the stream of current into a region of small cross section. Such a configuration is often unstable, and the pinched stream of carriers destroys itself by emitting radiation. This explanation, however, does not fit the properties observed by Gunn. First of all, the pinch should occur at a critical self-magnetic field and therefore at a critical current; Gunn had shown that his phenomenon sets in at a critical electric field but at no special current. Furthermore, the pinch effect requires equal numbers of mobile positive and negative charge carriers; the material Gunn was using was *n*-type material and therefore had a preponderance of negative charge carriers. The pinch effect was clearly not the explanation.

Gunn also considered the possibility that the current through the crystal was exciting a very-high-frequency sound wave in the crystal. Sound waves can have frequencies as high as 10^9 cycles per second in certain solids; such waves travel with the velocity of sound (about 10^6 centimeters per second). A coherent sound wave—a wave in which the crests and troughs are all in step—cannot be established in a crystal, however, in a shorter time than it takes the sound wave to cross the crystal. One can calculate that for Gunn's specimens this would take at least 10^{-7} second, but he had already determined that his particular oscillations switch on and off in times of 10^{-9} second or less. Another explanation was abandoned.

A third conceivable mechanism depends on the fact that the atoms of gallium and arsenic are not electrically neutral when they form a crystal of gallium arsenide. The electron distribution around the atoms in the crystal is such that the gallium has a small positive charge associated with it, whereas the arsenic has an equal negative charge associated with it. It is easy to envision that as a negatively charged electron passes by these atoms and interacts with them the electron will exert electrostatic forces in one direction for the gallium and in the opposite direction for the arsenic, and it is conceivable that such behavior will stimulate a coherent oscillation of the gallium-arsenic system in which the gallium atoms and the arsenic atoms move in opposite directions. This particular mode of vibration is called the optical mode, because it is the one most likely to be excited by the electric field present in a light wave. The problem presented by this explanation is that the optical mode in gallium arsenide has a characteristic frequency close to that of optical waves (about 10^{13} cycles per second), and there is no obvious way in which this frequency could be reconciled with the 10^{10} cycles per second observed in Gunn's experiment. This seems to rule out direct emission of radiation by the optical mode, but it does not eliminate the possibility that the optical mode is an intermediary in a more complex process.

A fourth possible explanation considered by Gunn is that the effect arises from a "negative differential resistance" characteristic of the gallium arsenide resulting from the excitation of electrons in the crystal to energy states much higher than those they normally occupy. At an early stage in his work Gunn seriously considered this possibility but rejected it on the basis of some rough calculations. Since it turns out that this effect is almost certainly the origin of the microwave oscillations, I shall discuss it here in somewhat greater detail and explain the meaning of the term "negative differential resistance."

A normal conductor of electricity has a positive electrical resistance in the sense that the current passing through it increases with an increase in applied voltage. In some systems it is possible to have a situation in which the current first increases with an increase in voltage but then decreases with an increase in voltage [*see illustration on this page*]. Increasing the voltage still further finally results in the current's rising again. The region in which the current decreases as the voltage is increased is called a negative-resistance region, or more precisely a region of negative differential resistance, since it is only the slope of the current-voltage curve that has changed sign. It is a well-established fact of electrical circuitry that if one has an element with a negative differential resistance, a circuit can be designed in which this component will cause the system to oscillate. There are several negative-resistance devices in use for producing oscillations; in the solid-state area the best-known is the tunnel diode, which has been used to build oscillators that attain frequencies as high as 10^{10} to 10^{11} cycles per second.

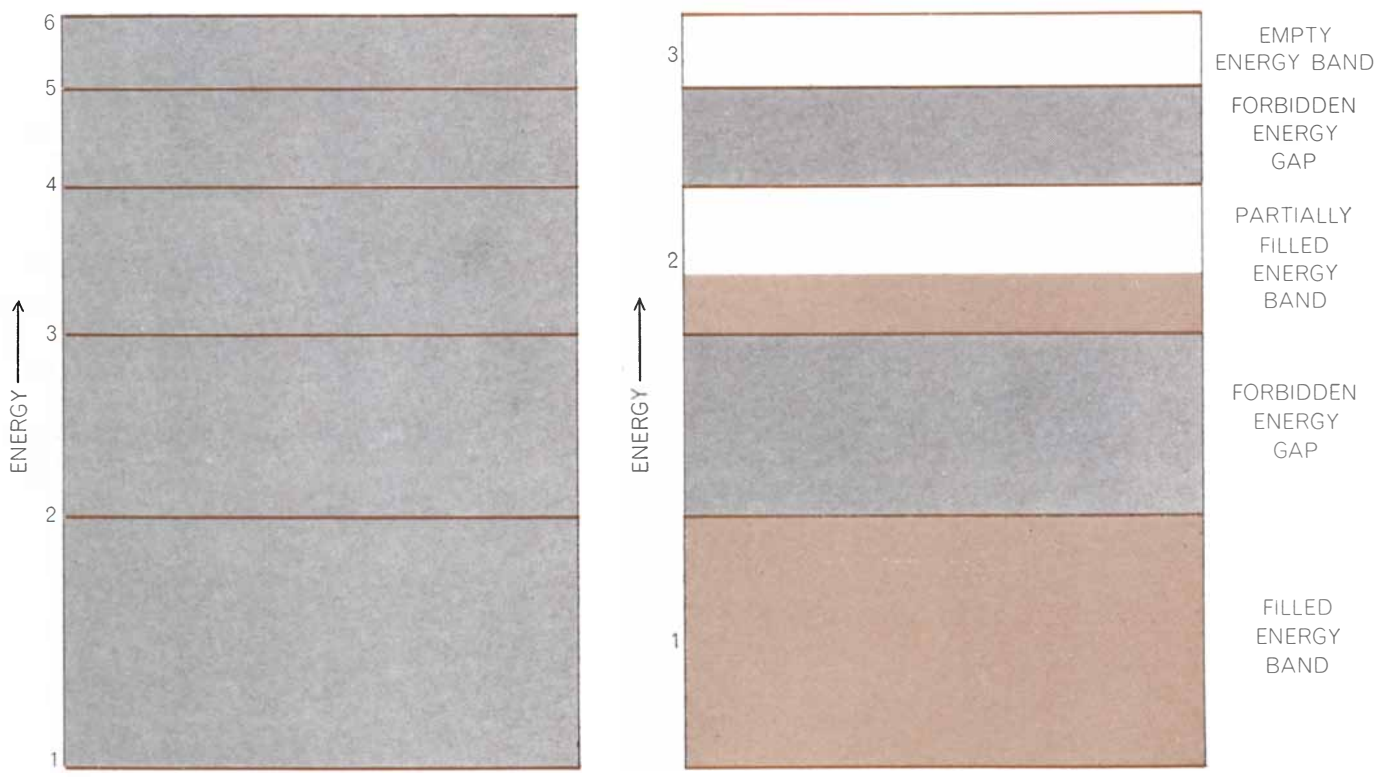
The problem of explaining the microwave emission in gallium arsenide as a negative-resistance oscillation is to find a plausible mechanism that could produce a negative resistance in the material. Because of the obvious application to the building of oscillators,

several investigators have speculated on the possibility of producing such a characteristic in a uniform solid, and papers concerned with this problem can be found in the literature for several years before Gunn's discovery. (By "uniform solid" I mean a material that is homogeneous throughout its length, and therefore I am excluding from this discussion any multilayer devices, such as the transistor, which consists of successive layers of *p*, *n* and *p* materials.) Most of the attempts to produce a uniform solid with a negative-resistance characteristic were based on effects caused by the special nature of the energy states an electron can occupy in a solid.

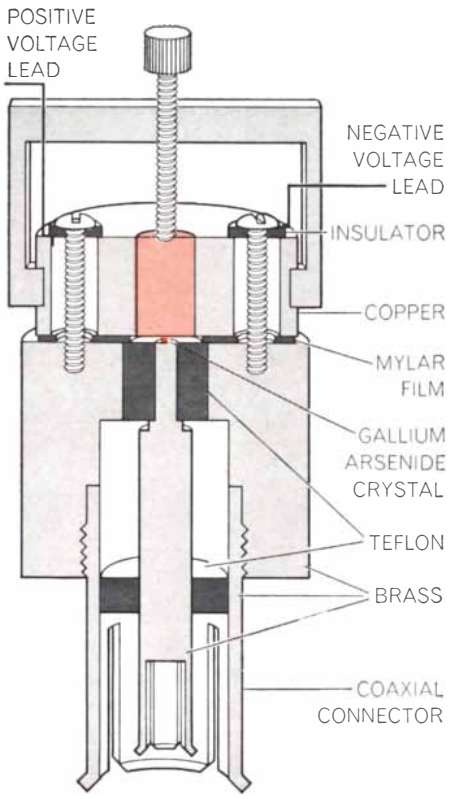
Electrons in a solid cannot possess any arbitrary energy but are restricted to certain definite energy states prescribed by the laws of quantum mechanics. The properties of an atom are determined by similar well-defined energy levels and by the distribution of electrons among these energy levels; some of the levels are occupied by electrons and some remain unfilled unless some external influence—for example a light wave—excites electrons into them from lower energy levels. A roughly comparable situation exists for the electrons that move in the interior of a solid, interacting as they move with the atoms that constitute the crystal lattice of the solid. Although there is a similarity in principle between these energy states and those in a simple atom, the energy-state structure in a solid is much more complicated than that in a simple atom. Instead of the sharp energy levels of a simple atom, one finds in a solid bands of energies that are "allowed" and bands of energies that are "forbidden" by the laws of quantum mechanics [*see illustration below*].

The conduction properties of a solid are determined by the distribution of electrons among the allowed-energy bands; another important factor is the magnitude of the forbidden-energy gaps separating the allowed-energy bands. It has been one of the major goals of solid-state physics during the past 30 years to determine in some detail the energy-band structure in solids. We now know a great deal about the permissible energy ranges in many semiconductors, including gallium arsenide. We know which bands are fully occupied by electrons and which bands are partially occupied. We know the position of other bands that are not normally occupied but that could be occupied by suitable excitation of the electrons. We also have some idea of how the electrons will react to an electric field when they occupy different energy bands, since the reaction of an electron to an external field will depend on the energy band in which the electron initially resides. Not only have some of these properties been directly measured; the experimental results have been fitted to theoretical schemes based on the quantum-mechanical equations that describe the motion of electrons in a crystal. The attempts to design a negative-resistance solid were based on this broad understanding of the electrons' energy bands in solids.

One particular suggestion for producing negative resistance in a uniform solid depended on the existence of unoccupied energy bands somewhat higher in energy than those occupied by the conduction electrons in gallium arsenide. If one looks at a negative-resistance curve such as the one on the opposite page, it seems clear that this curve might be achieved if, on accelerating the electrons by an electric field, one somehow begins to take electrons out of the conduction process on push-



ENERGY STATES of the electrons in an atom (*left*) and in a solid (*right*) are contrasted. The properties of an atom are determined by the distribution of electrons in well-defined energy levels (*colored lines*); some of the levels are occupied by electrons and some remain unfilled unless an external influence—for example a light wave—excites electrons into them from lower energy levels. The energy-state structure of the electrons that move in the interior of a solid is much more complicated. Instead of the sharp energy levels of a simple atom, one finds in a solid bands of energies that are "allowed" and bands of energies that are "forbidden" by the laws of quantum mechanics. The conduction properties of a solid are determined by the distribution of electrons among the allowed-energy bands; another important factor is the magnitude of the forbidden-energy gaps separating the allowed-energy bands.



APPARATUS depicted in this drawing is used to measure the current wave forms produced when a steady voltage is applied across a crystal of gallium arsenide (*solid color*). The crystal is mounted on a copper cylinder (*light color*), similar to the one shown in the photographs on page 23. The coaxial cable connected to the apparatus at the bottom leads to an adjustable short-circuit device, which is used in measuring the current across the crystal. The apparatus shown here is less than three inches long.

ing the electric fields beyond a certain level. A possible way to do this was suggested several years ago by the British physicists B. K. Ridley, T. B. Watkins and C. Hilsum. Their proposal was based on the fact that in certain semiconductors there exist empty electron energy levels whose energies are higher than those occupied by electrons, and that these higher energy levels have the property that electrons occupying them are less mobile under the influence of an electric field than they are in their normal state at the lower energy level.

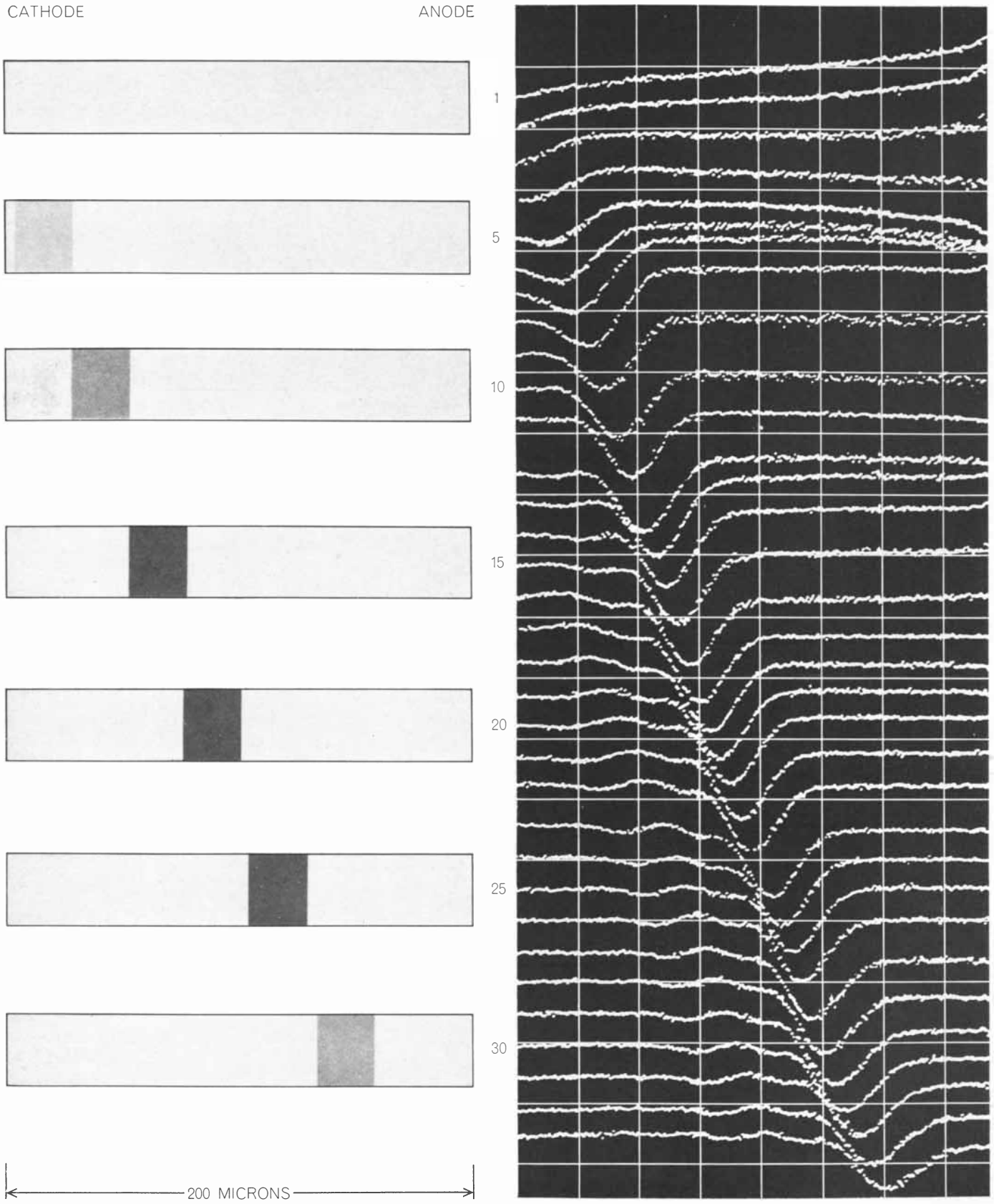
To simplify the explanation of this proposal, assume that the electrons in the higher level have essentially no mobility and therefore do not move when they are subjected to an electric field. If one applies an electric field to a semiconductor with this property, the current that flows will increase with an increase in voltage provided that the voltage is small, because one is accelerating the electrons in their initial energy band; if one makes the electric field high enough, however, it may be possible to excite electrons directly from the initial band into the higher band, where they become immobile. As the electric field is increased further, those electrons remaining in the initial band are made to move faster and faster, while those being excited into the upper band will in effect drop out of the conduction process. If the rate at which electrons are removed from the conduction process is high enough, the current will fall even though the electric field is being increased. There are certain semiconductors, in particular compound semiconductors such as gallium arsenide and gallium antimonide, whose energy bands come close to meeting these requirements. The trouble with this scheme was never one of principle but rather one of the practicability of achieving such a process in known materials. Even where suitable bands existed, they were often separated by such a large energy gap that it did not seem likely the electrons could gain enough energy in the electric field to jump from the lower band to the higher and less mobile band without dissipating this energy to the surrounding atoms. Moreover, other physical processes occur when an electron is accelerated to higher energies, and some of these may interfere with the desired redistribution among the energy states.

Gunn was aware of this possible means of producing negative resistance in gallium arsenide, and he gave it serious consideration in the early phase of his work. It was known from optical studies that such a low-mobility band exists approximately a third of an electron volt above the normally occupied electron bands in gallium arsenide. Gunn did a rough calculation of the likelihood that the electric fields used in his experiment would excite electrons into this upper band. He concluded that his electric fields were insufficient to produce appreciable electron transfer. In the absence of any other explanation, he preferred to think that the microwave emission was somehow connected indirectly with the optical mode.

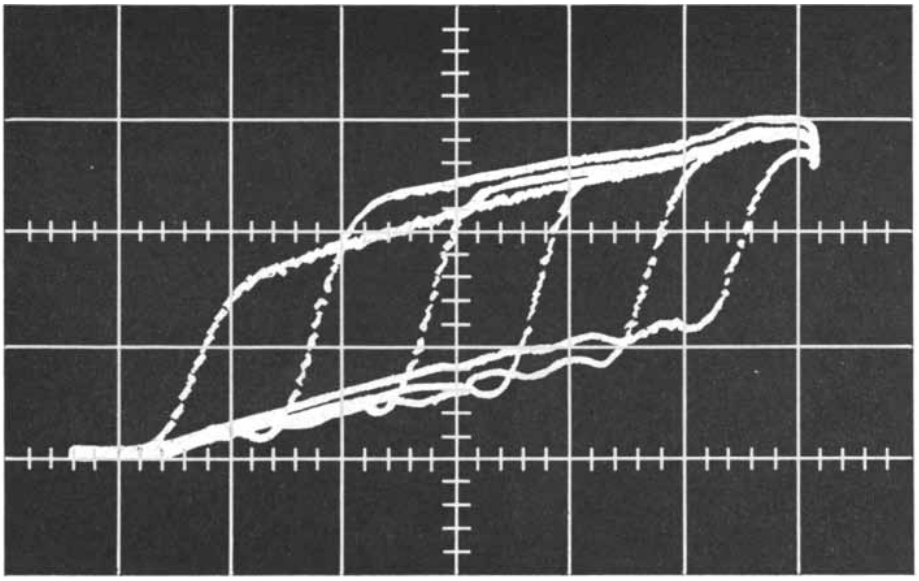
In spite of the fact that nobody had ever observed a negative-resistance effect known to be caused by the interband transfer of charge carriers, work continued on other aspects of negative resistance in solids. Other means of obtaining negative resistance were being proposed, some of which seemed to hold more promise of success. Ridley made an important investigation of the expected electrical characteristics of a negative-resistance semiconductor. He studied the question of how the electric field would distribute itself in such a medium if one applied a voltage in the negative-resistance region. His theoretical work was to prove crucial to the understanding of Gunn's experiment. Ridley examined in detail suggestions (made by William F. Shockley of the Bell Telephone Laboratories and by T. Reik of the Philips Laboratories at Aachen in Germany) that if one applied a voltage in the negative-resistance region, the crystal would not remain electrically homogeneous but would break up into regions with different electric fields. In particular a small domain would form in the sample within which the field would be very high, whereas in the rest of the sample, outside this domain, the electric field would have a very small value [*see illustration on opposite page*].

It is not hard to see that there is something unstable about such a negative-resistance domain. Consider what would happen if one were to disturb momentarily the electron density at some spot in the conductor. Suppose there is a sudden increase in electron density at some point in the crystal that tends to reduce the electric field to the left of the disturbance, while increasing the electric field to the right. If the resistance is positive, so that the current increases with increasing electric field, the decrease in the electric field to the left will result in a temporary decrease in the current flowing into the region from the left, and the increasing field to the right will result in a temporary increase in the current flowing out of the disturbed region. The excess electron charge will drain away. Thus a disturbance caused by a temporary local increase in the electron density will be dissipated as a result of this changing pattern of currents. The situation is quite different in the negative-resistance region; there the decreasing field to the left of the disturbance will cause an increase in current flowing into it, whereas the increase in the field to the right will tend to lower the current outside this region. This current pattern will have the effect of building up the charge disturbance even more; hence the situation will become unstable and will result in a redistribution of electric field within the specimen.

The idea of an inhomogeneous electrical distribution may be more familiar to most readers in a somewhat different



ELECTRIC-FIELD DOMAIN moving across a crystal of gallium arsenide is illustrated schematically at left and by means of the composite photograph of oscilloscope traces at right. The idea that if one applied a voltage in the negative-resistance region to such a crystal, the crystal would not remain electrically homogeneous but would break up into regions with different electric fields was developed by the British physicist B. K. Ridley from suggestions by William F. Shockley of the Bell Telephone Laboratories and T. Reik of the Philips Laboratories at Aachen in Germany. In particular their idea was that a small domain would form in the sample within which the field would be very high, whereas in the rest of the sample, outside this domain, the electric field would have a very small value. Such a domain would move across the sample from one electrode to the other, and as it disappeared at the anode a new one would nucleate, probably near the cathode. The composite, which was made by Gunn by means of a complex technique involving a moving voltage-sensing probe, shows the variation in electric field along a sample of gallium arsenide for the entire period of an applied pulse of voltage. This experiment removed any doubt that the Gunn effect is associated with a moving electric-field domain.



ANOTHER METHOD for displaying on an oscilloscope the movement of a high-field domain across a crystal of gallium arsenide was developed by Gunn to emphasize the cyclic nature of this process. Successive high-field domains appear at the cathode (*left*) and travel across the crystal to the anode (*right*). This particular sample was about 350 microns across.

connection. It is possible to obtain negative resistance by accelerating electrons to such a high energy that when they collide with atoms in the system, they produce more free electrons. Once this happens the voltage necessary to produce a given current declines. This is called "electrical breakdown." The current-voltage curve of the process has a negative-resistance region, but now the current has several values for a given electric field in contrast to the situation described earlier, in which the electric field has several values for a given current. The new situation is also unstable and results in electrical inhomogeneity; if voltage is applied across the sample, different regions of the material can conduct different quantities of current, and in fact filaments form across the sample, each containing a different current. The extreme example of this situation is an electric spark in a gas, which consists of a narrow filament of high current while the rest of the gas in the region is transporting much smaller currents. The spark is in some sense a current domain, whereas Ridley was concerned with electric-field domains. Ridley also pointed out that the electric-field domains will not be stationary, since the electric field acting on the electrons will cause them to move across the sample. The domain will travel across the sample from one electrode to the other, and as it disappears at the anode a new one will form, probably near the cathode.

We now come to the question of the relevance of the work of Ridley, Watkins and Hilsum to the phenomenon observed by Gunn. Their work had proceeded independently of Gunn's experiments, and some of it had even preceded the experiments. It was Herbert Kroemer of Varian Associates who pointed out that nearly all the known characteristics of the phenomenon observed by Gunn could be explained on the basis of the work of Ridley, Watkins and Hilsum. Kroemer asserted that the current oscillations observed by Gunn resulted ultimately from an intrinsic negative-resistance characteristic and that the oscillation of the current was due to the moving domains Ridley had described. Kroemer pointed out that such a process would have a characteristic frequency approximately equal to the inverse of the time it took the electrons to cross the sample. One would also expect that since the time for the electrons to cross the sample was proportional to the length of the sample, the frequency would be inversely proportional to the length of the sample. Both of these were prime properties of the Gunn effect. Kroemer further insisted, notwithstanding Gunn's earlier rejection of the mechanism, that the negative resistance resulted from the transfer of the electrons from a lower band to a higher one. He pointed out that Gunn has grossly underestimated the efficiency of transfer to the higher band. A more careful analysis of this effect by Hilsum had already shown that considerable interband transfer would occur at fields that were not much higher than those actually observed by Gunn. Kroemer's work has been compared to that of a marriage broker. When such work is done well, it requires great skill, and Kroemer brought to it a great deal of experience; he had in the past been the originator of several ingenious suggestions for obtaining negative resistance in solids.

It seems quite strange now that there should ever have been much doubt concerning this explanation of the Gunn effect. The explanation is entirely consistent with the observations that a magnetic field does not affect the oscillation, that there is a small temperature dependence, that changing electrical contacts have little influence and that the effect sets in at a critical electric field but not a critical current. Gunn's failure to observe the phenomenon in germanium is also consistent with this explanation, because the electronic energy-band pattern of germanium is not favorable for this mechanism. One can also understand why very short samples have a single frequency of oscillation, whereas long samples exhibit multiple frequencies. This is probably due to the fact that in long samples more than one domain can form within the sample, leading to a complicated oscillation pattern. In the period since Kroemer related the work of these various people a series of experiments and a number of calculations have been made concerning the detailed fit of theory with experiments. All of them show remarkable agreement between the experimental observations and the theory of domains coupled with the idea of interband transfer of electrons.

Even before Kroemer published his explanation Gunn had embarked on a series of experiments whose purpose was to study the details of the electric-field pattern in gallium arsenide. These elegant experiments provide the most direct evidence for the existence of domains that move across the sample. His new experiments consisted of placing a voltage-sensing probe on the surface of a gallium arsenide specimen at some position between the positive and negative electrodes. His object was to detect a domain moving across the sample from the signal induced in the surface voltage probe as the domain passed the probe. In order to prove that mobile domains were present it was necessary to probe the voltage along the length of the sample, but it was obviously not possible to move the probe as fast as the domains moved, since they crossed the sample in only 10^{-9} second. Gunn therefore resorted to a technique com-

parable to that used in producing animated cartoons, in the sense that it consisted of a sequence of single photographs. He placed the probe in a given position and arranged for the probe to measure the voltage at some definite time after the main pulse had been applied to the principal electrodes. He then slowly moved the surface electrode along the specimen, plotting out the voltage at each point for a given time delay. He repeated the process for a different time delay after the onset of the principal pulse. By repeating this process for different time delays, each longer than the preceding one by a certain fraction of 10^{-10} second, he obtained a series of photographs showing the variation in electric field along the sample for the entire period of the applied pulse [*see illustration on page 29*]. This experiment removed any doubt that the Gunn effect is associated with a moving domain.

It has been more difficult to demonstrate that the mechanism underlying this phenomenon is indeed the transfer of electrons to higher energy bands. A recent experiment by a group at Bell Laboratories, however, has provided strong evidence for this mechanism. This experiment involved subjecting a Gunn oscillator to a very high pressure (nearly 30,000 atmospheres), which has the effect of decreasing the separation between the energy bands thought to be responsible for the oscillation. The group found that the threshold electric field for the inception of microwave oscillation decreased with increasing pressure, as expected from the electron-transfer theory. A detailed analysis of these findings shows no substantial feature that is not consistent with the model of interband transfer. The relative positions of the bands can be changed by alloying the gallium arsenide with gallium phosphide; the results of experiments with such alloys are also consistent with the interband-transfer explanation.

The main features of the Gunn effect now seem to be understood, but there is a great deal of work continuing in order to improve our detailed understanding of this phenomenon. Attempts are being made to obtain quantitative information concerning the structure of the domain. With the aid of computers the details of the emission are being calculated from the basic theory and compared with experiment. Much effort is also being devoted to increasing the efficiency and the power output of the oscillator.

It is very difficult to assess at this stage the impact Gunn's device will have on microwave technology. It is not difficult to see where the new device will replace older tube devices in the jobs they are now doing. It is much harder to foresee whether or not the new oscillator has sufficiently novel properties to result in new applications of microwaves. The advantages of Gunn's device are fairly clear. It is extremely small, rugged and should be cheap to fabricate. In contrast to the klystron, it requires no vacuum, no filaments and a simpler power supply. At present its efficiency compares favorably with that of low-power klystrons [*see illustration below*].

The power output from a Gunn oscillator is already quite impressive. Using very small wafers, the group at Bell Laboratories has reported power outputs of 65 milliwatts at 2×10^9 cycles per second with an efficiency of between 5 and 6 percent while running continuously. The power output is limited in this case by the difficulty of removing heat generated in the sample; consequently much higher power outputs can be obtained for short-duty cycles. Power outputs as high as 200 watts at 14 percent efficiency have been reported for a pulse lasting 10^{-7} second. The Gunn oscillator is so small that it is conceivable that much higher power output can be achieved by using many wafers of gallium arsenide in a single source.

Up to the present the high cost of vacuum-tube microwave sources (a small klystron and its power supply cost about $100) has limited the use of microwaves to industrial and military applications. The development of an extremely cheap microwave source may open the way to widespread use of small radars on pleasure boats, small private planes and even automobiles. It is likely that the solid-state source will make its greatest impact in these novel uses rather than in competition with the very large vacuum tubes used in large-scale radar and cross-country communication. A great deal will depend on whether or not the Gunn oscillator is found to be reliable in long-term use. With no vacuum and no filament it has a head start.

I must not leave the impression that the Gunn oscillator is the only solid-state device that looks promising as a generator of microwaves. Competitors exist, the strongest being the "Read diode," named after W. Thornton Read of Bell Laboratories, who proposed it in 1957. After several years of dormancy this device has suddenly been revived, and its supporters claim that it has greater promise than the Gunn oscillator. It is a junction device that depends for its operation on "avalanche breakdown," that is, the creation of extra charge carriers by collisions with atoms. Other solid-state devices, some involving plasma effects in magnetic fields, are being watched with great interest, even though they appear to be less competitive than either the Gunn oscillator or the Read diode. Thus we are at an early stage of the advent of solid-state devices for microwave generation, and there are several contenders for the title of "most useful generator." Only a rash man would predict the winner at this stage, but the pace of work in this area is very rapid and we will not have to wait long to know the winner.

MICROWAVE GENERATOR	DURATION	POWER (WATTS)	EFFICIENCY (PERCENT)
SMALL KLYSTRON	CONTINUOUS	.1	2
GUNN OSCILLATOR	CONTINUOUS	.065	6
GUNN OSCILLATOR	PULSED (10^{-7} SECOND)	200	14
READ DIODE	CONTINUOUS	5	6

PERFORMANCES of several microwave generators are compared in this table. At its present stage of development the Gunn oscillator is already as efficient at producing microwaves as some low-power klystron tubes. The power output of the Gunn device when running continuously is limited by the difficulty of removing heat generated in the sample. Consequently much higher power outputs can be obtained for short-duty pulsed cycles. Read diode is a solid-state junction device named after W. Thornton Read of Bell Laboratories.

THE ORIGIN OF COSMIC RAYS

What cosmic accelerators generate these fantastically energetic particles? Calculations suggest that most cosmic rays may come not from within our galaxy but from extragalactic radio sources

by Geoffrey Burbidge

The salient fact about cosmic rays is their enormous energy. The primary cosmic rays—charged particles that enter the earth's atmosphere from somewhere outside it—have energies of between 10^8 (100 million) and 10^{20} (100 billion billion) electron volts. In contrast, the most powerful man-made accelerators can impart to a particle an energy of only some 30 billion electron volts. Any hypothesis as to the origin of cosmic rays must suggest some cosmic mechanism capable of accelerating charged particles (mostly protons but also some heavier nuclei) to fantastically high energies. The generally accepted view nowadays is that most cosmic rays come from supernovae, or exploding stars, within our galaxy, but that those with the highest energies must come from sources outside the galaxy. My own feeling is that much of the cosmic radiation, and perhaps the bulk of it, is generated by the strong radio sources in extragalactic space: radio galaxies and the recently discovered quasi-stellar sources.

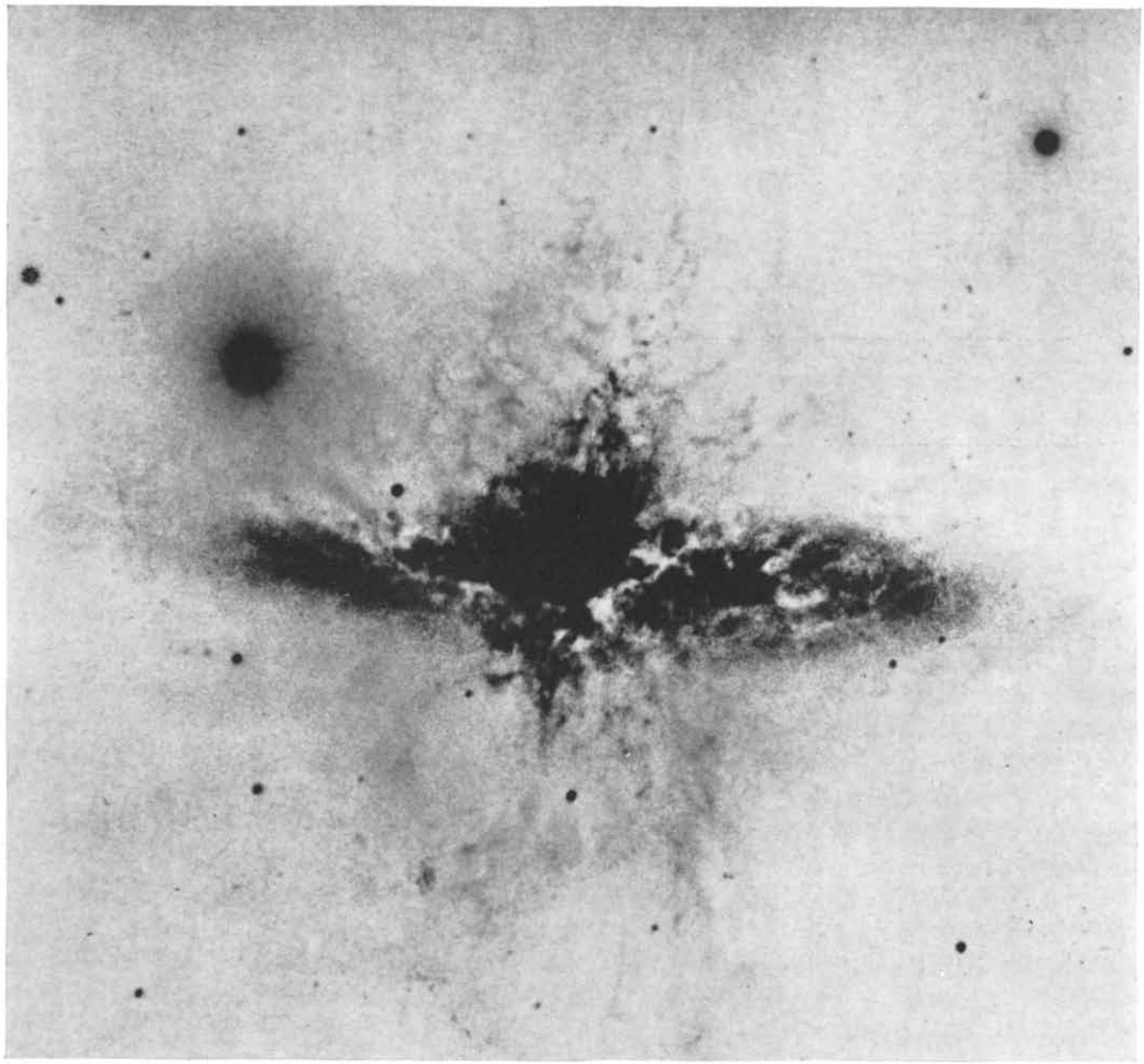
At first it seemed plausible to assume that cosmic rays originate in the sun. Solar flares do accelerate particles to high speeds, and there is an increase in the flux of cosmic rays in the earth's atmosphere at times of solar flares. It has been clear for some time, however, that the sun is not a major source of cosmic rays. For one thing, the energy spectrum of cosmic ray particles, which shows a marked falloff in the number of particles as their energy increases, has several slight changes of slope [*see top illustration on page 34*]. This suggests that several different mechanisms are involved in the production of the particles. Second, cosmic rays do not come predominantly from the direction of the sun. For a time it was argued that, since charged particles spiral along the lines of force in a magnetic field, their even distribution might be accounted for by the effect of the interplanetary and terrestrial magnetic fields. The fact is, however, that all but the lowest-energy particles are too energetic to be deflected by such magnetic fields. The particles could not be contained within the solar system at all; they must come from beyond it.

If most cosmic rays are not generated by the sun, they cannot come from many stars similar to the sun either: the sun is so much the closest star that it would have to "outshine" the others in cosmic ray energy as it does in light energy. This does not rule out the possibility that stars with certain peculiar properties may contribute. Are there, then, special places in the universe where conditions are right for the acceleration of charged particles to extremely high speeds? When supernovae were discovered more than 30 years ago, and Walter Baade and Fritz Zwicky proposed that they were catastrophic explosions in which much of the mass of a star was ejected, it was realized that such events could very well be sources of cosmic rays. Other workers have pointed out that there are other kinds of stars in our galaxy capable of generating high-energy particles. They include flare stars, in which electromagnetic eruptions much more intense than solar flares occur, and novae, which are comparatively minor stellar explosions. Enrico Fermi, on the other hand, suggested that the enormous energies of cosmic ray particles are due not to an explosion or some similar event in a specific structure in space but to repeated acceleration by magnetic fields in clouds of ionized gas between the stars.

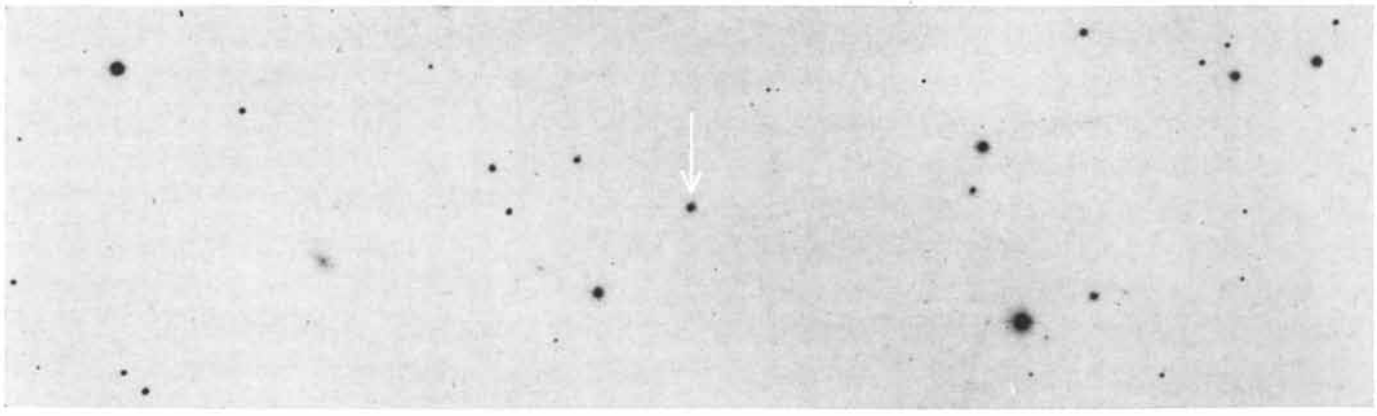
What was lacking in all these possibilities was any clear evidence that there were in fact fluxes of relativistic particles (particles moving with nearly the speed of light) in any astronomical objects other than the sun at times of flares. The evidence finally came from radio astronomy, with the realization in the 1950's that most of the "nonthermal" radio sources in our galaxy and beyond are emitting energy by the synchrotron mechanism: radiation from relativistic electrons spiraling along lines of magnetic force [*see bottom illustration on page 34*]. It was clear that if electrons are being accelerated in these radio sources to nearly the speed of light, protons and heavier nuclei should be similarly accelerated. Moreover, the energy spectrum of the electrons responsible for synchrotron radiation was found to be similar to that of cosmic ray particles. It was natural to suspect that the radio sources were major suppliers of cosmic rays.

Within our own galaxy the nonthermal sources are for the most part structures identified as the remnants of supernovae. The Crab Nebula, for example, is a remnant of a star that exploded in A.D. 1054 [*see illustration on page 35*]. The presence of such remnants, emitting by the synchrotron mechanism, indicates that supernovae inject relativistic particles into the interstellar gas of our galaxy. To estimate the importance of this contribution to the cosmic ray population it is necessary to determine how large a flux of particles is produced on an average by a supernova and also the rate at which such outbursts occur.

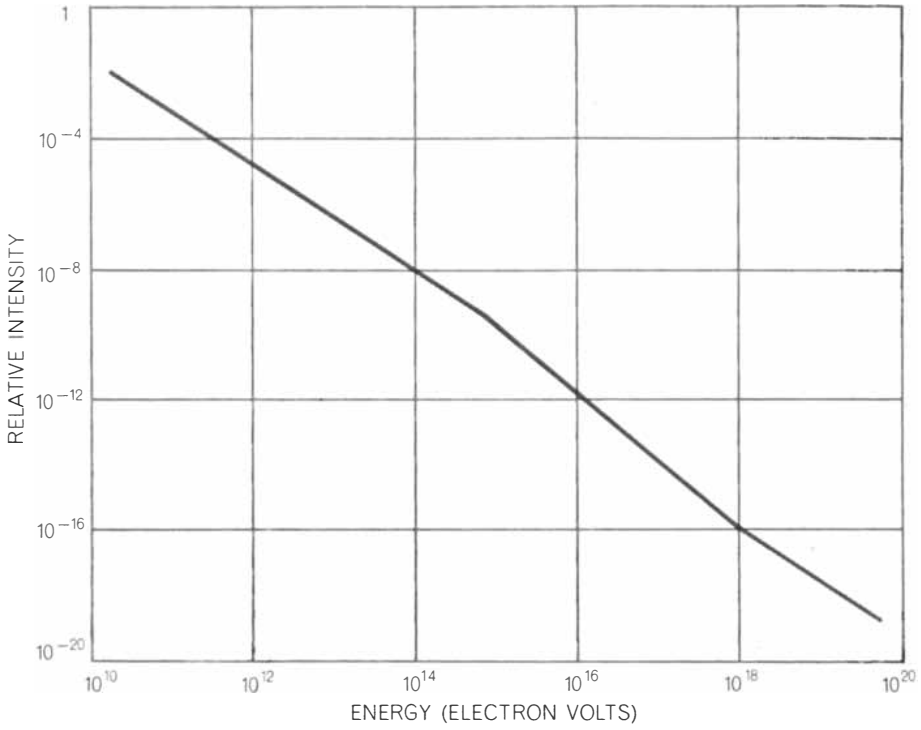
Neither of these quantities is known with any precision. On the basis of observation one can make estimates of the total amount of energy contained in the electrons in a supernova remnant such as the Crab, but it is now 900 years after the event. Moreover, what



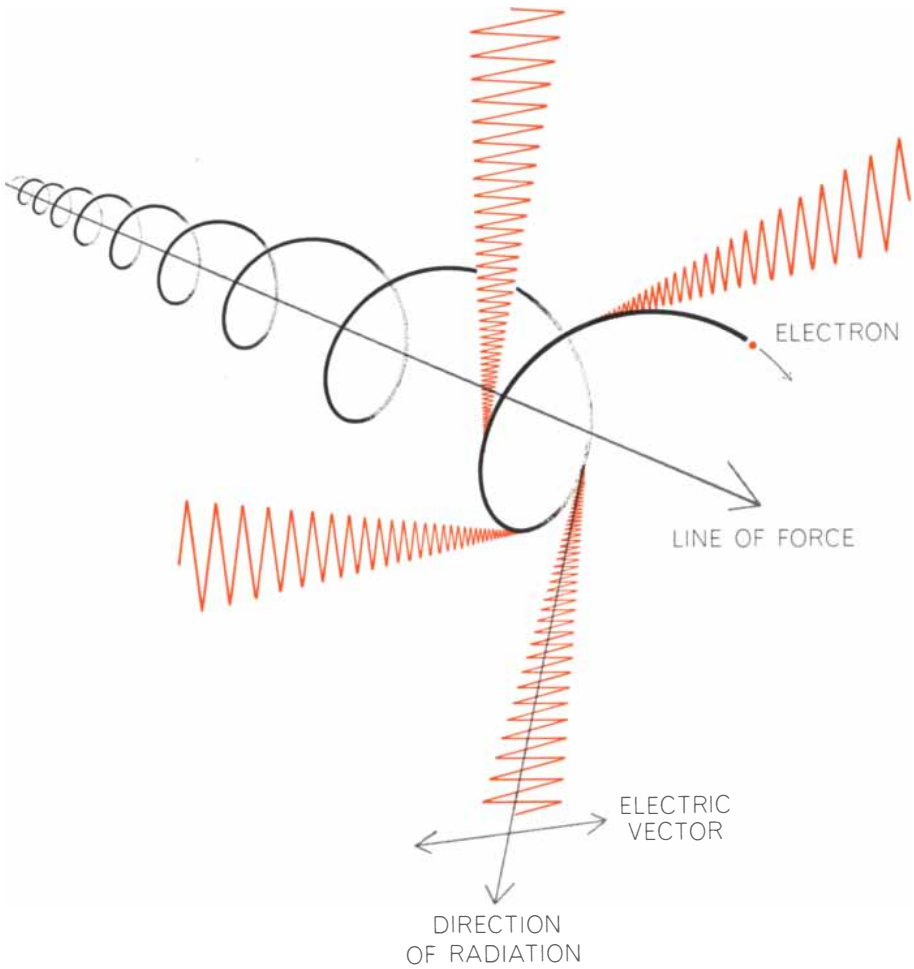
EXPLODING GALAXY M 82 was photographed in red light with the 200-inch telescope on Palomar Mountain by Allan R. Sandage of the Mount Wilson and Palomar Observatories. The photograph revealed turbulent filaments of hydrogen, extending some 14,000 light-years above and below the galactic disk, that are apparently the result of a violent explosion at the center of the galaxy. Explosions of this kind, which account for the energy of some radio galaxies, could provide the energetic particles of cosmic rays.



QUASI-STELLAR RADIO SOURCE 3*C* 48 is the object at the center of this photograph made with the 200-inch telescope. Although it looks like other objects on the plate, which are stars in our galaxy, it is probably four billion light-years away and brighter than any ordinary galaxy. Such quasi-stellar radio sources, like ordinary radio galaxies, may be major sources of cosmic rays.



ENERGY SPECTRUM of cosmic rays varies in slope, suggesting that it may reflect a number of different mechanisms of generation. The vertical scale reflects the relative number of particles that have more than a given amount of energy as shown on the horizontal scale.



SYNCHROTRON RADIATION is emitted by electrons spiraling along a line of force in a magnetic field. The radiation can be in the visible or radio part of the electromagnetic spectrum; the wavelength depends on the velocity of the particle and the strength of the magnetic field. Radiation produced by the synchrotron mechanism is highly polarized, with its "electric vector" perpendicular to the line of force and to the direction of radiation.

is observed is only electron activity; one knows nothing directly about the flux of the nuclei—largely protons—that accompany the electrons. As far as the frequency of supernovae is concerned, it can only be estimated by observing galaxies other than our own. Since the rate at which supernovae occur is almost certainly a function of the relative numbers of stars in different mass ranges in different galaxies, any estimate based on external galaxies may not be a good approximation for our galaxy. The values that have been obtained range from one every 100 years to one every 500 years.

In view of these uncertainties it is worthwhile to turn the problem around and ask at what rate particles have to be injected into the galaxy in order to maintain the flux of cosmic rays at an energy density of about one electron volt per cubic centimeter (the density at the top of the earth's atmosphere). This depends on the rate at which the nucleons are lost by nuclear collisions with the interstellar gas and dust and by escape from the galaxy. In a collision between what is essentially a stationary nucleus and a very-high-energy proton or other cosmic ray particle, a cloud of secondary particles (mesons and nucleon-antinucleon pairs if the energy is high enough) will be produced. These will decay, the only stable end products being electrons and positrons, gamma rays and neutrinos and antineutrinos. The neutrinos and antineutrinos will escape directly from the galaxy because their interactions with other particles are so feeble; the gamma rays have a larger cross section for interaction than the neutrinos do but are also likely to escape. Only the electron-positron component will remain. The electrons lose energy by radiation in the interstellar magnetic field and by various atomic collisions and radiation processes and by escape. Calculation of these energy-loss processes demands knowledge and detailed understanding of the life history of a cosmic ray particle and the density of the gas in which it spends different parts of its life, and of the configuration and distribution of the magnetic field in and around the galaxy. What is the structure of the field and how effective is it in trapping cosmic rays?

Some 10 years ago John Baldwin of the University of Cambridge concluded from his observations of background radio noise from the sky that the radio emission of our galaxy comes not from within its disk of stars but from an extended region with a roughly spheroidal shape: a "halo" or corona [*see*

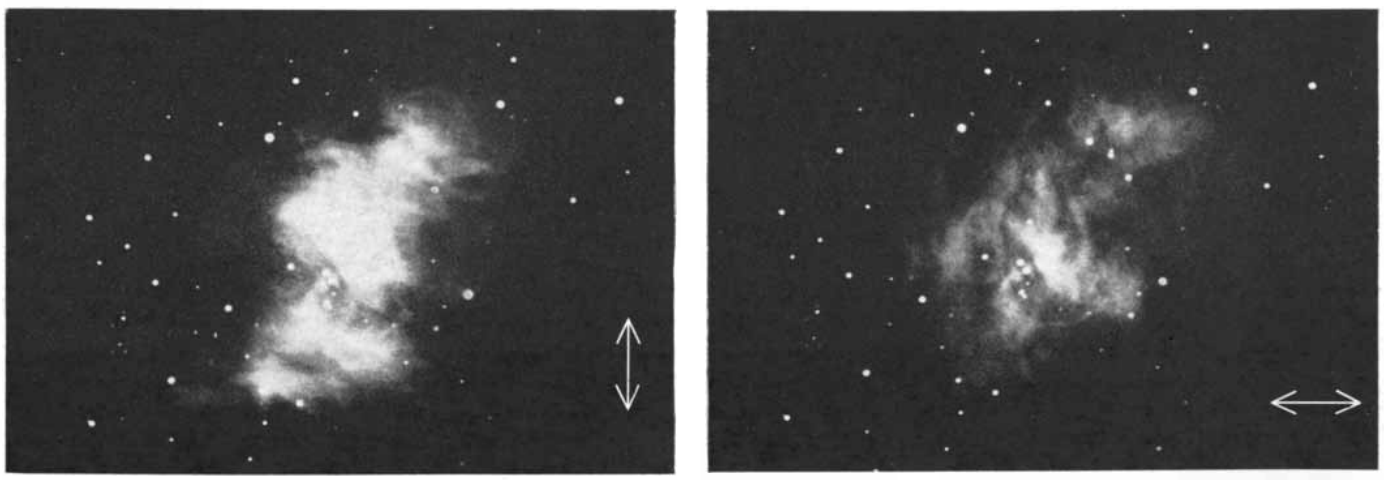
illustration on next page]. Since the radio emission is due to the synchrotron process, the entire extended volume of the halo must contain a weak magnetic field and high-energy electrons—presumably the electron component of cosmic rays. This suggested that cosmic rays must fill the halo. Soon afterward R. Hanbury-Brown and Cyril Hazard, working at the Jodrell Bank radio observatory of the University of Manchester, discovered just such an extended distribution of radio emission around the Great Nebula in Andromeda [*see illustration on page 37*]. More recently, however, other radio astronomers in Australia and at the National Radio Observatory in Green Bank, W.Va., have observed many other nearby spiral galaxies and have concluded that this extended halo distribution is more often absent than present; in many cases the radio distribution is confined largely to the flattened region and central bulge in which the stars are concentrated. Re-examination of the observations of the radio emission from our own galaxy has led to the conclusion that the contribution from the halo is considerably smaller than was first thought. Some radio astronomers maintain that the observations can largely be explained without invoking the presence of a halo at all.

On the theoretical side it has never been easy to understand how a halo containing weak magnetic fields and low-density gas could remain stable for periods as long as the age of a galaxy (about 10 billion years). For gas to be supported high above the plane of a rotating galaxy it must have motions comparable to the rotational motion—and that means velocities of the order of 200 kilometers per second—either as turbulent motions in the gas or as thermal velocities reflecting temperatures near a million degrees. In either case the rate at which the energy would be dissipated is such that a halo would collapse in a time that is short compared with the age of the galaxy. About three years ago Fred Hoyle and I therefore suggested that a halo is a transient phenomenon with a lifetime of only a few tens or hundreds of millions of years, and that it is caused by an explosion at the center of the galaxy. Such an explosion would be similar to, but probably on a much smaller scale than, the explosions that apparently are responsible for the radio emission of the bright elliptical galaxies [*see top illustration on page 33*]. A violent event of this kind might well also account for the outward-moving gas that is seen in the disk of our galaxy.

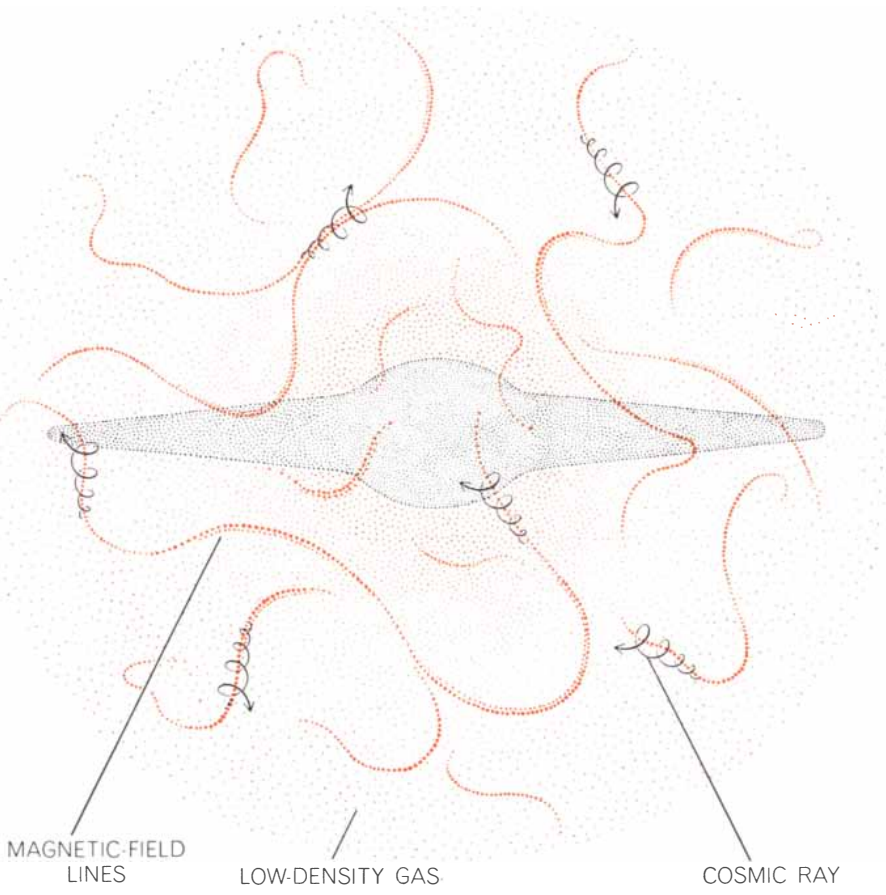
If this type of event is the origin of galactic halos, a halo can be considered as a kind of magnetic bottle that traps cosmic rays. It is probably an exceedingly leaky bottle, however (as is suggested by the irregular nature of the Andromeda halo), and periodically it may disintegrate altogether. In that case, if all the cosmic rays arise in supernovae, a very high rate of input is required. The Russian astrophysicists V. L. Ginzburg and S. I. Syrovatsky, taking into account the possibility that the halo is quite leaky, concluded that an input of cosmic rays at about 10^{39} to 10^{40} ergs per second (the higher figure is probably more appropriate) would be required. If supernovae occur at a rate of about one every 100 years, this means that on the average a supernova would have to inject about $10^{40} \times 3 \times 10^{9}$, or 3×10^{49}, ergs of protons.

From direct observation we simply do not know whether this is a reasonable figure or not. However, Stirling A. Colgate of the New Mexico Institute of Mining and Technology has recently proposed a mechanism of particle acceleration in supernova explosions. He and his colleagues have considered the final evolution of a supernova and have made calculations of the conditions associated with the shock wave that moves outward from the central part of the highly condensed star. In the outer parts of the star the shock wave will turn into a blast wave that removes the material at high speed. Colgate concluded that a small fraction of the gas will reach relativistic velocities through this mechanism, and he showed that under suitable conditions the distribution of energy—the energy spectrum of these particles—is identical with that of cosmic rays. He also believes he can explain the observed composition of cosmic rays by this mechanism. His results are important because they show that particle acceleration can occur at this early phase in the injection of cosmic rays by explosive means, and no subsequent mechanism of acceleration is necessarily required. Still, because of the uncertainty concerning both the frequency with which supernovae occur and their energy input, it is not clear whether or not they could inject enough particles to account for the cosmic rays. Other possible sources must therefore be considered.

I have already mentioned the possibility that an explosion took place in the center of our galaxy some tens of millions of years ago. When Hoyle and I first suggested this possibility, we did not consider that such an outburst would have been a particularly strong source of cosmic rays, although it would surely have determined the conditions under which existing galactic cosmic rays would evolve. More recently Ginzburg and Syrovatsky have considered



CRAB NEBULA is a strong radio source inside our galaxy. It is the remnant of a supernova, a star that exploded in A.D. 1054. These photographs, made in polarized light (*arrows indicate the direction of the electric vector*), show that it emits by synchrotron radiation.



HALO is thought to surround the disk of some galaxies, including our own. The halo appears to be a roughly spheroidal region containing low-density gas (*color*) and weak magnetic fields. It may act as a leaky magnetic bottle that traps cosmic rays (*spirals*).

that explosions in our galaxy might be powerful injectors of cosmic rays and might even be as important as the supernovae. To understand their relative importance one would have to determine the detailed characteristics of an explosion in a spiral galaxy, and we have little knowledge of such matters at the present time.

Let us turn to possible sources outside our galaxy. Discussion of the existence of violent events on the galactic scale leads naturally to consideration of the role of sources of strong radio emission as sources also of cosmic rays. The places where the largest amounts of energy are known to exist in the form of relativistic particles are the strong extragalactic radio sources. It is easy to calculate from the synchrotron theory that there are fluxes of electrons amounting to some 10^{59} ergs and up for the strongest of these sources. The total energy contained in the cosmic rays in our own galaxy (assuming again that the energy density throughout the galaxy and the halo is about one electron volt per cubic centimeter) is only about 10^{56} ergs. Thus the energy contained in the electrons alone in some radio sources is several orders of magnitude greater. The radio sources give us no direct evidence on how much of their total energy may be in the form of protons and heavier nuclei, but most of the mechanisms of production of such fluxes of relativistic particles (about which, it must be admitted, we know very little at present) suggest that far more energy will be contained in the proton flux than in the electron flux. Calculations indicate that the total amount of energy in the strongest radio sources, largely in the form of cosmic ray protons, may be of the order of 10^{61} ergs or more.

There is high interest at the present time in understanding the mechanisms by which such tremendous fluxes of particles can be generated. I shall not touch on this aspect of the problem here but only accept that such fluxes do exist. What I shall attempt to show is that similar fluxes of particles may make a considerable contribution to the cosmic ray flux in our own galaxy if the particles can escape from the vicinity of the radio sources in a comparatively short time and eventually make their way to the vicinity of our galaxy.

I should stress at this point that I am mainly concerned here with fluxes of protons and heavier nuclei, and not of electrons. Any electrons that escape from radio sources will suffer large energy losses in the intergalactic medium. In particular, they will collide with photons in the microwave region of the electromagnetic spectrum. Investigations by Arno A. Penzias and R. W. Wilson of the Bell Telephone Laboratories and by a group at Princeton University have established that such a flux exists; it may be a relic of the "big bang" origin of the universe. This flux is so powerful that it presumably eliminates the bulk of the intergalactic electrons as cosmic rays, converting the energy into X rays and gamma rays by what is known as the "inverse Compton process." (Detailed calculations of this effect have been made by James Felten of the University of California at San Diego and by Philip Morrison of the Massachusetts Institute of Technology.) As a result the overall energy density of electrons between the galaxies is much less than either in the strong radio sources or in our own galaxy. Therefore, whereas the bulk of the cosmic ray nucleons may be extragalactic in origin, the small fraction of cosmic ray energy that is contained in electrons must come from collisions between the nucleons and atoms of gas in our galaxy or from supernova remnants in the galaxy, or from both.

A good example of a strong and extended radio source quite close to us is the source called Centaurus *A*, which is associated with a remarkable galaxy [*see illustration on page 38*]. Centaurus *A* is extremely large, with a total extent of nearly two million light-years, and it is only about 12 million light-years away from us. In this particular case, then, it is entirely possible that some part of the flux of the particles that have been generated in the radio source will eventually reach us. If one knows the average lifetime of a radio source and the frequency with which such sources occur among the total population of galaxies, and if one makes some estimates of the average energy generated in the form of relativistic particles in each radio-source event, it is possible to calculate what the total contribution of such strong radio sources to the intergalactic energy density of cosmic rays may be.

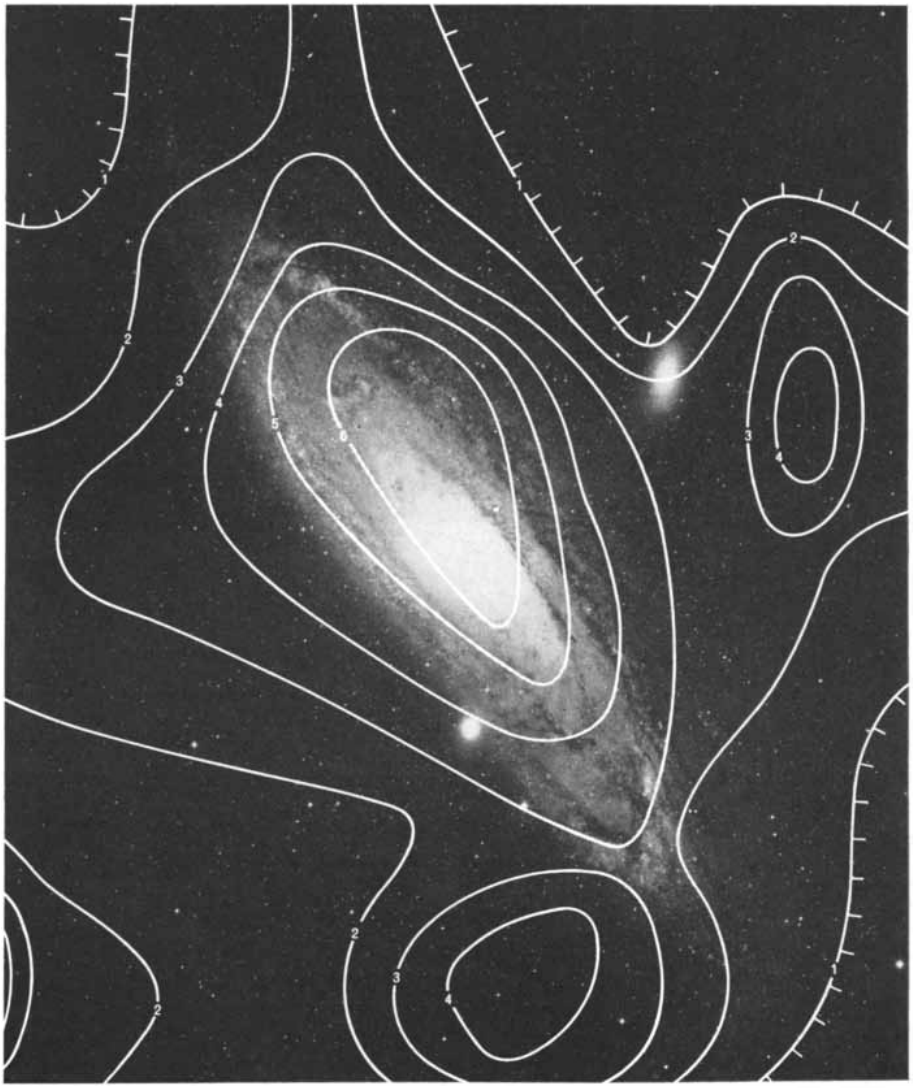
Four years ago I made a calculation along these lines, restricting myself to the radio sources known to be present in the Virgo cluster, a grouping of galaxies at the outskirts of which our own galaxy is situated. It is clear that the average lifetime of the radio sources

is quite uncertain, although it is probably comparatively short—only about a million years. The average energies are also most uncertain. In my investigation I concluded that the strong radio sources in the Virgo cluster, of which there are about six, might contain at the present time something of the order of 10^{60} ergs of particles. There are reasons for believing the bulk of these are high-energy protons. Assume that the rate at which radio sources have been arising in the Virgo cluster has remained constant over a time considered to be the "age" of the universe, which I shall take to be about 2×10^{10} years. If each of the radio sources has an average lifetime of a million years, there have been 2×10^4 "generations" of radio sources. Then the total energy in the particles they have produced is about 2×10^{64} ergs. Although these sources continue to radiate energy through their radio-emitting properties, that accounts for only a small fraction of the total energy contained in these particles; the bulk of the energy will escape from the radio sources. Assume that this energy is now spread uniformly throughout the supercluster; the total energy density of cosmic rays throughout the cluster will be about .1 electron volt per cubic centimeter. It is obvious that this number is rather uncertain. Still, it is close enough (within an order of magnitude) to the estimates of the energy density at the top of the earth's atmosphere for one to suggest tentatively that the contribution to the cosmic ray flux by sources such as this one outside our galaxy can be considerable.

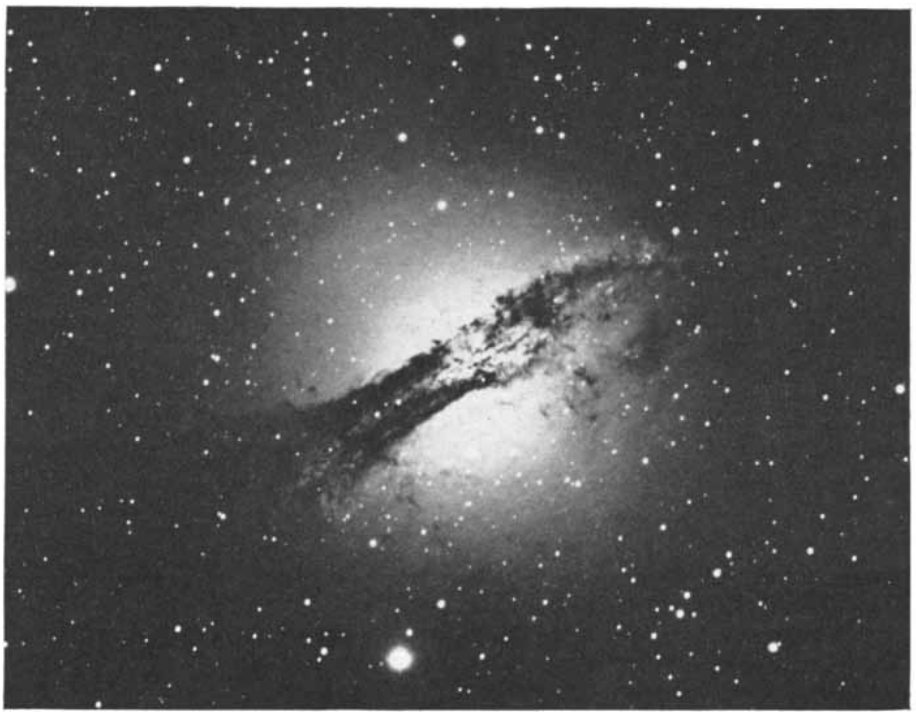
I have assumed that the energy is spread through the supercluster. How long might it actually take to fill up a whole cluster of galaxies by a mechanism of this kind? The cluster is about 50 million light-years in diameter. If the cosmic ray particles, which have velocities nearly equal to the velocity of light, were able to travel in straight lines, their travel time would be only 50 million years, and it might be expected that particles would diffuse throughout the volume of the cluster in a time that is quite short compared with the total time over which they have been produced.

But since the space between the galaxies is probably not completely empty (it may contain a very low density of gas and magnetic fields) the particles will in fact be guided by the magnetic fields. There are reasons to suppose that the gas between the galaxies may consist of rather large clouds that probably move with the same kinds of random velocities as the galaxies, that is, random velocities of about 1,000 kilometers per second. On this basis the cosmic ray particles that escape from the radio sources will diffuse through the cluster much more slowly, because instead of moving in straight lines from their point of origin they will move from one cloud containing magnetic fields to another, and their rate of diffusion will be rather slow. The total time it takes a particle to travel across a cluster of this size may depend on a velocity that is characteristic of the random velocities of the clouds and not of the velocity of light. It is easy to show that the diffusion time may be of the order of several billion years. If this is the case, it is quite possible that in the time available (if the cluster formed only 10 to 20 billion years ago) the particles have not yet had a chance to diffuse uniformly throughout the cluster; if they have diffused uniformly, they have done so only comparatively recently, as far as the total time scale is concerned.

On the other hand, the pressure exerted by such a flux of cosmic ray particles within a cluster, if this type of mechanism is operating, is considerable. If the density of gas between the galaxies in such a cluster is very low (of the order of one atom per 10^4 to 10^5 cubic centimeters), the cosmic ray pressure is considerably larger than either the gas pressure or the pressure exerted by the magnetic field; that is, it will build up to values much greater than these. As more and more cosmic rays are pumped into the cluster by the radio sources they will exert greater and greater pressure, and the effect will be that they will be able to diffuse more rapidly through the cluster and eventually begin to escape from it. If there are no limits on the time scale, then in tens of billions of years such cosmic ray particles will escape from the clusters



RADIO EMISSION from the Great Nebula (M 31) in Andromeda comes from an extended area around the galaxy, suggesting the presence of a halo. The map, plotted by John D. Kraus of Ohio State University, shows the relative intensity at various points of energy emitted at 1,415 megacycles. The photograph was made with the 48-inch Palomar telescope.



RADIO SOURCE called Centaurus *A* is associated with the unusual galaxy, NGC 5128, shown in this photograph made with the 200-inch telescope. The dark band is apparently a dust cloud. Radio energy emanates from a region many times larger than the optical galaxy.

of galaxies and begin to fill the space between them. Only under these conditions can we suppose there are truly intergalactic cosmic rays.

My investigations were made before the discovery of the quasi-stellar radio sources, or quasars, which were discovered only in 1963. These too presumably contribute to the cosmic ray flux, the extent of their contribution depending on how numerous they are compared with the radio galaxies. On the basis of rather poor statistics the quasars are now thought to constitute perhaps 30 percent of the identifiable radio sources. The total energy they contribute may therefore not significantly increase my estimates. But if there exists a more numerous class of quasi-stellar objects that have so far not been detected as radio sources (as Allan R. Sandage of the Mount Wilson and Palomar Observatories has proposed), and if each of these is a manifestation of an explosive event, the contribution may be much greater.

The idea that the strong radio sources may provide a significant contribution to the cosmic ray flux is still somewhat unorthodox. Although it is generally agreed that the very highest-energy cosmic rays are probably of extragalactic origin, most cosmic ray physicists still adhere to the view that the bulk of the cosmic rays probably originate with supernovae. To the extent that cosmic rays are generated outside our galaxy, these particles must be present throughout the universe. It can be objected that the total energy density of such universal cosmic rays could not be accounted for. I would argue that it is really only reasonable to compare the energy density of cosmic rays with the mass-energy density (applying the usual Einstein relation) of the intergalactic medium. Let us suppose the mean density of matter in the universe is about 10^{-5} atom, or 10^{-29} gram, per cubic centimeter. Then, since the square of the speed of light is 10^{21} centimeters per second, the mass-energy density (Mc^2) is 10^{-8} erg, or about 10,000 electron volts, per cubic centimeter. In the light of this relatively large total energy density a cosmic ray energy density of only one electron volt per cubic centimeter—all that is required to fill the universe uniformly with cosmic rays—is after all a negligible amount.

A more serious objection that has been raised involves the source of this energy. If it comes from the fusion of hydrogen into helium inside stars, which has been thought to be the most powerful source of energy available, there is a conflict with the known abundance ratio of hydrogen to helium. That is, it would appear that all the hydrogen in the universe would by now have been converted to helium. The fact is, however, that accounting for the vast energy in the quasars and perhaps in other strong radio emitters is so difficult that processes other than fusion are already being considered. One possibility is that a significant fraction of mass has been converted into the energy of relativistic particles through the mechanism of gravitational collapse: One can imagine that a supermassive star, having exhausted its thermonuclear fuel, would collapse under the gravitational influence of its own mass, and that at a critical radius much of the mass might be released as gravitational energy. Although this hypothesis is in difficulty at the moment, many of us believe such energy conversion is in fact possible.

Another problem associated with the extragalactic theory is that if the cosmic rays have a large energy density, they might heat up the intergalactic gas. The time it would take for this to happen, however, would be very long and might not be incompatible with the upper temperature limit (a few million degrees) set by rocket observations of celestial X rays. Finally, the entire argument developed here depends on the hypothesis that a large flux of relativistic protons and heavier nuclei accompanies the flux of relativistic electrons detected indirectly through synchrotron emission; there is no direct evidence, it might be objected, that such fluxes of nucleons are in fact produced. The same objection can be raised to the supernova hypothesis for the origin of cosmic rays, however. Here again the argument in its modern form has been developed by consideration of the radio-emitting characteristics of the supernova remnants and the realization that this means there is a large flux of relativistic *electrons* in the sources; the supernova hypothesis is just as lacking in direct evidence for the presence of relativistic protons.

To sum up, the discovery of the strong radio sources and the realization that they contain immense fluxes of relativistic particles has suggested that they may have something to do with the origin of cosmic rays. We do not know how large a contribution such external galaxies may make in the course of the explosions that give rise to the relativistic particles. It is entirely possible, however, that they do make a sizable contribution, and it is not out of the question that they may be the dominant source of cosmic rays in the universe. If such a viewpoint is accepted, one should point out that at least some cosmic rays are samples of material from other galaxies—the only samples we are likely to obtain for a very long time.

Success one way and another

The KODAK INSTAMATIC Camera has helped us outperform the civilian economy average in a manner most beautiful and heartwarming. Wives and mothers and, yea, husbands, fathers, sons, and daughters proved to us by the gratifying millions that all they wanted were results and that drawing their attention to technical details only made them nervous. So we told them to leave everything to us.

Concurrent with this success is one of even greater importance in respects other than financial that has been attained at the other end of the spectrum of technical concern. Here the customers are absolutely, positively fearless. To ask such customers to leave everything to us is to speak foolishly in a hostile tongue. They are the integrated-circuit makers, whose accomplishments are doubtless well represented on other pages of this magazine. Five years ago we were writing about use of our light-sensitive resists, plates, and chemicals to manufacture electronic circuits the size of one of our periods but were just barely believing it. Now we believe. It wasn't just a stunt. Electronics has changed to sound like this:

Q. Were these unexposed wafers?

A. No, these have been exposed.

Q. Were they developed?

A. No, I said they were exposed to a high-pressure mercury source, but they were not developed. They were exposed because they would have to be exposed during the course of measurement.

Q. How thin a film can you measure?

A. VAMFO can measure films as thin as 800A (by means of a violet filter). There are no minima for thicknesses between about 1250A to 2100A. By using the thinnest possible oxide layer under the resist, it should be possible to measure a short range of extremely thin resist films—how precise such measurements would be I cannot say. In these studies, the oxide layer was 950A-1100A (in order to use the bright 5461 filter), and it should be possible to measure a resist film of about 1000A; but with the model I used, the thinnest film I was able to measure was about 1250A.

Q. How thick a film can you measure?

A. The thicker the better; there are more minima in thicker films and the results are more precise. In this series the thickest film was 3.2 microns.

Q. What kind of spin table did you use?

A. One that was designed at IBM.

Q. Where was the spin table used?

A. In a standard Whitfield hood.

Q. What happens to the resist as it is spun on the wafer?

A. It just spins off into the cup that fits around the vacuum chuck. If the cup is kept clean, there is a better chance that the spin table will stay trouble-free.

Q. Have you evaluated the effect of applying the resist to a spinning wafer?

A. We had done a very few experiments and I would say that the thickness is somewhat less under these conditions, but we have not pursued this. One of the reasons is that when we started the work, the spin table had to be manually controlled, and it was difficult to control the Variac and apply the resist simultaneously; so we standardized the procedure to apply resist from the stationary position. Perhaps there is a reduction in thickness of about 5 to 10 percent when it is applied to a spinning wafer, but I can't be definite about that figure.

Q. Is there a resist rim on the wafer?

A. Yes, but I confess that it doesn't bother us too much because those devices at the edge are mangled by tweezers sometimes. Until we run into trouble with mask contact it's a problem we just don't worry about.

Q. Can you see the 100A step?

A. Perfectly.

This bit of by-play gives the flavor of the question period following one of the 12 presentations recorded in *Proceedings of the 1965 Kodak Seminar on Microminiaturization*, a document we had better get fast into the hands of those who have professional need for it, before the passage of a few more months adds hopelessly to its antiquity.

Address requests to Dept. 454, Eastman Kodak Company, Rochester, N.Y. 14650. It is quite unlike the old pamphlets about delightful snapshooting. We seem to have made photofabrication possible but not very easy, though amazingly successful.

Those who have no direct need for the Proceedings *might want to buy a copy from us anyway for $1, just to watch the delicate interplay among gifted people from companies trying to exchange help in a great technological endeavor without abandoning too much hard-won intellectual property.*

Friends of physics in white overalls

• To the Quantum Electronics Conference of the American Institute of Physics and the Institute of Electronic and Electrical Engineers came word on April 13, 1966 from United Aircraft Research Laboratories by A. J. DeMaria and associates that EASTMAN 9740 Q-Switch Solution, fruit of our flasks, could do significantly more for 1.06μ neodymium lasers than just Q-switch them. It also mode-locks.

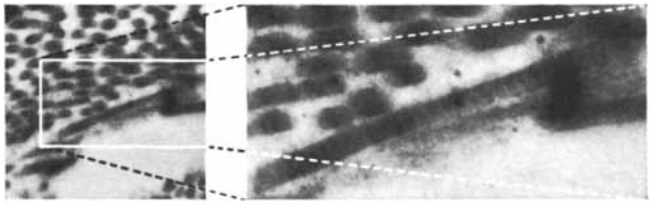
The Q-switches available before our dye-makers were called to the service of quantum electronics simply blocked light first and then opened up. Our product isn't just go or no-go. It attenuates low intensities preferentially. Furthermore, our dye recovers its opacity quicker than light takes to make a round trip between the laser mirrors. In consequence of these two points of distinction, the axial modes all come into phase at regular intervals.

Axial modes are the various discrete frequencies jointly permitted by the Nd^{+++} energy levels and by the necessity that inter-mirror distance divided by wavelength must be an integer, albeit a large one. The glassy environment of Nd^{+++} in KODAK Laser Glass unsharpens its transitions to the point that DeMaria is exciting some 30,000 axial modes (= frequencies). Every time they go into phase with each other, the interference effects work out to concentrate the radiation into a short pulse. The more modes the shorter the pulse, just as the more lines in a diffraction grating the better the resolution. EASTMAN 9740 thus turns the spectral breadth of KODAK Laser Glass emission into an asset by packing the energy into pulses calculated to be around 2×10^{-13} sec wide. Slugs of light like that are only 0.006 cm long, or 60 wavelengths. In a span of 30 optical cycles instantaneous power level rises from zero to several gigawatts. That's a lot of naked power to get out of a paltry thousandth of a joule of energy in each pulse. Interesting nonlinear optical effects may not be all that will come out of this.

• A coordination compound of sulfuric acid with that well-known and popular amino acid glycine is ferroelectric. Memory and switching devices employ it. The volume of solid-state discourse already in print about it alerts us to the possibility that solid-state physics will soon turn its thoughts in a big way to the wonderful world of organic molecules. We are ready with *Glycine Sulfate* as EASTMAN 9921.

One of the early lessons learned by serious newcomers to the wonderful world of organic molecules is that the great index of off-the-shelf availability is the catalog of EASTMAN *Organic Chemicals. The 44th edition is just off the press. It,* EASTMAN *9740 Q-Switch Solution, and* EASTMAN *9921 are available from Distillation Products Industries, Rochester, N.Y. 14603 (Division of Eastman Kodak Company). Absence of a molecule from the catalog is no indication we couldn't be persuaded to make it.*

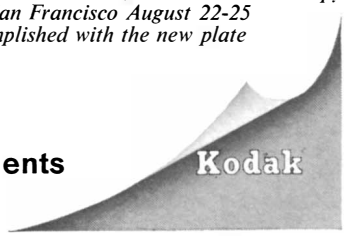
To understand life



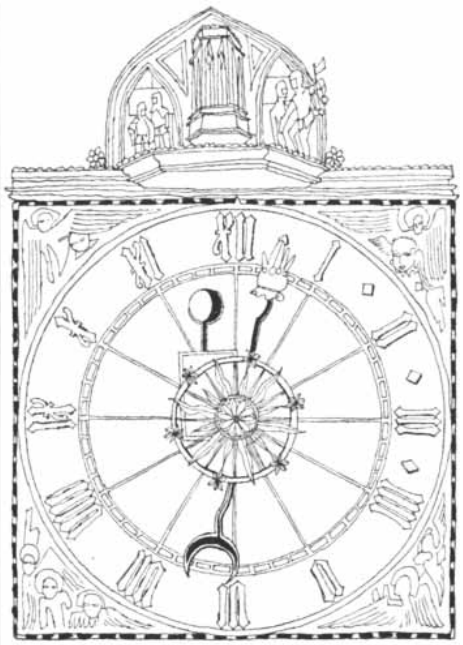
Left, without change of the original 10,000× magnification obtained from 100-KV electrons, we show the new KODAK Electron Image Plate rendering collagen fibers in human skin. We also try to show how much detail is available in the plate for further exploitation by optical enlargement after the plate manufacturer has taken measures against fuzziness from high-energy electrons that penetrate all the way through the emulsion and then bounce back. Whether the improvement will contribute to a better understanding of life processes, time will tell (but probably only in a murmur).

Eastman Kodak Company, Special Applications, Rochester, N.Y. will be delighted to name local sources of supply for the new plates, should the information be required. Any electron micrographers who would care to stop in at our exhibit at the Electron Microscopy Society of America meeting in San Francisco August 22-25 will be shown what can be accomplished with the new plate through variations in processing.

The hope of doing each other some good prompts these advertisements



SCIENCE AND



The Underground-Test-Ban Debate

A sharp debate continues within the U.S. Government over whether or not to seek a ban on underground nuclear tests. In mid-June it was reported that the Administration was leaning toward a ban on larger underground tests, which could be readily monitored by sensitive new seismic arrays (see "The Detection of Underground Explosions," by Sir Edward Bullard, SCIENTIFIC AMERICAN, July). The ban would apply to all tests that produced a seismic signal of 4.75 or more on the nine-point Richter scale. The size of explosion needed to produce such a signal would range from about 20 kilotons (if the shot were set off in the volcanic rock called tuff) to perhaps 50 kilotons (if it were set off in an unconsolidated alluvium). Late in June it appeared that the Administration was having second thoughts and would not propose the limited ban after all. According to *The New York Times* the basic objection "was that the small political gains of such a step were outweighed by the possible military risks."

This report appeared only two days after Jerome B. Wiesner, provost of the Massachusetts Institute of Technology and scientific adviser to President Kennedy, had testified before the Senate Foreign Relations Committee that the U.S. would incur "very little risk" even if it agreed to a complete ban on underground testing without provision for inspection. Said Wiesner: "The detection system is adequate to safeguard against any clandestine activity that would be a significant threat to our security." He observed that the U.S. would be better off today if it had signed a complete test ban in 1958, inasmuch as the U.S.S.R. has made greater progress in nuclear weapons than the U.S. since that time. Wiesner deplored the tendency "to judge arms control in the light of the most dangerous possibility, no matter how unlikely, and to give no weight at all to the consequences of failing to halt the arms race."

Meanwhile American and Russian officials, who attended a four-day nongovernmental conference in Canada, supported a proposal that the nuclear powers accept a moratorium on all underground tests for a limited "trial period" and agree to a system of "verification by challenge or invitation." The conference, which brought together disarmament specialists from 25 nations, was called the International Assembly on Nuclear Weapons. It was sponsored by the Canadian Institute of International Affairs, the Institute for Strategic Studies of London, the Carnegie Endowment for International Peace and the American Assembly of Columbia University. Participants at the conference included Adrian A. Fisher, deputy director of the U.S. Arms Control and Disarmament Agency; Vasily S. Yemelyanov, chairman of the Soviet Academy of Sciences' Commission on the Scientific Problems of Disarmament, and Lord Chalfont, the British Minister for Disarmament.

One clue to the reluctance of some U.S. officials, particularly in the Atomic Energy Commission, to support a ban on underground tests was provided by Lord Chalfont in an interview with a correspondent for *The New Yorker* in Geneva. "At this particular point," he said, "I have no hesitation in stating that Plowshare [the AEC program to use nuclear explosives for civilian engineering purposes] and the considerations it raises are definitely impairing the efforts by this conference to arrive at a comprehensive test-ban treaty."

Bias for the Positive

An absolute way to determine whether a body anywhere in the universe is composed of matter or antimatter has been established. Previously it had been thought that if we were in communica-

tion with intelligent organisms on another planet there would be no unequivocal way to tell them what we meant by a positive (or negative) charge. If their planet happened to be composed of antimatter, any experiment we might propose using what we call particles (protons, neutrons and so on) they could perform with antiparticles (antiprotons, antineutrons and so on) and get the same result.

The decisive experiment that makes it possible to define what physicists, by convention, know as a positive charge was performed at the Brookhaven National Laboratory. It involves the decay of the neutral eta meson (which is its own antiparticle) into three pions, or pi mesons: one positive, one negative and one neutral. If particle-antiparticle symmetry were strictly observed, one would expect that the positive and negative pions—which are antiparticles of each other—would, on the average, carry away equal amounts of energy. Such a result would be evidence for *C*-invariance, or charge-conjugation invariance, the term given to the symmetry of matter and antimatter. It had been suggested, however, by Tsung-Dao Lee of Columbia University and Lincoln Wolfenstein of the Carnegie Institute of Technology that *C*-invariance might be violated in the decay of the eta meson. In that case either the positive or the negative pion might emerge from the reaction with the greater energy.

To make the test 435,000 pictures were taken of events in a 30-inch bubble chamber filled with liquid deuterium. The eta mesons were produced by the collision of positive pions and deuterons; the pions, in turn, were produced by protons accelerated in the 30-billion-electron-volt Brookhaven synchrotron. Detailed measurements of the tracks in 80,000 photographs led to the selection of 1,441 examples of eta decay on which the results were based. It was found that the positive pion emerged with more energy than the negative pion in 7.2 percent of the decays, with an uncertainty of ± 2.8 percent. The odds are 1,000 to one that this result could not have happened by chance.

A civilization anywhere in the universe that could repeat this experiment—even if it began with antiprotons accelerated in a synchrotron made of anti-

matter—should get the same result and thus know what we mean by a positive charge: it is the charge on the more energetic of the two charged pions produced by an eta decay.

The eta-decay experiment was reported in *Physical Review Letters* by Charles Baltay, Paolo Franzini, Jewan Kim, Lawrence Kirsch and Dino Zanello of Columbia University and Juliet Lee-Franzini, Richard Loveless, John McFadyen and Harold Yarger of the State University of New York at Stony Brook. Similar results were obtained by a team under E. C. Fowler of Duke University and by a consortium of workers from Columbia University, the University of California at Berkeley, Purdue University, the University of Wisconsin and Yale University.

Drugs Revisited

The National Academy of Sciences–National Research Council, at the request of the Food and Drug Administration, is about to undertake an evaluation of the effectiveness of some 3,000 to 4,000 drugs introduced during the period from 1938 to 1962. It was in 1962 that the Kefauver-Harris amendments to the Food, Drug and Cosmetics Act required manufacturers to submit substantial evidence supporting therapeutic claims before receiving FDA approval of new drugs. The same amendments called for an evaluation of the efficacy of drugs marketed between 1938 and 1962, when only proof of safety was required.

The NAS-NRC study, which will include most of the drugs now in general medical use, will be directed by an advisory committee under the chairmanship of William S. Middleton of the University of Wisconsin School of Medicine. The advisory committee will be responsible for the selection of approximately 30 review panels totaling 150 specialists in the various categories of drug usage established for the study. The committee will also develop guidelines to be followed by the panels in rendering their judgments and will coordinate the panels' recommendations for submission to the FDA.

Smoking Dogs

Emphysema, a lung disease that caused more than 17,000 deaths in the U.S. in 1963, has been produced in dogs by inducing them to smoke cigarettes. The disease is about 13 times more common among cigarette smokers than among nonsmokers. The death rate from emphysema has increased nearly sixfold in the past 10 years. The disease now afflicts more people than lung cancer and tuberculosis combined. Lung cancer, however, is more frequently fatal; it caused more than 40,000 deaths in 1963.

The experiment with dogs was designed to duplicate human cigarette smoking as closely as possible. The dogs (beagles) inhaled cigarette smoke through tubes inserted in their tracheas. Of 10 dogs in the original group five died in the course of the experiment. The deaths were caused by blood clots in the heart and lungs and by pneumonia. The five surviving dogs were sacrificed after smoking about half a pack of cigarettes a day for 60 weeks. The lungs of all 10 dogs exhibited pathological changes indicating varying degrees of emphysema. The changes, indistinguishable from those that characterize emphysema in humans, were absent in 10 dogs used as controls.

The experiment was conducted by Oscar Auerbach and David Kirman of the Veterans Administration Hospital in East Orange, N.J., and by E. Cuyler Hammond and Lawrence Garfinkel of the American Cancer Society. They reported that dogs reacted to smoking much as humans do. At first some of the dogs became dizzy and nauseous. Later some "showed evidence of liking cigarette smoking . . . by wagging of tail and jumping into the smoking box voluntarily."

The Chemistry of Memory

A biological chemist, using goldfish as experimental animals, has found that injections of a drug that inhibits the synthesis of protein do not affect the fishes' ability to learn but strongly affect their ability to store what has been learned. Writing in *Proceedings of the National Academy of Sciences,* Bernard W. Agranoff of the University of Michigan suggests not only that short-term memory is physiologically distinct from long-term memory but also that chemical changes are vital to the development of long-term memory.

Agranoff's goldfish were trained by electric shock during a 20-trial session to swim from the light to the dark end of a tank; in uninjected fish, memory of the training persisted for at least 30 days. The antibiotic puromycin, the molecular structure of which is similar to that of the ribonucleic acid that transfers amino acids to the growing protein chain ("transfer RNA"), was injected into the skulls of some of the fish either immediately before or immediately after the training session. The drug temporarily suppressed from 50 to 80 percent of normal protein synthesis in the fishes' brains. When reexamined three days later, the injected fish were no more proficient at avoiding shocks than untrained fish. When the injections preceded training by 20 minutes or followed it by an hour, the test fish achieved almost as good results as did trained but uninjected fish when both were reassessed after an identical three-day waiting period. It was thus apparent that the puromycin had exercised its effect within a limited span of time.

A further experiment assessed the retention of memory by goldfish that had been injected immediately after training at intervals one, three and six hours and again 24, 48 and 72 hours later. As much as six hours after injection the fish gave no evidence of memory decay. After 24 and 48 hours, however, their performance had become increasingly poor; after 72 hours they scored no better than untrained fish did.

Agranoff interprets his findings to mean that, although the goldfish form a short-term memory during training that is resistant to the effect of puromycin, none of this memory remains after 72 hours and the puromycin meanwhile has prevented any of it from being transformed into long-term memory. He concludes that protein synthesis may be a key factor in the fixation of long-term memory, perhaps because it fosters the growth of nerve cells, synaptic processes or other structures of the central nervous system.

Dairy Proteins from None

Dairy cattle fed a synthetic diet entirely lacking in protein continue to produce milk with the usual protein content and to drop calves whose meat is of a quality equal to that from cattle on normal feed. This achievement, recently announced by the Department of Agriculture, has considerable significance not only for underdeveloped areas that are short on the high-protein feeds usually thought necessary in cattle husbandry but also for such affluent areas as the Hawaiian Islands, where a shortage of adequate pasturage has traditionally meant inferior dairy products from local herds.

The achievement is the work of the Finnish Nobel laureate A. I. Virtanen, director of the Biochemical Research Institute in Helsinki, whose experiments have been supported by U.S. funds

Sylvania ECG finds the way to space-proof readout panels

Problem: Find a way to make illuminated readout panels withstand all the rigors of extended space travel.
Solution: The Sylvania Electronic Components Group turned to the solid-state reliability of electroluminescence.

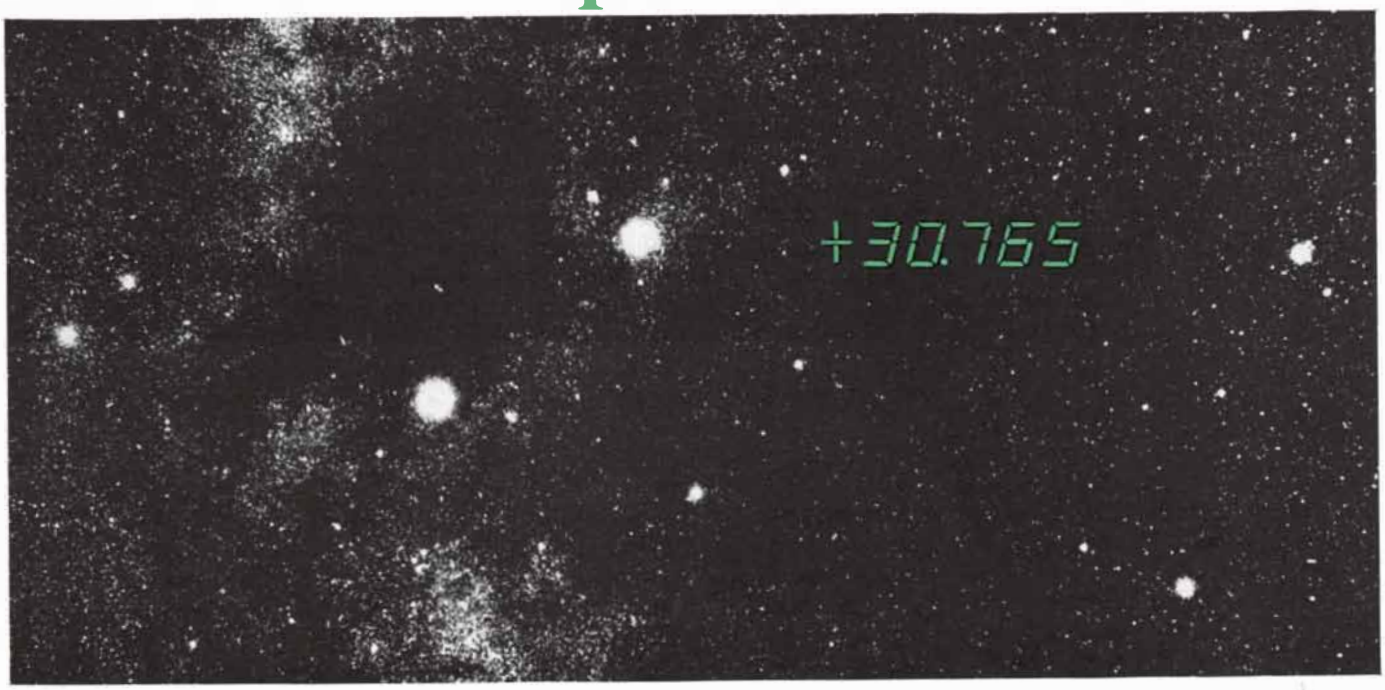
The result is a new generation of ultra-compact electroluminescent readout displays built in sandwich form and which can be operated completely from solid-state devices. Each one is capable of reading out numerals or letters at speeds greater than the eye can detect.

The units are hermetically sealed, and built to rugged specifications so that they can easily withstand 50-G shock, and provide continuous illumination for 10,000 hours with negligible current drain from the space capsule's power source.

These new Sylvania EL readout panels are being used by the Sylvania Electronic Systems Division in Project Apollo.

Making readout devices spaceworthy is another example of advanced component design resulting from Sylvania ECG *integrated* research and engineering, and its pioneering in EL readout development. It's a point to keep in mind the next time you have a design problem.

Sylvania Electronic Components Group, Sylvania Electric Products Inc., Seneca Falls, N. Y. 13148.



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since 1959. Essentially the process depends on the gradual development in each cow's rumen of a microbial population that is capable of synthesizing essential amino acids from nitrogen supplied to the animal in the form of urea and ammonium salts. Each of the six milk cows in the experiment was gradually fed an increasing proportion of synthetic food during its dry period until finally its daily ration consisted of 20 pounds of briquettes containing starch, cellulose, sucrose, urea and ammonium salts, together with eight pounds of a cellulose-rich wet paste and small amounts of corn oil and vitamins A, D and E. To assist rumination the cows also received strips of cellulose, impregnated with silicic acid, in lieu of hay; to assist salivation they were allowed to chew on hard-rubber tubing.

Nourished only by this synthetic diet, Virtanen's six Ayrshires produced an average of 9,460 pounds of milk annually, a yield nearly equal to the average of their breed in Scandinavian countries. Chromatographic analysis of their milk reveals some differences from normal milk in the content of volatile substances. Virtanen reports, however, that the milk tastes like any other milk and has no odd flavors; its nutrient content of fat, nonfat solids, sugar and proteins is identical with that of milk from cows fed on normal rations.

Experiments on Man

A distinguished medical investigator has raised disturbing questions with regard to the ethics of clinical research, or research conducted in the course of treating human patients. In an article in *The New England Journal of Medicine* Henry K. Beecher of the Harvard Medical School addresses himself specifically to "experimentation on a patient not for his benefit but for that, at least in theory, of patients in general." A primary component of an ethical approach, Beecher writes, is informed consent by the patient or his guardian; such consent is often not obtained, he maintains. Moreover, the anticipated gain from an experiment should be commensurate with the risk. Beecher cites examples of studies in which known methods of treatment were withheld in spite of a known risk, new techniques were tested that had no relation to the patient's needs, drugs known to be toxic were administered in order to study their degree of toxicity and physiological experiments were performed on sick patients.

In one case, according to Beecher, penicillin was withheld from a control group of servicemen with streptococcal infections even though the antibiotic is a known preventive for rheumatic fever; several men thereupon developed the disease. A different antibiotic, suspected of interfering with liver function, was administered to inmates of a children's center to treat nothing more serious than acne; several cases of liver damage resulted. During a series of surgical operations carbon dioxide was injected into the anesthetic breathing mixture until toxic levels were reached and the patients' heart rhythm was disturbed. Eighteen children undergoing heart surgery served incidentally as subjects of a study of skin-graft survival with and without removal of the thymus gland.

Beecher points out that in view of the proved value of human experimentation unethical practices are likely to increase as more money is made available for research and as the pressure on young physicians to "investigate" builds up. He suggests that perhaps editors of medical journals should reject reports, no matter how valuable, based on improperly obtained data and thus possibly discourage unethical experimentation.

Endless Bread

A traditional distinction in manufacturing processes is made between a batch process and a continuous process, the former being unavoidable in the manufacture of many products and the latter being favored for its efficiency. Now a process that has seemed the quintessence of batch manufacture has been converted to the continuous system. It is the making of bread.

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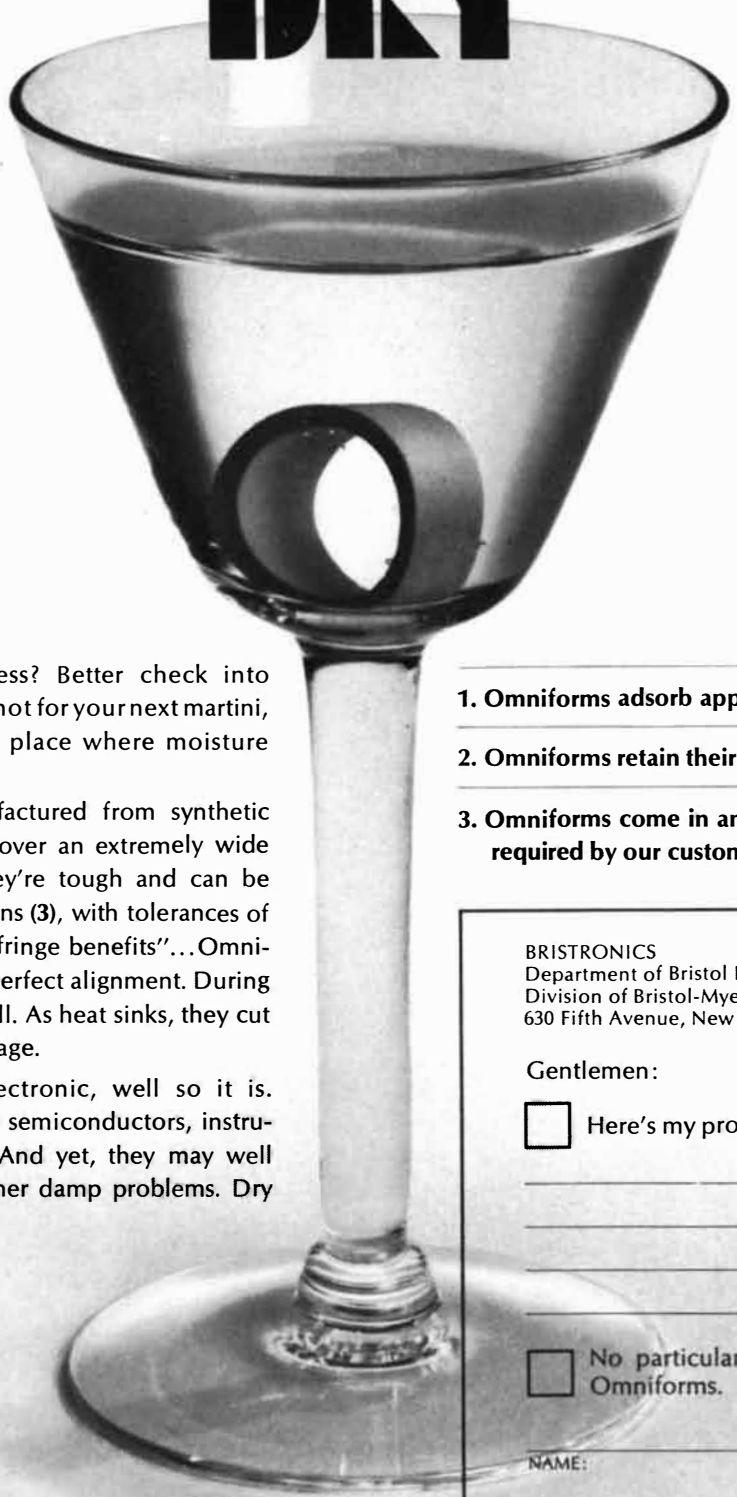

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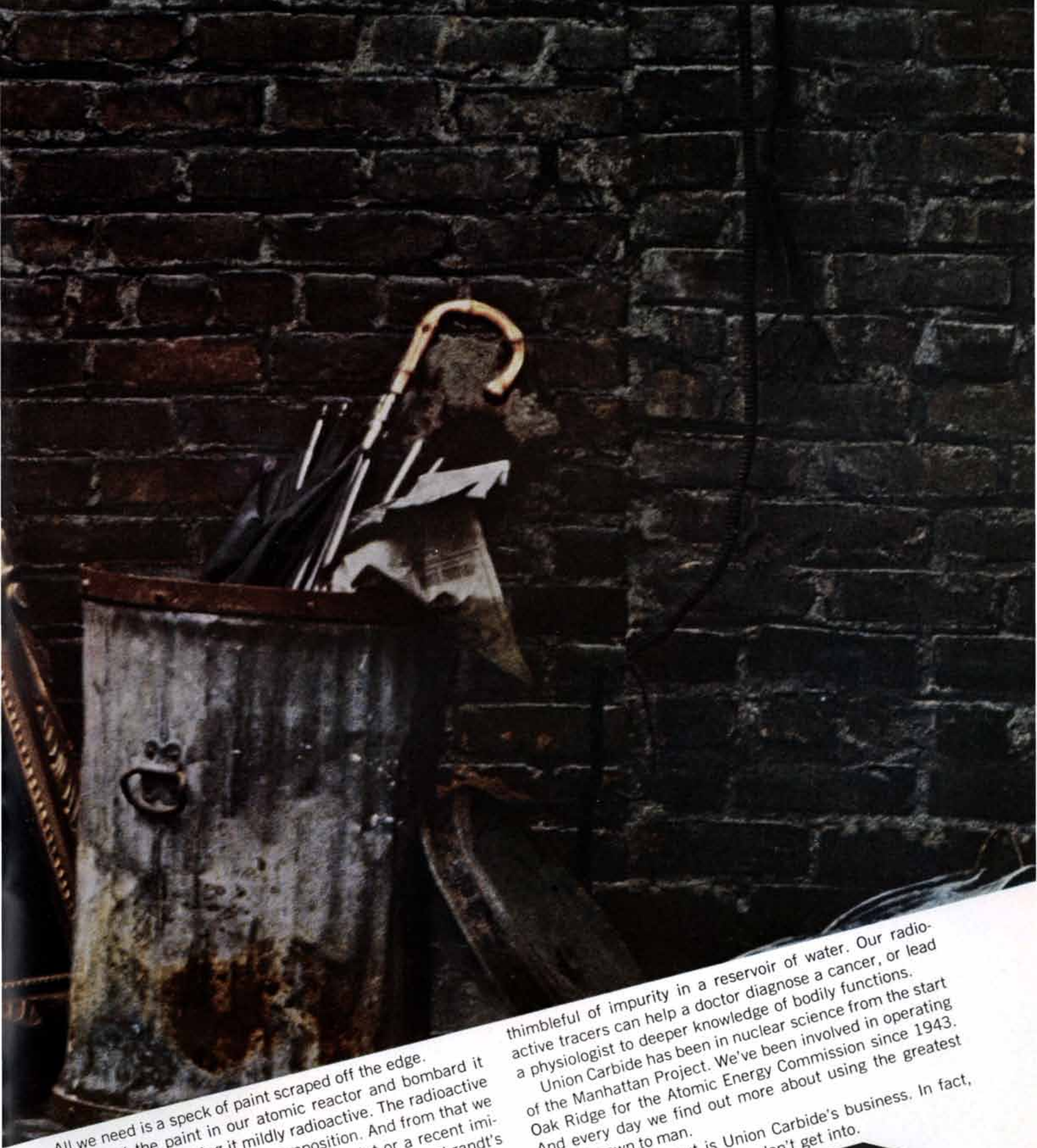

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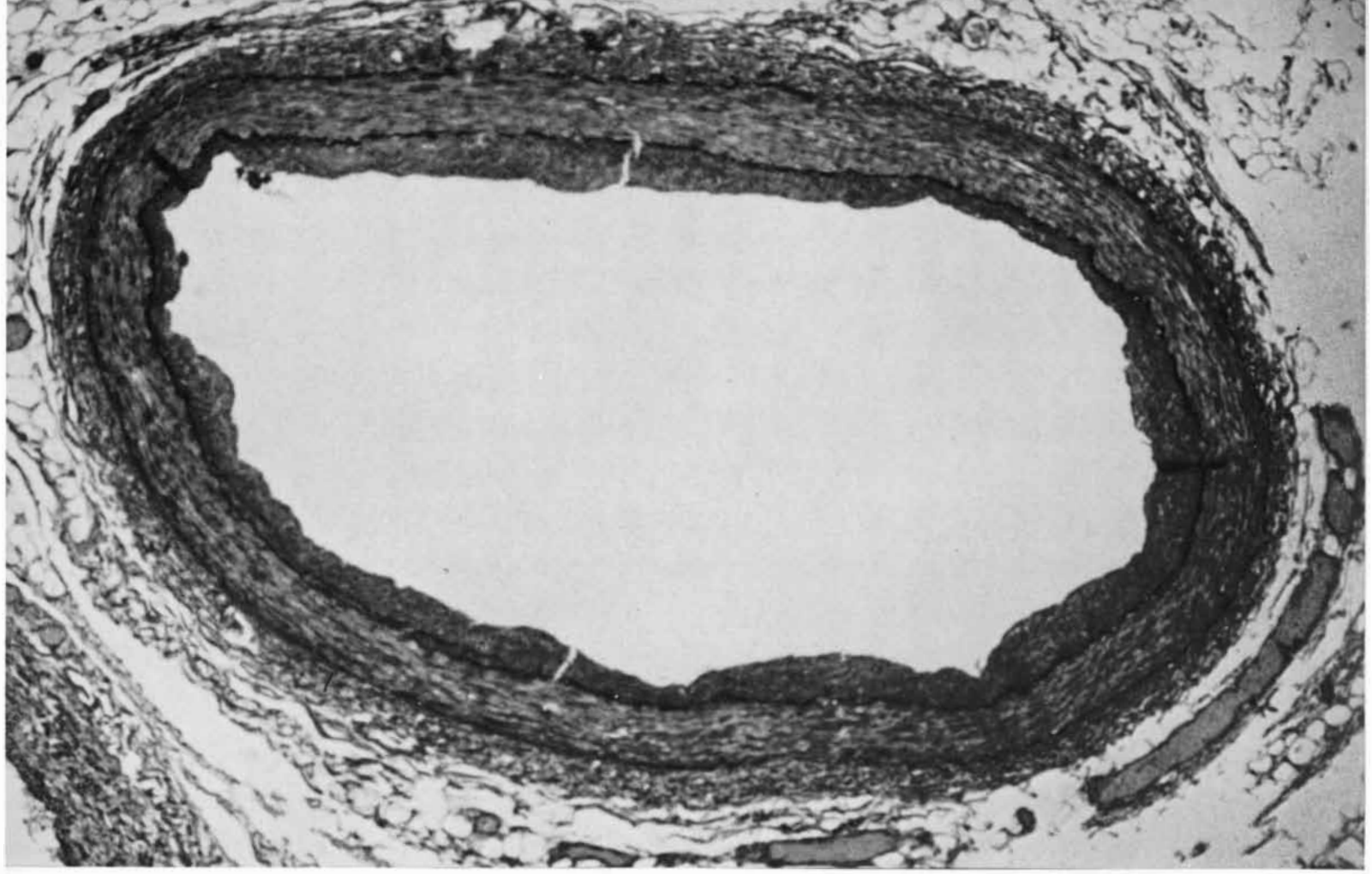
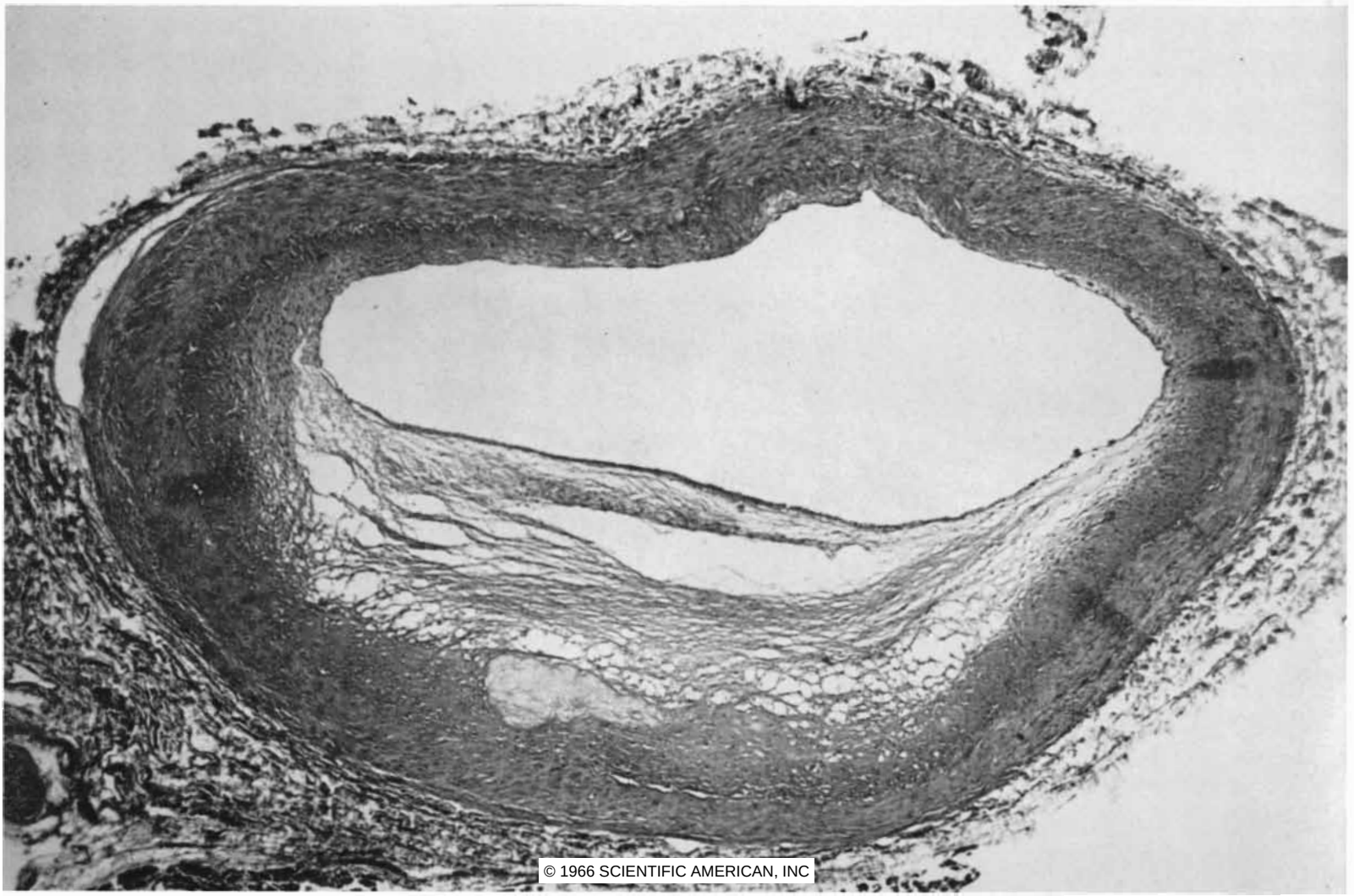


HUMAN CORONARY ARTERY is enlarged about 38 diameters in these photomicrographs made by the author. A normal artery is seen in cross section (*above*). In a diseased artery (*below*) the channel is partially occluded by atherosclerosis. Fibrous scar tissue, with fatty deposits (*clear areas*) in it, and other materials have thickened the arterial wall, reducing the blood-carrying capacity.



ATHEROSCLEROSIS

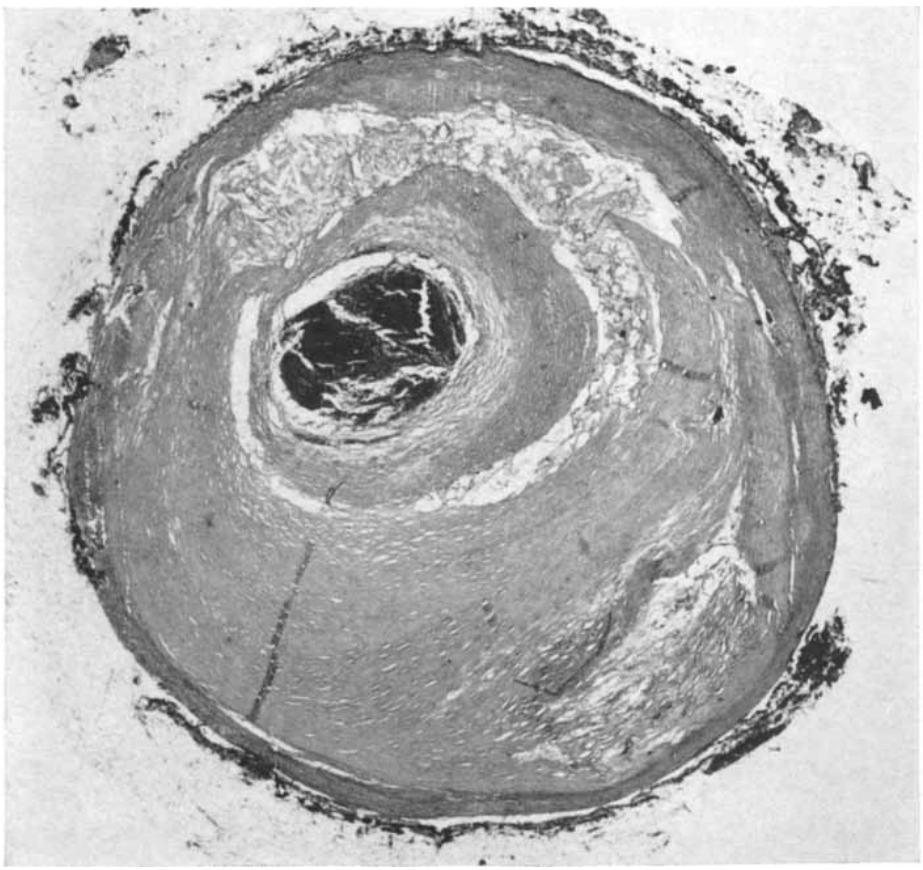
The artery disease that is responsible for most heart attacks is on the rise in the U.S. Its prevalence seems to be related to diet, so there is hope that the epidemic can be controlled

by David M. Spain

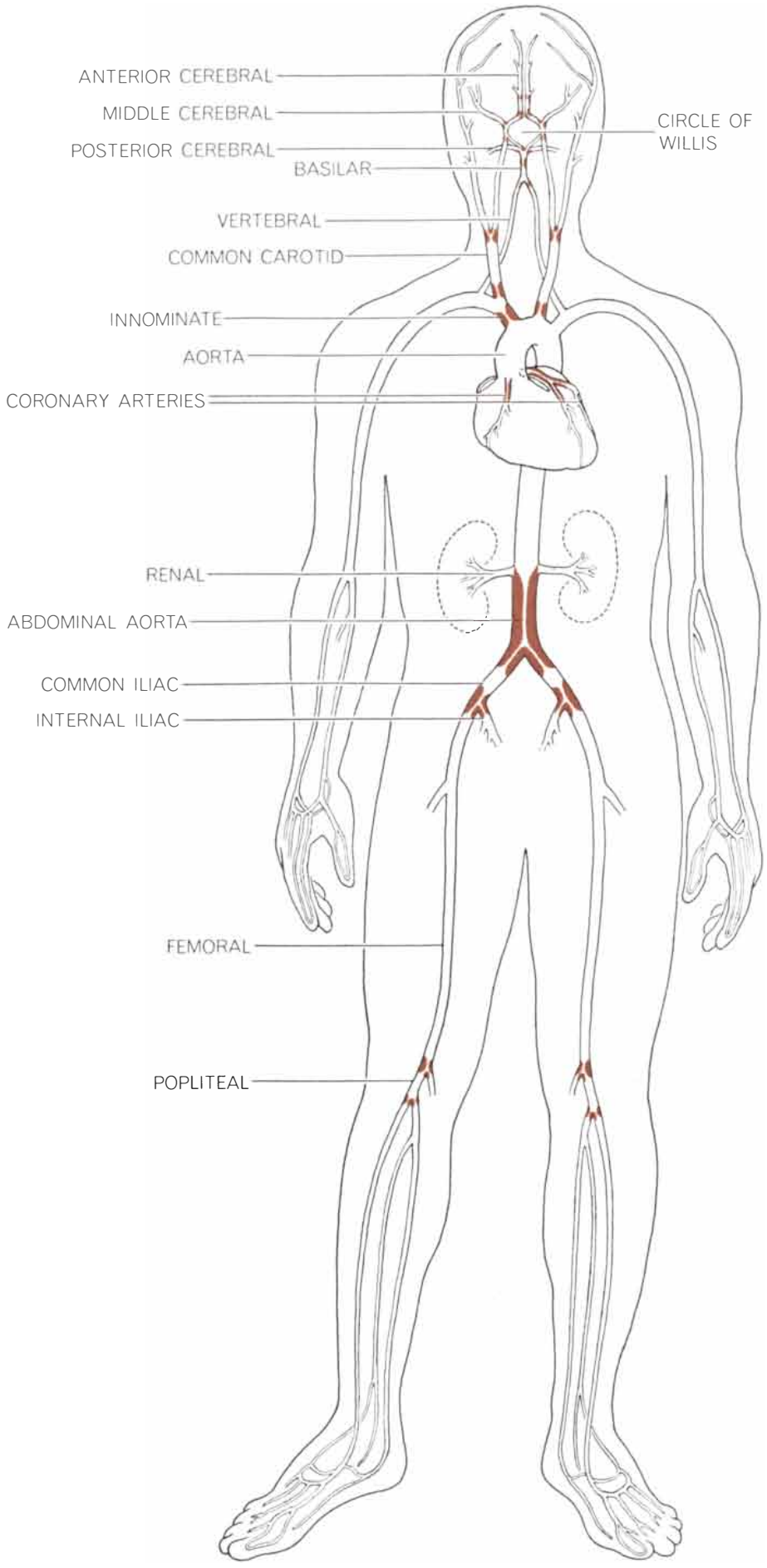
The incidence of heart attacks among adult white males in relatively affluent occupations in the U.S. has reached epidemic proportions. From such attacks (coronary artery occlusions) the overall U.S. death rate is now 500,000 a year, and 200,000 more die from strokes. At least 5 percent of the adult males in the nation show signs of some form of heart disorder. The basic disease responsible for most of these disorders and deaths is atherosclerosis. There is every indication that the prevalence of atherosclerosis in the U.S. is steadily increasing.

It used to be thought that atherosclerosis was a disease of old age and that its rising incidence might be due simply to the lengthening of the average life-span by the control of infectious diseases. This idea has now been refuted by a number of studies. My colleagues and I have made a comparative examination in Westchester County, New York, of two samples of the population taken 20 years apart. The samples were comparable in that both groups covered the same age range (from 20 to 60), had records of good health before a fatal episode, had died of sudden causes not connected with heart disease and had been autopsied after death, so that the extent of atherosclerosis in their coronary arteries and aortas was known. The first sample consisted of people who had died of acute infections in the period between 1931 and 1935; the second was made up of people who had been killed in automobile or industrial accidents between 1951 and 1955. We found that the second group, representing a period 20 years later than the first, had a significantly greater amount of atherosclerosis. This was true for every age level: the young people in the second group had more atherosclerosis than the young ones in the first. A similar autopsy study in Sweden yielded the same finding; the degree of coronary atherosclerosis in a population sample in 1958 was greater than in a sample from 1934.

Laboratory studies of experimental animals and postmortem examinations of human infants have established that the development of atherosclerosis often begins shortly after birth. Fatty streaks signaling the beginning of atheromas have been found in many human aortas as early as the age of three. In a group of U.S. soldiers killed in the Korean war whose average age was only 23, examination showed that most had extensive formations of atherosclerotic "plaques" in their arteries. In our study of accident victims in Westchester County we found that many 35-year-old males who had shown no indication of heart disease nevertheless had their coronary arteries so thickened by atherosclerosis that the channels were narrowed by 50 percent. It has become



CRITICAL STAGE in the process under way at the bottom of the opposite page occurs when the atherosclerosis has advanced and a blood clot almost fills the constricted channel.



FAVORED SITES of atherosclerosis are indicated in color in this diagram of the major arteries. There is a tendency for the disease to begin at points where an artery branches.

quite clear that atherosclerosis is a widespread disease of the young as well as the old.

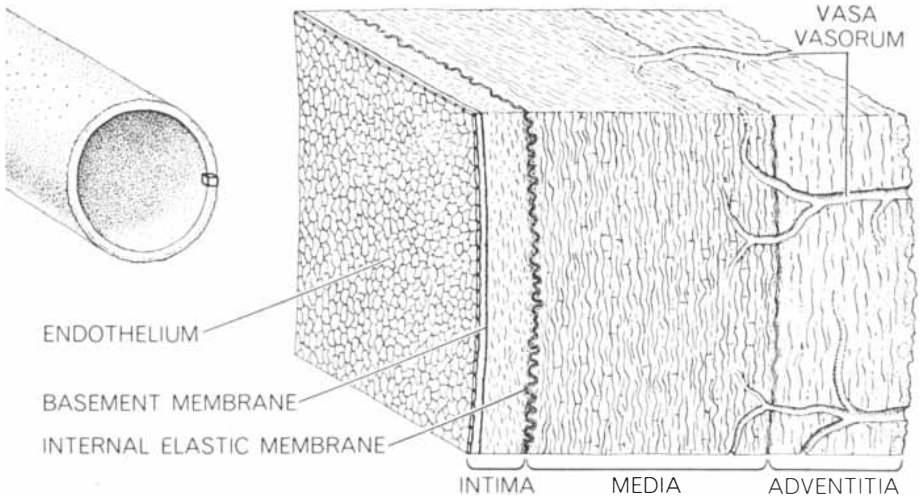
The Nature of the Disease

Atherosclerosis appears to be at least as old as the civilization of mankind. The aortas of some Egyptian mummies that were entombed more than 3,500 years ago show the typical lesions of atherosclerosis. The modern name of the disease is derived from two Greek words: *athere,* meaning "porridge" or "mush," and *skleros,* meaning "hard." This apparently contradictory combination describes the fact that the lesion begins as a soft deposit and hardens as it ages. Materials that have been deposited from the bloodstream in the inner lining of the major arteries penetrate the arterial wall; they form plaques that gradually grow and thicken the wall, thus narrowing the blood channel. Eventually the thickening may close the channel entirely, or pieces of the plaques may break off and travel with the bloodstream until they are stopped in a smaller artery and thereby plug it. When the blockage occurs in the coronary artery, it produces a heart attack by cutting off the blood supply to the heart muscles; in the brain it produces a cerebral stroke; in the lower extremities it can lead to gangrene.

The circulatory system of the human body is a pipeline through which blood is pumped at a rate amounting to 4,300 gallons a day through 60,000 miles of pipe reaching every cell of the body. We might liken the atherosclerotic deposits in an artery to the rustlike encrustations that may form on the inner wall of a pipe. The living system, however, is vastly more complex than any ordinary pipeline. The fluid coursing through the arterial pipes contains living cells and a mixture of liquids that are continually changing in chemistry and physical characteristics. The flow is pulsatile, varying from moment to moment in velocity, volume and pressure. The living walls of the arteries themselves partake of the same changeability. They undergo a continual metabolism, conduct exchanges with the blood and the fluids bathing them externally and are subjected to various kinds of stress. In this dynamic system, subject to so many internal and external influences, unraveling the process that is responsible for atherosclerosis is akin to trying to solve a many-body problem in astronomy without knowing how many bodies are involved.

The atherosclerotic lesion is a complicated affair. When fully developed, it is composed of a considerable variety of structures and substances: blood and blood products, fibrous scar tissue, calcium deposits, complex carbohydrates, cholesterol (a fatlike, waxy substance normally present in the blood and body tissues), fatty acids and lipoproteins. Apparently the fatty acids and cholesterol are the crucial substances responsible for the development of the lesion, because they provoke inflammation and scarring of the arterial-wall tissue.

How does the process leading to atherosclerosis begin? Examination with electron and light microscopes shows that the first visible event is the invasion of the inner lining of the artery by fatty substances. These substances appear mainly in smooth muscle cells and foam cells found within the lining. In the spaces between the cells small amounts of cholesterol can be detected. Very fine fibers of a material that behaves like fibrin (a natural product of blood coagulation) also show up, both within the lining and on its surface. At this early stage the forerunner of the atherosclerotic lesion can be recognized in the form of fatty streaks, which when stained with a suitable dye are visible to the unaided eye as red streaks or spots on the lining surface.



STRUCTURE of the wall of an "elastic" artery, the type usually involved in atherosclerosis, is shown in a somewhat schematic diagram. There is an inner lining of endothelial cells. The wall itself has three ill-defined layers of elastic tissue and muscle: the intima, media and adventitia. The vasa vasorum are small blood vessels that supply the artery wall.

Fats in the Arterial Wall

To solve the mystery of the origin of atherosclerosis one of the first questions we must answer is: How are the fatty materials deposited in the arterial wall? There are several current hypotheses. The one most widely accepted is that the fatty substances are transported into the wall by plasma, the blood fluid, and are trapped within the wall. It is believed that the plasma itself, under the force of the blood pressure, can leak all the way through the wall of the artery in small amounts, which then return to the bloodstream by way of the lymph-circulating system. The large lipoprotein molecules or complexes, on the other hand, cannot filter through the wall so easily; consequently they may tend to pile up within the wall, particularly if the plasma carries an excessive quantity of them.

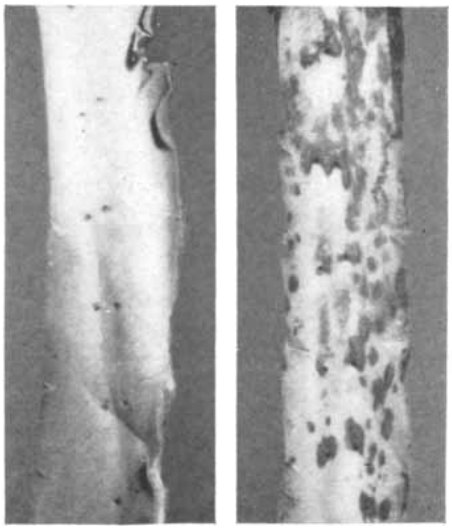
The known structure of the walls of the major arteries gives support to this view. The wall of an artery consists essentially of three layers: outer, middle and inner. The outer layer and part of the middle one are nourished by a system of fine blood vessels (called vasa vasorum) that come from the outer coat and go inward only as far as the middle layer. The nourishment of the inner portion of the arterial wall is taken care of by nutrients filtering into it from the bloodstream in the channel of the artery. Between the inner and the middle layer of the wall there is a curtain of elastic tissue. This tends to impede the flow of fluids through the wall. Hence it may act to trap substances that follow the gradient of flow, which in an artery is from inside to outside. Significantly, atherosclerosis rarely develops in veins, where the flow gradient is from outside to inside.

That lipids and other large molecules from the bloodstream can penetrate the arterial walls has been demonstrated conclusively by experiments with radioactively labeled cholesterol and other materials. These labeled materials usually turn up in highest concentration in areas in the walls that are already atherosclerotic. It has also been learned that in the early lesions of atherosclerosis the pattern of lipids present in the lesion is strikingly similar to the pattern in the blood.

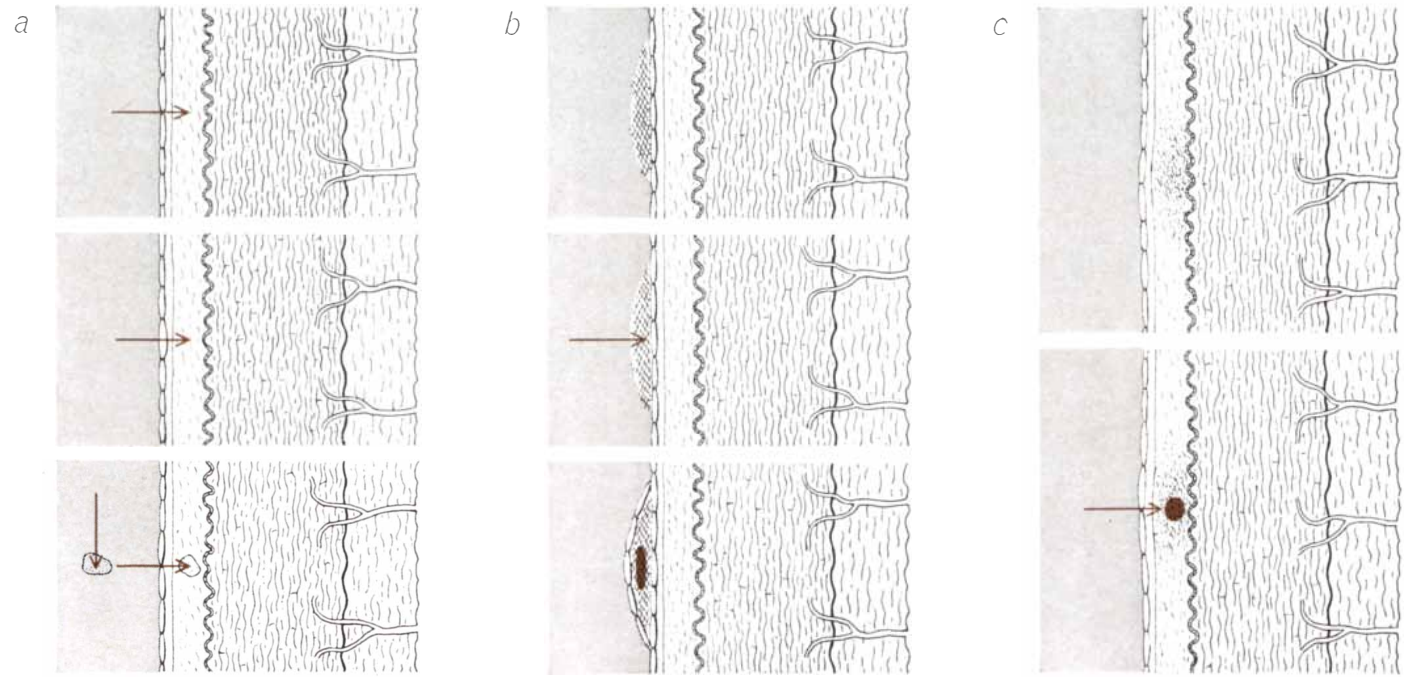
Are there special conditions that favor the infiltration of lipids into the arterial wall? At least one interesting finding points in that direction. It was found that the administration of high doses of vitamin C to experimental animals inhibited the accumulation of lipids in the walls of their arteries. Conversely, when animals were fed a diet on which they developed a vitamin C deficiency, the inner lining of their arteries became more permeable: its cells were more widely spaced.

Abel Lazzarini-Robertson, Jr., of the Cleveland Clinic, who has studied the behavior of arterial-lining cells in tissue cultures, suggests that there may be a self-feeding process that generates expansion of an atherosclerotic lesion. Some of these cells, he says, respond to an excess of lipids by requiring more oxygen. When they fail to obtain enough oxygen to satisfy this increased need, the cell membranes become more permeable to lipids. Thus a vicious circle is set up: the more lipid enters the cells, the easier it is for additional lipid to invade them.

As I have mentioned, hypotheses other than the lipid-infiltration theory have been proposed to account for the



INNER SURFACES of the aortas of two rabbits were stained to visualize fatty material. Both animals had been fed cholesterol but one had also received estrogen, a female hormone. The aorta of that rabbit (*left*) was found to be almost free of atherosclerosis, whereas the other one was heavily affected.

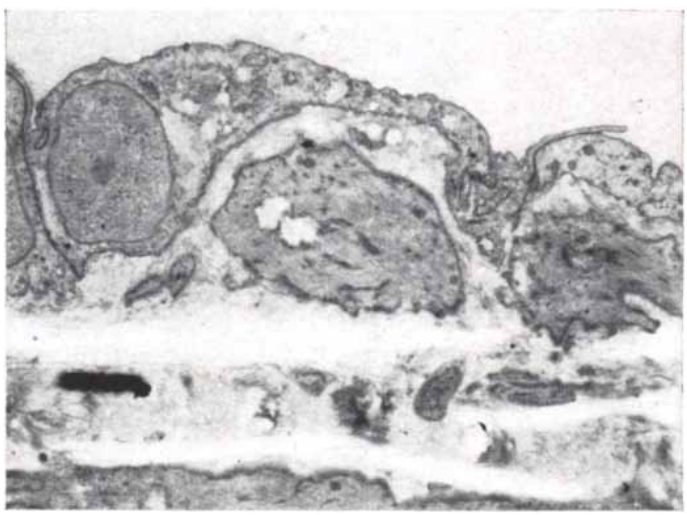


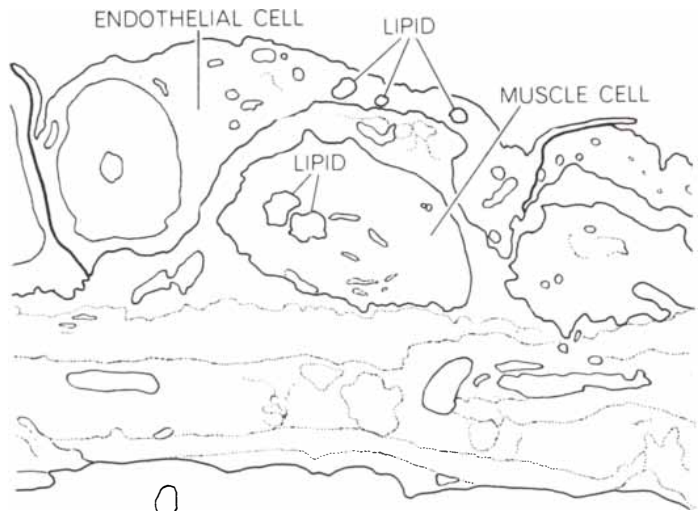
ENTRY OF FATTY MATERIAL into the arterial wall is the first sign of atherosclerosis. One theory holds that fat molecules infiltrate from the bloodstream (*a*) either by moving between endothelial cells or through them or by being carried between them by large cells called foam cells. Another theory is that the first event is the formation of a blood clot that is subsequently invaded by fats (*b*). A third idea is that an injury alters the wall's cementing substance so that fats can invade from the blood or be synthesized (*c*).

origin of atherosclerosis. One of these suggests that a disturbance of the blood-clotting mechanism, in combination with an injury to the inner wall of the artery, may result in the formation of a fibrin clot on the surface of the wall. Fatty substances from the bloodstream may then accumulate in the clot, particularly if there is a considerable amount of such substances in the blood, and this focus may generate the atherosclerotic lesion. Another hypothesis proposes that some alteration of the cementing substances (mucopolysaccharides) in the artery wall that occurs after an injury to the wall may open the way to local invasions or synthesis of lipids. It may be, indeed, that there is some truth in all the hypotheses. There is reason to believe that atherosclerosis can originate in a number of different ways.

Once the process has started it develops a kind of life of its own. Enzymes within the artery wall break down the fatty complexes, liberating cholesterol and fatty acids. These act as noxious foreign agents and excite inflammation of the wall tissues. Scar tissue develops. Fragile capillaries growing into this tissue tend to rupture and thus lead to more inflammation. The artery lining may ulcerate, and blood from the bloodstream clots around these breaks. Gradually the atherosclerotic lesion expands in size, and as the scar tissue and calcium deposits accumulate, the lesion stiffens and renders the arterial wall brittle and weak.

Atherosclerosis may occur simultaneously in many of the body's major arteries. There are, however, certain favored sites. Much depends on the shape and position of the vessel. For example, the coronary arteries, which receive the full impact of the pulsatile blood pressure against their walls during systole (the heart's pumping cycle), have a high tendency to develop atherosclerotic le-





SECTION OF AORTA of a rabbit that had been fed cholesterol for two weeks is enlarged 5,000 diameters in an electron micrograph (*left*) made by Frank Parker and George F. Odland of the University of Washington School of Medicine. As the drawing (*second from left*) shows, an endothelial cell of the artery lining contains vacuoles filled with lipid, or fatty material. A single smooth-muscle

sions; on the other hand, the renal arteries, which branch from the aorta at right angles and have a low resistance to blood flow and therefore do not feel the pulsatile impact nearly as much, are relatively free of the disease. The vessels that are most often, and most critically, attacked are the coronary arteries, the aorta, the arteries in the neck and brain and the iliac and femoral arteries supplying blood to the lower extremities.

When thrombosis (formation of a blood clot) occurs in a narrowed coronary artery, the resulting partial or complete shutoff of blood supply to a portion of the heart muscle may have various effects: angina pectoris (pain in the chest), a myocardial infarct (destruction of part of the heart wall), irregularity or weakening of the heartbeat or sudden death due to complete failure of the heart. If the arteries to the brain become clogged, the result is a massive stroke causing paralysis or death. "Small" strokes, causing only slight or temporary paralysis of particular functions, may arise from fragments that break off from the atherosclerotic lesion and flow on to clog small vessels in the brain, thereby killing small areas of brain tissue. When atherosclerosis and clots clog a major artery to the legs, the result may be severe pain in these extremities and sometimes so much destruction of tissue that the gangrenous limb must be amputated.

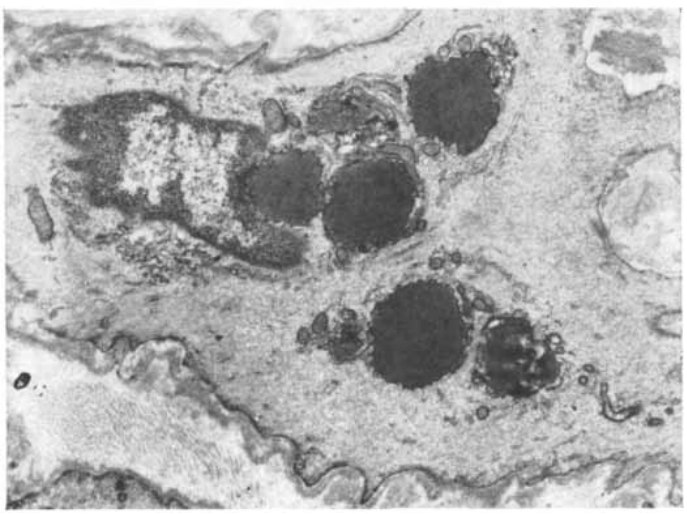
In the aorta the lower section, passing through the abdomen, is particularly subject to atherosclerosis. The disease may so weaken the arterial wall that a portion of it balloons out, forming an aneurysm. Aneurysms of the aorta may press on the important organs in this area, interfering with their functions and causing pain. The rupture of one of these aneurysms usually produces massive hemorrhage and death.

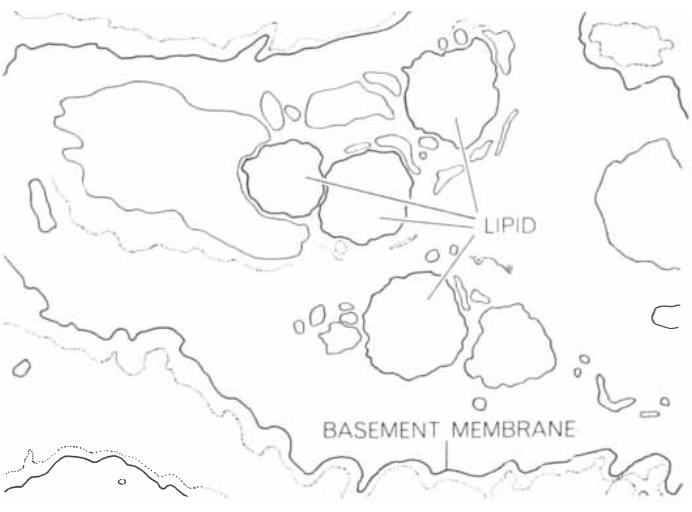
One of the peculiarities of atherosclerosis is that even among the susceptible arteries it often selects particular ones for attack. For example, an individual may have severe atherosclerosis in his coronary arteries but very little of the disease in the cerebral arteries, or extensive lesions in the aorta with very little involvement of the coronary arteries. This form of selectivity is reflected in the disease rates of certain peoples. In Japan, for instance, strokes are common but heart attacks are relatively rare.

The Role of Diet

It is natural to suspect that diet has a great deal to do with atherosclerosis, and for more than a century the primary suspicion has focused on cholesterol. As early as 1847 a German anatomist, J. Vogel, reported that atherosclerotic arteries invariably contained cholesterol. In 1909 a Russian army medical officer, A. Ignatowski, observing that the army officers, who were of the meat-eating class, had many more heart attacks than the vegetarian peasants, undertook an experiment. He fed rabbits animal products and found that their aortas did indeed develop atherosclerotic lesions. A few years later a pair of Russian investigators, N. Anitschkow and S. Chalatow, followed up with a series of careful studies that became classic references in this field. When they fed rabbits fat and cholesterol, they observed that the cholesterol level in the animals' blood rose and atherosclerotic plaques appeared in their arteries. After cholesterol feedings were discontinued, lipids gradually disappeared from these plaques.

Cholesterol is indeed an inevitable suspect, because the formation of the atherosclerotic lesion is essentially an inflammatory response to this substance. The involvement of cholesterol in the disease has been demonstrated in many different ways. Experimenters have produced the disease by cholesterol feeding in many animals, including rabbits, rats, guinea pigs, chickens, dogs and monkeys. In almost every case in which the disease is induced experimentally the animals' serum shows a rise in cholesterol as a prelude to the atherosclerosis. In primates the disease exhibits all the features that occur in human beings. At the human level a cooperative study in Britain and the U.S. found that peptic ulcer patients who were treated with the Sippy diet (rich in milk and cream) had elevated levels of cholesterol in their serum and suffered twice as high a rate of heart attacks from coronary atherosclerosis as ulcer patients who did not use this diet. Conversely, patients with multiple myeloma, a malignant disease that tends to lower the serum-cholesterol level as one of its effects, have an unusually low rate of heart attacks. People who have died of so-called wasting diseases (essentially malnutrition) show a low lipid content in their arteries, which suggests that the loss of fat may have reduced their atherosclerotic lesions. On the other hand, people with diseases or conditions that are usually accompanied by a high cholesterol level (diabetes, nephrosis, hereditary elevation of lipids in the body) tend to develop atherosclerosis at





cell under the lining has two lipid vacuoles. In the other electron micrograph (*third from left*), made by Jack C. Geer and Marion A. Guidry of the Louisiana State University School of Medicine, a portion of a fatty streak from a human aorta has been enlarged 8,000 diameters. As indicated in the drawing (*right*), a smooth-muscle cell in the intima contains four lipid inclusions.

an earlier age and more extensively than usual.

Yet it has become increasingly clear that atherosclerosis cannot be explained simply in terms of cholesterol, or even a fatty diet. Certain species of pigeons spontaneously develop atherosclerotic lesions closely resembling those of human beings although these birds eat no animal fat. (Spontaneous atherosclerosis is also found in dogs, baboons, ostriches, pigs and whales.) Laboratory experiments have shown that exposure to cold, elevation of the blood pressure, antithyroid substances, high doses of vitamin D, lack of oxygen and other factors can contribute to the development of atherosclerosis. On the other hand, the disease process can be inhibited in animals by undernourishment, thyroid hormones, heparin (the anticlotting agent), fat-eliminating agents, unsaturated fats and sitosterol (a precursor of steroid hormones).

Epidemiology

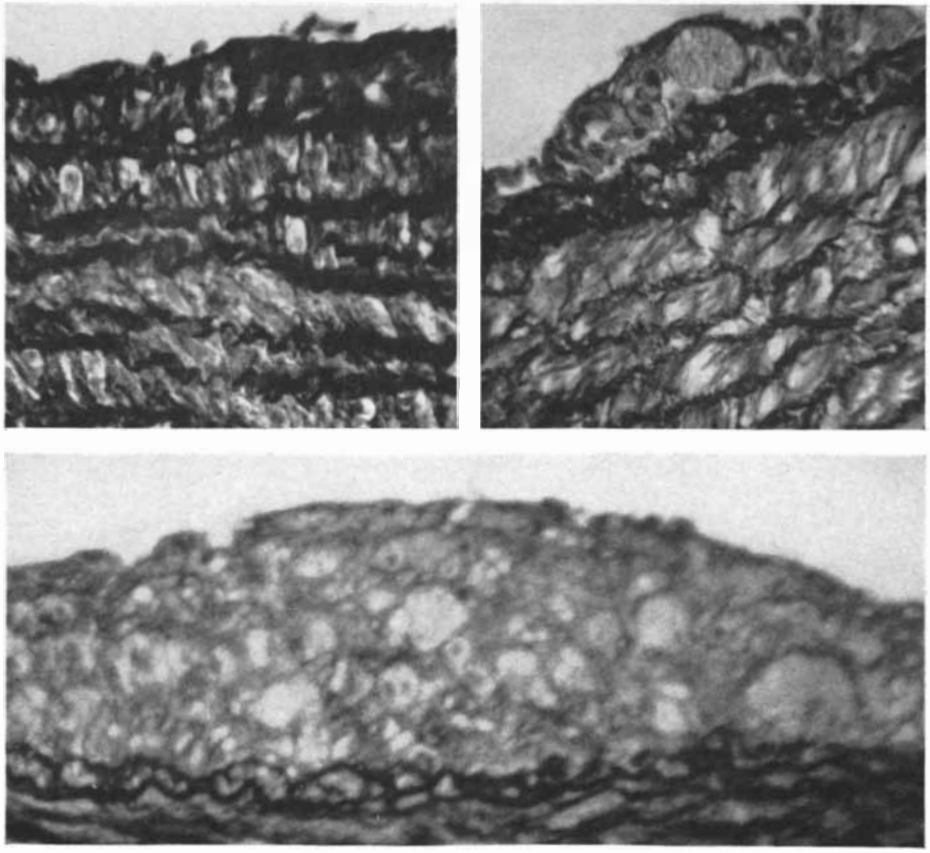
Even the evidence of epidemiology is not entirely clear. It is true that populations whose diet contains a relatively small amount of saturated animal fats and cholesterol tend in general to have a low blood-cholesterol level and a low incidence of heart attacks. To illustrate with some often cited statistics: The South African Bantu, among whom death from coronary atherosclerosis is exceedingly rare, have a diet very low in fats (average: 17 percent of the total caloric intake) and a mean serum-cholesterol level of only 166. In Europe, where death from this disease is common, the average fat intake amounts to 35 percent of the diet and the serum-cholesterol level is 234. In the U.S., where the coronary death rate is very high, the average fat intake is between 40 and 45 percent and the serum-cholesterol level is about 250. Moreover, there is some evidence that people who migrate from a country with a low heart-disease death rate to one with a high death rate, and adopt the diet and cultural pattern of the latter country, tend to acquire a rise in the cholesterol level and an increase in the rate of heart attacks. This, at least, has been found to be true of Yemenite Jews and Japanese who have migrated to the U.S.

Nonetheless, it is not easy to determine exactly what factors separate the immune populations from the vulnerable ones, or the sheep from the goats. Among the peoples distinguished by exceptionally low rates of heart attack are the farmers of Guatemala, the Yemenite Jews, the South African Bantu, the Chinese, the Japanese and the Apache Indians living on reservations. Very high heart attack rates, on the other hand, are found among the adult white male inhabitants of New York, New Orleans, England, Sweden and parts of Finland. What do the latter populations have in common that differentiates them from the first group? This is one of the principal problems that today engages the attention of many investigators of the causes of atherosclerosis.

To narrow down the search for the significant environmental, biological or dietary factors, it would be very helpful if we could identify the individuals in each population who have atherosclerosis. Unfortunately this is difficult to do in a live population. Atherosclerosis has aptly been called an "iceberg" disease, because only five to 10 percent of those whose arteries are affected show any clinical sign of illness. Recently a method has been developed for examining the arteries in the body by X ray. In this method, called angiography, a radiopaque dye is injected into the bloodstream and the artery is then X-rayed to show whether or not the flow is normal. A narrowing or other abnormality of the channel is taken to indicate atherosclerosis. The technique is not, however, sufficiently simple, accurate or safe to be used as a screening procedure for the general population.

The cholesterol level in the blood is not itself a reliable index of the disease. In any population the level varies as a continuous spectrum, and one cannot find a dividing line that separates the atherosclerotic individuals from those with healthy arteries. Indeed, many people with low serum-cholesterol levels have heart attacks whereas many with high levels do not.

The investigation of atherosclerosis must therefore rely mainly on post-mortem examinations and studies of people who clearly show signs of the disorder by their coronary disease or heart attacks. As everyone knows, there is now a very large accumulation of epidemiological studies that have sought to shed light on the factors associated with heart disease. These include the worldwide studies of Ancel Keys of the University of Minnesota and his associates, the famous mass studies in Framingham, Mass., Albany, N.Y., and Chicago and our own recently completed study of 10,000 males in Westchester County. All these studies have



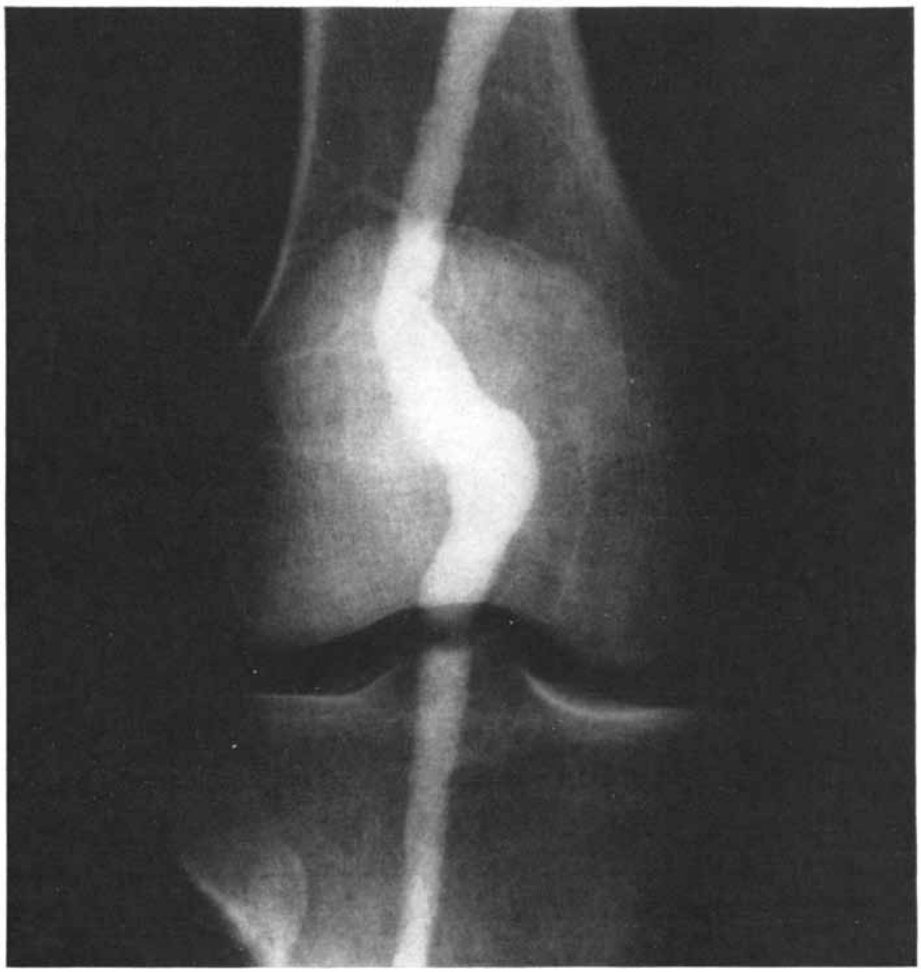
DEVELOPMENT of an atherosclerotic "plaque" in an arterial wall of a cholesterol-fed rabbit is traced in a sequence of photomicrographs made by the author. A normal section is shown at the upper left. A few foam cells penetrate the endothelium (*upper right.*) The bottom micrograph shows a larger accumulation of lipid—an early atherosclerotic plaque.

arrived at remarkably similar conclusions about the high-risk factors associated with coronary atherosclerosis. To sum them up in one profile, the most vulnerable person would be an adult male who has a high lipid content in his blood and high blood pressure, who engages in little physical activity and is markedly obese and who is a heavy smoker of cigarettes.

The difference between men and women in the rate of heart attacks from coronary atherosclerosis is striking. Our observations indicate that, in the age levels up to 55, deaths from such attacks are at least 10 times more common among men than among women. It seems that the factor protecting women is the female hormone estrogen. Women who have had their ovaries removed (thus reducing the estrogen output) tend to have more atherosclerosis than those with their ovaries intact. Injections of estrogens have been found to be capable of lowering the cholesterol level in the blood and of altering lipoproteins from the type associated with the development of atherosclerosis. At the Michael Reese Cardiovascular Research Institute in Chicago, Jeremiah Stamler and his colleagues demonstrated that the development of atherosclerosis in the coronary arteries of young male chickens that had been fed cholesterol could be stopped by injecting estradiol benzoate, a variant of the female hormone. On the strength of all the experimental evidence, estrogen injection has been tried as a treatment to inhibit atherosclerosis in men, but it is not promising for widespread use because of its feminizing effects.

High blood pressure is a serious contributor to atherosclerosis only when it is combined with a high cholesterol level in the blood, in which case the pressure forces cholesterol into the artery walls. The Apache Indians commonly have high blood pressure but seldom suffer heart attacks, probably because their blood content of cholesterol is low. Our studies of New York men indicated that the combination of high blood pressure and high cholesterol carries a high risk. In the age group between 36 and 50 men with this combination had a rate of atherosclerotic heart disease more than four times higher than that of men with normal blood pressure and lower serum cholesterol; the respective disease rates were 7.6 percent and 1.8 percent.

In the cases of the other risk factors revealed by the epidemiological studies —lack of physical activity, obesity, cigarette smoking—no direct tie to the atherosclerotic process has been found. Just how these conditions contribute to heart disease remains to be determined.



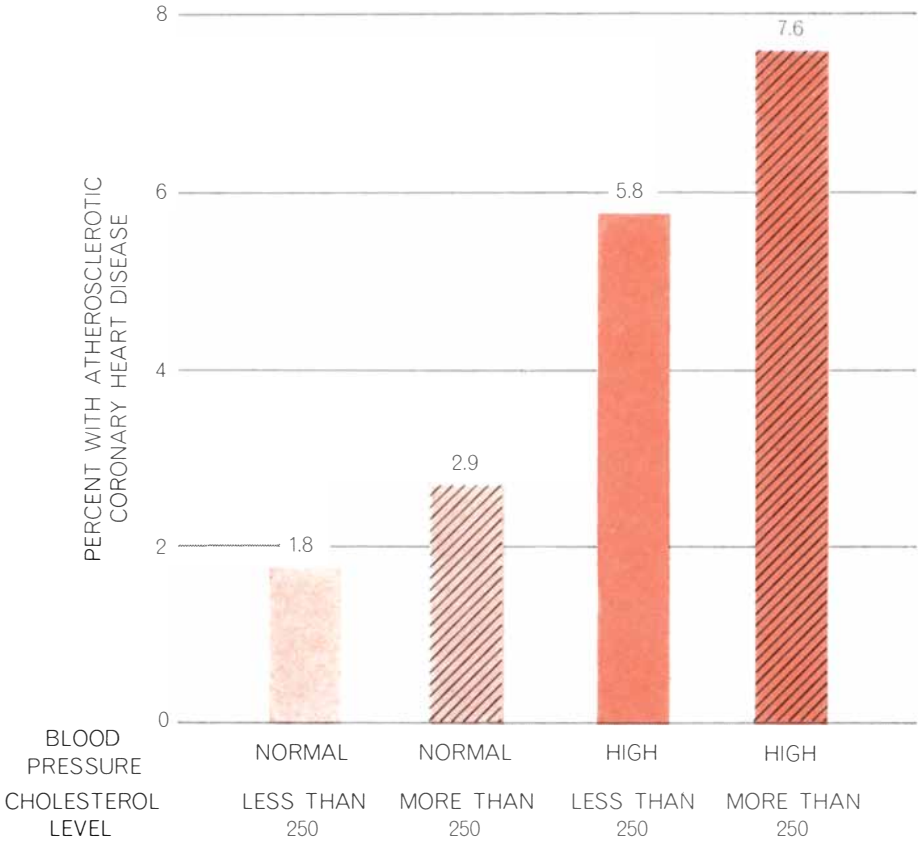
ANGIOGRAM, an X-ray photograph of a blood vessel injected with a radiopaque dye, can sometimes locate atherosclerotic damage. This one shows an aneurysm, or abnormally dilated segment, in a popliteal artery caused by atherosclerotic weakening of the arterial wall.

Nondietary Factors

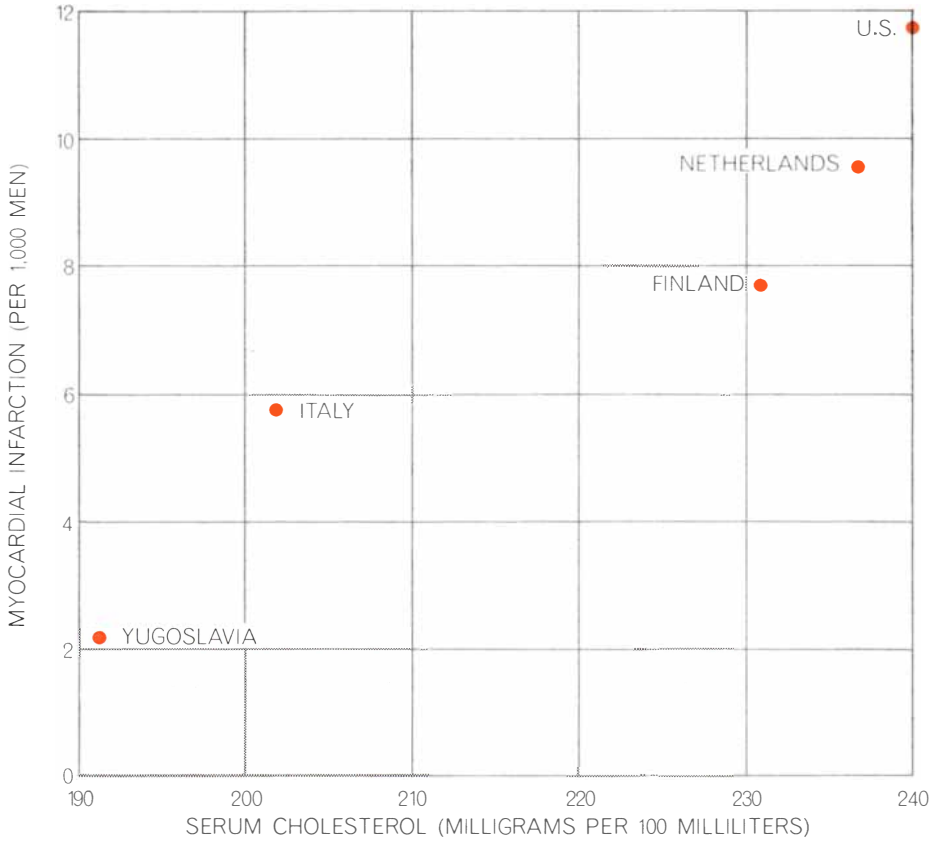
Many other elements that are suspected of contributing to atherosclerosis have been investigated. Undoubtedly heredity is an important factor. Atherosclerosis is frequently associated with diabetes and hypertension, diseases that are known to stem from genetic causes. Moreover, it seems likely that an individual's relative ability to metabolize and otherwise handle lipids plays a large part in his susceptibility to atherosclerosis. Studies have shown that identical twins tend to have about the same blood-cholesterol level, whereas twins who are not identical are much more likely to differ from each other in this respect. There have also been dramatic cases in which identical twins have had heart attacks at the same time in the prime of life.

Another factor that has had much attention is emotional stress, arising either from the individual's mode of life or his constitutional disposition. Unfortunately most of the studies of this factor have been so poorly conceived or executed that the conclusions are uncertain or questionable. There is no firm information so far to prove or disprove the hypothesis that emotional stress contributes to heart attacks.

We come back finally to the diet, which today holds the center of research attention as the factor most likely to be primarily responsible for the epidemic of atherosclerotic heart disease. There is no gainsaying the fact that this disease is a dominant feature of industrialized, affluent societies. If we look at metropolitan New York, where the disease has increased strikingly in the past 30 years, we can see that in the same period there has been a marked change toward a more luxurious and more passive manner of life, characterized by great increases in the use of the automobile, in automation of occupations and domestic tasks and in the animal-fat content of the average diet. The insurance companies have been compelled at frequent intervals (about 10 times in the past 30 years) to revise



STUDY by the author of some 6,000 men showed that blood pressure and cholesterol level are correlated with the incidence of atherosclerosis. A diastolic blood pressure of 90 or less was called "normal"; that figure and the cholesterol count of 250 are necessarily arbitrary.



STATISTICS collected by Ancel Keys's group at the University of Minnesota indicate a correlation between the average cholesterol level in male populations and the amount of myocardial infarction, or heart-muscle damage. Cholesterol count may in turn be related to diet.

upward their statistical tables of average weights.

In a report to the White House Conference on Children and Youth, Stanley Marion Garn of the Fels Research Institute noted a disquieting trend in the eating habits of the younger generation in the U.S. today.

"If 35 percent of his calories comes from fats, is Junior being prepared, starting in nursery school, for a coronary occlusion?" asked Garn. "Reviewing the dietaries of some of our teen-agers, I am struck by the resemblance to the diet that Olaf Mickelsen uses to create obesity in rats. Frappes, fat-meat hamburgers, bacon-and-mayonnaise sandwiches, followed by ice cream, may be good for the farmer, good for the undertaker and bad for the population.... Through the stimulation of advertising, tap water is being replaced by sugared juices, milk and carbonated drinks. Snacks have become a ritualized part of the movies and are inseparably associated with television viewing."

To what extent can the animal-fat diet be specifically incriminated on the basis of the research done so far? The epidemiologist Ernest L. Wynder has suggested four criteria to determine whether or not a given factor can be regarded as a cause of a disease: (1) the incidence of the disease in a population must be proportional to the population's exposure to the factor; (2) the distribution of the disease—in geography, time, by sex and among various population groups—should be consistent with the distribution of the suspected factor; (3) the factor should produce the same disease, or one corresponding to it, in experimental animals in the laboratory, and (4) the removal of the factor or the reduction of exposure to it by the human population should reduce the incidence of the disease in the population.

The animal-fat diet has fulfilled the first three of these criteria for atherosclerosis in many tests. The fourth piece of incriminating evidence—reduction of the disease in man by reduction of the exposure—has not yet been established. It is currently being tested, however, in a massive dietary study, expected to involve ultimately 100,000 men, that is being conducted at five major centers under the auspices of the National Institutes of Health. If this and similar studies demonstrate that the fatty diet is indeed a major cause of atherosclerosis, there may be hope that the epidemic increase of the disease can be halted and reversed.

Outcast glass is in at Western Electric

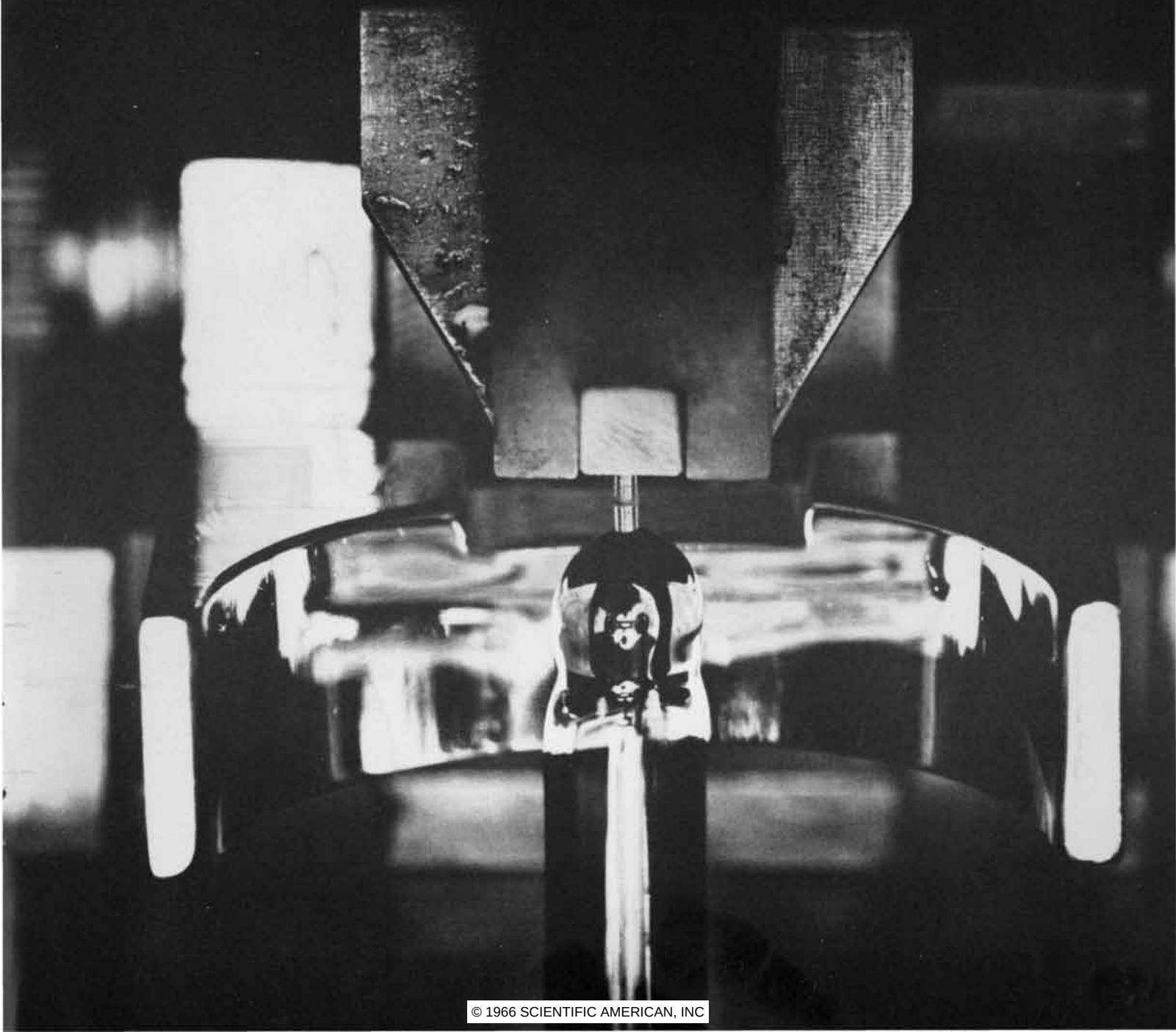
Glass has several qualities that make it a choice encapsulant for electronic components. But to seal glass around a component, the glass must be heated to temperatures well above 600°C. Western Electric found that long exposure to these temperatures would damage sensitive components. In fact, ordinary glass required so much heat, applied for so long a time, that both damage and delay occurred in the sealing process.

Glassmakers have long struggled to keep glass free of contaminants, especially the oxides of iron. However, manufacturing engineers at Western Electric's North Carolina works discovered that specific quantities of FeO in glass cause it to absorb infrared energy very readily.

Specifically, glass doped with FeO rapidly absorbs energy from infrared waves in the region of 1.2 microns. This region corresponds to the output of a small, powerful infrared heater developed at Western Electric's Engineering Research Center. When adapted to the sealing process, the heater's ellipsoidal reflector concentrates energy from a quartz iodine lamp at one focus onto the seal area at the other focus.

Today, Western Electric uses FeO-doped glass tubes, sealed by infrared heating, to protect diodes and ferreed switch contacts. A superior seal is made around the component's wire leads — using less energy and consequently causing less damage to components. This is another way Western Electric helps its Bell System teammates to continue to bring you the world's most dependable telephone service at low cost.

Western Electric
MANUFACTURING & SUPPLY UNIT OF THE BELL SYSTEM



The Peoplefinder

Polaroid has a new way to get people in focus. We used a little anthropology.

This is our Model 104. It's the Color Pack Camera that costs under $60. Which makes it less than half the price of the original model. How did we do it? By inventing The Peoplefinder, for one thing.

There were a number of problems designing a camera for everybody. We had to devise economies down the line. And still come up with a fine instrument.

One of the crucial problems was the focusing system. A system like the one on the original Color Pack Camera—a superimposed-image rangefinder—was just too costly. The 104 had to have something a lot simpler, yet accurate and easy to use.

The Peoplefinder was our unconventional answer. This focusing system is actually a very old idea combined with some new ones of our own. Basically, it's a stadimeter: a type of rangefinding device that's been around since 1890 and scarcely used in modern cameras.

A stadimeter measures distances by measuring the size of a reference object (whose dimensions are known) as it appears in your field of view. A stadimeter becomes a focusing device when it's linked to a camera's lens mount.

Once we decided that the stadimeter would make a comeback in our 104, the next question was "What do we use for a reference object?" It had to be something of constant size and something people would want in the picture. (One of the old stadimeters used flagpoles—which didn't exactly meet our requirements.) The ideal answer for us was to use people because people mostly take pictures of people. But how? We couldn't use the whole body for two reasons. People come in all sizes. And close-ups would be impossible.

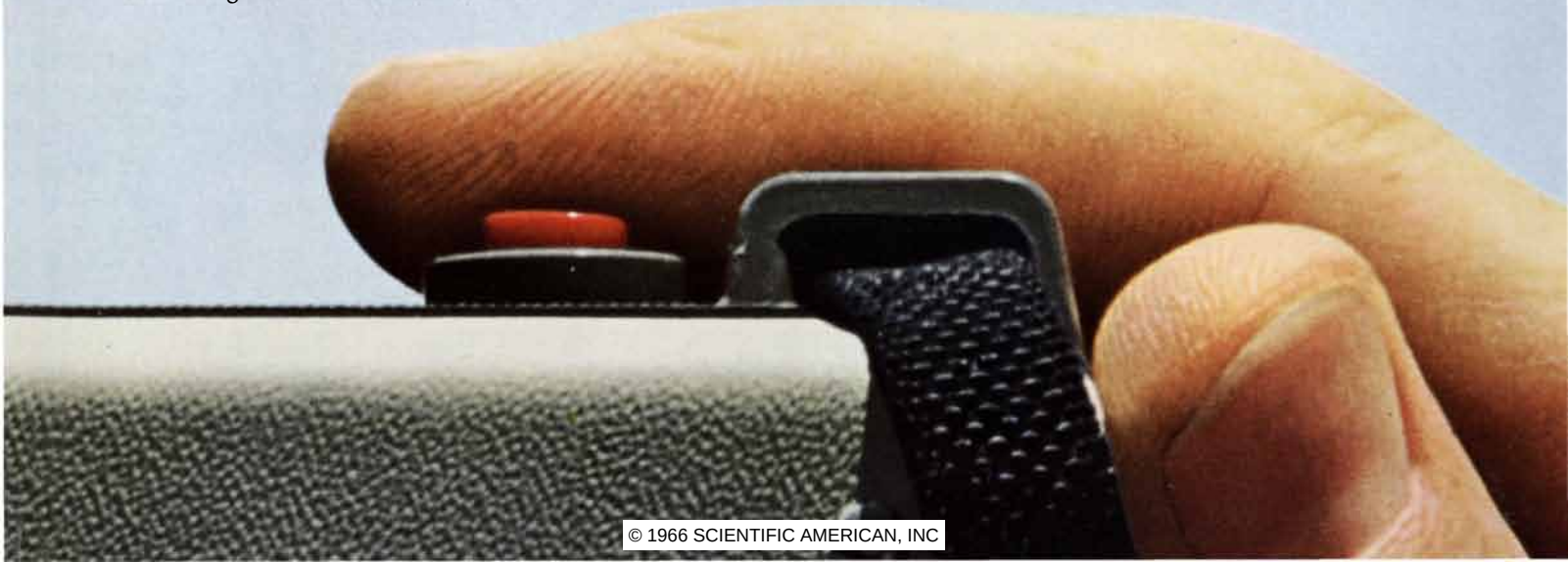
This is where a little anthropology came in. We found that people's head dimensions, from hairline to chin, known as the Crinion-Gnathion dimension, don't vary much. In fact, there's less than two inches' difference between a tot's head and a man's head. So, our reference measure became the average adult's head. It works with anybody except children under three (with them you measure from the *top* of the head instead of from the hairline).

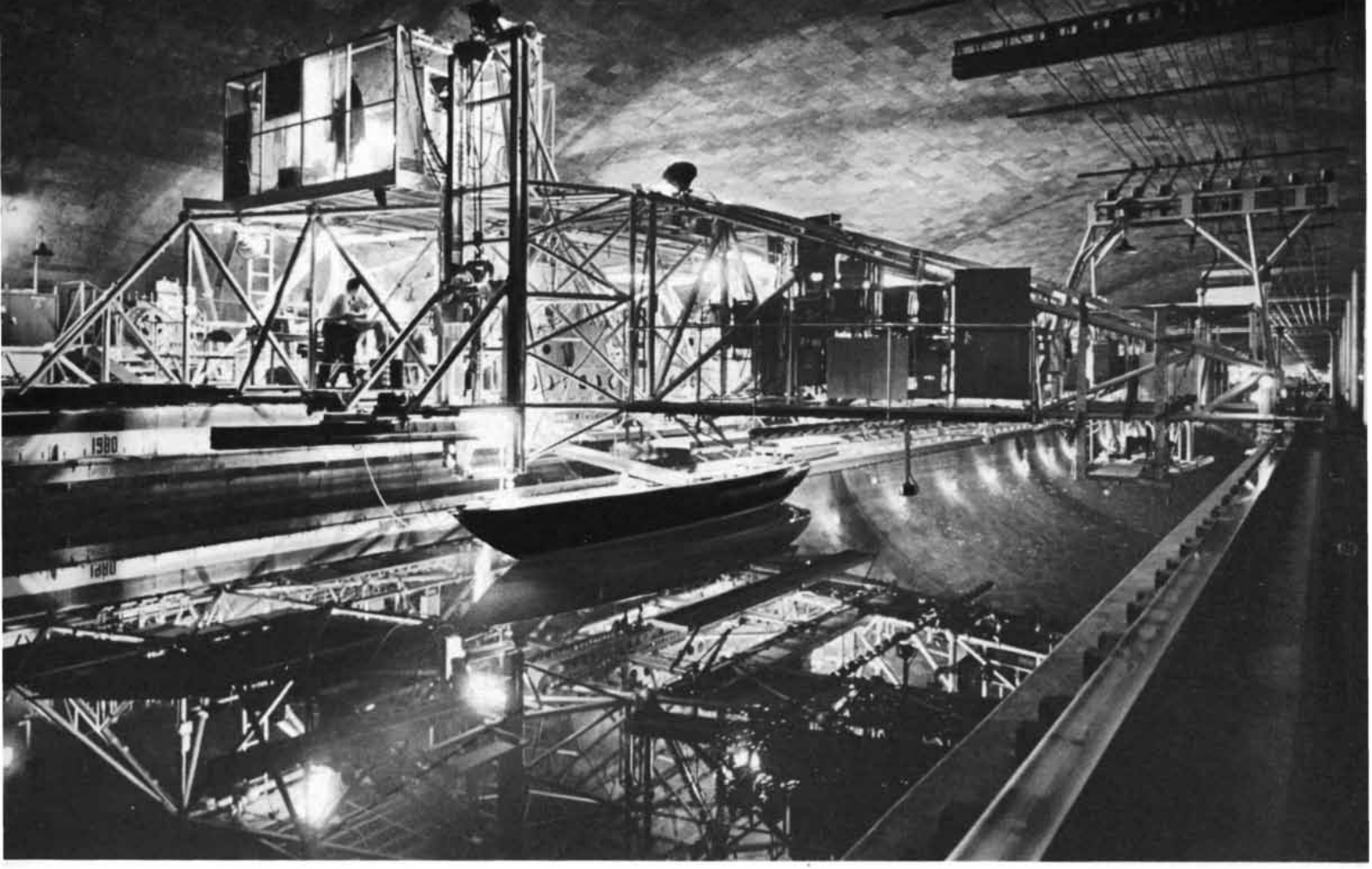
How do you take this measure when you take a picture? It's very easy. When you look through the rangefinder window (it's also the viewfinder window) you see two horizontal lines. You move the bottom line up and down by pushing the focusing buttons back and forth. When you get your subject's head between the lines, you shoot.

Of course, an anthropological reference won't work when your subject isn't a person. Then you use the distance scale and the arrow at the left of the finder window, estimate your distance and move the arrow to the estimated range with the focusing buttons.

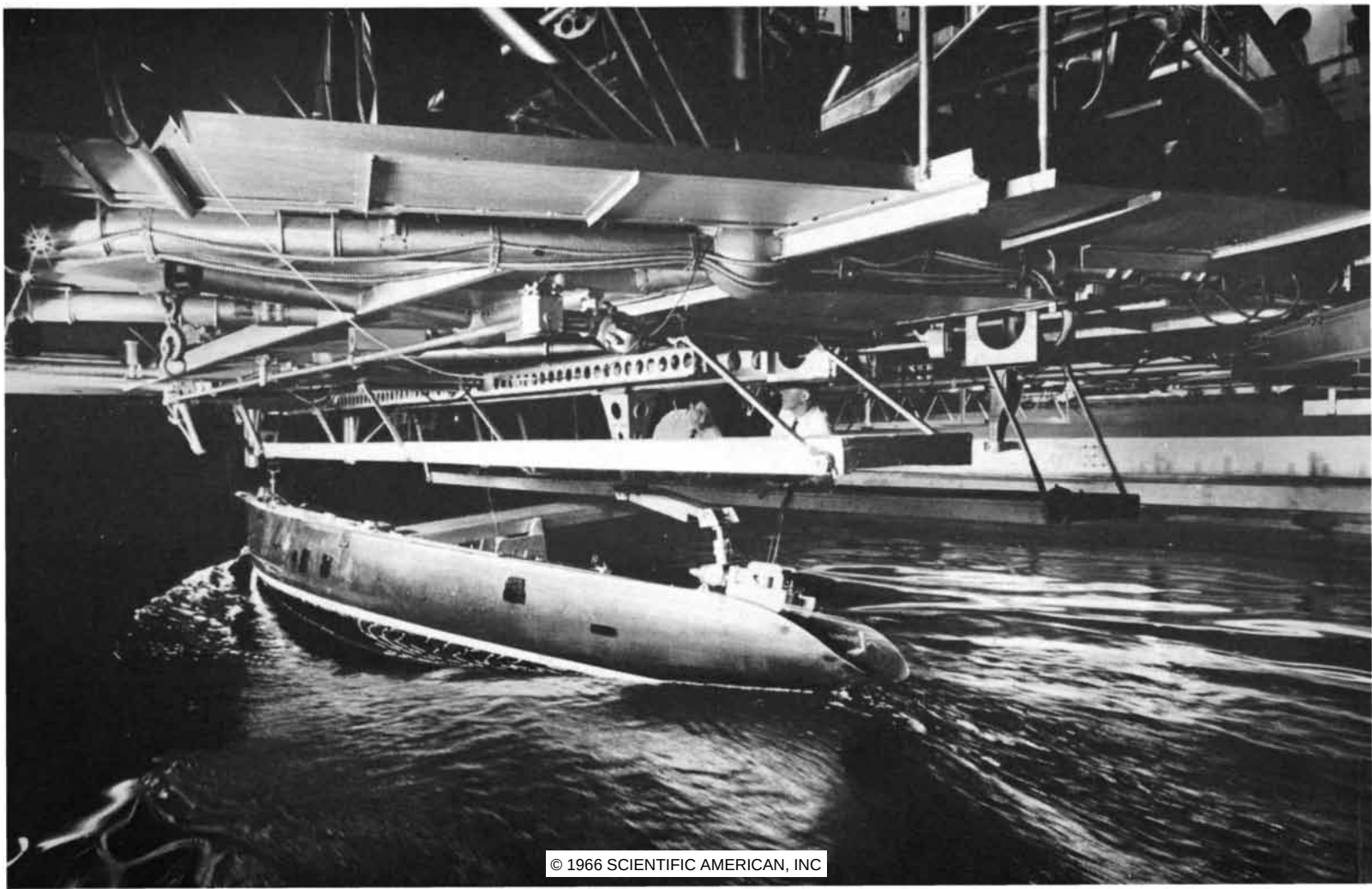
It takes a couple of seconds either way. And 60 seconds later you have a color picture. In perfect focus.

Polaroid Corporation
Cambridge, Massachusetts





YACHT *ANTIOPE* undergoes tests in the towing tank of the U.S. Navy's David Taylor Model Basin near Washington. Above is a general view of the hull in the 1,700-foot tank; below, a closer view of a test in progress. In the close-up actual sailing conditions have been simulated in two ways: the hull has been given a "heel" to starboard partly by means of weights in a box on the platform at midships, and the bow has been offset toward the camera to simulate yaw angle. Several sensing devices are attached to the hull.



The Study of Sailing Yachts

The design of their hulls is assisted by experiments with models. Now tests of the full-scale hull of a racing yacht in a towing tank are aiding the evaluation of results obtained from work with models

by Halsey C. Herreshoff and J. N. Newman

The modern sailing yacht has evolved from one of man's oldest efforts to harness natural forces for the purpose of locomotion. It is also a unique vehicle in that its performance depends on fluid flow in two mediums: water and air. For centuries the design of sailing vessels proceeded on the basis of practical experience, shrewd observation and intuition. Nonetheless, the successful design of fast sailing vessels played an important part in the fate of nations and the founding of empires.

Now that the sailing vessel is used almost solely for recreation and racing competition one can appreciate anew the complexity of the problem of designing a wind-driven craft that will move through both water and air with high efficiency. Nations that have no difficulty making the most advanced technological devices have discovered that building a superior sailing yacht is a task of considerable subtlety.

The principal means of reducing the unknown factors in sailing-yacht design is to test scale models of yacht hulls by towing them in an experimental tank. This procedure can be checked against the ultimate performance of the full-scale vessel at sea. Such confirmation is never entirely satisfactory, however, because of the many variables, such as wind and waves, that must be taken into account. In the case of a sailing yacht this is particularly true because the craft's ultimate performance is so largely controlled by the conditions of wind and sea, the skill of the crew and the quality of the sails.

Recently a full-sized sailing yacht has been tested in a towing tank, allowing for the first time a direct comparison of the yacht's behavior under controlled conditions with that of its scale model. The experiment was made possible through the interest and support of the Society of Naval Architects and Marine Engineers and the availability of large towing-tank facilities at the Navy's David Taylor Model Basin near Washington.

A sailing yacht must be designed to perform with maximum speed and seaworthiness over a wide range of conditions. The wind can blow from any direction with strength ranging from calms to storms, and the sea conditions are equally variable. Thus the boat must be fast not only when it is sailing downwind (when its course coincides with the wind direction) but also when it is sailing on a "reach," or at right angles to the wind [*see illustration on page 63*]. In the latter condition thrust from the sails is accompanied by a large sidewise force that tends to heel the boat over. Above all, a racing yacht must be able to perform well sailing upwind, when its course is at an angle of perhaps 40 degrees to the direction of the wind and when a delicate balance of circumstances determines the small difference between racing success and failure. It is not uncommon for well-matched yachts, such as those that compete for the America's Cup, to sail a four-mile leg of a course against the wind with a variation in elapsed time of only a few seconds, which amounts to a difference in speed of only a few parts in several thousand.

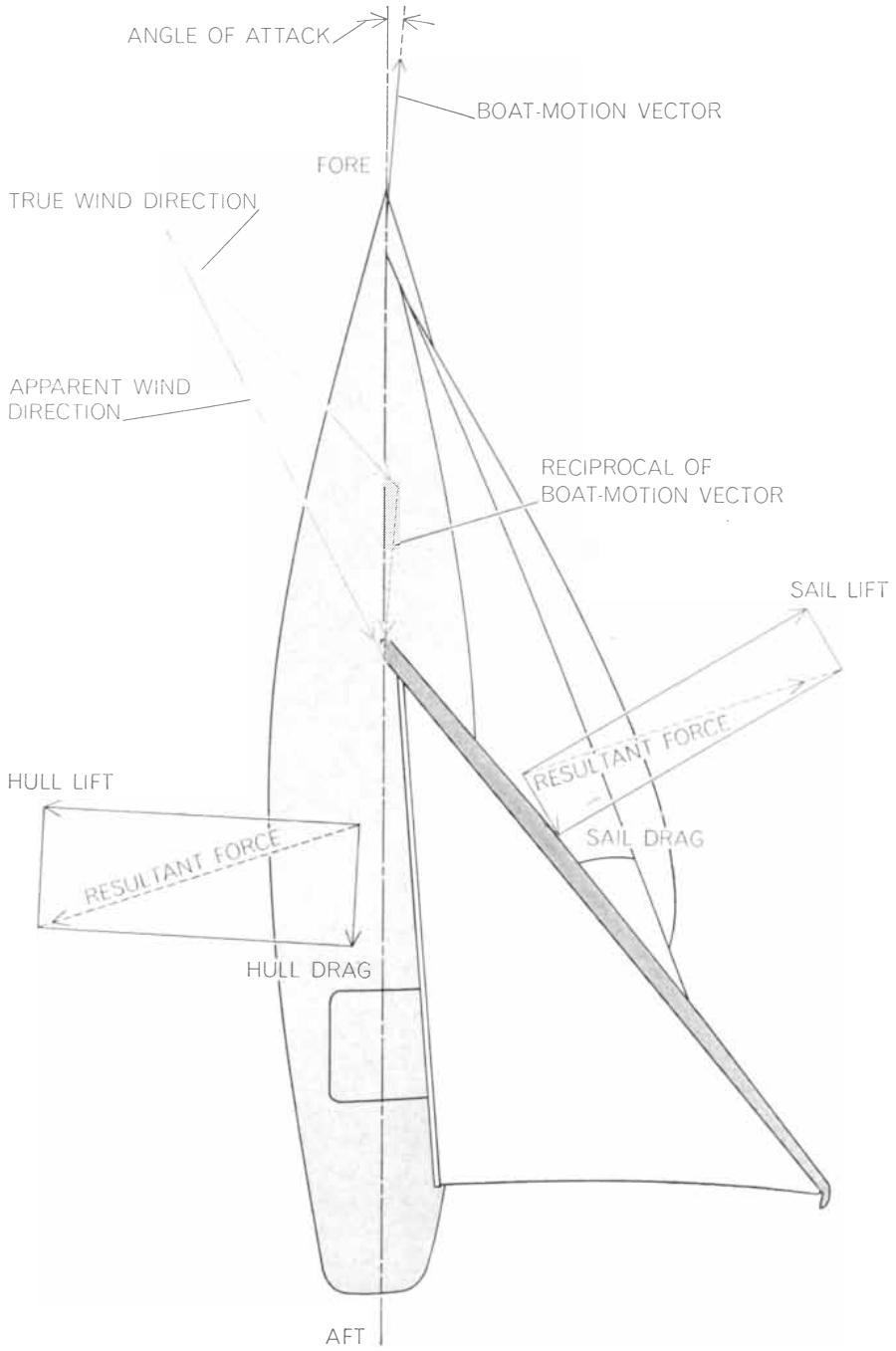
Indeed, an important stimulus to research in yacht performance is the prospect of continued challenges to U.S. possession of the America's Cup by Britain, Australia and probably other countries. Since 1851 U.S. Cup defenders have successfully met all challengers, but a close match is in prospect for September, 1967, when newly designed U.S. and Australian 12-meter boats will compete in the waters off Newport, R.I.

In discussing the mechanics of sailing we shall consider the two extreme conditions of operation: when a yacht is running before the wind, that is, sailing with the wind at its stern, and when it is sailing to windward, or against the wind. The mechanics of intermediate heading angles are essentially combinations of these two extremes. In running before the wind the sails act simply as an aerodynamic drag to the wind; it follows that the boat speed will be less than the wind speed. The only relevant hydrodynamic force exerted by the water on the hull is a drag, which obviously should be minimized for maximum speed. In sailing to windward, on the other hand, the sails and hull both act as wings: lifting surfaces that meet the oncoming wind and water at various angles of attack and develop not only adverse aerodynamic and hydrodynamic drag forces but also favorable lift forces.

In principle there is no limit to the boat's speed in sailing to windward, particularly because the relative wind speed is increased by the boat's own speed. In practice, however, the sails are most efficient and the boat's speed is greatest when the course is approximately at right angles to the wind; in that condition the forward component of the lift force on the sails is at a maximum. In sailing to windward there is an optimum heading angle with respect to the wind, generally 40 to 45 degrees. Accordingly for a boat to proceed in a direction opposite to the wind it is necessary to sail a zigzag course, which is termed "beating to windward." In sailing before the wind the hull is essentially upright and moving straight ahead, whereas in sailing to windward the large sidewise component of sail force causes the boat to heel on its longitudinal axis. In order for the hull to

develop an equal and opposite sidewise force it must move through the water with a small angle of attack, or yaw angle, defined as a rotation around the hull's vertical axis. This angle is analogous to the angle of attack of the wind acting on the sails. The yaw angle is usually so small as to escape notice; it is generally less than three degrees, and in highly developed boats it is as small as one degree. Nevertheless, it is of fundamental importance to the entire process of sailing to windward [*see illustration below*].

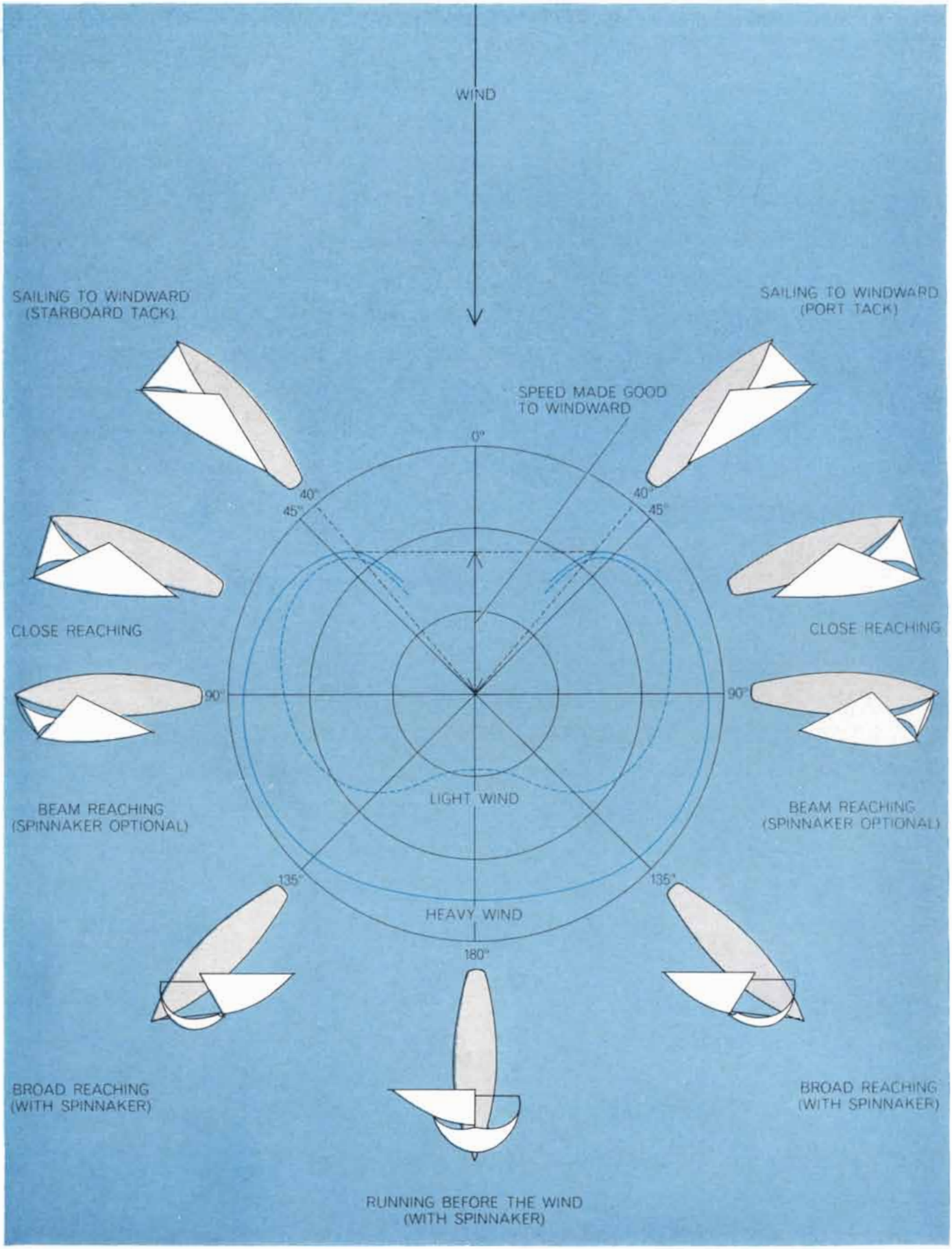
The mechanism by which a hull generates a horizontal lift is identical with that producing vertical lift in an airplane. The main body of a sailing-yacht hull, like the fuselage of an airplane, is in itself an inefficient lifting surface; lift is provided by a thin keel or retractable centerboard, which functions as a wing.



FORCES ON SAILING YACHT are produced by the flow of air past the sails and the flow of water around the hull, including the effect of keel and rudder. The lift and drag produced by the sails are conventionally represented as being respectively perpendicular to and parallel to the apparent wind direction. Similarly, the lift and drag produced by the hull are shown as being perpendicular to and parallel to the direction of boat motion. When the yacht is sailing at constant speed, the resultant forces produced by the sails and hull are equal and opposite. In this diagram the yacht is sailing to windward, or within about 45 degrees of the true wind direction. Because of the boat's forward motion the angle between the boat's course and the apparent wind is only about 30 degrees. The hull meets the oncoming water at a small angle of attack, necessary to produce a lift force on the hull.

Also of fundamental importance is the equilibrium of hydrodynamic and aerodynamic moments: the turning influences exerted by water and wind. The aerodynamic heeling moment, arising from the sidewise force acting on the sails, is substantial. In order to resist this moment the hull must have a large restoring moment. This is provided in many large sailing yachts by a heavy lead ballast at the bottom of the keel and in small, light craft by a shifting of the crew's weight, which acts as "live ballast." The yaw, or vertical, moments are also significant; if they are unbalanced, the boat will tend to turn rather than sail a straight course. Small turning moments around the vertical axis are inevitable because the centers of hydrodynamic and aerodynamic pressure cannot be predicted with certainty and are subject to variation with sailing conditions. In general small angular adjustments of the rudder are required to maintain a steady course. It is necessary, however, to have the boat well balanced to obviate the need for large rudder angles, which induce additional drag forces. Moreover, the sign (plus or minus) of the turning moment, or the direction of the corrective rudder angle, is of crucial importance. It is desirable to design the hull and sails to produce a small turning moment in the direction that makes the bow head into the wind. This requires a small compensating rudder angle that increases the sidewise force on the hull—a force pushing the hull to windward—by giving an effective camber, or favorable curvature, to the combination of keel and rudder. A good sailor appreciates the importance of this balance and adjusts the fore-and-aft position of his mast and sails accordingly.

The improvement of sailboat hulls requires a quantitative study of the hydrodynamic forces and moments acting on the hull at various speeds and attitudes. Yacht design has advanced to the point where extremely small differences between yachts are important. Improving the average speed of an America's Cup contender by .01 knot would be a significant achievement; .1 knot would be a major breakthrough. Since no satisfactory theoretical predictions are available, hull shapes can be evaluated only by the observation of



SAILING CONDITIONS depend on the intensity of the wind and the heading the boat has in relation to the wind. An angle of 40 to 45 degrees to the left or right of the direction from which the wind is coming is as close a heading as a sailboat can achieve efficiently when sailing to windward. Typical speeds for all possible headings are indicated by the two curves (*color*); the farther a point on a curve from the center of the circle, the higher the speed. The spinnaker is the large, ballooning sail at the bow.

actual sailing performance or by the direct measurement of the relevant forces in a towing tank.

The first intensive use of a towing tank for sailing craft was the pioneering effort of K. S. M. Davidson at the Stevens Institute of Technology in the 1930's. Davidson's tank studies played a central role in the development of the highly successful America's Cup yacht *Ranger*, which in 1937 defeated the British challenger *Endeavour II* in four straight races. Since that time model tests have been a key factor in developing the America's Cup contenders and many other racing yachts as well. Most of the test facilities used for this purpose are on the order of 100 feet long, eight feet wide and four feet deep, and they are equipped with carriages that span the tank and move along accurately aligned rails with controlled speeds of a few feet per second. The model hulls, usually about five feet long, are connected to the towing carriage through precision linkages and dynamometers that restrict the yaw and heel angles to specified values. The linkages must be designed so as not to restrain the vertical position and attitude of the hull, which change slightly with speed because of dynamic pressure effects. The gauges for measurement of drag and sidewise forces must be extremely sensitive; on this scale the forces and moments are very small and nearly infinitesimal differences between models are being sought.

***ANTIOPE* RACING sails to windward in an international race. The wind is about 40 degrees off the bow; the sails are trimmed almost flat with a small angle of attack to the wind.**

Even assuming a perfect experimental regime, towing-tank studies present the investigator with a fundamental problem: There is no way to duplicate in miniature and in proper scale all the dynamical relations that affect the full-sized hull of a ship or yacht. In essence the problem is that the motion of the water moving along the hull is governed not only by the frictional properties of water but also by wave effects, which depend on gravity. When a hull is scaled down to model size, there is no way to scale down in equal degree the frictional effects and the wave effects. The frictional effects are scaled according to the Reynolds number (named for the British engineer Osborne Reynolds), which states that such effects can be scaled accurately only if the velocity of a body moving through a fluid is inversely proportional to its length (assuming that the viscosity of the fluid is held constant). The Reynolds number is more precisely defined as the product of the body's speed and length, divided by the kinematic viscosity coefficient of the fluid. This nondimensional parameter must have the same value for the full-scale vessel and its model.

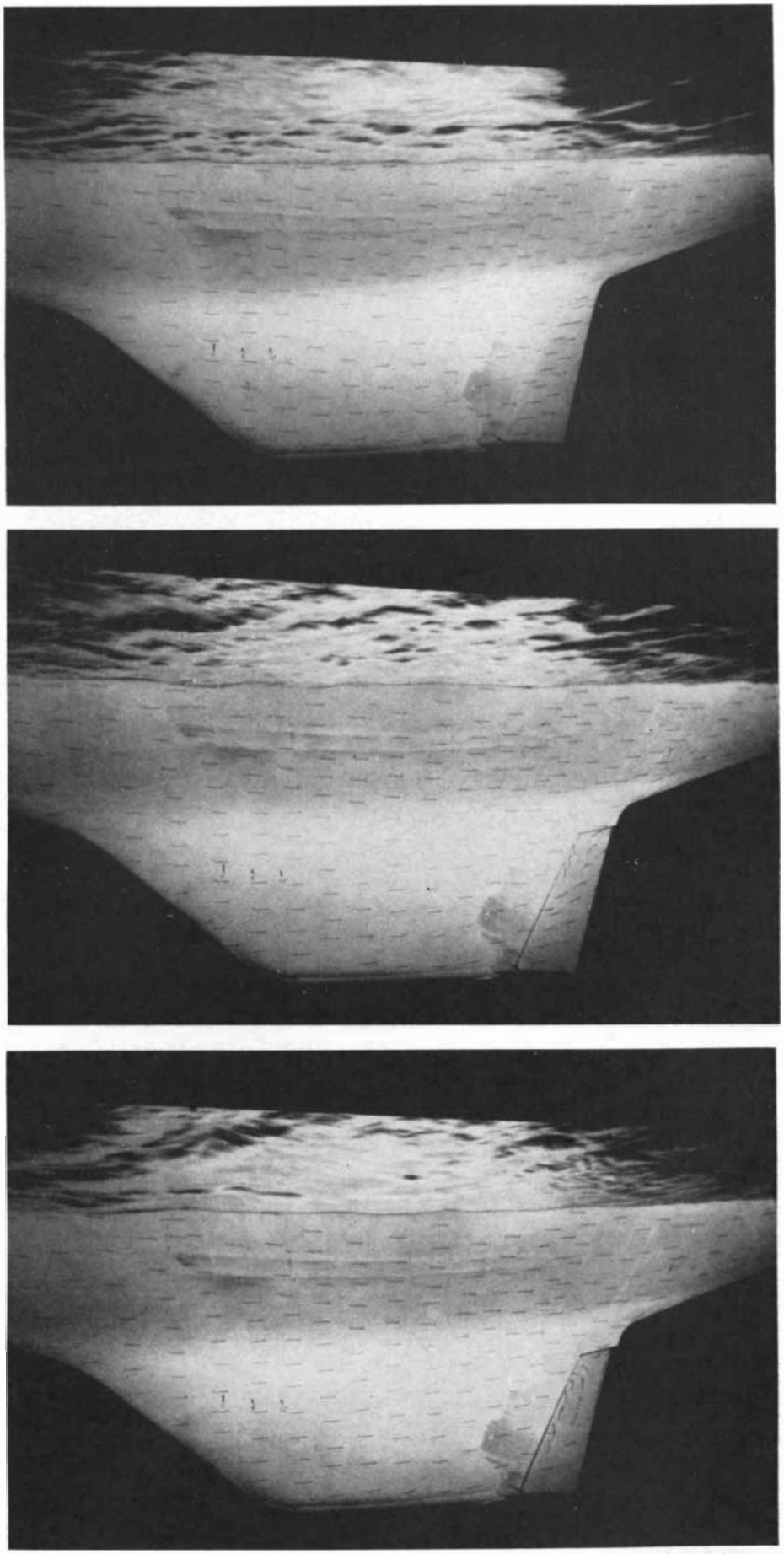
Wave effects, on the other hand, are scaled according to the Froude number (named for another British engineer, William Froude), which states that the wave drag can be scaled only if the velocity of a hull is proportional to the square root of the length of the hull (assuming that the acceleration of gravity is held constant). The Froude number is defined as the ratio of the hull speed to the square root of the product of the hull length and gravitational acceleration.

Thus if one wants to carry out an experiment with ship models in which the dynamical forces are in proper scale, one must be able to adjust either the viscosity of the fluid or the force of gravity. Altering gravity is clearly impractical, and there is no fluid whose viscosity corresponds to that needed to represent water for models of practical size. Therefore one is forced to choose between test measurements that preserve the Reynolds number by varying the speed of the model inversely with the length of the model hull or that preserve the Froude number by varying the speed directly with the square root of the hull length.

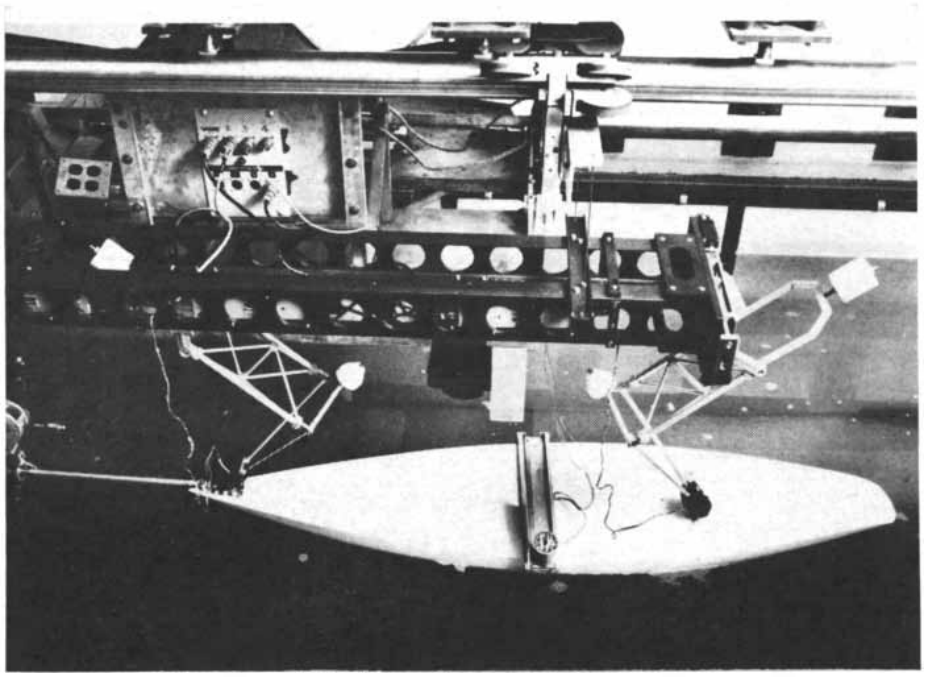
Late in the 19th century Froude devised a practical procedure for separating the hull drag, or hull resistance, into two distinct components, one frictional and one residual. This procedure has made it possible to carry out towing-tank studies in spite of what appear to be the conflicting requirements set by the Reynolds number and the Froude number. Although the two components in Froude's method are not completely independent, they can be regarded as such for engineering purposes.

The frictional component of drag is derived from the transmission of viscous shearing forces that act in a boundary layer of fluid adjacent to the surface of the hull. This component contributes nearly all the drag at low speeds and about half of the total at the highest speeds of conventional ships and yachts. The residual component of drag is composed primarily of the wave resistance, which is the force required to transfer energy to the familiar system of waves that forms behind the hull of a moving ship. There are smaller secondary components, such as the drag produced if the flow of water over the hull becomes "separated" (that is, no longer flows smoothly). Other secondary components include the normal pressure forces that originate with the viscosity of water and the induced drag associated with the lift on a yawed hull. These components are arbitrarily included in the residual component. For a given hull shape and attitude the residual component of resistance is considered to depend solely on the Froude number, whereas the frictional component is assumed to depend solely on the Reynolds number.

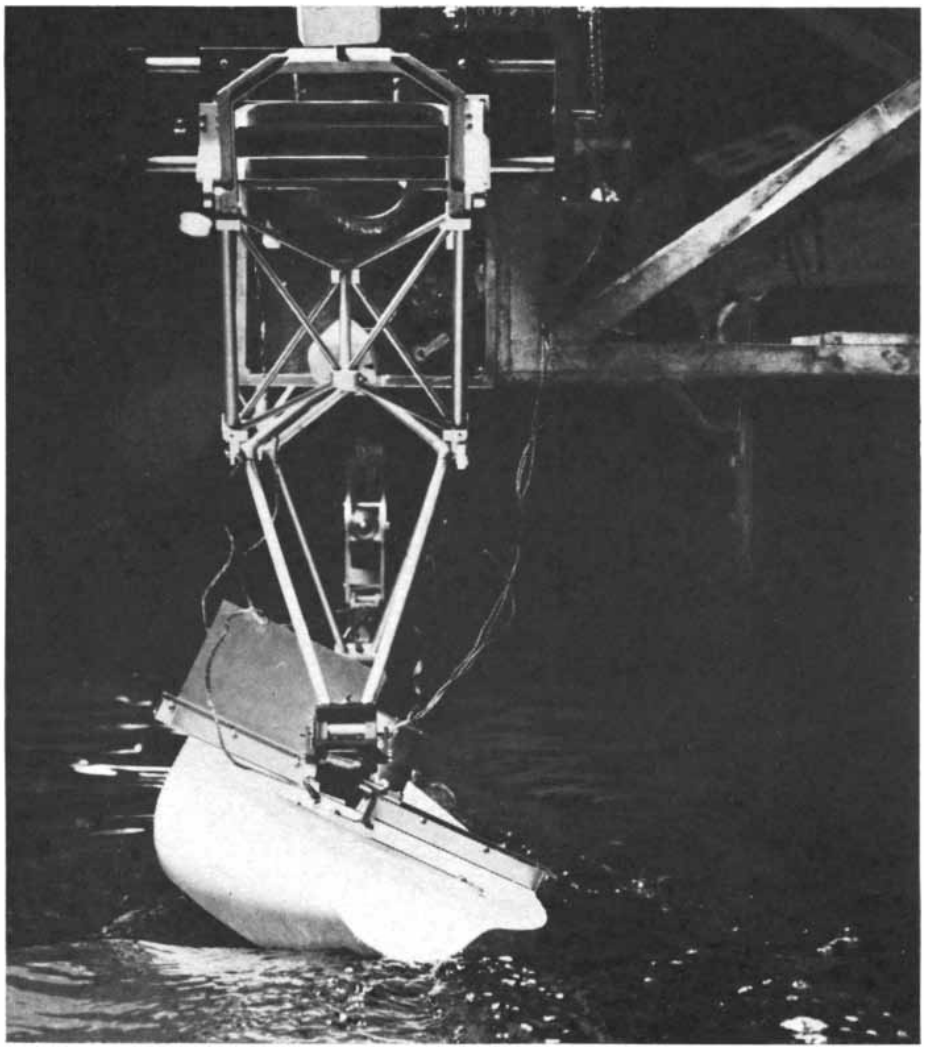
Before this approach can be applied one must know how to separate the total drag into its frictional and residual components. Extensive research on flat plates and ship hulls has led to a useful technique for predicting the frictional component; this component is regarded as being simply proportional to the submerged surface area of a ship or its model and independent of geometrical form. Accordingly models are run at a speed set by the Froude scaling, so that the waves generated by the model are geometrically similar to those of the real ship. Frictional resistance is calculated from empirical formulas and subtracted from the total model drag to provide the residual component. This component is then multiplied by the cube of the scale ratio (yacht length divided by model length) to yield the residual component for the full-scale hull. To



RUDDER ANGLE affects drag, as shown by strips of nylon yarn attached to the hull of the *Antiope*. The hull is in the David Taylor Model Basin's flow tank, in which the water moves but the vessel does not. At top the rudder angle is zero and the strips indicate an even flow. At middle a slight stalling effect appears with a rudder angle of five degrees; at bottom it is intensified with a 17-degree angle. Visible portion of hull is below waterline.



SCALE MODEL of the *Antiope* is fitted for tests in the ship-model towing tank of the Department of Naval Architecture and Marine Engineering at the Massachusetts Institute of Technology. Forces and moments are measured by means of the sensing devices mounted fore and aft; device at midships imparts heel. The model is about one-sixth the size of *Antiope*.



TEST RUN is conducted with the model of the *Antiope* in the M.I.T. tank. A typical test consists of 90 runs covering all the practical sailing attitudes and speeds. The tests provide a basis for predicting how the full-scale vessel will perform under various conditions.

this is added the frictional drag of the full-scale hull, calculated as in the case of the model but for the full-scale Reynolds number, to obtain a predicted value for the total resistance.

Unfortunately there is some uncertainty about the calculation of frictional drag. This is particularly true of yachts, because their hull forms differ so greatly from those of the conventional ship hulls for which the empirical formulations of frictional drag were derived. Moreover, since the frictional drag constitutes the largest portion of the total drag produced by a towed model, an accurate prediction is necessary for the overall Froude method to be valid. The scaling of the lift, or sidewise force, due to yaw is also a source of potential trouble, but this is usually assumed to scale down strictly according to Froude's law for wave effects, with frictional effects being of secondary importance.

Such was the state of the art when two years ago the Society of Naval Architects and Marine Engineers formed Panel H-13 (Sailing Yachts) as part of its technical and research program. This group, consisting primarily of yacht designers and towing-tank operators, immediately focused its attention on the scale-effect problem and possible experiments that might provide a correlation between full-scale and model results. It had been amply demonstrated that there was scant hope of obtaining reliable dynamic measurements on a real boat at sea or even in protected waters. The alternative was clear: to find some way to study a full-scale boat in a large towing tank. Through a chain of fortunate events this seemingly unlikely project quickly materialized. The Navy's large experimental facility at the David Taylor Model Basin is directed by charter to perform commercial testing services for the American maritime industry. The proposed experiment met the requirements of the charter.

The towing tank selected for the experiment is about 1,700 feet long, 51 feet wide and 20 feet deep. Normally this facility is used for towing scale models of ships and submarines. It is big enough, however, to accommodate the hull of a full-sized sailing yacht up to about 30 feet in length. Although larger hulls could be placed in the tank, they would be subject to wall effects (for example wave reflections from the sides of the tank) that might influence the measurements.

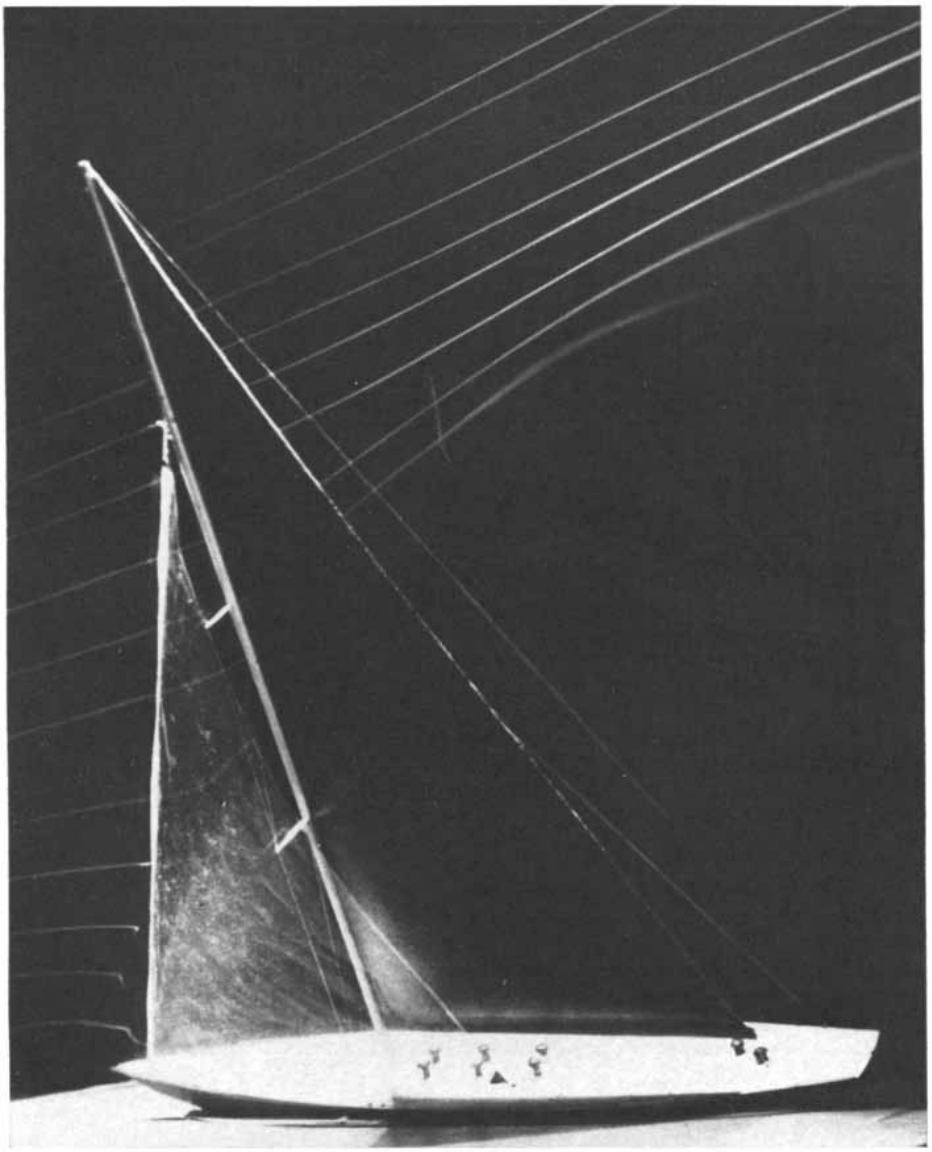
After considering various possibili-

ties it was decided that a yacht from the highly competitive International 5.5-Meter Class would make a fine test subject. Designations such as "5.5-meter" and "12-meter" are derived not from the actual length of the boats but from international rules based on an empirical formula. The formula includes length, sail area, displacement and other factors to yield a figure, expressed as length, that is assumed to be a fair measure of the speed of the boat. Unlike "one design" yachts, each of which has a standard hull form and sail plan, the "meter" classes permit variations of design that lead to the development of new hull shapes and sail combinations. An analogous development process contributes to the improvement of ocean racing yachts.

One of the leading designers in the 5.5-meter class, A. E. Luders, offered his own boat the *Antiope* for the proposed tank tests. Her length at the waterline is 23 feet; her length overall, 31 feet. Financial support for the tests was obtained not only from the Society of Naval Architects and Marine Engineers but also from interested yachtsmen and naval architects. In November of last year the *Antiope* was shipped to the David Taylor Model Basin, where she was fitted onto the towing carriage by means of specially prepared linkages and equipped with gauges to record the three components of force at each end of the boat [*see illustrations on page 60*]. Yaw angle was adjusted by setting the bow off-center; heel angle was varied by moving 400 pounds of lead ballast along a 14-foot aluminum platform that extended from one side of the hull.

Testing then proceeded for a week, both day and night, with runs spaced at half-hour intervals to ensure calm conditions of the tank water. Speed, heel and rudder angle were varied systematically, and some tests were duplicated with small brass studs fastened near the leading edge of the keel to stimulate turbulence. These tests produced 100 sets of data, which were automatically converted to digital form and reduced on a computer to give for each test condition the magnitude of the drag and sidewise forces and the center of the sidewise force.

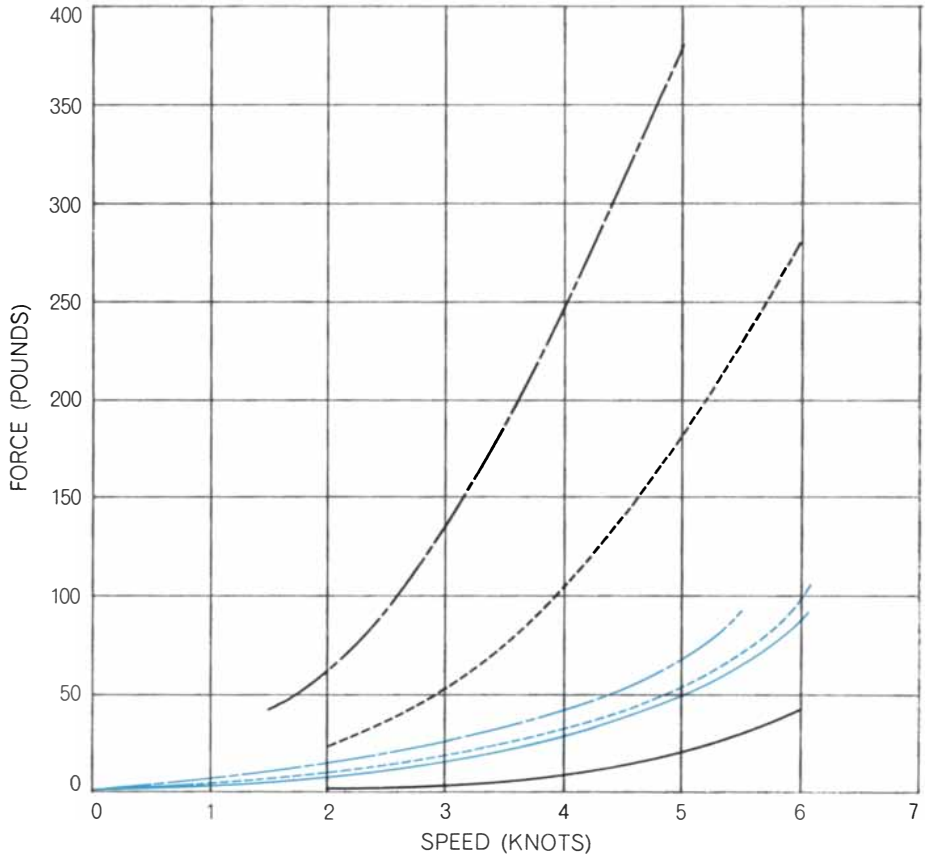
The results obtained with the *Antiope* are substantially the same as predictions based on testing small-scale models of similar hulls in the 5.5-meter class, and a preliminary comparison shows no sign of drastic scale effects on either the resistance or the sidewise force. Now in progress is the step of providing a detailed comparison with exact scale models of the *Antiope*, which are being tested under identical conditions in the smaller towing tanks at the Massachusetts Institute of Technology, the Stevens Institute of Technology and other laboratories in this country and abroad. The resulting exact comparison will undoubtedly lead to detailed refinements in future test procedures.



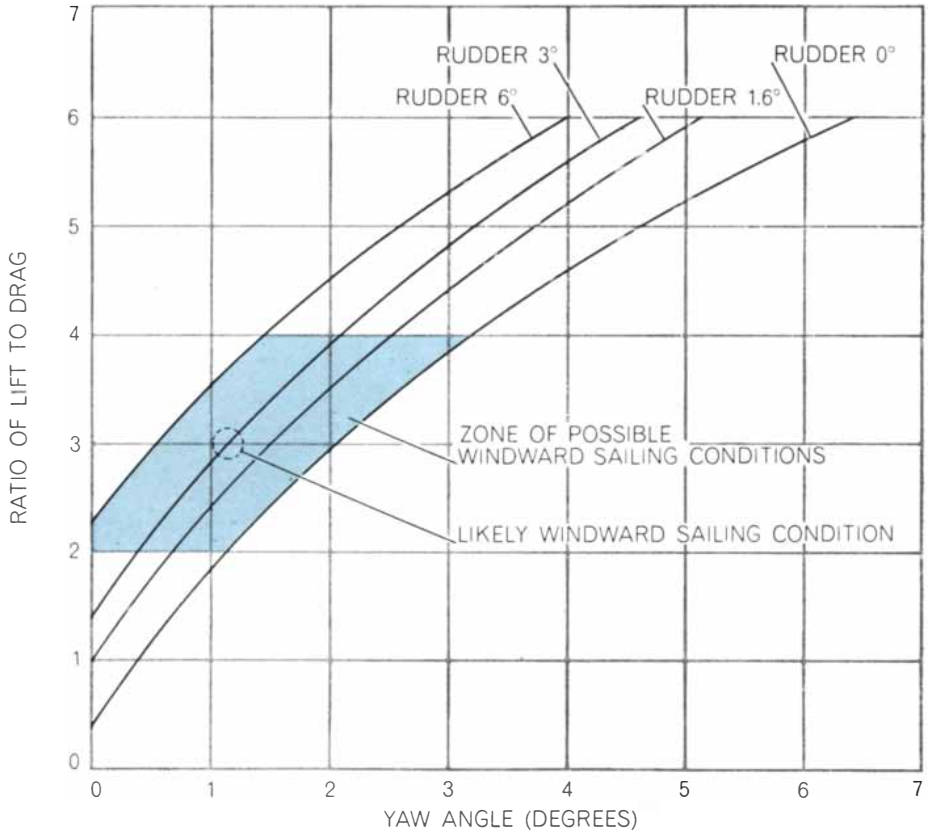
SAIL TEST is conducted in the flow-visualization wind tunnel at the U.S. Naval Experimental Station in Philadelphia. This is a 1:37-scale model of a 12-meter boat. The jib, or forward sail, is made of Mylar, the mainsail of solid plastic. Jets of smoke demonstrate that the flow of air begins to deflect well forward of the leading edges of the two sails.

While the *Antiope* was at the David Taylor Model Basin she was also studied in another large test facility: a flow-observation channel. In this facility the hull is held stationary while the water is made to flow at specified velocities, in a manner analogous to the testing of airplanes in a wind tunnel. Strips of yarn were fastened to the hull to show the flow pattern, which was observed and photographed through underwater windows in the sides and bottom of the channel [*see illustration on page 65*]. The flow studies revealed a rather regular, unseparated flow over most of the hull for the practical range of sailing conditions. Significant separation of flow did not occur until the yaw angle of the hull was increased to 10 degrees, far beyond the angles normally encountered in sailing. At less extreme yaw angles, characteristic of normal sailing conditions, considerable cross flow was observed at the bottom of the keel. This flow is indicative of the "tip vortex" associated with all lifting surfaces. Such a vortex is sometimes visible at the wing tip of an airplane when the reduced pressure at the core of the vortex causes the condensation of water vapor.

Parallel to the research on yacht hulls,



DATA FROM TESTS of *Antiope*'s hull in the model basin include relation of drag to speed (*color*) and side force to speed (*black*). Each set of curves shows, from bottom, yaw angles of zero, 2.65 and 6.45 degrees; heel angles vary from zero to 30 degrees. Small side force occurs even with no yaw angle because of asymmetry of hull resulting from heel angle.



LIFT-TO-DRAG RATIO of *Antiope*'s hull is plotted against yaw angle for windward sailing at a speed of five knots and various rudder angles. Color shows possible and likely windward sailing conditions as derived from lift-to-drag ratio of sails on a 5.5-meter yacht.

experiments and analyses are under way in the study of sails. The scaling of force measurements on sails in a wind tunnel is simpler than the scaling of hydrodynamic forces on hulls; wave effects are no longer a factor and Reynolds scaling is valid. In the case of the sails, however, there is the additional problem that the shape is not constant: it varies with wind conditions because of the elasticity of the sail fabric and the distortion of the rigging that holds the sails. Moreover, the number of variables governing the choice of sails is large. Tests of jib, mainsail and hull combinations are now under way at the M.I.T. Wright Brothers Wind Tunnel and at the U.S. Naval Experimental Station in Philadelphia [*see illustration on preceding page*]. As in the towing-tank tests, dynamometers are used to measure the aerodynamic forces and moments on the sails. The test sails are made of aluminum or of a rigid fiberglass-reinforced plastic in order to maintain control over their shape.

Although it is useful for design and research to separate the treatment of the hull from that of the sails, the two are closely interrelated. A sail that is optimum for one boat is not optimum for boats of a different class or type. As an extreme example, an iceboat is capable of high speeds, and it can exert through its runner blades a high sidewise force with practically no drag. Under these circumstances flat sails with small angles of attack are appropriate; such sails produce rather small driving forces but have a high ratio of lift to drag. In contrast, a 12-meter sailing-yacht hull is subject to a considerable hydrodynamic resistance to forward motion and can develop a sidewise force of a large (but limited) extent. The sail design used in an iceboat would provide insufficient forward thrust for a 12-meter yacht, which needs a more cambered sail set at a larger angle of attack in order to produce the necessary drive.

The tremendous popularity of recreational boating and in particular the recent upsurge of interest in sailing vessels have stimulated renewed interest in yacht development. Yacht designers have long been aware that much research is needed to fill the existing gaps in information about the dynamics of sailing craft. It is hoped that model experiments and full-scale correlation, such as the *Antiope* tests, will lead to a better understanding of the fundamental mechanics of sailing-yacht performance.

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Nuclear 'Pig' goes to market.

It looks like a farmyard pig, but it's the world's first commercial radioisotopic generator. After one fueling with nuclear material, it will produce 25 watts of electricity non-stop, around-the-clock for at least five years. It was created in the nuclear laboratories of our Martin division, but it's no laboratory curiosity. Martin will sell you one right now for $63,320 f.o.b. Baltimore, guaranteed.

This LCG-25 commercial nuclear unit had its genesis in a small device discovered over a hundred years ago.

In 1826 a German named Seebeck joined two wires of different metals so they made a circle. When he heated one of the junctions where the wires came together, a faint current flowed around the circle.

He had produced electricity directly from heat. The device (since called a thermocouple) was long regarded as of no practical value.

After World War II, researchers were experimenting with uses for radioactive wastes. When these wastes are confined in heavy metal containers, their radiations are blocked and absorbed by the metal. This produces heat which can reach 1000°F and continue sometimes for decades.

Working with the Atomic Energy Commission, scientists at Martin set about marrying the thermocouple to this heat source to produce electricity.

By 1959, Martin built a small generator weighing about 4 pounds for the AEC. It was capable of producing 2.5 watts continuously for 7 months.

Since then, Martin has built generators that can produce as much as 60 watts continuously for 10 years. A 400-watt unit is now in the design stages, as are tiny units weighing only a few ounces.

Martin nuclear generators have supplied electricity near the North and South Poles, at sea and in space, wherever conventional power is impossible or too expensive.

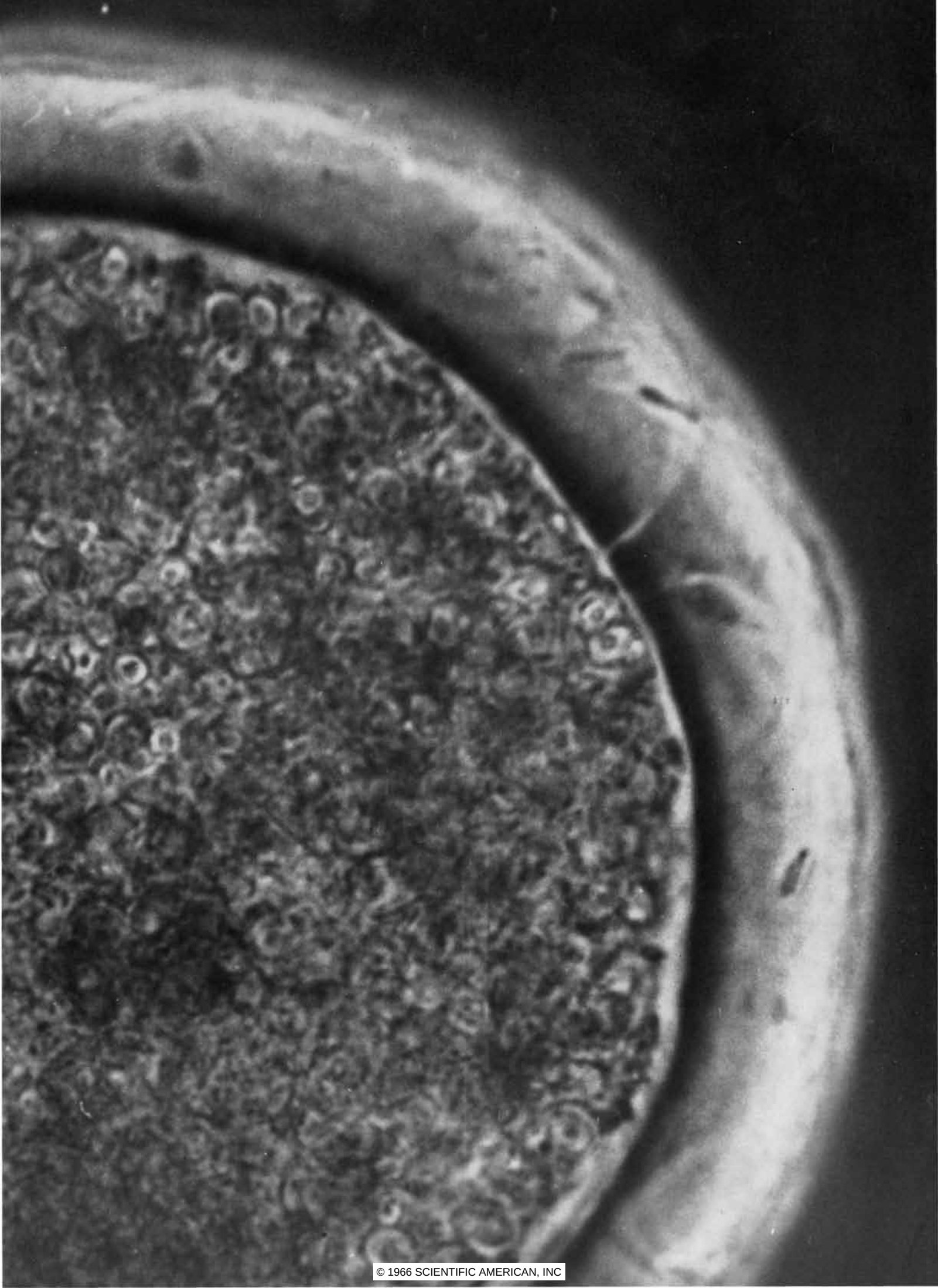
The pig-shaped LCG-25 is Martin's first strictly commercial system, and the first compact nuclear generator privately developed and offered for sale. It is guaranteed to produce a minimum of 25 watts continuously for 5 years on one fueling. It measures 30 x 35 inches and weighs a hefty 3000 pounds (mostly shielding).

It's considered just the thing for remote weather stations, navigation aids at sea, seismological stations, microwave repeater stations, aircraft beacons and offshore oil installations. Or for anything else that must operate reliably for long periods in remote areas.

LCG-25 has virtually no operating cost. So when you amortize the initial price over its long operating life, the nuclear generator is quite a practical thing to have working for you.

The nuclear generator is representative of a broadly diversified range of products, including space launchers, missile systems, spacecraft, electronic systems, chemicals and construction materials. Martin Marietta Corporation, 277 Park Avenue, New York, N.Y.

MARTIN MARIETTA



MAMMALIAN EGGS IN THE LABORATORY

The earliest stages of human development may be opened to study by bringing the eggs of mammals to maturity in a culture medium, fertilizing them in vivo or in vitro and observing the embryos

by R. G. Edwards

Much of what is known about animal reproduction has been learned from such organisms as the sea urchin and the chicken. This is partly because the eggs of these organisms are readily accessible to observation during such crucial stages of the reproductive process as fertilization and embryonic development. During the past quarter-century the eggs of certain mammals—rodents, rabbits and some farm animals—have become more accessible to study. This increasing availability of mammalian eggs arises largely from advances in knowledge of how ovulation is controlled by hormones. The eggs of man and other primates, however, are still secured very rarely. It has long been recognized by workers in the field that, if a significant number of viable mammalian eggs were available on a regular basis, a host of questions about the early stages of mammalian reproduction would be open to investigation.

Experiments that my colleagues and I have conducted at the University of Cambridge and Johns Hopkins University indicate that such a situation may soon obtain. So far the experiments have been concerned mainly with oocytes, which are immature eggs. In most mammalian species, including man, the female has her full complement of oocytes when she is born. The development of the oocytes into mature eggs ready for fertilization is a long process that goes through many stages. Our experiments have involved removing oocytes from the ovaries of various mammals and stimulating them to proceed to maturity. We have also worked with some human oocytes removed surgically from women for medical reasons. Our experiments have included the fertilization of some of the animal eggs brought to maturity in vitro and attempts to fertilize the human oocytes. In discussing these experiments it will be useful to begin by describing briefly two of the key processes in the reproduction of mammals and other higher organisms: mitosis and meiosis [*see illustration on page 75*].

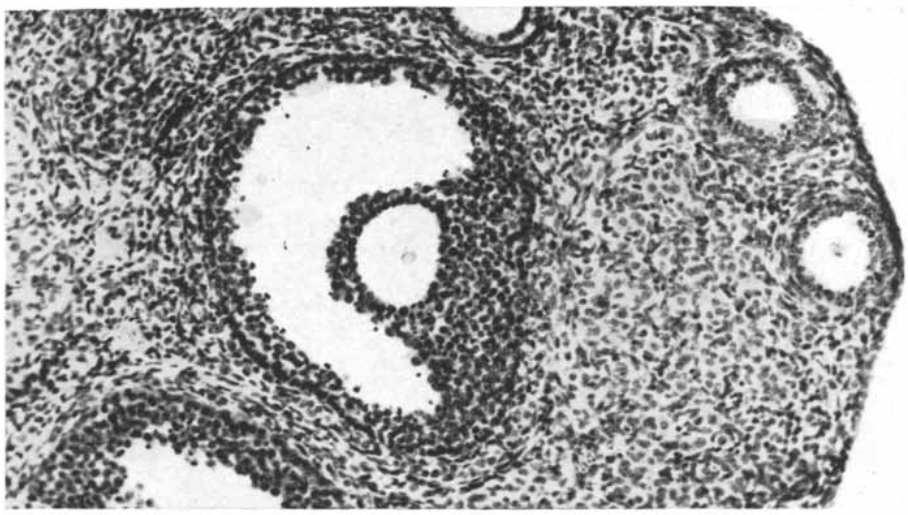
PIG EGG was matured in culture and fertilized in the animal. In the photomicrograph on the opposite page a segment of the egg and the zona pellucida, or outer membrane, appears at an enlargement of 1,400 diameters. The small, dark objects in the zona pellucida are sperm heads; the lighter curved lines are trails made by spermatozoa as they penetrated the zona pellucida. Penetration by such a large number of spermatozoa is an unusual condition that appeared in initial experiments with cultured eggs.

Mitosis is the name for the processes that take place in most cells (both plant and animal) when the cells reproduce by dividing. The events of mitosis are usually regarded as occurring in four more or less distinct phases: prophase, metaphase, anaphase and telophase. The process can be described simply for a hypothetical organism in which each cell contains four chromosomes: the bodies that carry the cell's genetic information. Two of the chromosomes, say a long one and a short one, were inherited from the mother and two from the father. The two long chromosomes are similar to each other, as are the two short chromosomes. When the members of each pair are matched in this way, they are called homologous chromosomes; the four-chromosome cell would have two pairs of homologous chromosomes. At the beginning of mitosis each chromosome has divided into two strands, which are held together by a central body called the centromere.

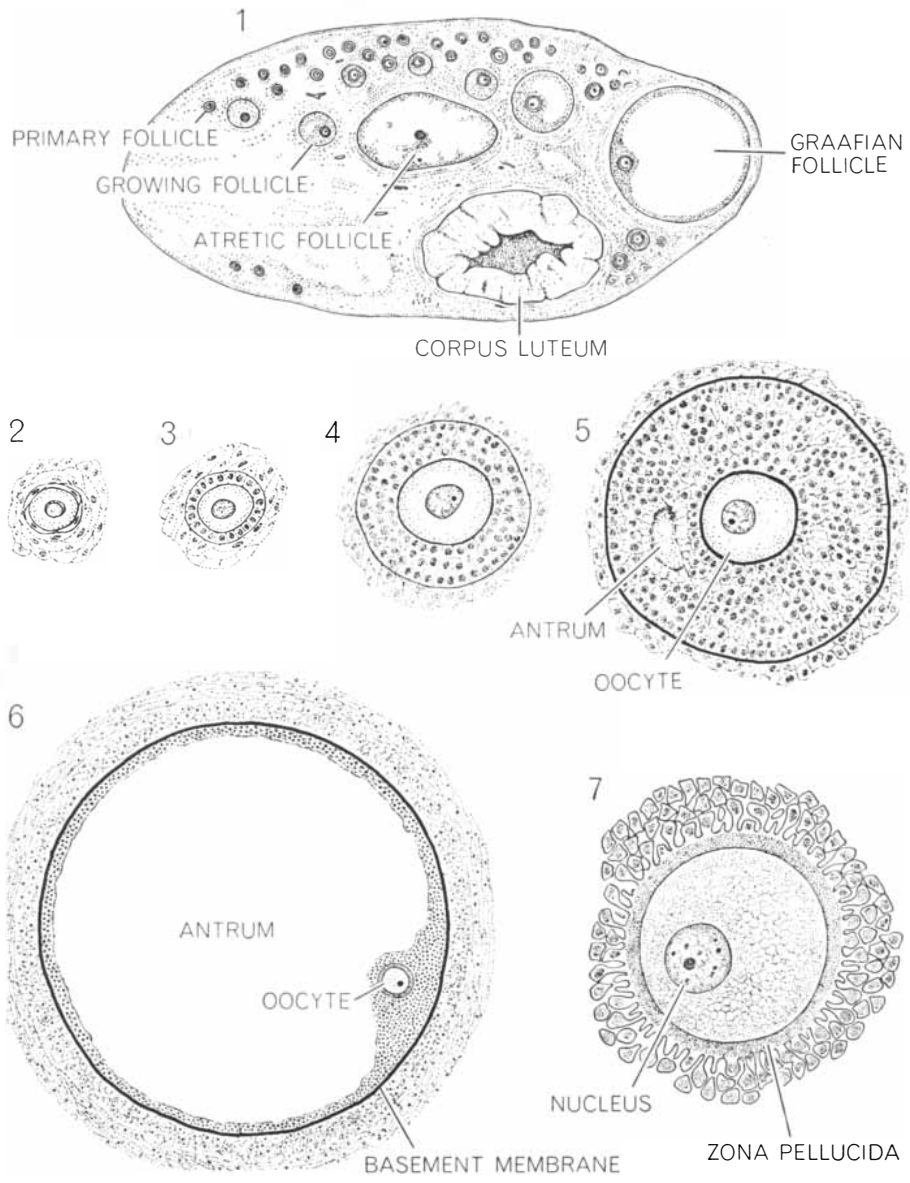
In prophase the chromosomes begin to shorten and thicken, and the remarkable structure called the mitotic spindle starts to form. The spindle consists of fibers in an array resembling the meridian lines of a globe that has been stretched at the poles. In metaphase the centromeres migrate to the equator of the spindle. In anaphase the centromeres divide, and the two daughter centromeres resulting from each division move toward opposite poles of the spindle, pulling their chromosome strands with them. In telophase the separation is complete; the cell divides into two daughter cells, each with a nucleus containing four chromosomes and thus the same complement of genetic information that was contained in the original cell. This completes mitosis; until one of the new cells itself begins mitosis it is said to be in interphase. Toward the end of interphase the chromosomes again divide into two strands.

Meiosis is a special form of mitosis that occurs in the cells that give rise to sperm and eggs. Before the process begins, these cells, like others in the body, are diploid: they have a normal complement of chromosomes. Since mammalian reproduction involves the union of a spermatozoon and an egg, the cells of the offspring would have a double complement of chromosomes if there were not some mechanism by which the spermatozoon and the egg became haploid, meaning that the chromosome complement of each was reduced by half. That mechanism is meiosis. It occurs in two cell divisions, known as meiosis I and meiosis II [*see top illustration on pages 76 and 77*].

The prophase of meiosis I is highly specialized and occupies a comparatively long period of time. For these reasons it is subdivided into five stages: lep-



MOUSE OVARY in cross section is enlarged 200 diameters. The light circular areas are oocytes, or immature eggs, enveloped by follicles, which are composed of granulosa cells. The large, light, semicircular area at left center is the antrum, or cavity, of a Graafian follicle; when a follicle has developed to that stage, the oocyte is ready for ovulation.



MATURATION OF OOCYTES occurs continually. At top is an ovary with several follicles containing oocytes at various stages of development. At center four stages in the maturation of a follicle are shown. At bottom are a fully grown Graafian follicle (*6*) and a mature egg (*7*).

totene, zygotene, pachytene, diplotene and diakinesis. Each relates to the activities of the chromosomes. Essentially what happens in meiosis, as distinct from mitosis, is that the homologous chromosomes pair up and duplicate. At metaphase the homologous pairs line up on the spindle. In anaphase one member of each pair, without splitting, goes to each pole. Thus after the cell divides at telophase each daughter cell has only one member of each pair of homologous chromosomes.

In meiosis II there is no further duplication of chromosomes. The twin-strand chromosomes simply line up on the spindle and separate. When the two cells that resulted from meiosis I divide in meiosis II, each of the four resulting cells has only half the original number of chromosomes. In the case of our hypothetical four-chromosome cell the result of meiosis would be four cells with two chromosomes each. By this process sperm and eggs are made haploid; when they unite through fertilization and begin the mitotic divisions known as cleavage (the first steps in the growth of an embryo), all the resulting cells are diploid.

Let us now examine the normal maturation of a mammalian oocyte. It undergoes the first four stages of the first meiotic division in the ovary of the fetus. In other words, before a female mammal is born her oocytes have completed the leptotene, zygotene and pachytene stages and are well into the diplotene stage. Meiosis halts, however, late in the diplotene stage. At this point a nucleus, called the germinal vesicle, forms in the oocyte.

These developments coincide with the envelopment of the oocyte by an array of cells known as granulosa cells. These gradually form the follicle in which the oocyte will remain enclosed until ovulation. This situation—in which the oocyte is in an arrested state of meiosis, contains a nucleus and is enveloped in a follicle—prevails at the birth of the female and persists during growth to adulthood. During the entire span of this time (up to some 40 years in the human species) the homologous chromosomes remain paired in the germinal vesicle. To many biologists this long period is known as the dictyate stage of oocyte development; others call it the dictyotene stage or the diffuse diplotene stage.

Near puberty many of the oocytes undergo atresia: they degenerate and are resorbed. This process results in a large reduction in the number of

oocytes. Those that remain resume their progress toward maturity in the adult ovary. With the onset of puberty, follicles mature in groups during each sexual cycle. The follicles grow by a rapid increase in the number of granulosa and other cells. The oocyte also increases in size, usually before the follicle shows much enlargement; for the time being, however, the oocyte remains in the dictyate stage.

The later stages of follicular growth are characterized by the formation of a cavity, the antrum, in the granulosa layer; the structure is now known as a Graafian follicle. At this stage the follicle is responsive to the hormone called FSH (for follicle-stimulating hormone). FSH is secreted by the anterior part of the pituitary gland during the early part of the sexual cycle and stimulates the final enlargement of the Graafian follicle.

Now the Graafian follicle becomes sensitive to a second pituitary hormone, luteinizing hormone (LH), which has a dual action: it stimulates the oocyte to resume meiosis and it initiates changes in the follicle that lead to ovulation. Under the influence of LH the oocyte completes its first meiotic division, progressing through diakinesis, metaphase, anaphase and telophase. The daughter cells that result from this division are far from identical. One of them, the secondary oocyte, receives a disproportionate share of the original cell's cytoplasm; hence the other, the first polar body, is much smaller.

The second meiotic division begins as soon as the first ends. It reaches metaphase within minutes. Except in a few mammalian species ovulation occurs while the oocyte is in metaphase II.

In the process of ovulation the Graafian follicle fills with fluid, moves toward the surface of the ovary and erupts, releasing the oocyte. The cells of the ruptured follicle are converted to a new structure, the corpus luteum. This is the structure that produces the hormone progesterone, which conditions the walls of the uterus for the development of the fertilized egg.

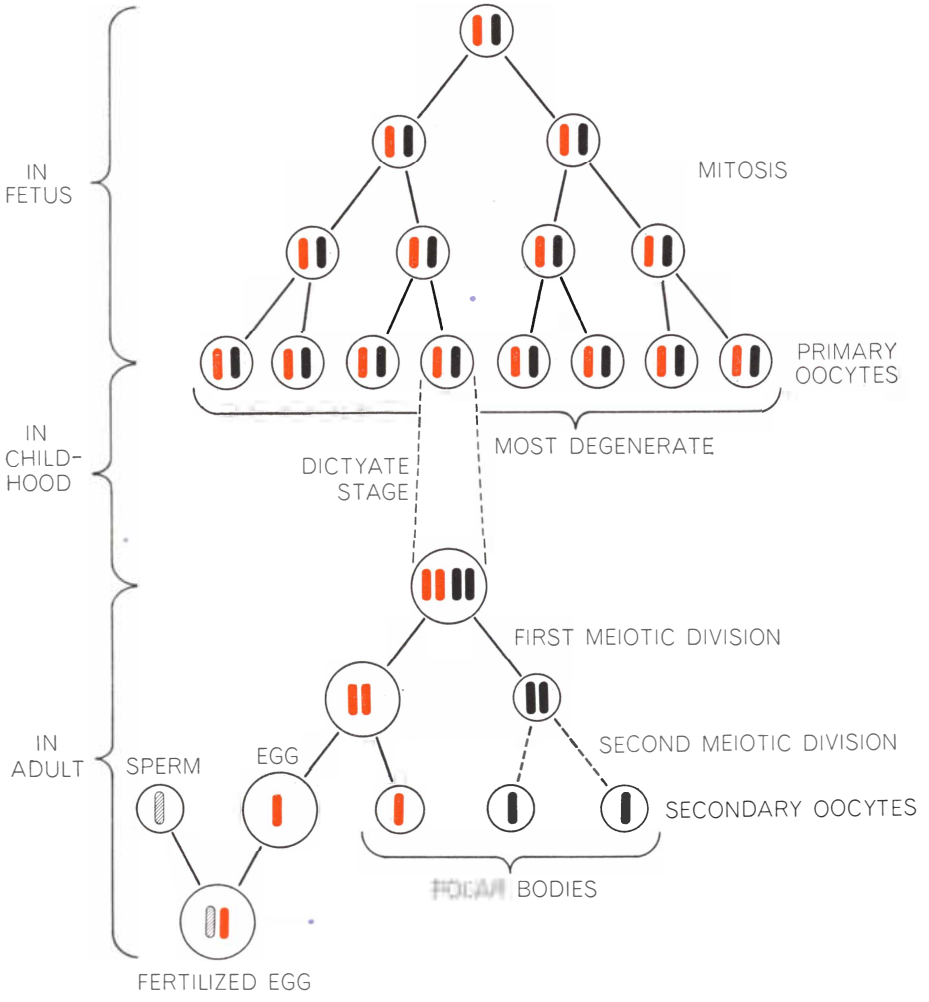
At this stage meiosis is still not complete. It awaits fertilization in the fallopian tubes. Only when the fertilizing spermatozoon enters the egg is meiosis II ended by the extrusion of the second polar body. The entire process—the first stages of which took place in the fetal ovary, the middle stages in the adult ovary and the final stages in the fallopian tubes after fertilization—is now complete.

In this account of the maturation of a single oocyte the reader may well have lost sight of the setting in which these developments occur. It has been estimated that there are some 500,000 oocytes in the female human fetus, a number vastly exceeding the reproductive needs of the female. Indeed, many mammals shed only one egg during each ovulation. Others—for example mice, rabbits and pigs—produce several eggs in one ovulation, but the number is still tiny in relation to the original population of oocytes. During each sexual cycle FSH stimulates the development of many follicles, but only a few of them progress as far as ovulation. Most of them degenerate, although the oocytes in some of these atretic follicles can complete meiosis as far as metaphase II.

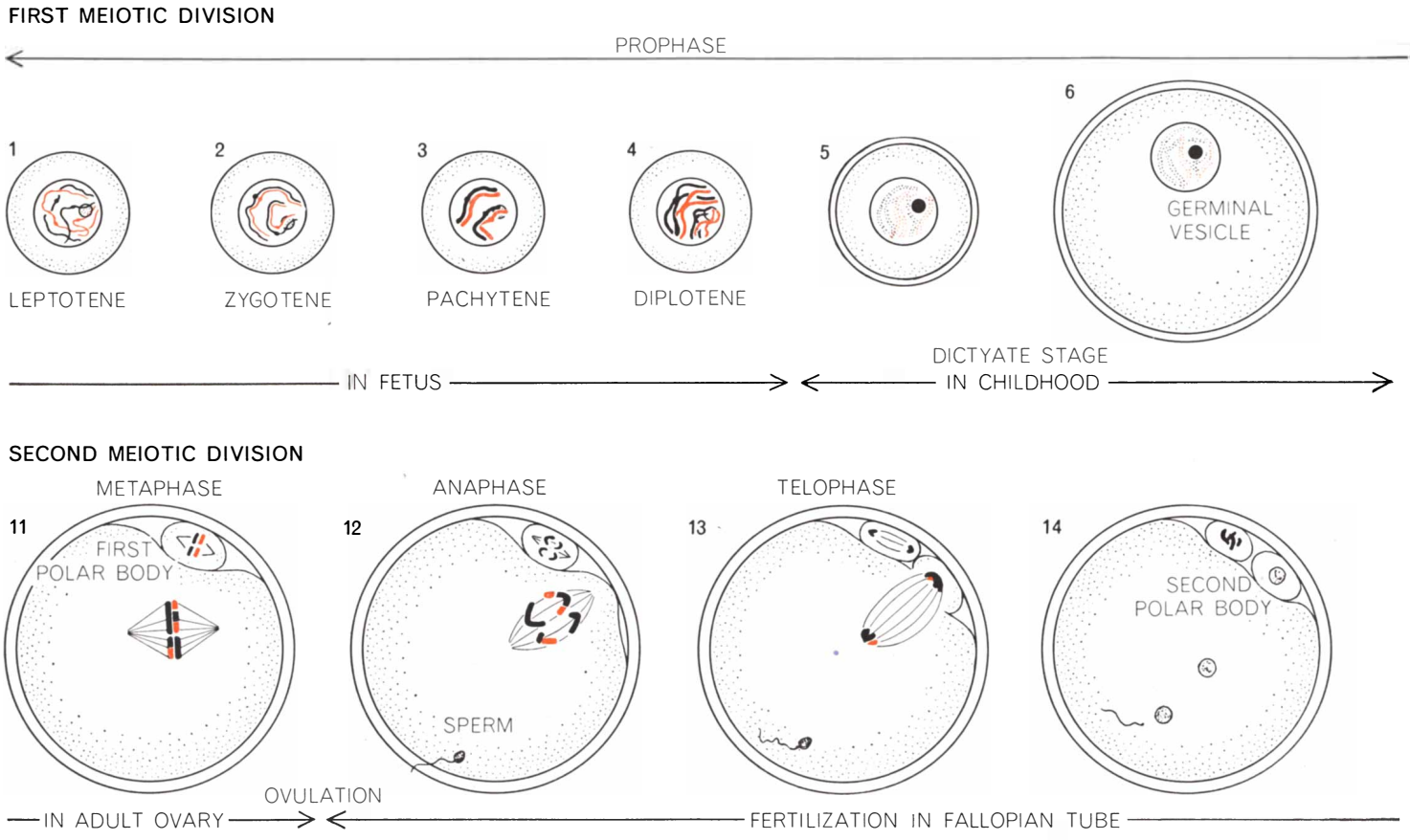
Atresia evidently begins when the amount of FSH becomes insufficient to maintain the growth of all the follicles developing during the female cycle, because if extra FSH is provided by injection, large numbers of follicles continue their growth. In response to LH they will proceed to ovulation.

Treatment with FSH and LH will thus induce the ovulation of large numbers of eggs—several in man, as many as 70 in mice. These eggs can be fertilized, although for many years they were regarded as being somewhat abnormal because a large proportion of the embryos to which they gave rise died during pregnancy. It is now known, primarily from evidence in mice, that such embryos are perfectly capable of normal development provided that the uterus is not overcrowded.

With FSH and LH an experimenter can therefore obtain oocytes from many or all of the Graafian follicles developing during a particular cycle. The method can, however, be laborious and



EVOLUTION OF AN EGG is traced through the processes of mitosis and meiosis. The original cell (*top*) is diploid: it has a set of chromosomes from the father (*color*) and one from the mother (*black*). This arrangement is repeated in the daughter cells that result from mitotic divisions to produce oocytes. In meiosis successive divisions produce an egg that is haploid: it has half the normal complement of chromosomes. When the egg and a sperm join to produce fertilization, the resulting cells of the growing embryo are again diploid.

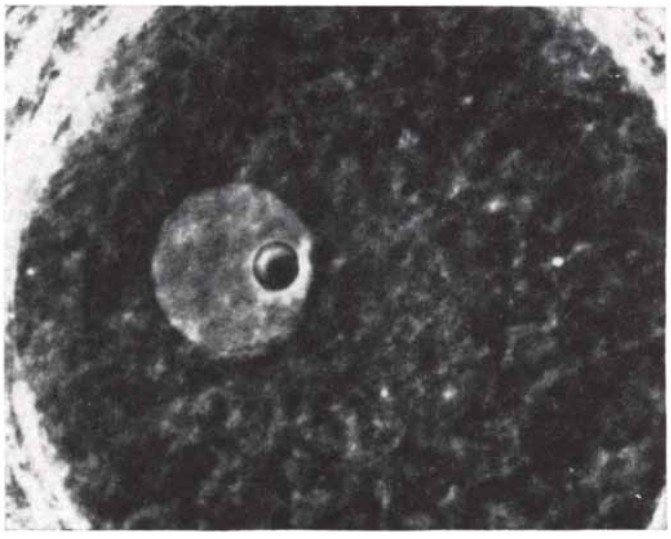


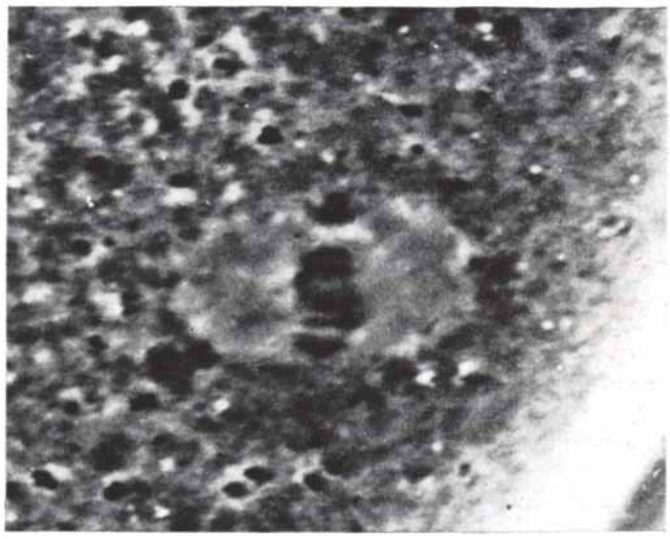
DURATION OF MEIOSIS can be as long as 40 years in human oocytes. Its prophase has a particularly long duration and several chromosomal events; hence it is subdivided into five stages, beginning with leptotene and ending with diakinesis. Homologous, or similar, chromosomes, one (*black*) from the father and one (*color*) from the mother, are paired during much of the process. Meiosis halts late in the diplotene stage and the germinal vesicle appears. Meiosis is resumed in adulthood under the influ-

uncertain. In many species it requires the detailed recording of the female cycle, and in large animals it calls for organizing surgical operations or slaughtering to obtain the eggs from the fallopian tubes. For various reasons it is exceedingly difficult in its application to man. Nonetheless, it is clear that a large supply of oocytes can be tapped in the ovary at any time during the reproductive life of the female.

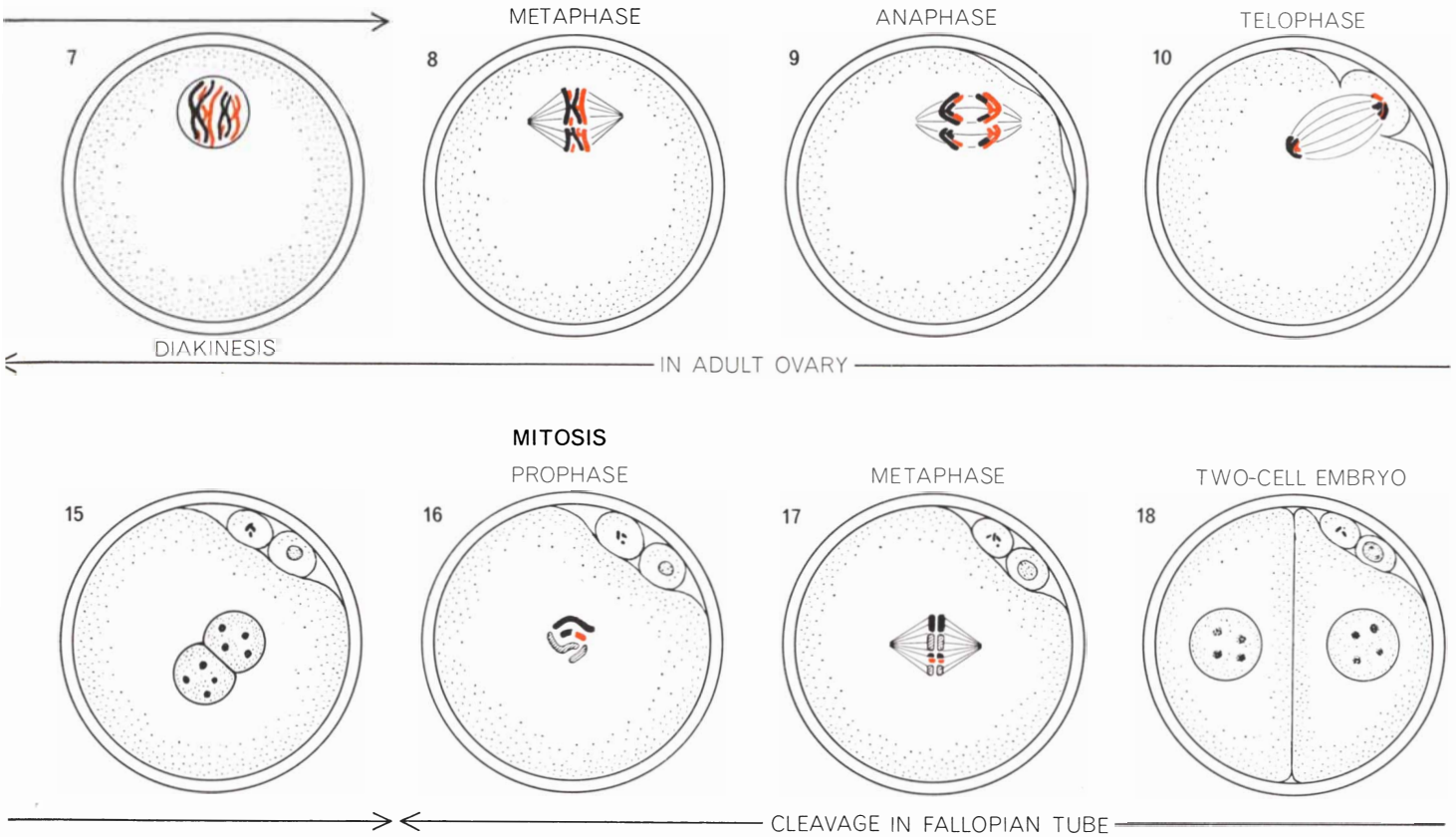
Once an experimenter removes an oocyte from its follicle he is confronted by two main problems. First, the oocytes (particularly those taken from atretic or underdeveloped follicles) may be abnormal. Second, the oocytes will have to be stimulated in some way to complete their meiosis to metaphase II so that they will be comparable to eggs ovulated normally.

The problem of abnormality is manageable. Oocytes from atretic follicles can usually be recognized quickly and





STAGES OF MEIOSIS appear in various oocytes matured in culture. At left is a living monkey oocyte in the dictyate stage; its germinal vesicle, or nucleus (*light circle*), contains a single nucleolus (*dark circle*). The next photomicrograph shows a living rat oocyte in metaphase I; the light oval area is the spindle, with chromosomes on its equator. The third photomicrograph shows a pig

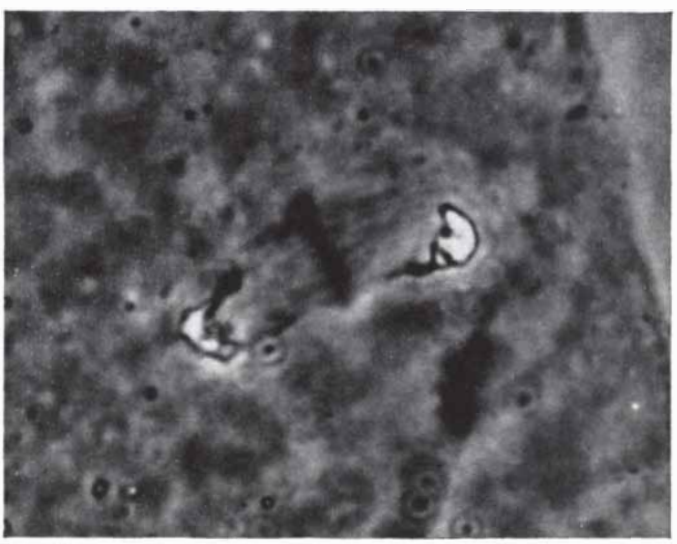


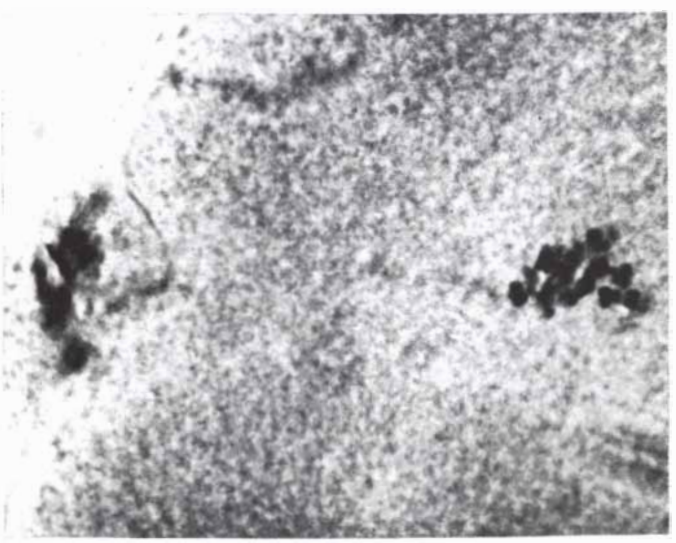
ence of luteinizing hormone. At the end of meiosis I the cell divides; one of the daughter cells, the secondary oocyte, receives more of the original cell's cytoplasm than the other, the first polar body, and so is larger. Meiosis II begins when the first ends and proceeds quickly to metaphase. At this point ovulation occurs in most mammalian species. The second meiotic division is completed in the fallopian tube after entry of a spermatozoon into the egg. Meiosis thus begins in the fetus and ends long afterward.

excluded from experiments. Underdeveloped follicles either can be recognized or will end up as experimental failures.

An obvious solution to the problem of stimulating oocytes to resume meiosis was to grow them in culture outside the body. A reasonable assumption was that the culture medium would need to contain LH. It turned out, however, that LH was not needed, and the techniques required to induce the resumption of meiosis proved quite simple. Oocytes had only to be removed from the follicles and placed in a standard culture medium for meiosis to recommence in a manner seemingly identical with that in the ovary after stimulation by LH.

These observations were first made in rabbits by Gregory Pincus, now at the Worcester Foundation for Experimental Biology, and his collaborators in 1935. They also made the initial attempts with human oocytes. Our recent work has





oocyte fixed and stained in telophase I; the dark vertical band is the center of the spindle and the chromosomes have moved to opposite poles. At right is a human oocyte fixed in metaphase II; it has extruded its first polar body (*left*). The chromosomes are the dark structures. The enlargement of each photomicrograph except the third is about 1,200 diameters; that of the third is 2,000.

shown that their method can be applied successfully to the oocytes of many mammalian species.

We first noted that oocytes from mice, rats and hamsters would recommence meiosis in culture. A clear sign of resumed meiosis is a receding of the germinal vesicle; it becomes indistinct as the chromosomes condense. The germinal vesicles of most oocytes in these species regressed after two hours, and meiosis proceeded from diakinesis to metaphase II within 12 hours. These rates are similar to those in the ovary after LH has done its work.

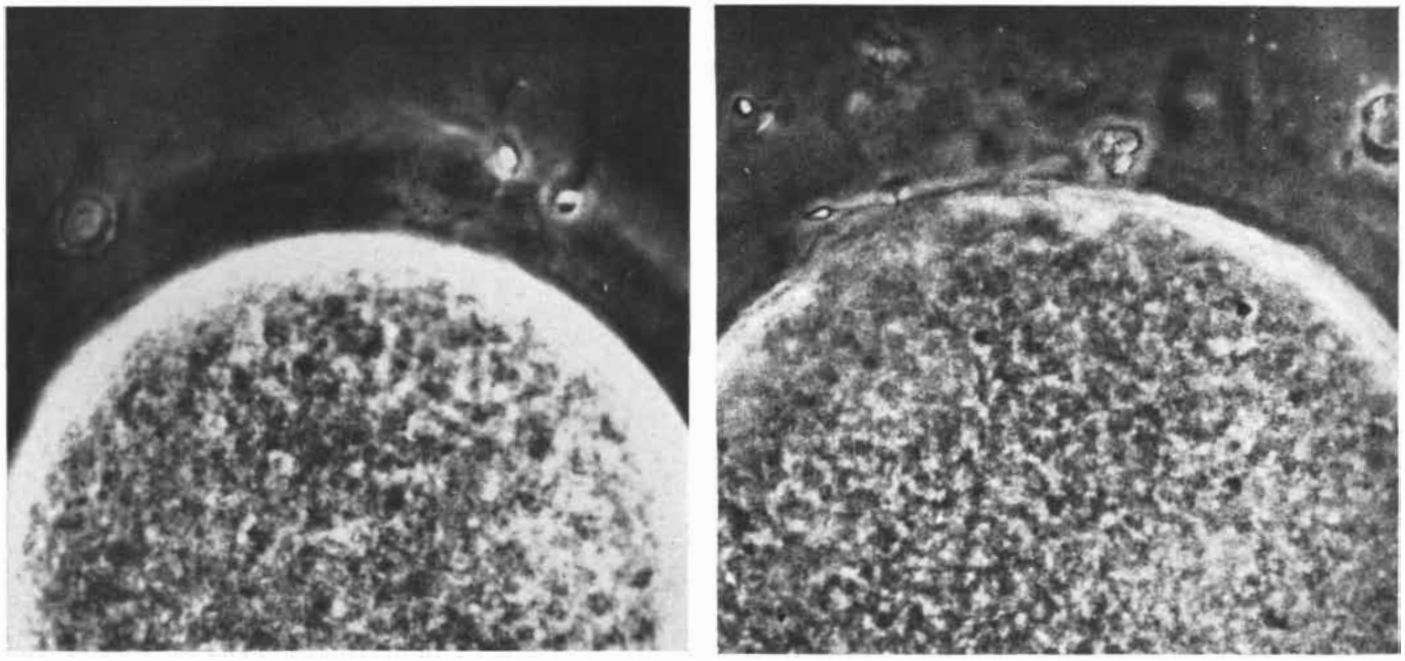
We then assumed (mistakenly) that the oocytes of mammals other than rodents and rabbits would mature after similar periods in culture. When it became clear that in dog, monkey, baboon and human oocytes the germinal vesicle was still intact after as long as 20 hours in culture, we erroneously concluded that oocytes from species with a prolonged sexual cycle required an extra stimulus for the resumption of meiosis. Therefore we added various plant and animal hormones to the culture. They had no effect whatever. Finally we found that by simply extending the period of culture we could induce between 60 and 80 percent of the oocytes from all the animals with which we worked to resume meiosis. In certain species—cow, sheep, monkey and probably baboon (we have had too few baboon oocytes to be sure)—20 to 24 hours passed before the germinal vesicle regressed.

Obviously we had to ensure that the persistence of the germinal vesicle in certain species for as long as 24 hours in vitro mirrored the events in the ovary after stimulation by LH. It was therefore fortunate that Christopher Polge and Ronald Hunter of the British Agricultural Research Council had made detailed estimates of the pig oocyte's meiotic stages in vivo after the pigs had been injected with LH. These estimates showed that the germinal vesicle persisted for 20 to 24 hours after the injection and that meiosis was then resumed. Polge and I examined cultured oocytes and found that they matured at a rate closely comparable to the rate of maturation in the ovary. This was most encouraging to us. If pig oocytes were maturing normally in vitro, we could reasonably conclude that the same was true of oocytes from other species in which there was a long delay before the germinal vesicle regressed.

In all species most oocytes matured to metaphase II. Some oocytes, however, proceeded to anaphase of the first meiotic division and meiosis then halted. The chromosomes failed to segregate along the spindle. The number of oocytes showing this arrest in anaphase was found to depend on the culture medium used. For the most part we now have mediums in which the number of oocytes that fail to reach metaphase II is very small, although in some species—notably the pig and the mouse—we have not fully solved this problem.

A remarkable phenomenon in the culturing of oocytes was that within each species the oocytes matured synchronously, even though they had been taken from females in widely differing stages of the sexual cycle. In other words, it made no difference how near to or far from ovulation an oocyte might have been at the time of removal; once put into the culture medium all the oocytes matured together. As a result of this phenomenon we were able to predict with considerable accuracy the stage of meiosis the oocytes from a particular species of mammal would reach after specific periods in culture. Indeed, by timing the interval between the release of oocytes from their follicles and metaphase II in vitro we can now predict the interval in vivo between the secretion of LH from the pituitary gland and ovulation in cases where this interval is unknown.

Our success with the culturing of oocytes from various experimental and domestic animals presented a major challenge: Would human oocytes respond similarly? After preliminary trials it became abundantly clear they would. In culture the germinal vesicle persisted for 24 hours; the chromosomes condensed at diakinesis between 25 and 28 hours; metaphase I occurred between 26 and 35 hours, and the first polar body was extruded between 36



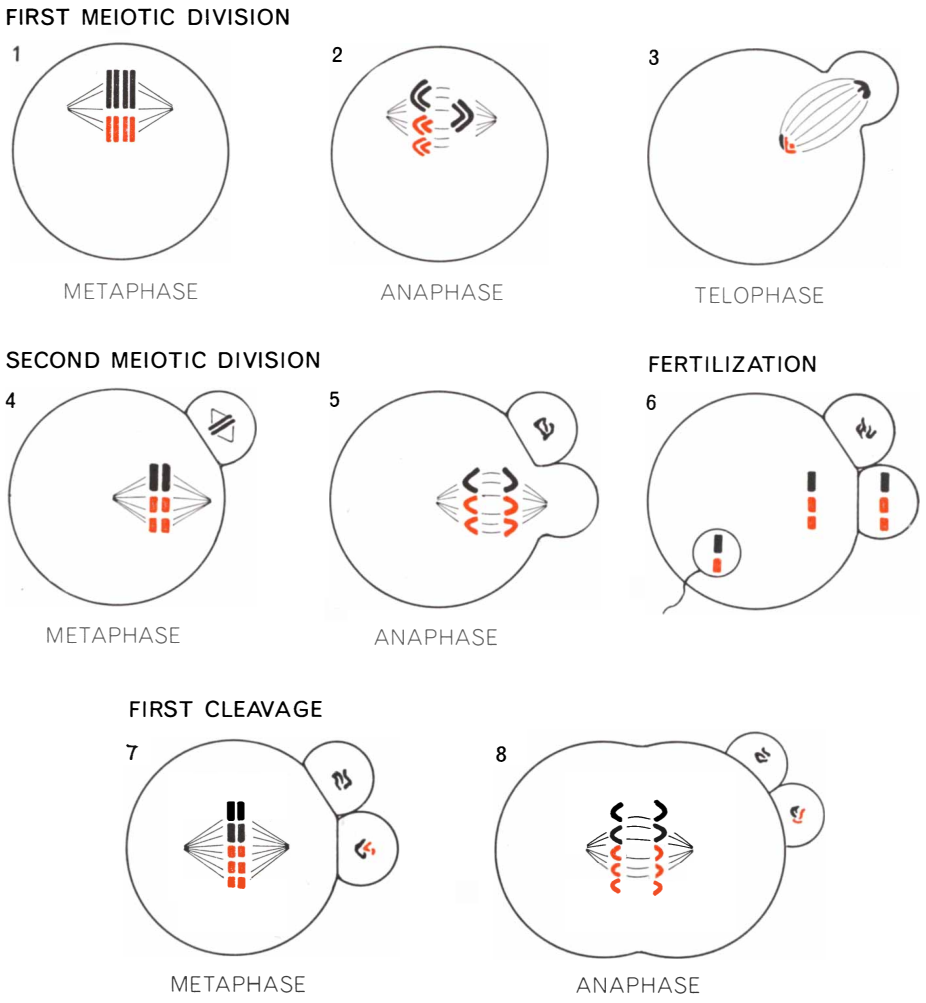
HUMAN EGGS have proved difficult to fertilize in vitro. At left is a human egg with several spermatozoa that have failed to penetrate fully the zona pellucida. In the photomicrograph at right a spermatozoon (*top left*) has passed through the zona pellucida and reached the surface of the egg, but that is inconclusive evidence of fertilization. Some eggs showed other inconclusive evidence of fertilization.

and 43 hours. A large majority of the oocytes examined after 43 hours were in metaphase II and had a polar body.

Even though the oocytes were necessarily taken from women who were ill and undergoing surgery and who were at widely differing stages of the menstrual cycle, approximately 80 percent of the oocytes thus obtained resumed maturation in culture and progressed synchronously through meiosis to metaphase II. From our observations we could therefore estimate that the interval in man between the secretion of LH and ovulation during the menstrual cycle is probably 36 to 43 hours. Moreover, the results showed that we could induce large numbers of oocytes to proceed in culture to the stage where fertilization normally occurs.

Our experiments in the culture of oocytes provide some indications of the mechanisms involved in the normal evolution of oocytes in the ovary. There is evidence that cultured oocytes resume their meiosis when the follicular architecture is destroyed by the rupture of a membrane (variously called the basement membrane or membrana propria) as the oocytes are removed from the ovary. This implies that the intact basement membrane plays a role in restraining the maturation of the oocyte. If it does, that would shed light on several phenomena. For example, in some atretic follicles the oocyte resumes meiosis before the complete degeneration of the follicle. Secondly, the basement membrane is associated with the granulosa cells, and the dictyate stage actually begins when the granulosa cells first enfold the oocyte in the ovary. Moreover, there is evidence that the granulosa cells will begin the changes leading to the formation of a corpus luteum when the follicle is ruptured. It would be most interesting to establish that both of the changes induced in the ovary by LH —the resumption of meiosis in the oocyte and the transformation of a Graafian follicle into a corpus luteum—could be set in motion by rupturing the follicular membrane.

Since it is now possible to induce at will any stage of meiosis between diakinesis and metaphase II, the way is open to investigate how and at what stage chromosome abnormalities arise. In recent years it has been clearly established that in man one such abnormality is associated with mongolism. Many mongoloids have 47 chromosomes per cell instead of the normal 46. The extra chromosome is No. 21, that is,



ORIGIN of chromosomal abnormalities such as that leading to mongolism can probably be studied by growing eggs in culture and watching the chromosomes. Such abnormalities might arise in several ways; here paired chromosomes (*color*) fail to separate normally during anaphase I and hence move together to one pole of the spindle. Thus their distribution in the egg and first polar body is faulty and could result in abnormalities after fertilization.

there are three homologous No. 21 chromosomes instead of the two usually found. Mongolism occurs much more frequently among the children of older mothers. Evidently the defect arises early in embryonic development, or perhaps during meiosis in the oocyte. The immediate cause might be an infection.

Several explanations have been put forward to explain the mechanism of this and other chromosomal abnormalities. The reader will recall from the description of meiosis that homologous chromosomes are paired at the beginning of the dictyate stage and should remain paired until meiosis is resumed under the influence of LH. If homologous chromosomes were gradually to separate during the dictyate stage so that they were no longer paired when meiosis was resumed, they would move independently along the spindle at anaphase. Their distribution in the egg and first polar body would become a matter of chance. This failure of the controlled segregation of the chromosomes would inevitably lead to abnormal karyotypes, or arrays of chromosomes, in some embryos.

Another source of abnormalities might be the nucleolus, the structure that contains much of the ribonucleic acid in the nucleus. Nucleoli are formed from nucleolus-organizer regions in certain chromosomes. The five pairs of human chromosomes carrying nucleolus organizers are involved in a high proportion of chromosomal anomalies. Each of these chromosomes can produce a nucleolus, although in the later stages of maturation an oocyte usually has only one nucleolus because of nucleolar fusion. The close relation of these chromosomes with the nucleolus during the prolonged dictyate stage might lead to abnormal segregation at anaphase. In many of the oocytes that we grew in culture we saw several chromosomes—probably those carrying nucleolus organizers—in intimate association with

the nucleolus during diakinesis. In other oocytes all the chromosomes appeared to be associated with the nucleolus or to be sticking together.

Having caused oocytes to mature in culture to the point of development at which fertilization occurs, we decided to see if they could be fertilized. Our technique with animal oocytes was to transfer them into the fallopian tubes of females of the same species. The females were then normally mated.

In earlier work on the rabbit M. C. Chang of the Worcester Foundation for Experimental Biology found that as many as 80 percent of cultured oocytes were fertilized when transferred into a doe. The rate of fetal abnormality, however, was high. Only three normal fetuses and 14 that had died during pregnancy were recovered from 81 oocytes transferred in the experiments.

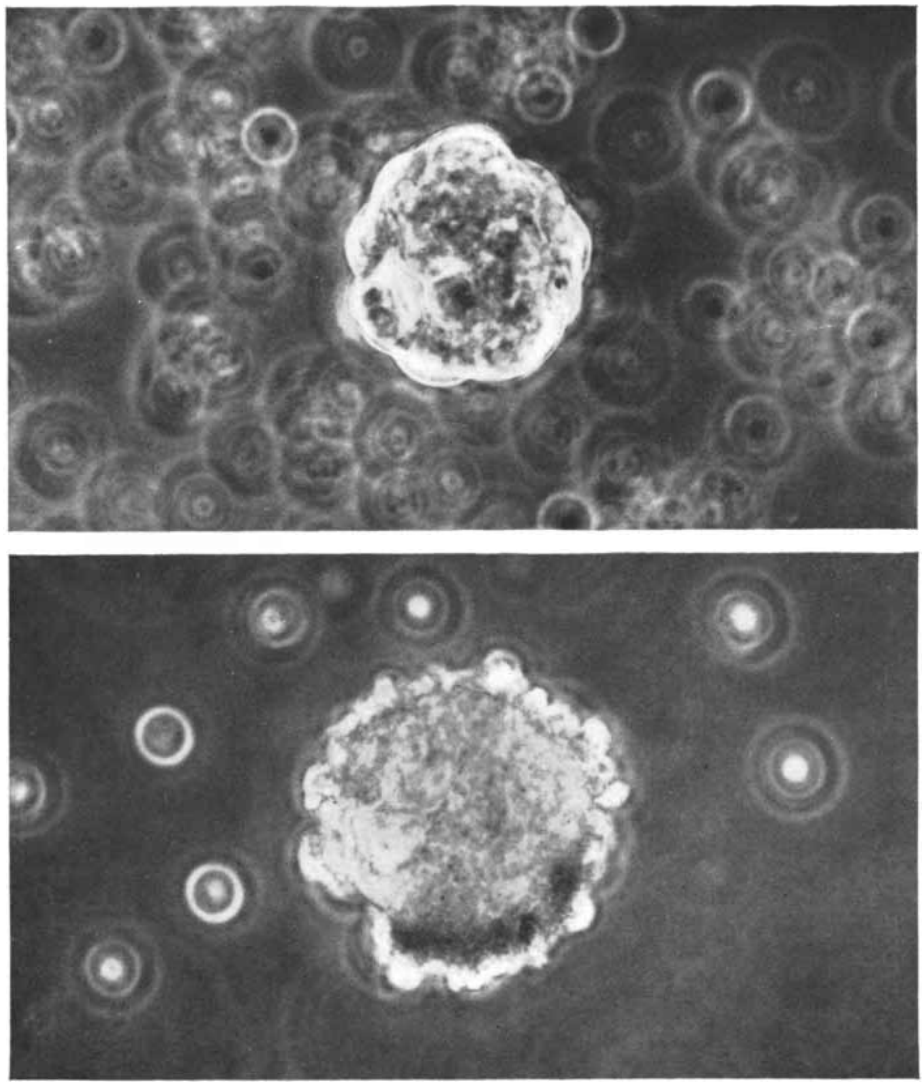
We worked with the pig oocyte, because it matures at a rate similar to that in man and other large mammals. Our initial attempts produced a high incidence of anomalies. For one thing, large numbers of spermatozoa penetrated the egg instead of the normal one or two [*see illustration on page 72*]. In addition there was considerable fragmentation of the eggs. After we had improved this situation by modifying the culture medium the results of fertilization grew progressively better, although many eggs are still anomalous. This result may be partly due to a fact mentioned earlier: that the pig oocyte has a tendency to halt its development in anaphase I. Apparently our conditions of culture are still insufficient for the pig oocyte. So far we have examined all the eggs immediately after fertilization. Our immediate tasks are to improve the culture mediums and to study the further development of fertilized eggs. We have learned already that we can use fluid from the Graafian follicle itself to culture the oocytes.

Since pig ovaries can be obtained easily and cheaply, pig oocytes can be matured and perhaps fertilized in large numbers. On three occasions we have had some 700 pig oocytes maturing synchronously in vitro; we could have had many more. Such large numbers of oocytes should facilitate investigation of the biochemical aspects of early mammalian development.

Among the questions that might be thus elucidated is the matter of where and when DNA and RNA are synthesized. Some evidence suggests that DNA is synthesized during the interphase of each cleavage division of mammalian eggs; there appear to be no large stores of DNA in the cytoplasm. The type of RNA being synthesized probably varies with the stage of development. Large amounts of RNA are found in fully grown follicular oocytes, although it is not certain when the RNA is synthesized. It would be of interest to characterize the types of RNA in mature oocytes and early embryos. Apparently little, if any, "messenger" RNA or protein is synthesized until the early embryonic stage. An intriguing fact is that the earliest evidence of gene action appears in this stage, as does the genetic inactivation of one of the two "*X*" chromosomes in female embryos. These events suggest that some delicate genetic mechanism has begun to operate.

If rabbit and pig eggs can be fertilized after maturation in culture, presumably human eggs grown in culture could also be fertilized, although obviously it would not be permissible to implant them in a human recipient. We have therefore attempted to fertilize cultured human eggs in vitro. Here we promptly encountered a problem involving what is called capacitation of the spermatozoa. Capacitation, without which most mammalian eggs cannot be fertilized, is a poorly understood change undergone by spermatozoa in the female reproductive tract. Noncapacitated spermatozoa are unable to penetrate through the zona pellucida: the outer membrane of the egg.

We attempted to overcome this problem by removing the seminal fluid from the spermatozoa, since this fluid is reported to suppress capacitation. Then we added spermatozoa thus treated to 40 oocytes in vitro a few hours before



MOUSE EMBRYOS tested for antigens indicate possibilities of the work with eggs. At top is a negative result; red cells fail to adhere to a living embryo. Adherence of red cells to the embryo at bottom is a positive test for an antigen. A distant possibility is detecting female embryos by the presence of sex chromatin in cells excised from living embryos.

the extrusion of the first polar body. Except in rare cases spermatozoa had attached themselves to but not penetrated the zona pellucida 24 to 36 hours later [*see illustration on page 78*]. Three eggs had two or more nuclei, which might have been a sign of fertilization but was inconclusive evidence. These results were similar to those obtained in earlier attempts by Landrum B. Shettles of the Columbia University College of Physicians and Surgeons. It is undoubtedly significant that when we attempted to fertilize rabbit and pig eggs in vitro after their maturation in culture, the result was the same: spermatozoa failed to pass through the zona pellucida, although they did so, often in large numbers, when the oocytes were transferred into a mated recipient.

We accordingly tried to capacitate human spermatozoa. Small pieces of human fallopian tube were added to some cultures, but this brought no increase in fertilization. Next we transferred some oocytes, together with human spermatozoa, into the fallopian tubes of rabbits or monkeys. None of the oocytes were fertilized in the rabbit; those put into monkeys simply disappeared after about 12 hours.

Then we tried placing human spermatozoa in the fallopian tubes or uterus of a rabbit, flushing them out later and adding them to human oocytes in vitro. None of the oocytes were fertilized. Finally, in an attempt to imitate the situation in animals, we took spermatozoa from the uterine cervix of women 10 hours after coitus. The addition of these spermatozoa to human oocytes in vitro produced no fertilization.

So far, then, we have either failed or have at best achieved a very limited success in fertilizing human eggs in vitro. We intend to continue these experiments; the ability to observe cleaving human eggs could be of great medical and scientific value. For example, sterility caused by faulty passage of embryos along the fallopian tube could probably be alleviated by removing oocytes from the ovary, growing and fertilizing them in vitro and then transferring them back into the mother. Another possibility, arising from the number of oocytes that can be obtained from a human ovary (up to 65 in our experiments), is that oocytes and embryos showing anomalies could be eliminated in favor of those developing normally. This achievement might one day permit some choice to be made in the type of offspring born to particular parents.

CONFLICT AND AROUSAL

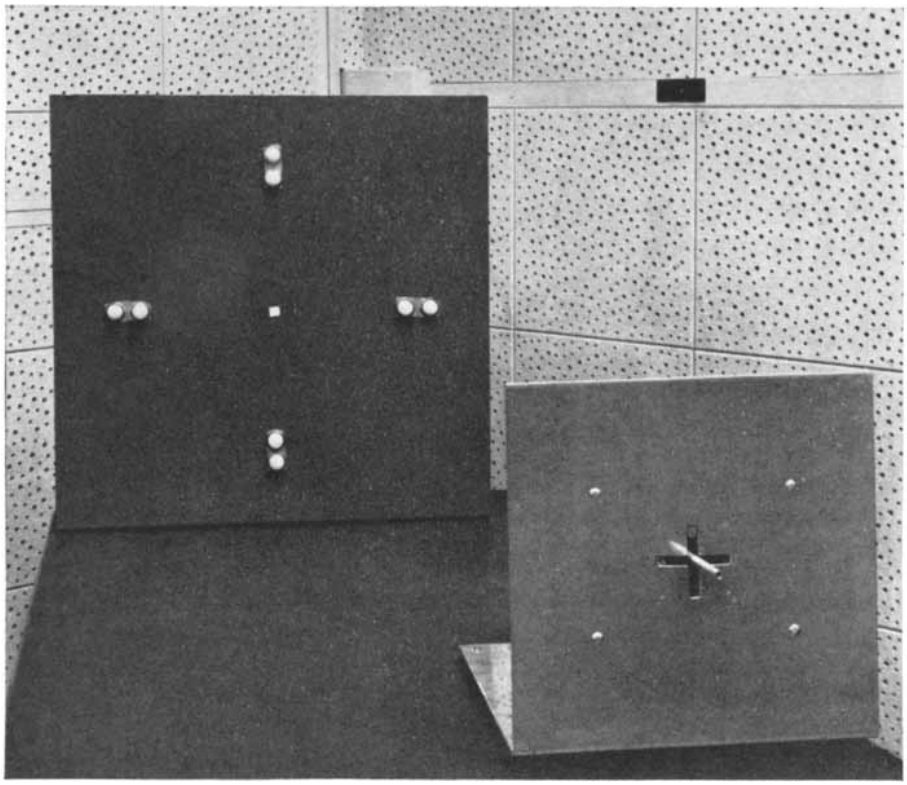
Arousal involves a heightening of attentiveness that helps individuals to act and to learn. The inner conflicts that ambiguous, surprising or complex stimuli produce, in turn, help to arouse the individual

by Daniel E. Berlyne

Ever since psychology became a scientific discipline the experimental psychologist has sought to relate human and animal behavior to properties of objects and events in the environment. He has concentrated on different kinds of properties at different times. A century ago, when experimental psychology began, the "psychophysicists" measured human reactions to the weight of an object held in the hand, the loudness or pitch of a tone, the length of a black line on a white background, and the like. These stimulus properties all depend on how energy is distributed in space and time, and energy had been a powerful unifying concept in the science of the early 19th century. Later, under the influence of the theory of evolution, experimental investigators of behavior focused on the kinds of factors that govern natural selection. They examined the psychological effects of stimuli that are beneficial or harmful, satisfying or annoying, rewarding or punishing.

In the 20th century the measurement of information and of its opposite—uncertainty—is revealing new interrelations in many different areas of science. Psychologists are now becoming interested in certain aspects of behavior that hinge on how novel, surprising, complex, puzzling or ambiguous a stimulus is. Such characteristics are closely bound up with how much information or uncertainty attaches to the stimulus. The term "collative stimulus properties" has been proposed as a convenient device for referring to all these characteristics collectively. They involve collation or comparison: they are all a matter of how far a particular environmental feature resembles or differs from others that are presented at the same time or that have been experienced in the past.

These factors can have a wide variety of motivational effects on behavior. An extremely strange phenomenon, especially if it consists of a mixture of familiar and unfamiliar elements, can induce fear and flight. D. O. Hebb of McGill University discovered several harmless but novel or surprising sights that would terrify a chimpanzee. They included a model of a chimpanzee's head without the body and a familiar attendant wearing another attendant's coat. Charlotte Bühler's experiments, conducted in Vienna in the 1920's, similarly showed how infants could be distressed by the sound of a strange voice coming from a familiar face or by a familiar voice coming from a strange mask. Animals and young children will often stand gazing in frozen fascination



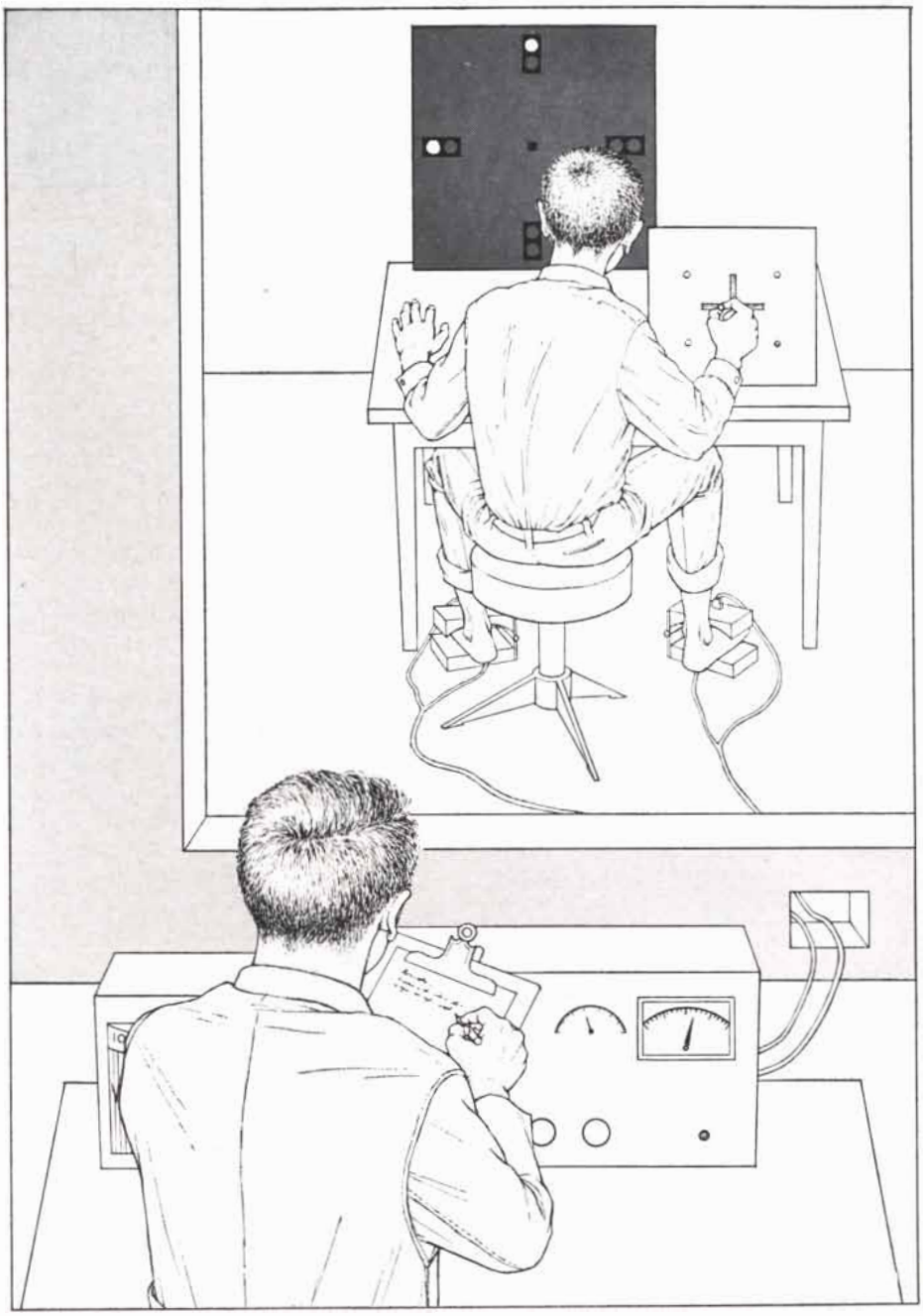
CONFLICT APPARATUS consists of a panel on which four pairs of lights form a diamond pattern (*rear*). A switch (*front*), operated by the subject, can be moved in four directions that correspond to the four corners of the diamond. The subject is told that whenever any light is lit on the panel he is to move the switch to the corresponding position. In each trial two lights are lit. When both are at the same corner of the diamond, the subject can make an unequivocal movement of the switch; this is a "low conflict" trial. When the lights are lit at different corners of the diamond, the subject is told to move the switch toward whichever of the two lights he may choose. This kind of trial contains "high conflict."

at something they have never seen before, or vacillate between moving toward or away from it. By the same token the appreciation of art and humor turns quite subtly on the degree of novelty, surprise and complexity. If a joke is too predictable or too simple, it falls flat; if its content is too farfetched or too intricate, it seems labored or ponderous.

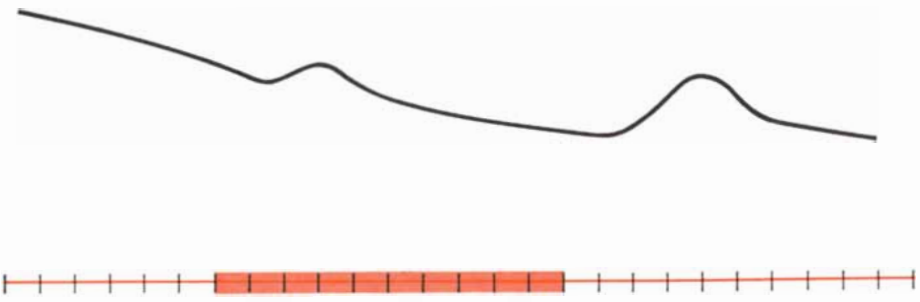
Moderate amounts of unpredictable change are, however, sought out and welcomed. The kinds of behavior that we label as "play" or "recreation" are cases in point. An environment where stimulation is kept to a minimum or is unduly monotonous will generally become intolerable before long. As numerous experiments on sensory deprivation have demonstrated, boredom can impair several perceptual and intellectual functions. It seems that the nervous system of a higher animal is made to cope with environments that present a fair amount of challenge to its capacities. It is not at its best when the demands that are made on it are either too exacting or not exacting enough.

Perhaps the most interesting psychological effects of novelty and complexity, and certainly the ones that have received the most investigation so far, are those that belong under such headings as "attention" and "curiosity." A term current among psychologists is "exploratory behavior." In one of our experiments pictures of animals were exposed two at a time and side by side on a screen and the subject's eye movements were observed. The same picture was presented trial after trial on one side, while pictures of different animals were successively exposed on the other side. In such a situation a human subject will spend an increasing proportion of the time looking at the side on which the pictures vary from trial to trial. In other words, novel stimuli attract more inspection than familiar stimuli. Similarly, human subjects will spend more time looking at more complex or more incongruous pictures, unless complexity becomes extreme [*see bottom illustration on next two pages*].

What do such properties as novelty, surprisingness, complexity, puzzlingness and ambiguity have in common to give them their motivational significance? Various answers have been proposed, but the most satisfactory one, which covers the diversity of collative stimulus properties most adequately, seems to be that they all give rise to conflict. Environmental events that pos-



CONFLICT EXPERIMENT puts a barefoot subject at the switch of the conflict apparatus (*top and in illustration on opposite page*). An observer (*bottom*) records variations in the galvanic skin response of the subject's feet as he reacts to a series of low-conflict and high-conflict trials. The response, produced by sweating, gives an index of increased arousal.



SAMPLE RESPONSE to a conflict trial is shown by the two peaks in the curve of the graph (*top*). The solid bar (*color*) on the bottom line indicates the 10-second interval in which the lights of the conflict apparatus are lit. The first of the peaks, each of which marks an increase in the conductance of the subject's skin, is a response to the start of the trial. Changes in the size of this peak enabled the author and his colleagues to compare the degree of arousal that each subject experienced in the face of high-conflict and low-conflict stimuli.

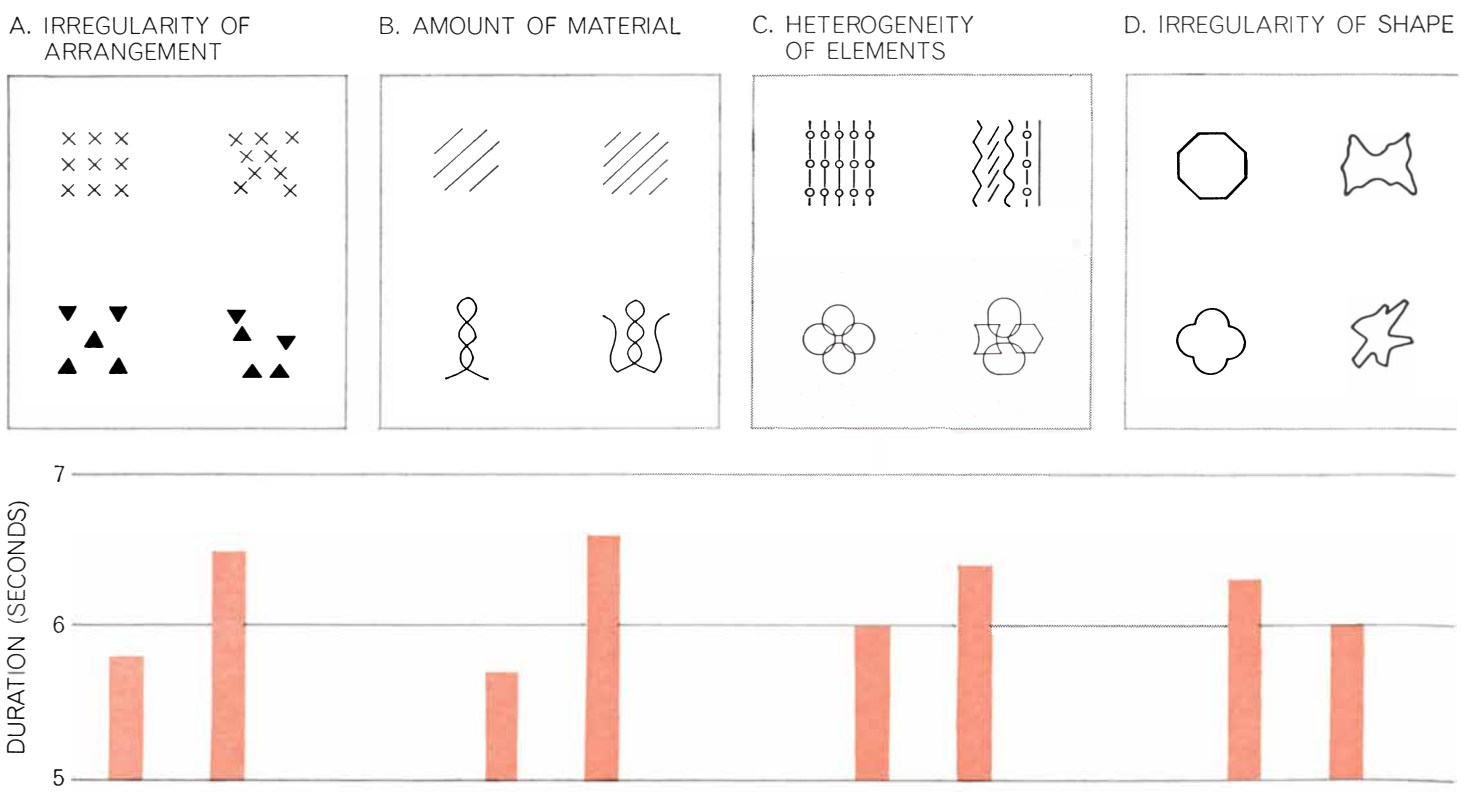
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GROUP I	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	A	A	B	A	B
GROUP II	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	A	A

EFFECTS OF SURPRISE were measured in an experiment that put the conflict apparatus to a different use. Two groups of subjects were told that the top and right-hand lights of the diamond would blink alternately (just as the letter *A* alternates with the letter *B* in the two sequences above). This was true until Trial 16 for Group I and Trial 19 for Group II, when the top lights went on three times in succession (*color*). The conductance of the "surprised" group then became substantially greater than the skin

sess such properties to a high degree do not bring one predominant reaction immediately to the fore. They initiate discordant and mutually interfering processes in the central nervous system. Different aspects or components of the stimulus tend to evoke several competing bodily movements. It is not clear how the stimulus event should be classified, what its hidden characteristics are like, what is likely to follow it. If the nervous system did not have means of dealing with conflict due to collative stimulus properties, a chaotic melee of disparate responses, each prevented by its competitors from reaching fruition, would soon make adaptive behavior impossible. Fortunately there are several resources on which we can call to forestall this danger. Perceptual and thought processes impose order on the external world by classifying, interrelating, interpreting and organizing the information that comes in through sense organs. But often this incoming information is not enough. Further information may then be sought through exploratory behavior. If, however, the disturbance is too severe and too threatening, the organism may be inclined to withdraw attention, or even to flee, from the troublesome stimulus, and signs of fear and stress may appear.

Psychologists are becoming more and more impressed with the crucial role played by curiosity and other motivational effects of conflict in human emotional and intellectual development. Jean Piaget of the University of Geneva, the outstanding figure in contemporary developmental psychology, believes that "disequilibrium," or discomfort arising from inconsistency and lack of certainty in judgment, is the main force pushing the child toward mature, logical ways of organizing thoughts and perceptions. Some of the new techniques of instruction being tried out in schools expose children to experiences designed to make them aware of the gaps and contradictions in their knowledge or understanding. There are indications that learning motivated by curiosity can give rise not only to particularly rapid and lasting acquisition of knowledge but also, above all, to knowledge in which ideas are fruitfully pieced together in coherent structures.

These developments, and others pointing in the same direction, have encouraged a reappraisal and broadening of the concept of "drive," which has dominated discussions of motivation for about 40 years. A condition of high drive has usually been regarded as a condition of discomfort, tension and restlessness. It manifests itself in three principal ways: (1) it activates or energizes the organism as a whole, making



IMPACT OF IRREGULARITY was studied by the author in an experiment that recorded subjects' brain rhythms with an electroencephalograph as they viewed first one and then another of the paired diagrams reproduced here. In each pair the left figure is the

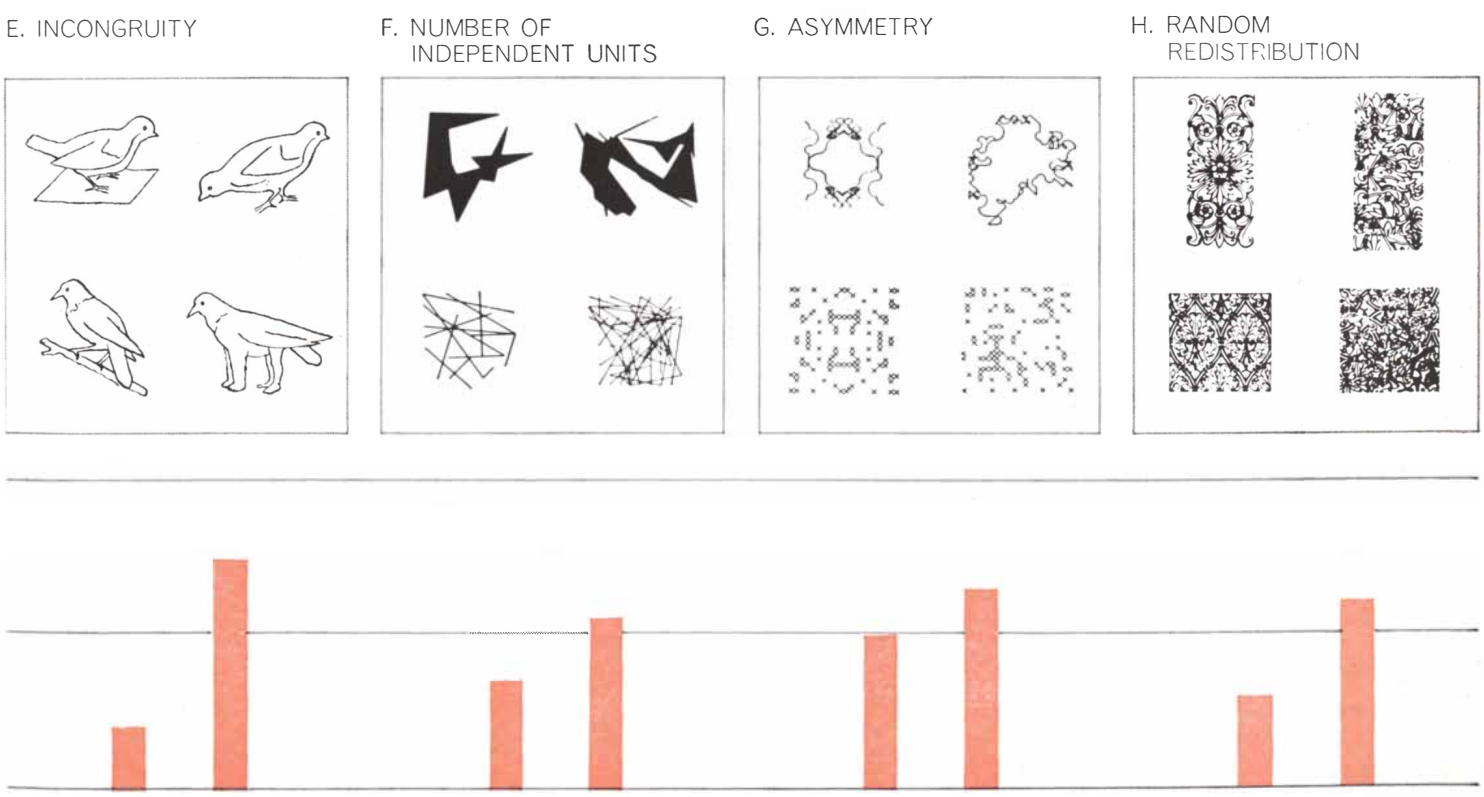
conductance of the "unsurprised" group during the corresponding trial (*see matching white letter A*). The two bars (*above*) compare the mean amplitudes of both responses.

responses more vigorous and intensifying trial-and-error behavior; (2) it inclines an organism toward a particular class of behavior that is likely to relieve the drive—food-seeking in hunger, aggressive behavior in rage, and so on—and (3) it enhances learning by making the organism particularly sensitive to appropriate reinforcing events. Ivan Pavlov found it difficult, if not impossible, to condition a dog to salivate at the sound of a bell when the dog was not hungry. Neal E. Miller and Richard C. DeBold of Yale University, using a device that forces rats to swallow water, have determined that drinking will act as a reward only when rats are thirsty. In short, the level of drive and the particular kind of drive that is operating play a large part in determining what an animal will do, and how energetically, and what new responses it will acquire, and how effectively, through learning.

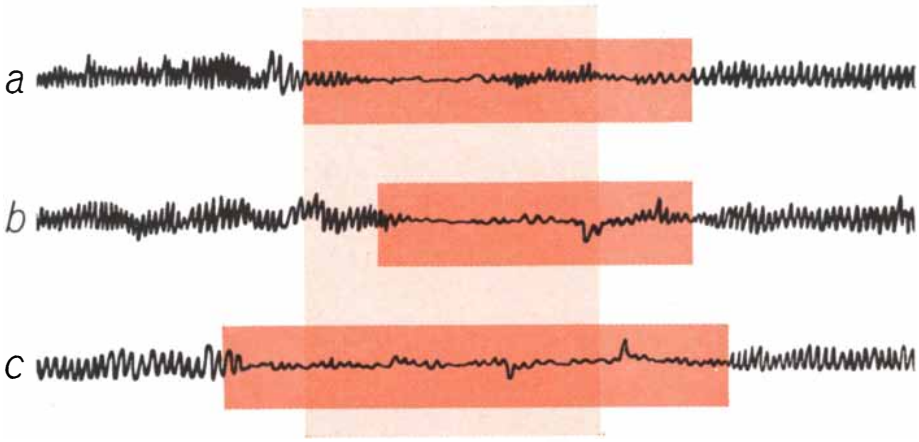
Over the years there have been many unsolved problems regarding the nature of drive: how it operates and what physiological mechanisms underlie it. Recently new findings and ideas with a bearing on these problems have come from progress in brain physiology. One especially significant body of work has been concerned with the processes on which "arousal" depends.

A higher animal's arousal level—how wide-awake, attentive or excited the animal is—fluctuates from moment to moment. It can range between sleep or coma at one extreme and frenzy at the other. It is manifested by changes in almost every system of the body: by the brain's electrical activity, the heart rate, the pattern of respiration, the electrical properties and temperature of the skin, the dilation and constriction of peripheral blood vessels, even the diameter of the pupil of the eye [see "Attitude and Pupil Size," by Eckhard H. Hess; SCIENTIFIC AMERICAN, April, 1965]. With increasing arousal the body mobilizes and sharpens all its functions, including the readiness of the skeletal muscles for action, the acuteness of the sense organs and the ability of the central nervous system to analyze and process incoming information. A great deal of knowledge is accumulating about the parts of the brain that control arousal level. The essential role of the reticular formation of the brainstem has been demonstrated by many experimental findings [see "The Reticular Formation," by J. D. French; SCIENTIFIC AMERICAN, May, 1957]. It has more recently become apparent, however, that interactions of the reticular formation with other brain structures (particularly the hypothalamus and the cerebral cortex) are of crucial importance.

Considering the entire picture, one can find good grounds for concluding that arousal and drive are closely related. Many of the conditions that produce high drive—hunger, thirst, sexual receptivity, pain, cold—also produce bodily signs of high arousal and activate the reticular formation. A highly aroused animal displays the excitability and intensity of behavior that have long been associated with high drive. Furthermore, when arousal becomes inordinately high, performance is impaired, which recalls the deleterious effects that have long been ascribed to "overmotivation." The justification for equating drive and arousal is most apparent when we consider the first of the three aspects of drive discussed earlier, namely the general activating or energizing effects. As far as the other two functions of drive are concerned—direction toward particular forms of behavior and sensitization to particular kinds of reinforcement—the situation is less clear, and more research is needed. There are,



simpler or more congruous and the right figure the more complex or incongruous one. The bars below each pair of figures show in seconds the time during which subjects switched from the standard waking "alpha" rhythm to a wave pattern indicative of alertness.

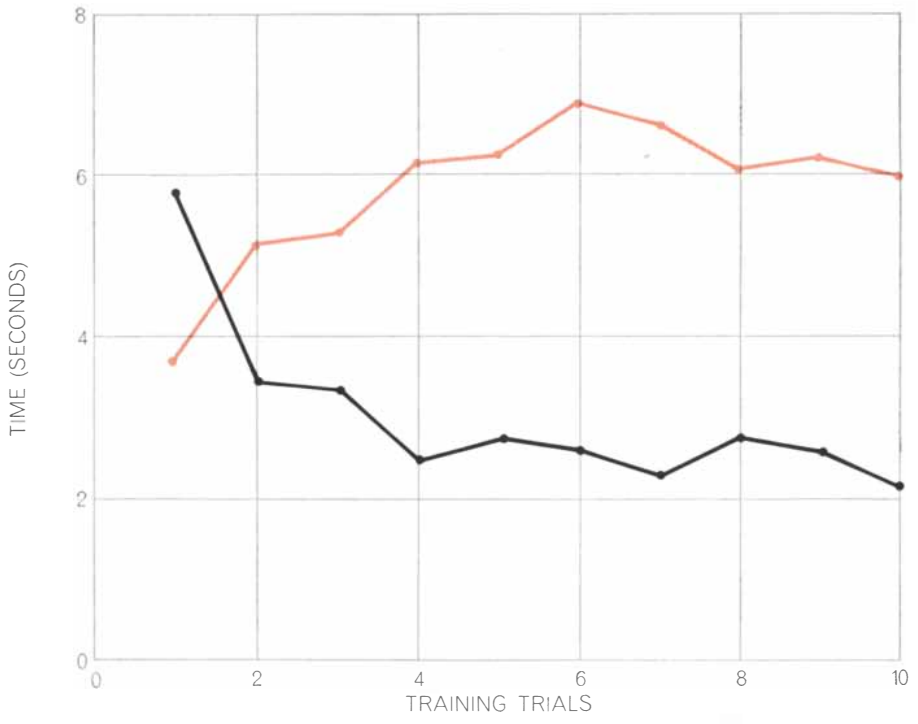


DIFFERING RESPONSES by subjects to the stimulus of visual patterns are indicated in three electroencephalograph tracings. In *a* the break from alpha rhythm to desynchronization (which indicates alertness) starts simultaneously with the start of stimulus (*light color*). In *b* there is a delay before the alertness pattern appears. In *c*, however, a conditioned response appears; the subject's pattern of alertness begins before the stimulus is received. All subjects' brains resume the alpha rhythm soon after the stimulus is halted.

however, already indications that different centers in the brainstem control different kinds of arousal, corresponding to different biological needs, and that changes in arousal are intimately connected with the reinforcement of learned responses.

What has all this to do with conflict-producing stimuli? For one thing, there appears to be a close relation between arousal and the exploratory activities that are so often evoked by novel, complex or ambiguous stimuli. Some investigators, particularly those in the U.S.S.R., have found that exploratory responses form part of a comprehensive network of psychophysiological processes called the "orientation reaction." This represents a broadened usage of a term introduced in Pavlov's laboratory. The orientation reaction includes, in addition to processes that direct sense organs toward the source of stimulation and raise their sensitivity, most of the bodily signs of heightened arousal.

We are therefore tempted to ask whether or not the motivational effects of stimuli that produce conflict work through increases in arousal. The implications reach beyond exploratory behavior. If we may conclude that conflict can increase arousal and if arousal may be equated with drive, conflict will have to be added to the list of conditions from which high drive can result. Heretofore internal physiological disturbances (such as those associated with hunger, thirst or sexual appetite) and external irritants (such as painful stimulation and excessive heat or cold) have been recognized as sources of primary drive. Neutral stimuli that have frequently accompanied these conditions can, through a conditioned-response mechanism, come to induce secondary drive (for example learned fear or anger). Our view of motivation will be broadened considerably if we are obliged to accept conflict as an additional source of drive. This will imply that animals can be impelled to action and, if necessary, to the learning of new responses not only by visceral disturbances and noxious external stimulation but also by conditions that set up discordant processes in the central nervous system.



EFFECTS OF MONOTONY are evident in this record of a subject's eye movements as he viewed 10 consecutive pairs of pictures. One picture in each pair was the same throughout the 10 trials; the other one was different at each trial. This varying stimulus (*color*) soon attracted the subject's attention (measured by the attention given to each 10-second exposure) more than the recurring stimulus, which came to be ignored.

With several collaborators, first at the National Institute of Mental Health and later at Boston University and at the University of Toronto, I have been engaged in experiments designed to verify that conflict and collative stimulus properties can heighten arousal in human subjects. The first experiment was concerned with conflict, and we attempted to separate conflict from other factors with which it is often combined in everyday life.

The subject sat before a panel bearing eight lights, two at each corner of a diamond. "Low conflict" and "high conflict" trials were interspersed. A low-conflict trial consisted of turning on two lights at one corner of the diamond, whereupon the subject was to press a key in the direction of that corner. For high-conflict trials two lights appeared at two corners, and the subject had to press the key one way or the other.

In order to make sure that the results would be due to differing degrees of conflict and not simply to the two kinds of lighting pattern, there was a prelimi-

nary run in which pairs of lights at the same corner and at different corners appeared in a random order but no key-pressing response was required of the subject or even mentioned.

Changes in arousal were measured by means of the galvanic skin response (a transient rise in the conductance of the skin), recorded from electrodes attached to the soles of the feet. If the subject had been instructed to act as soon as the lights appeared, the resulting galvanic skin response would have reflected the joint influence of the stimulation and the bodily movement. To obviate this difficulty the lights were always on for 10 seconds, and the subject was instructed to move the key as soon as they went off. Two galvanic skin responses generally appeared, one just after the illumination of the stimulus lights and one just after their extinction. The first response was the one of interest, since it reflected the impact of a stimulus pattern associated with a greater or lesser degree of conflict. The mean amplitude of the galvanic skin response immediately after the onset of the stimulus was significantly higher for high-conflict trials than for low-conflict trials, confirming the prediction. The difference did not appear when we examined the galvanic skin response that followed the pressing of the key at the termination of the stimulus or the galvanic skin response that occurred during the preliminary phase when the combinations of lights were presented without requiring manual responses. We can conclude that this was due to differences in degree of conflict.

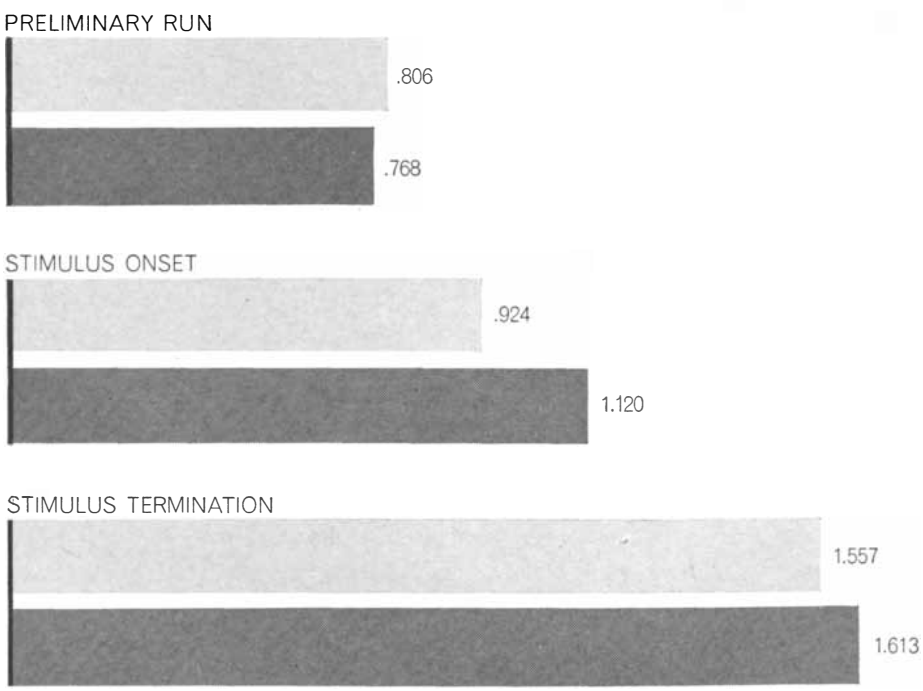
We went on to test effects of the principal collative stimulus properties one by one. There was no need to demonstrate that novelty affects arousal. Many previous experiments had shown that, say, a monotonously repeated tone gradually loses its power to cause arousal, whereas as soon as it is replaced by a tone of a different pitch the orientation reaction revives.

Accordingly our next experiment focused on surprisingness. In everyday life surprising stimuli are often novel and novel stimuli are often surprising, but we had to find a way of inducing surprise without novelty. This was done by breaking an expected sequence. Using the apparatus described above, we told the subject in advance that the two lights at the top of the diamond and the two lights at the right-hand corner would light up alternately. This alternation was maintained until a stage toward the end of the experiment, when lights appeared at the same corner for two successive trials. The second of these trials thus presented a stimulus that was surprising (since it violated the subject's expectation) without being novel. The results of this experiment, which was carefully designed to control for spatial and temporal position, showed a galvanic skin response to be more intense with surprising stimuli than with nonsurprising stimuli that were otherwise identical. This was so whether or not the subject was instructed to respond by pressing a key.

At Toronto we later studied effects of complexity and incongruity on arousal. Some of the visual patterns that had been used in the experiments on exploratory behavior served as stimuli. Our subjects sat in a comfortable chair in a dark room watching a screen. Different subjects saw the patterns in different orders, so that effects of temporal position could be counterbalanced. This time the patterns were drawn in white on a black background, because the dazzling effects of a white rectangular background would have overwhelmed the effects we were seeking.

In these experiments changes in arousal were measured through electroencephalographic (EEG) recordings of brain waves. In a relatively relaxed but waking state the brain produces regular "alpha" waves at a frequency of about 10 cycles per second. In response to arousing stimulation these waves are usually replaced by a flatter, more irregular, predominantly high-frequency tracing: the "desynchronization" pattern. The duration of desynchronization can be taken as a measure of the intensity of the orientation reaction. It turned out that the more complex, irregular or incongruous stimuli evoked, on the average, significantly longer-lasting desynchronizations than the others. Hence we have some evidence that the arousal system is responsive to the complexity or incongruity of an incoming stimulus as well as to its novelty, surprisingness and in general its potentiality for inducing conflict.

These findings are only part of much evidence, coming in from many different areas of research in psychology and neurophysiology, with convergent implications. It is becoming clear that we must enlarge and refine our view of the motivational aspects of human and animal behavior. We must recognize and study an entire new spectrum of sources of motivation, depending on conflict, uncertainty and collative stimulus properties. Corresponding to them there must be a range of powerful and hitherto neglected factors that can provide reinforcement for learning. When we have investigated them further, we shall have a better understanding of how learning works. We may also be in a better position to produce it effectively in the classroom.



EFFECTS OF CONFLICT are shown in the average of 25 subjects' skin responses during trials involving low conflict (*light bars*) and high conflict (*dark bars*). The latter produced significantly greater response than the former only at the onset of stimulus (*center bars*).

THE MACDONALD
PHYSICS BUILDING

McGill Univ
Montreal
April 29 1902

Dear Sir William

I have to thank you for the reprints of your two Royal Society papers which I received yesterday and in which I was very interested. The blue mercury button on the Hydrogen tube is a most extraordinary manifestation and shows how much is still to be investigated in that field.

I am forwarding to you some reprints of my papers on Radioactivity.

I am sending you by this mail an M.S.S. by Mr Soddy & myself on the "Radioactivity of Thorium which we are forwarding at the same time to the Chemical Society.

We have found that the Th X like Ur X loses its radioactivity in a G.P. unto the time while the deactivized Thorium regains at the same time its activity with time. I think we have conclusively shown that most of the radioactivity is due to a production of Th X at a uniform rate by the thorium & that this Th X decays at such an equilibrium point is reached when the rate of production is balanced by the rate of decay. We have strong evidence that Uranium & radium behave similarly only that the time rate of change is different.

All these processes are independent of chemical & physical conditions & we are driven to the conclusion that the whole process is Sub-atomic. Although of course it is not advisable to put the case too bluntly to a Chemical Society, I believe that in the radioactive elements we have a process of disintegration & transmutation steadily going on which is the source of the energy dissipated in radioactivity.

If you have time to glance over the paper I think you will see the evidence is all experimental & that the various deductions from the facts are included in the last section.

I am afraid that I have already troubled you sufficiently with my views but Mr Soddy & myself would be obliged if you could do anything to facilitate the publication of the paper if difficulties arise over "atomic" views.

Yours sincerely
E Rutherford

Sir William Crookes P.R.S.
London

How the "Newer Alchemy" Was Received

The startling announcement in 1902 of the Rutherford-Soddy theory of the transmutation of elements by radioactive decay met surprisingly little opposition. A historian of science examines this curious reception

by Lawrence Badash

The year 1902 saw a turning point in the history of science. It was the year that two young investigators, the 31-year-old physicist Ernest Rutherford and the 25-year-old chemist Frederick Soddy, announced their theory of the transmutation of elements, a discovery that genuinely overturned men's ideas about the nature of matter. How was this revolutionary announcement received by the scientific community? For historians and others interested in the advance of science the reception of such a bombshell is often as fascinating a subject for study as the discovery itself. In this instance the reaction to the event seems in retrospect quite surprising, and it invites examination.

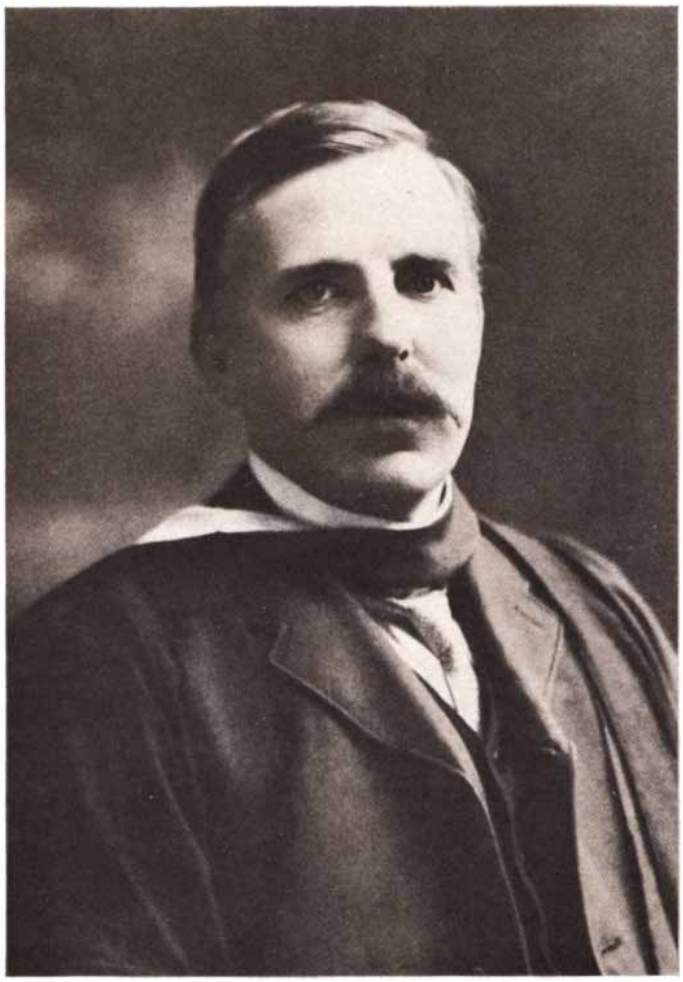
Consider the setting in which the event occurred. A century of theoretical and experimental work had for most chemists and physicists established the atoms of the elements as unchangeable units of matter. The old concept of alchemy—indeed, any notion of transformation of one element into another—had long been in disrepute. The prevailing view of the atom was expressed trenchantly by James Clerk Maxwell in his 1873 address to the British Association for the Advancement of Science: "No theory of evolution can be formed to account for the similarity of atoms [that is, their apparent family relations], for evolution necessarily implies continuous change, and the atom is incapable of growth or decay, of generation or destruction."

So firmly held was this view that when Henri Becquerel discovered radioactivity in 1896, most students of the phenomenon insisted that the energy streaming from the interior of the atom could not reflect any basic change in the atom itself. Becquerel believed the radiation was a long-lived form of phosphorescence. Marie Curie argued that the Becquerel rays were a secondary radiation whose emission by uranium and thorium was stimulated by the elements' absorption of "rays analogous to Roentgen rays" that pervaded all of space. Sir William Crookes, the noted chemist who was also editor and publisher of *Chemical News,* attributed the radioelements' radioactivity to their selective absorption and reradiation of energy from fast-moving molecules of air. Various other theories were offered, most of them based on the conviction that the energy producing radioactivity must come from a source other than the atom itself.

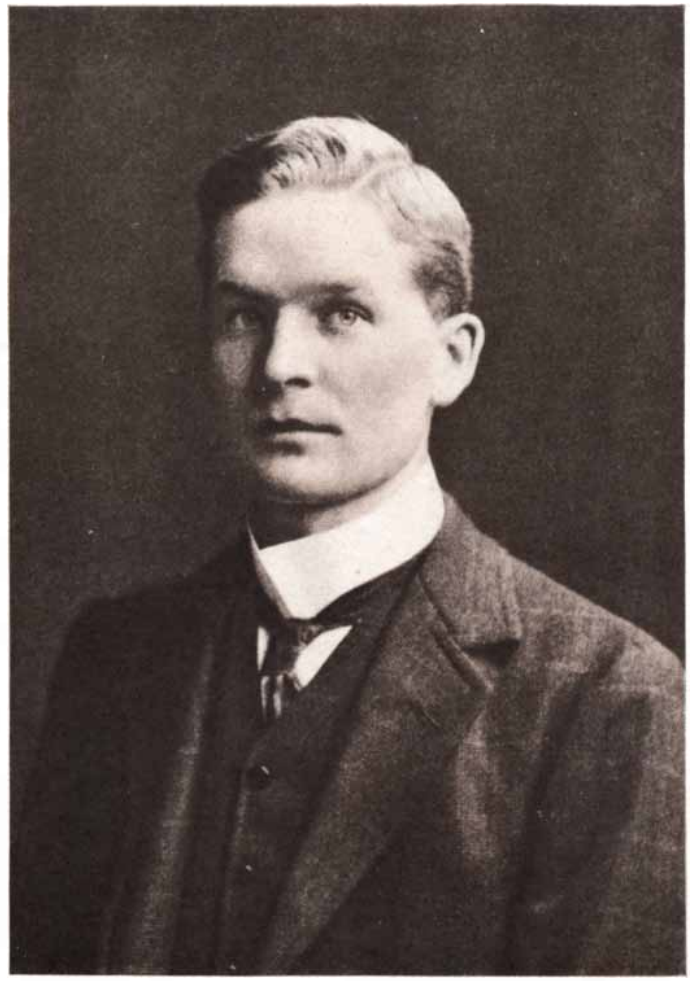
LETTER from Rutherford to Sir William Crookes (*opposite page*) was intended to solicit the good offices of Crookes to help in acceptance by the *Transactions of the Chemical Society* of a paper by Rutherford and Soddy setting forth their theory of the transmutation of elements by radioactive decay. "Dear Sir William," Rutherford wrote, "I have to thank you for the reprints of your two Royal Society papers which I received yesterday and in which I was very interested. The blue mercury button in the hydrogen tube is a most extraordinary manifestation and shows how much is still to be investigated in that field. I am forwarding to you some reprints of my previous papers on Radioactivity. I am sending you by this mail an M.S.S. by Mr Soddy & myself on the 'Radioactivity of Thorium' which we are forwarding at the same time to the Chemical Society. We have found that the Th X [thorium X] like Ur X [uranium X] loses its radioactivity in a G.P. [geometric progression] with the time while the deactivized thorium regains its activity with time. I think we have conclusively shown that most of the radioactivity is due to a production of Th X at a uniform rate by the thorium & that this Th X decays with time. An equilibrium point is reached when the rate of production is balanced by the rate of decay. We have strong evidence that uranium and radium behave similarly only that the time rate of change is different. All these processes are independent of chemical and physical conditions & we are driven to the conclusion that the whole process is sub-atomic. Although of course it is not advisable to put the case too bluntly to a chemical society, I believe that in the radioactive elements we have a process of disintegration or transmutation steadily going on which is the source of the energy dissipated in radioactivity. If you have time to glance over the paper I think you will see the evidence is all *experimental* & that the obvious deductions from the facts are included in the last section. I am afraid that I have already troubled you sufficiently with my views but Mr Soddy & myself would both be obliged if you could do anything to facilitate the publication of the paper if difficulties arise over 'atomic' views. Yours sincerely E. Rutherford." Letter is at University of Cambridge Library.

Among the few investigators who were willing to entertain the thought that a change within the atom might be responsible for the radiation were the German physicists Julius Elster and Hans Friedrich Geitel and the British physicist J. J. Thomson. Thomson, the discoverer of the electron, suggested that the source of radioactivity might be a "regrouping of the constituents of the atom," giving rise to "electrical effects such as are produced in the ionization of a gas." This provocative suggestion was not lost on Rutherford, a student of Thomson's in the Cavendish Laboratory at the University of Cambridge.

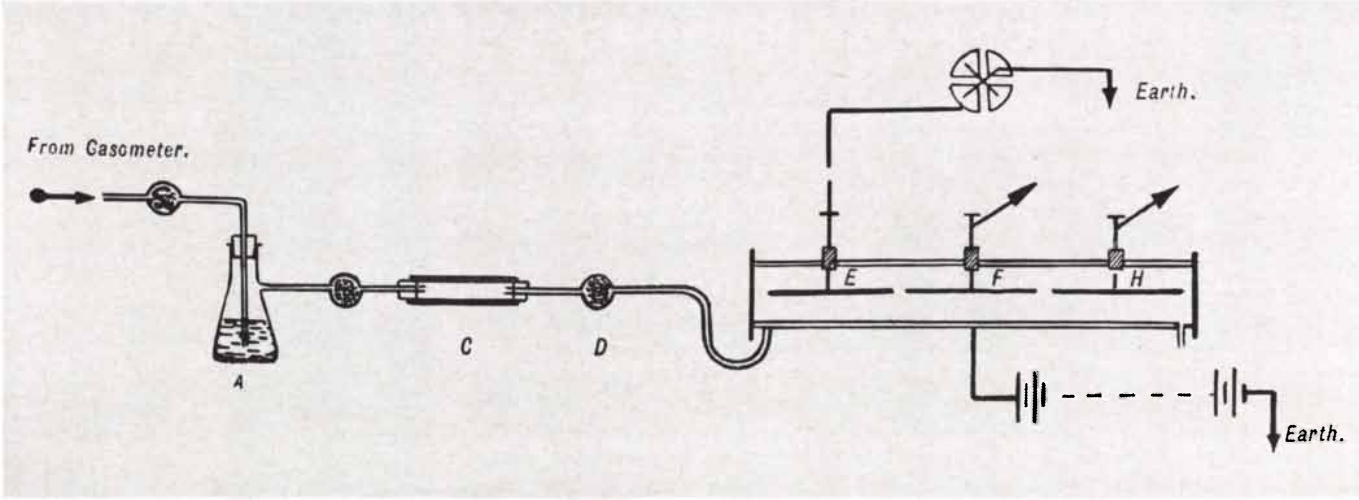
In 1898 young Rutherford went to McGill University in Montreal as a professor of physics, and he devoted himself there to an investigation of the radioactivity of thorium. Three years later Soddy, who came to McGill from the chemistry laboratory at the University of Oxford, joined Rutherford in this



ERNEST RUTHERFORD (1871–1937) was appointed professor of physics at McGill University in 1898. It was there that he undertook the investigation that led to the 1902 papers on the radioactivity of thorium compounds. This photograph was made in 1908.



FREDERICK SODDY (1877–1956), a demonstrator in chemistry at McGill, joined Rutherford in 1901. His chemical analyses provided the first clue that led to the theory of the transmutation of elements by radioactive decay. This photograph was made in 1905.



EXPERIMENTAL SETUP was used by Rutherford and Soddy to compare the "emanating" power of various substances. The substance (for example thorium oxide), in the form of a fine powder, was placed in a shallow lead vessel inside a glass cylinder (*C*). A current of air from a large gas bag was passed through a bulb containing cotton wool to remove dust particles and was bubbled through sulfuric acid (*A*). The air then passed through a second bulb containing cotton wool to prevent any spray from being carried over. The "emanation" from the thorium oxide mixed with the air and was carried from the glass cylinder (*C*) through a third plug of cotton wool (*D*), which completely removed all the charged particles carried with the emanation. The emanation then passed into a long brass cylinder, which was connected to one pole of a battery, the other pole of which was connected to the earth. Three electrodes of equal length (*E, F and H*) were placed along the axis of the cylinder, supported by brass rods passing through ebonite corks in the side of the cylinder. The current through the gas resulting from the presence of the emanation was measured by means of a quadrant electrometer. This drawing appeared originally in the *Transactions of the Chemical Society* for 1902.

study. With the help of Soddy's chemical analyses they learned that the radioactive "emanation" came not from thorium itself but from a chemically separable product they named "thorium X," and that the emanation was a chemically inert gas of the argon family (it is now called thoron or radon).

As Rutherford related many years later, the great contrast in physical and chemical properties between thorium X and its emanation was the "first definite clue" that led them to the theory of the transformation of elements by radioactive decay. They were themselves startled by the discovery and its implications. Soddy, according to his own later account to his biographer, turned to his colleague and blurted: "Rutherford, this is transmutation: the thorium is disintegrating and transmuting itself into an argon gas." Rutherford rejoined: "For Mike's sake, Soddy, don't call it *transmutation*. They'll have our heads off as alchemists."

Anticipating a shocked reaction from both chemists and physicists, the two young men proceeded to cautious and conservative publication of their findings. Their first report was a paper printed in the *Transactions of the Chemical Society* early in 1902 that simply announced their discovery of thorium X and their identification of the radioactive emanation as a chemically inert gas. When they submitted a second paper setting forth their interpretation of their discovery, they solicited the good offices of Crookes to help in acceptance of the paper by the *Transactions*. Rutherford wrote Crookes a private letter:

"Although of course it is not advisable to put the case too bluntly to a chemical society, I believe that in the radioactive elements we have a process of disintegration or transmutation steadily going on which is the source of the energy dissipated in radioactivity.... Mr. Soddy and myself would both be obliged if you could do anything to facilitate the publication of the paper if difficulties arise over 'atomic' views."

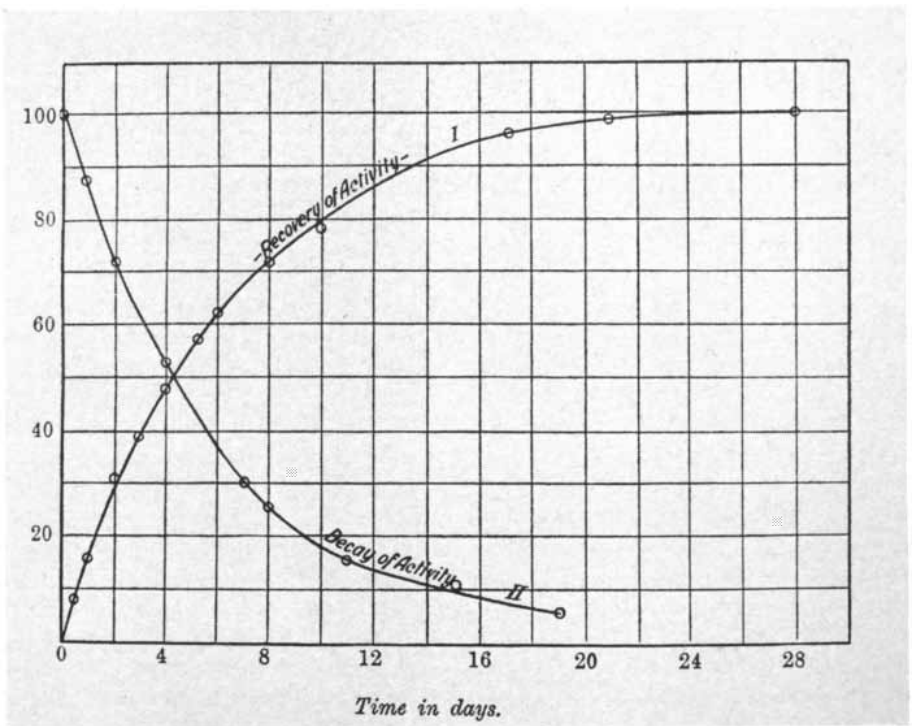
The paper was published in the *Transactions* in the issue of July, 1902. In it Rutherford and Soddy presented their evidence that radioactivity must arise from within the atom and that it resulted in elemental changes that had not previously been encountered in chemistry. "The position is thus reached," they wrote, "that radioactivity is at once an atomic phenomenon and the accompaniment of a chemical change in which new kinds of matter are produced. The two considerations force us to the conclusion that radioactivity is a manifestation of sub-atomic chemical change."

Rutherford and Soddy were careful to use the term "transformation" rather than "transmutation." They also took pains to point out to their chemical brethren that the theory of radioactive transformation could not be said to violate any known chemical laws, because it evidently involved "causes," or forces, not encountered in ordinary chemistry.

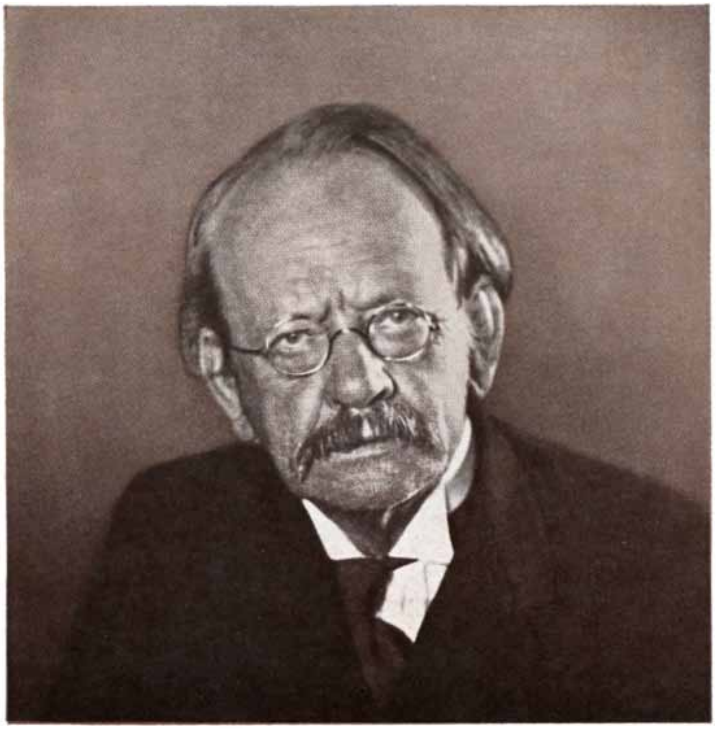
Presumably their selection of a chemical journal to announce their discovery was made to enhance Soddy's career, as he was only a beginning teacher whereas Rutherford was already a full professor. After publication of the two papers in the *Transactions of the Chemical Society* Rutherford addressed his own peers in physics with redrafts of the papers in the *Philosophical Magazine*, the leading physical journal of the day. Further, their iconoclastic theory was given wide exposure by publication in Crookes's popular weekly *Chemical News*.

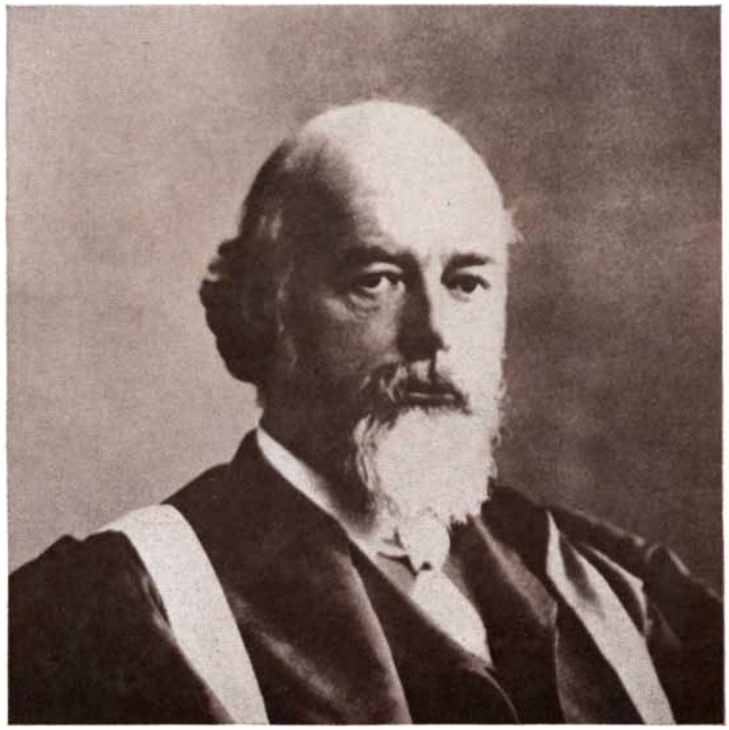
What, then, was the reaction to this theory? Without doubt it evoked high excitement. Crookes described their interpretation of radioactivity as having "undermined the atomic theory of chemistry, revolutionized the foundations of physics, revived the ideas of the alchemists...." Herbert Newby McCoy, a leading U.S. radiochemist, recollected later: "It was all so astounding that chemists and physicists by the score dropped old problems to take up the new work." A. S. Eve, Rutherford's official biographer (and a successor to his chair at McGill), recalled that when he met Rutherford in January, 1903, "Rutherford was already famous, radium was the rage, and the radioactive theory of the break-up of atoms was a topic of supreme interest. Journalists besieged the Physics Laboratory [at McGill] and wrote fabulous and fantastic stories until they were forbidden the sacred precincts." Rutherford was elected to the Royal Society, and as he prepared to go to spend the summer of 1903 in Britain, Joseph Larmor, secretary of the society, wrote him: "You may be the lion of the season, for the newspapers have become radioactive." Soddy was not idle, either. He joined Rutherford in a definitive account of their theory for the *Philosophical Magazine*, and *Nature* published an abstract of a Soddy paper giving the so-called Canadian view of radioactivity. Moreover, Soddy left McGill to work with Sir William Ramsay, discoverer of several noble gases, in his famous laboratory in London.

I am concerned here, however, not with the general acclaim and excitement



PARTIAL RESULTS of the Rutherford-Soddy experiments on the radioactive emanations of thorium compounds were originally presented in this graph. They found that the rate of recovery of the radioactivity of thorium (*curve I*) was related to the rate of decay of radioactivity of a chemically separable product they named "thorium X" (*curve II*).





EARLY SUPPORTERS of the Rutherford-Soddy theory of the transmutation of elements are portrayed on these two pages. They included Rutherford's former mentor in the Cavendish Laboratory at Cambridge, J. J. Thomson (*extreme left*); the physicist and

but with the reception of the theory itself as a blow to the strongly held view of the atom. Samuel Glasstone, in his *Sourcebook on Atomic Energy* (published in 1950), says that the theory "caused consternation in the realms of science during the early years of the present century... many chemists and physicists expressed strong opposition to the theory, because they felt that it was contrary to the established views on the permanence of the atom." Among Rutherford's and Soddy's contemporaries, McCoy (in an address to the American Chemical Society 35 years later) pictured the chemists of the time as highly indignant: "What right had physicists to tell chemists their atoms could disintegrate?" And Sir Henry Tizard (a leading scientific adviser to the British government during World War II) wrote in his sketch of Rutherford for the *Dictionary of National Biography:* "The new theory was so completely at variance with the long accepted views of the indestructibility of matter that it was received with extreme skepticism, and even with contempt, by many prominent scientific men."

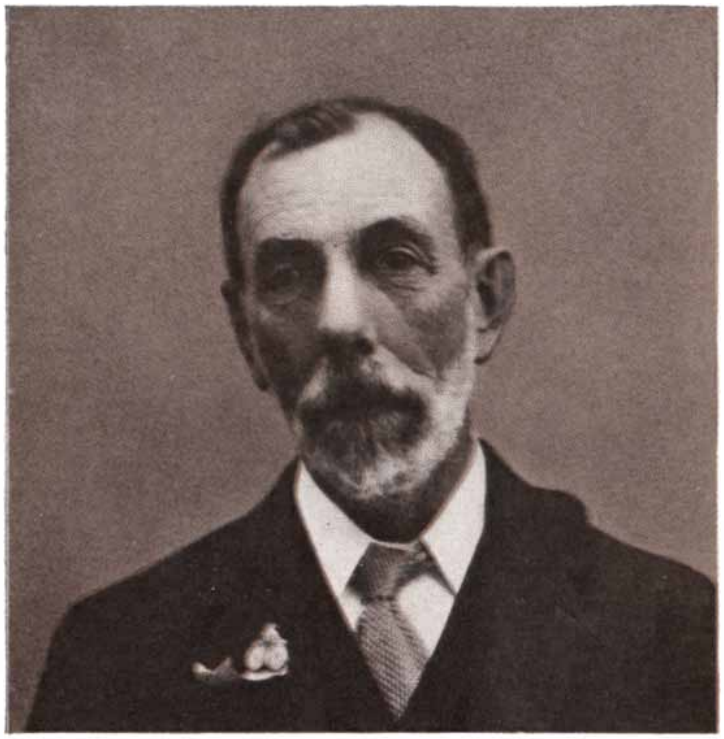
All of this is only what one should have expected. A careful search through the archives of the time, however, fails to support any such assertion! The pages of *Nature* and *The Times* of London, which were then as they are now leading outlets for argumentative "letters to the editor," are absolutely barren of protests, or indeed any argument at all on the subject of transmutation, in 1902. Nor can any papers in opposition to the new theory be found in the special scientific journals. At the annual meeting of the British Association for the Advancement of Science in September of 1902, a few months after the publication of the theory, there was only one paper on radioactivity (by J. J. Thomson), and it appears that this did not mention the Rutherford-Soddy theory. One can only conclude that either the memories of Tizard (who was a lad of about 17 in 1902) and McCoy (speaking 35 years later) were faulty or the "many" opponents of the theory maintained a surprising silence in their publications. The latter seems hardly likely, considering the history of scientific controversy.

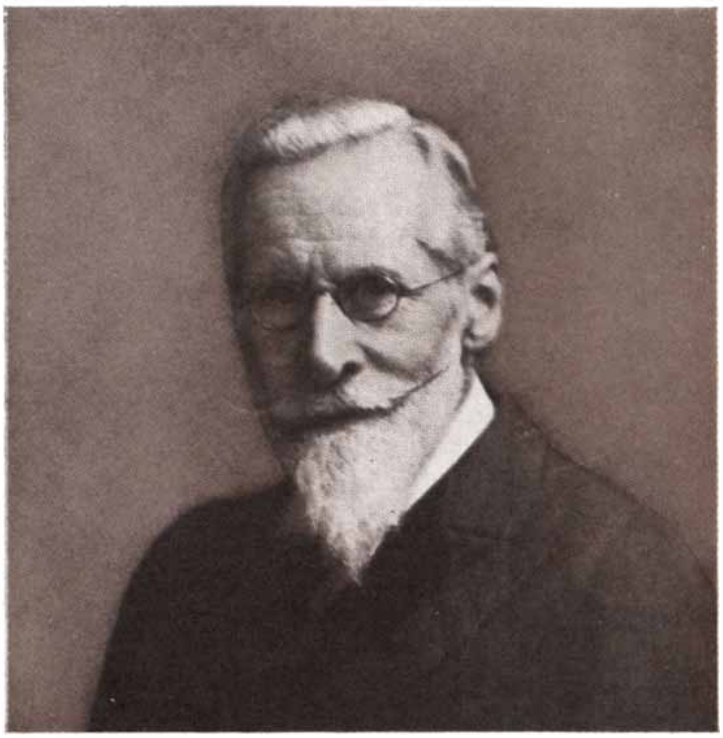
This is not to say that the transformation theory met with unanimous approval. In the years following 1902 a few determined voices were raised against the theory. Prominent among these objectors was a distinguished and forceful personality: the physicist Lord Kelvin.

Among the first to express public support of the Rutherford-Soddy theory were J. J. Thomson, Rutherford's former mentor, and Johannes Stark of Germany (both of whom later won Nobel prizes in physics). Another, and more persistent, champion of the theory was Sir Oliver Lodge, a noted scientific spokesman and authority on electrical matters, who had done no research in radioactivity but nevertheless took up the cause of transmutation.

In July of 1903 Ramsay and Soddy produced the most impressive single piece of evidence in confirmation of the theory that radioactive atoms decayed into other elements. Using liquefied air, they condensed the gaseous emanation from radium, and by spectral examination of the residue they discovered that it contained helium. There could be little doubt that the helium was a breakdown product from the radium—a clear case of one element giving rise to another. At about the same time Rutherford presented another strong indication that radium emitted atomic-sized particles. Pierre Curie and Albert Laborde had discovered that a sample of radium continuously generated heat. Rutherford offered what proved to be the correct explanation: the heat was produced, he said, as a result of internal bombardment of the mass by energetic alpha particles (later identified as helium nuclei) that were emitted by decaying radium atoms.

Crookes at first held out against the transmutation theory, clinging to his own hypothesis that radioactivity was generated by the active elements' absorption of energy from energetic air molecules. He soon capitulated, how-





authority on electricity, Sir Oliver Lodge (*second from left*); the discoverer of several noble gases, Sir William Ramsay (*second from right*), and the noted chemist who was also editor and publisher of *Chemical News*, Sir William Crookes (*extreme right*).

ever; in an address to the Congress of Applied Chemistry in Berlin in 1903 he conceded that the atom might undergo "a katabolic transformation." The Curies also were reluctant to accept the theory, but in June of 1903 they too acknowledged that radioactivity might be explained by some kind of transformation of the atom. The following year Pierre Curie, after confirming by his own experiments that radium did indeed yield helium as a decay product, finally agreed that "M. Rutherford's point of view" seemed to be correct.

The most vigorous challenge to the Rutherford-Soddy theory came at the annual meeting of the British Association for the Advancement of Science in September of 1903. The meeting of Section A (mathematics and physical science) opened with a certain degree of excitement, for it was rumored that Lord Kelvin would attack the Rutherford-Soddy "point of view." Although in ill health and unable to be present, Kelvin had arranged for distribution to the members of a paper presenting a theory in opposition to transmutation.

Young Rutherford, understandably nervous about the challenge from the 79-year-old elder statesman of physics, privately appealed to his friends in advance to support him at the meeting if necessary. In the tense, crowded hall Rutherford himself opened the discussion. He reviewed the facts of radioactivity and explained in detail how the transformation theory was consistent with all the observed facts. He was followed by Lodge, who had been asked to read Kelvin's paper. Lodge began by congratulating Rutherford and Soddy and asserting his own support of their theory. He then presented Kelvin's view. Kelvin argued in effect for what is now known as J. J. Thomson's "plum pudding" model of the atom, picturing the atom as a uniform mass of positive electricity, studded here and there with lumps of negative electricity. Radioactivity, Kelvin went on, was the result of violent oscillations set up within atoms by energy coming from the ether, "where it exists in a form which we have not yet found a means of detecting." As for the products discharged from radium during its convulsions, the beta rays were simply "plums" of negative electricity that were released, the gamma rays were a vapor and the alpha particles were actually radium atoms, or perhaps molecules, shot out of the agitated mass of radium or its compound.

Next rose Henry E. Armstrong, an eminent professor of chemistry at the Central Technical College in London. Known as "a man of forceful personality who, once having formed an opinion on a subject, held to it strongly and advocated it vigorously," Armstrong minced no words. He declared himself "astonished at the feats of imagination" in which Rutherford and his associates had indulged themselves. Chemists, Armstrong insisted, could find "no evidence of atomic disintegration on the earth." He personally favored Kelvin's theory of the origin of radioactivity.

The Kelvin-Armstrong attack provoked a discussion that went on throughout the day, extending into an afternoon session. Larmor, Soddy and others defended the transformation theory, and Rutherford delivered a reply to Kelvin's and Armstrong's arguments. By the end of the session it was clear that the Kelvin point of view had no serious support and that transmutation had carried the day. As Soddy remarked later, this meeting "assisted materially in the favourable reception accorded the disintegration theory." The opposition, brought into the open, was all but demolished by the strength of the demonstrated support for the theory.

Rutherford and other investigators proceeded to establish the half-lives and the decay series of the known radioactive elements. Several more eminent scientists publicly expressed their support of the Rutherford-Soddy "view." Much of the scientific community, however, maintained some reserve in its acceptance of the theory, taking the cautious position that although transmutation appeared to be a sound working hypothesis, its correctness still awaited conclusive proof. The only vo-

cal opponents were Kelvin, Armstrong and the German chemist Clemens Winkler, who suggested that radioactivity might be simply a physical property of matter: "a phenomenon which may adhere to matter without influencing its chemical composition, something like the magnetism of magnetic iron ore."

Kelvin kept up his fire. In May, 1904, Rutherford and Kelvin encountered each other as guests at the estate of the physicist Lord Rayleigh (the codiscoverer of argon with Ramsay). Rutherford, in a letter to his wife, gave a lighthearted account of their meeting: "Lord Kelvin has talked radium most of the day, and I admire his confidence in talking about a subject of which he has taken the trouble to learn so little.... He won't listen to my views on radium, but Strutt gives him a year to change his mind. In fact, they placed a bet to that effect last evening." R. J. Strutt (the baron's son, who later became the fourth Lord Rayleigh) won his five-shilling wager. At the British Association meeting in the fall of that year Kelvin publicly abandoned his own theory about the origin of radioactivity. He now rejected the external source of energy but would not go so far as to embrace transmutation. There was to be one more round, therefore, before the controversy finally expired.

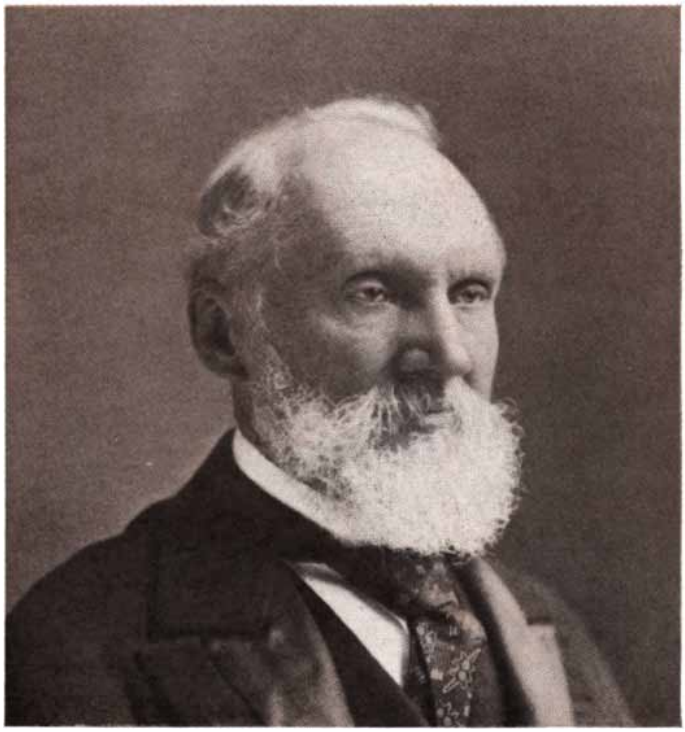
The occasion was the 1906 meeting of the British Association. Soddy led a discussion before Section A on the transmutation of elements. On reading the report in *The Times*, Kelvin, who again was absent from the meeting, wrote a letter to the editor. He protested that the emission of helium from radium was not a proof that the radium atom had changed; radium might merely "contain" helium. He also protested a suggestion by Strutt (accepted by Rutherford and others) that the earth's heat was derived from radioactivity as well as from the planet's original contraction. After Kelvin's letter appeared, Armstrong jumped into the fray with a letter of his own, denouncing the physicists' drawing of conclusions from microscopic quantities of what they assumed to be pure radium: "Workers in the radium school appear to have cast caution to the winds...."

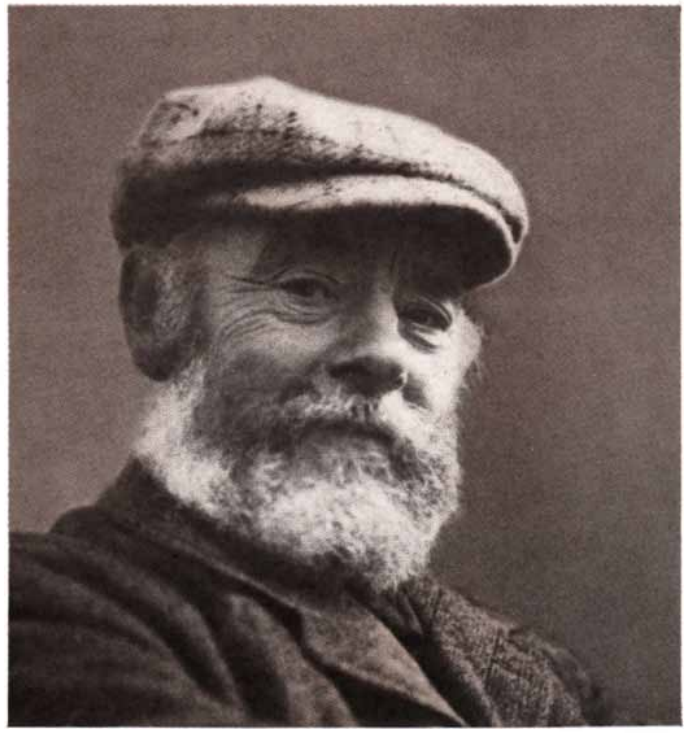
Lodge replied to these letters with persuasive logic but made the error of including a personal remark about Kelvin: "The fact that physicists have been unable to carry their veteran leader with them in some recent developments has been regretfully known... but it is also known that his brilliantly original mind has not always submitted patiently to the task of assimilating the work of others by the process of reading, and our hope has been that before long he would find time and inclination to look into the evidence more fully."

Kelvin quickly rejoined in *The Times* that he doubted "any other person has spent more hours in reading the first and second editions of Rutherford's *Radioactivity* than I have." *The Times* itself in a leading article stiffly upheld Kelvin's reputation and turned the tables on the advocates of transmutation by accusing them of "spinning cobwebs about it without having bestowed upon the facts anything like the amount of critical industry required to give their novel theories validity."

There followed a series of letters in which Soddy, as well as Lodge, expressed his high regard for Kelvin and his right to his opinion but convincingly answered all his arguments. Throughout the letters Kelvin's resistance was regarded as ill-informed, and Armstrong's almost embarrassing assistance was not taken seriously. This exchange of letters essentially ended the controversy. Thereafter no important figure offered serious objection to the transformation theory. The "newer alchemy" won a complete victory, and the ease of its victory had only been emphasized by the few feeble voices that had been raised against it.

We must still ask why this revolutionary theory, so reminiscent of the discredited fantasies of the ancient alchemists, met so little opposition from the traditionally skeptical scientific community. No doubt the most important reason was that the transmutation theory explained the facts of radioactivity well and no other reasonable theory





EARLY OPPONENTS of the Rutherford-Soddy theory included the "elder statesman of physics" William Thomson, better known as Lord Kelvin (*left*), and a professor of chemistry at the Central Technical College in London, Henry E. Armstrong (*right*).

could do so. I should also like to suggest that the atmosphere of the time played a large part.

At the turn of the century the serious investigators of nature had been reduced to a state in which they were reluctant to reject outright any radical discovery or new idea. The discoveries of radioactivity, X rays, electrons, the photoelectric effect, quantum theory, the theory of relativity and other surprises followed one another in quick succession. Typical of the scientists' shell-shocked reaction to this series of startling announcements was a remark made to Rutherford by the brilliant investigator of electricity John Zeleny: "I am about ready to believe that most anything is possible."

Moreover, without detracting from the originality or insight of Rutherford and Soddy, it must be admitted that the idea of transmutation was already in the air. Two years before their announcement the Irish physicist G. F. FitzGerald, in a paper in *Nature* on "The Theory of Ions," had suggested that "an element of one kind may some day be transmitted [*sic*] into that of another" and had asserted that there was "no impossibility in the dreams of the alchemist." Becquerel himself, in a talk before the Royal Institution of London just four months before the publication of the Rutherford-Soddy theory, had observed that the questions concerning radioactivity "have raised new hopes on the transformation of matter." And the famous British astrophysicist Norman Lockyer, the discoverer of helium in the spectrum of the sun's atmosphere, had published in 1900 a book called *Inorganic Evolution,* in which he claimed to have found evidence suggesting the evolutionary build-up of heavy elements from light ones. His spectral studies, he said, showed that the atmospheres of the hot, young stars contained the light chemical elements, and the heavier elements could be found in the older, cooler stars.

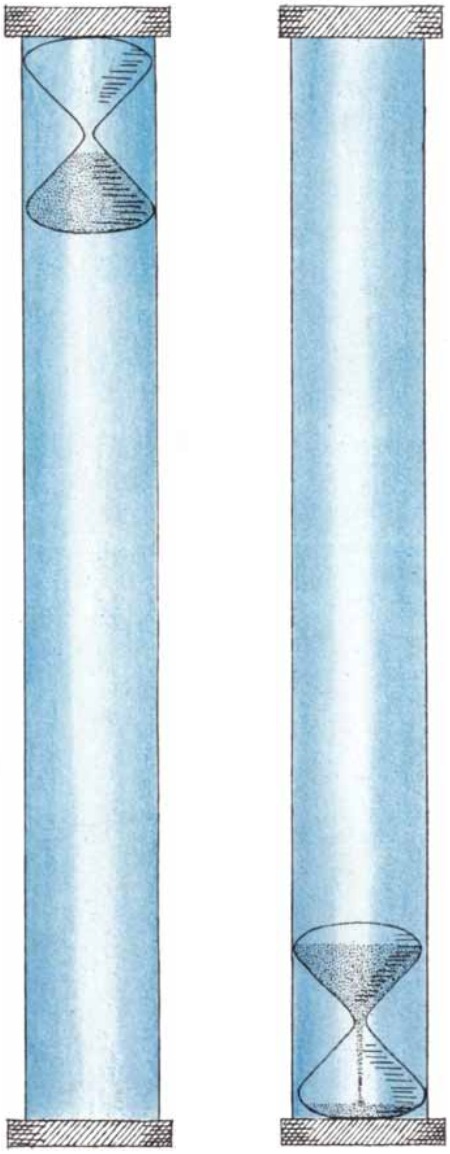
Nevertheless, these ideas about the growth and decay of elements were mere surmise and suggestion. Rutherford and Soddy must be credited with a thoroughly scientific accomplishment in presenting a definite theory that was soundly based on specific observations and explained the puzzling phenomenon of radioactivity. The timing of their announcement could hardly have been improved. A decade earlier it might have been dismissed as entirely too radical. When it came, it came at a moment not only of maximum acceptability but also of maximum impact.

MATHEMATICAL GAMES

Puzzles that can be solved by reasoning based on elementary physical principles

by Martin Gardner

This month's department, to vary things a bit, is a collection of short problems that are not so much mathematical as they are problems combining logical reasoning with some knowledge (mostly elementary) of physical laws. They could be called physics puzzles. In a few cases the questions are worded so as to misdirect the reader, but there are no joke solutions that depend on language quibbles. I want to thank David B. Eisendrath, Jr., John B. Hart, Jerome E. Salny and Derek Verner for problems 1, 12, 15 and 23 respectively. The answers will appear next month.



The hourglass paradox

1.

An unusual toy is on sale in Paris shops: a glass cylinder, filled with water, at the top of which an hourglass floats [*see drawing at left in illustration on this page*]. If the cylinder is inverted, as in the right-hand drawing, a curious thing happens. The hourglass remains at the bottom of the cylinder until a certain quantity of sand has flowed into its lower compartment, and then it rises slowly to the top. It seems impossible that a transfer of sand from top to bottom of the hourglass would have any effect on its overall buoyancy. Can you guess the simple *modus operandi*?

2.

A piece of solid iron in the form of a doughnut is heated. Will the diameter of its hole get larger or smaller?

3.

From a sheet of thin pasteboard cut a horseshoe shape that is a trifle longer than a toothpick [*see top illustration on opposite page*]. Lean the pick and horseshoe together on a tablecloth as shown. The problem is to lift both the horseshoe and the toothpick by means of a second toothpick held in one hand. You may not touch the horseshoe or the toothpick on which it leans with anything except the toothpick in your hand. Both objects must be lifted together and held suspended above the table. How is it done?

4.

An old joke concerns a truck driver who stopped his panel truck just short of a small, shaky-looking bridge, got out and began beating his palms against the sides of the large compartment that formed the back of the truck. A farmer standing at the side of the road asked him why he was doing this.

"I'm carrying 200 pigeons in this truck," explained the driver. "That's quite a lot of weight. My pounding will frighten the birds and they'll start flying around inside. That will lighten the load considerably. I don't like the looks of this bridge. I want to keep those pigeons in the air until I get across."

Assuming that the truck's compartment is airtight, can anything be said for the driver's line of reasoning?

5.

Fill a glass with water and drop a small cork on the surface. It will float to one side, touching the glass. How can you make it float permanently in the center, not touching the glass? The glass must contain nothing but water and the cork.

6.

In Chapter 7 of Lewis Carroll's *Sylvie and Bruno Concluded* the German Professor explains how people in his country need not go to sea to enjoy the sensations of pitching and rolling. This is accomplished, he says, by putting oval wheels on their carriages. An Earl, who is listening, says that he can see how oval wheels could make a carriage pitch backward and forward, but how could they make the carriage roll too?

"They do not *match*, my Lord," the Professor replies. "The *end* of one wheel answers to the *side* of the opposite wheel. So first one side of the carriage rises, then the other. And it pitches all the while. Ah, you must be a good sailor, to drive in our boat-carriages!"

Is it possible to arrange four oval wheels on a carriage so that it would actually pitch and roll as described?

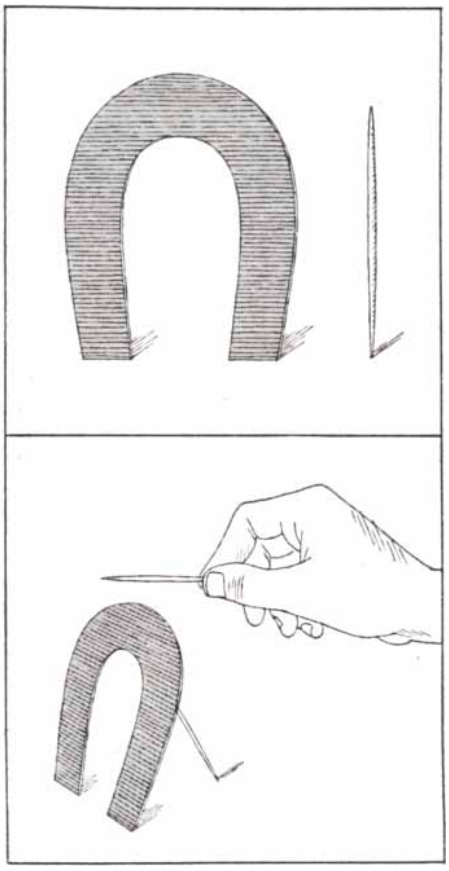
7.

Some friends were picnicking. "Did you bring the oil and vinegar for the salad?" Mrs. Smith asked her husband.

"I did indeed," replied Mr. Smith. "And to save myself the trouble of carrying two bottles I put the oil and vinegar in the same bottle."

"That was stupid," snorted Mrs. Smith. "I like a lot of oil and very little vinegar, but Henrietta likes a lot of vinegar, and——"

"Not stupid at all, my dear," inter-



Horseshoe and toothpick

rupted Mr. Smith. He proceeded to pour, from the single bottle, exactly the right proportions of oil and vinegar that each person wanted. How did he manage it?

8.

You are locked in a room that contains no metal of any sort (not even on your person) except for two identical iron bars. One is a bar magnet, the other is not magnetized. You can tell which is the magnet by suspending each by a thread tied around its center and observing which bar tends to point north. Is there a simpler way?

9.

A cube of ice floats in a beaker of water, the entire system at 0 degrees centigrade. Just enough heat is supplied to melt the cube without altering the system's temperature. Does the water level in the beaker rise, fall or stay the same?

10.

In the tower of a church two bell ropes pass through small holes a foot apart in a high ceiling and hang down to the floor of a room. A skilled acrobat, carrying a knife and bent on stealing as much of the two ropes as possible, finds that the stairway leading above the ceiling is barred by a locked door. There are no ladders or other objects on which he can stand, and so he must accomplish his theft by climbing the ropes hand over hand and cutting them at points as high as possible. The ceiling is so high, however, that a fall from even one-third the height could be fatal. By what procedure can he obtain a maximum amount of rope?

11.

A man walking at night along a sidewalk at a constant speed passes a street light. As his shadow lengthens, does the top of the shadow move faster or slower or at the same rate as it did when it was shorter?

12.

A garden hose is coiled around a reel about a foot in diameter placed on a bench as shown in the illustration at the right. One end of the hose hangs down into a bucket and the other end is unwound so that it can be held several feet above the reel. The hose is empty and there are no kinks or obstructions in it. If water is now poured into the upper end by means of a funnel, one would expect that continued pouring would cause water to run out at the lower end. Instead, as water is poured into the funnel it rises in the raised end of the hose until it overflows the funnel; no water ever emerges from the other end. Explain.

13.

You cannot push a peeled hardboiled egg through the neck of a glass milk bottle because the air trapped in the bottle keeps it from going through. If, however, you drop a piece of burning paper or a couple of burning matches into the bottle before you stand the egg upright at the opening, the burning will use up oxygen and create a partial vacuum that draws the egg inside. After this has happened a second problem presents itself. Without breaking the bottle or damaging the egg, how can you get it out again?

14.

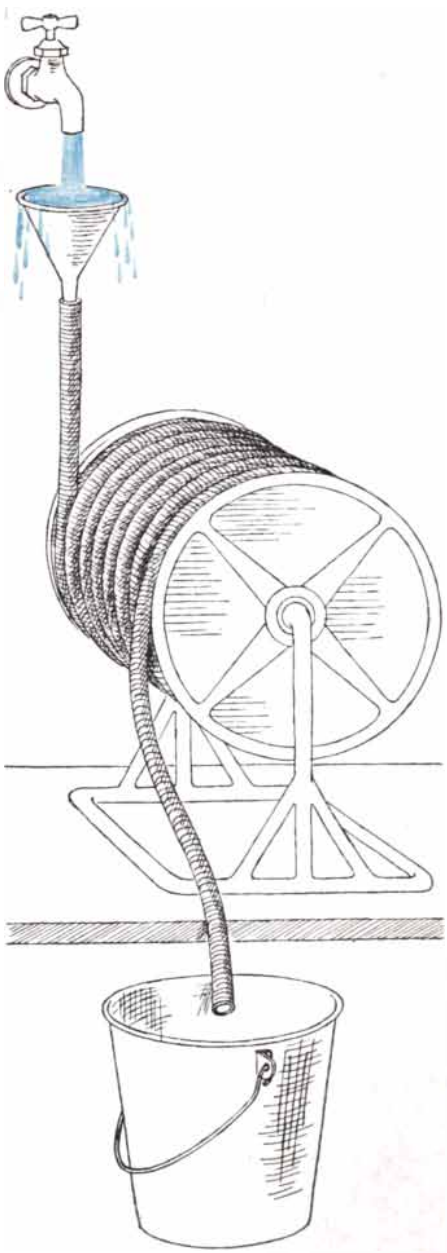
A small boy is sailing a plastic boat in the bathtub. It is loaded with nuts and bolts. If he dumps all this cargo into the water, allowing the boat to float empty, will the water level in the tub rise or fall?

15.

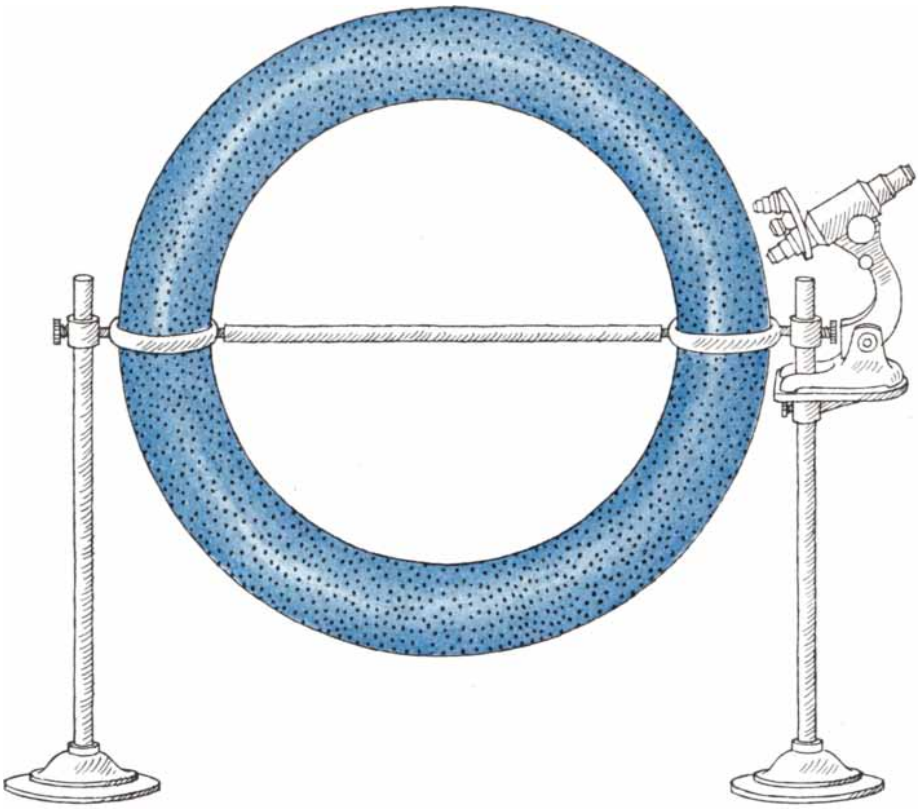
A family is out for a drive on a cold afternoon, with all vents and windows of the car closed. A child in the back seat is holding the lower end of a string attached to a helium-filled balloon. The balloon floats in the air, just below the car's roof. When the car accelerates forward, does the balloon stay where it is, move backward or move forward? How does it behave when the car rounds a curve?

16.

It has been suggested that in the far future it may be possible to hollow out



The hose paradox



The Compton tube

the interior of a large asteroid or moon and use it as a mammoth space station. Assume that such a hollowed asteroid is a perfect, nonrotating sphere with a shell of constant thickness. Would an object inside, near the shell, be pulled by the shell's gravity field toward the shell or toward the center of the asteroid, or would it float permanently at the same location?

17.

A bird has a small, lightweight oxygen tank attached to its back so that it can breathe on the moon. Will the bird's flying speed on the moon, where the pull of gravity is less than on the earth, be faster, slower or the same as its speed on the earth? Assume that the bird carries the same equipment in both instances.

18.

A little-known invention of the physicist Arthur Holly Compton is shown schematically above. A glass torus several feet across is completely filled with a liquid in which small particles are suspended. The tube is allowed to rest until there is no movement of its liquid and then is quickly flipped upside down by a 180-degree rotation about the horizontal axis. By viewing the suspended particles through a microscope one can determine whether or not the liquid is now flowing around the torus and, if so, in what direction. If you were in a basement with this device and did not know the direction of north, how could you use the Compton tube to determine the four points of the compass?

19.

A bowl, three-quarters filled with water, rests on a scale. If you drop a live fish into the water, the scale will show an increase in weight equal to the weight of the fish. Suppose, however, you hold the fish by its tail so that all but the extreme tip of its tail is under water. Will the scale register a greater weight than it did before you dunked the fish?

20.

A rope is tied to the pedal of a bicycle as shown in the bottom illustration on this page. If someone pulls back on this rope while another person holds the seat lightly to keep the bicycle balanced, will the bicycle move forward, backward or not at all?

21.

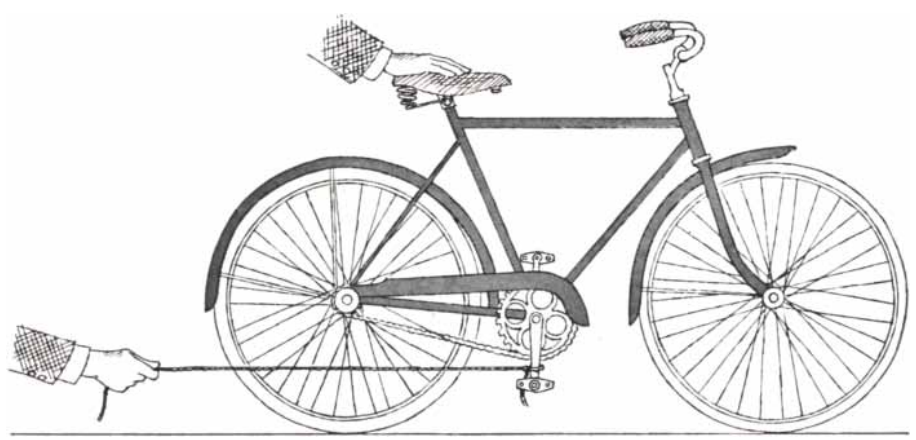
If a rope is tied to the stern of a rowboat, is it possible for a man standing in the boat to propel it forward through quiet water by jerking on the free end of the rope? Could a space capsule drifting in interplanetary space be propelled by a similar method?

22.

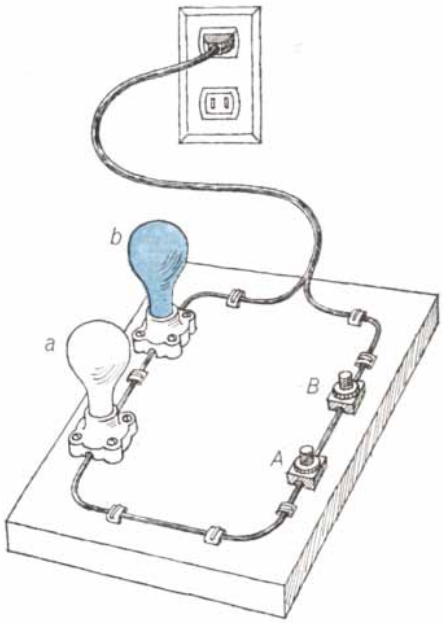
Which is worth more, a pound of $10 gold pieces or half a pound of $20 gold pieces?

23.

An entertaining curiosity that can be built easily consists of two small 110-volt bulbs (preferably one clear and one frosted) and two on-off switches connected in a simple series circuit plugged into any wall outlet carrying the usual alternating current [*see illustration on opposite page*]. When both switches are on, both bulbs light. If one bulb is unscrewed, the other goes out—as would be expected. When both switches are off, both bulbs are dark. But when switch *A* is on and *B* is off, only bulb *a* lights. And when switch *B* is on and *A* off, only bulb *b* lights. In short, each



A problem in mechanics



An electrical paradox

switch independently controls its corresponding bulb. Even more inexplicable is the fact that if the two bulbs are interchanged, switch *A* still controls bulb *a* and switch *B* still controls bulb *b*. Nothing is concealed in the wooden board on which the switches, bulb sockets and wire are mounted. What is the clever secret behind the construction of this circuit?

The first of the two problems given last month was to determine the largest number that cannot be expressed by substituting positive integers in the formula $23x + 28y$. The answer is $(23 \times 28) - 23 - 28 = 593$. For proof see the solution to Problem 26 in Roland Sprague's *Recreation in Mathematics* (Blackie, London, 1963).

The second problem was to determine when a person's biological chart, as worked out by the Swiss school based on the work of Wilhelm Fliess, will finish a complete cycle and start repeating the same pattern. The three superimposed cycles have periods of 23, 28 and 33 days. These numbers are prime to each other (have no common divisor) and so the combined pattern will not repeat until after a lapse of $23 \times 28 \times 33 = 21{,}252$ days, or a little more than 58 years. Since Fliess's system did not include the 33-day cycle, his cycle patterns repeat after a lapse of $23 \times 28 = 644$ days. Swiss Fliessians call this the "biorhythmic year." It is important in computing the "biorhythmic compatibility" between two individuals, since any two persons born 644 days apart are synchronized with respect to their two most important cycles.

THE AMATEUR SCIENTIST

Stimulating plant growth with ultrasonic vibrations; electrical discharges in a gas

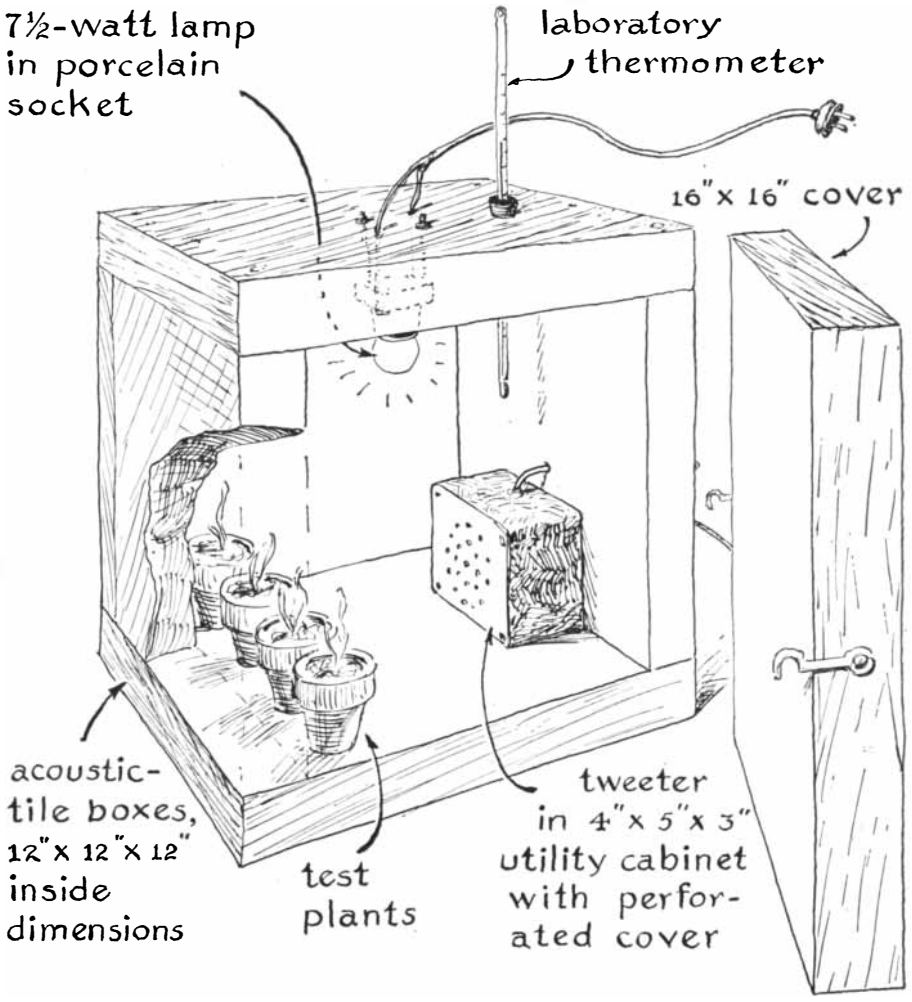
Conducted by C. L. Stong

In recent years several experimenters have observed that ultrasonic vibrations in air stimulate the growth of plants. The effect appears at frequencies above 20,000 vibrations per second and levels off above 50,000 vibrations. The possibility that plants might respond to sound waves was recognized more than a century ago. Charles Darwin attempted without success to stimulate the "sensitive plant" (*Mimosa pudica*) with sound waves generated by the bassoon and other musical instruments. Similarly negative results were subsequently reported before 1900 by many other experimenters, including the eminent German plant physiologist Wilhelm Pfeffer.

In the light of these reports interest in such experiments largely disappeared until the advent of electronic apparatus for generating ultrasonic vibrations. Last year Evalyn Horowitz, then a high school student in Bergenfield, N.J., won a prize at a science fair for a project based on the exposure of radish seedlings to vibrations of 50,000 cycles per second at an acoustic energy equivalent to about one watt. She demonstrated that the rate of growth is almost doubled during the three weeks following germination and that accelerated growth is observed even when the plants are kept in darkness.

The ultrasonic generator used by Miss Horowitz consisted of an electronic oscillator connected to a small loudspeaker of the kind used for the "tweeter" in high-fidelity phonographs. "The idea of doing the experiment," Miss Horowitz writes, "came to me when one of my teachers explained that the growth of plants can be influenced by light of a selected color. Somehow the words 'light' and 'sound' became linked in my mind; I wondered if sound of a certain pitch might not have a comparable effect on plant growth. The literature was not encouraging. Most investigators who had subjected plants to vibrations in the audible range reported negative results. A bulletin issued by the U.S. Department of Agriculture, however, stated that 'the effects [of sound] on flowering, growth and yields have not yet been evaluated with respect to time of treatment and intensity of treatment.' This implied that the question was not settled. So I decided to set up an apparatus for exposing potted plants to ultrasonic vibrations. I chose radishes for the experiment primarily because they are hardy and the seeds were available.

"Two groups of plants were grown for each experiment. One was exposed to ultrasonic energy and the other was insulated as a control. The apparatus used in the first series of experiments consisted of two cabinets with a volume of one cubic foot each. They were lighted by 7.5-watt incandescent lamps. The experimental cabinet also housed a tweeter, which is a small loudspeaker powered by an audio generator of the kind used by electronic-service technicians. The audio generator developed a maximum frequency of 50 kilocycles



Cabinet for experiments with plants

at about one watt. I bought these components, together with timing switches, from a dealer in amateur radio supplies.

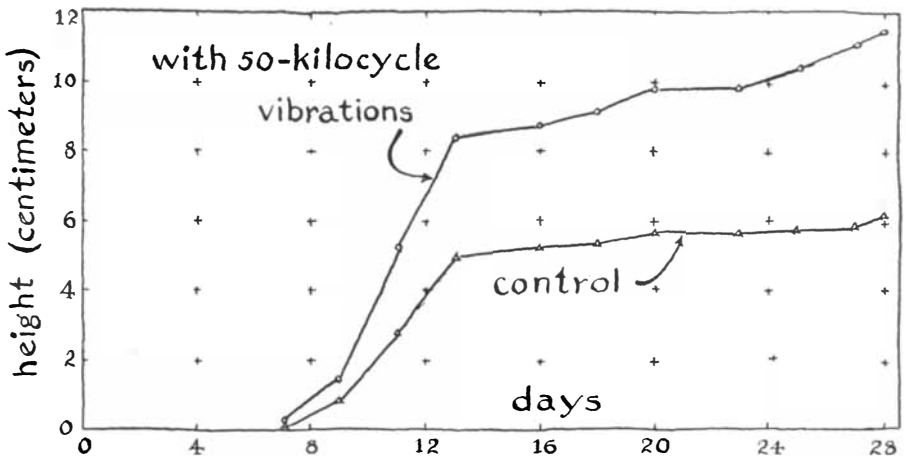
"The cabinets were constructed of acoustic ceiling tile two inches thick [*see illustration on opposite page*]. I obtained the tile from a lumberyard. The material was cut to size and assembled with wood screws. A small hole in the top of each cabinet admitted a thermometer for monitoring the temperature of the air. The assemblies were closed with snugly fitting, removable covers of the same material.

"I later learned that the sound would have been more effectively confined if I had made the cabinets by nesting two plywood boxes with an inch of space between them and filling the space with sand. My construction worked, however, perhaps because during operation the cabinets were separated by about 10 feet. At this distance little ultrasonic energy from the experimental cabinet penetrated the control cabinet.

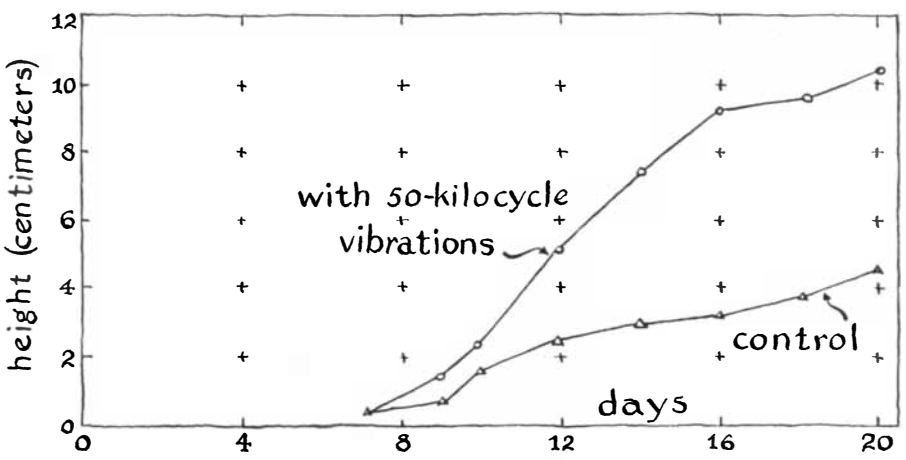
"Enough garden soil was procured for eight clay pots of two-inch diameter. The soil was thoroughly mixed in a cardboard box, tested for chemical composition, fertilized, moistened and packed lightly into the pots. Four radish seeds were planted in each pot at a depth of about an eighth of an inch. All the pots were watered equally and simultaneously. The time switches were set to turn on the lights and the audio generator at 8:30 A.M. daily and turn them off 12 hours later.

"Records were made of the dates of planting and sprouting. When the seeds germinated, each plant was identified by a numbered label affixed to the edge of the pot. Thereafter on Mondays, Wednesdays and Fridays notes were made of the general appearance of each plant, including height, leaf growth and coloring. The plants were measured in two ways: by straightening the stems and placing them against a ruler and by estimating the height against a background of metric graph paper. I am not satisfied with either method. The first entails handling the plants, with the risk of damage, and the second is subject to error. I did not succeed, however, in devising a better measuring scheme.

"The first experiment was stopped after 28 days, and I then plotted graphs of the relative growth of the experimental plants and the controls [*see upper illustration on this page*]. Plants that were treated with ultrasonic vibrations grew an average of 87 percent taller than the controls. In general appearance the controls were small and sturdy, with thick stems and bright green leaves. In contrast, the experimental plants were comparatively spindly. They were tall and shaky, with thin stems and dark green leaves.



Relative growth of experimental plants and controls



Results of further experiments

"This experiment demonstrates that exposure to ultrasonic vibration affects the growth of radishes, but it does not explain why. It has been suggested that the vibrations 'awaken' the plants, that is, that they first stimulate the metabolic processes as light becomes available for photosynthesis and that later they accelerate the biochemical reactions. If this were the case, the plants should produce more and larger leaves and thicker stems; in general they should become large counterparts of the controls. Instead they merely grow taller.

"The theory has also been advanced that the vibrations raise the temperature of the soil, thereby increasing the activity of soil microorganisms and providing the experimental plants with an abnormal amount of nutrients. A careful check of soil temperature by thermometers that could be read to within half a degree failed to show a significant difference in soil temperature between the two cabinets. Increased microbe activity should change the acidity of the soil. A careful check of soil acidity at the end of the experiment indicated a *p*H of between 3.5 and 4 in all pots.

"The plant hormones known as auxins can encourage elongated growth. It occurred to me that the most common auxin, 3-indoleacetic acid (IAA), might be involved. Perhaps the vibrations either increased its formation and activity or decreased the effectiveness of its inhibitors. As a rough check on this hypothesis I made up four solutions of the chemical: two test tubes containing five grams of a .1 percent solution of IAA (the approximate concentration found in plants) in ether, and another two test tubes containing five grams of a 1 percent solution of IAA in ether. One tube of each concentration was placed in the control and experimental cabinets respectively. The experimental solutions were exposed to 50-kilocycle vibrations 12 hours a day for 10 days. The .1 percent experimental solution

lost .08 gram more IAA than its control and the 1 percent solution lost .17 gram more than its control. These losses do not necessarily imply increased chemical activity as a result of the ultrasonic irradiation, but they indicate that some phenomenon other than evaporation is at work.

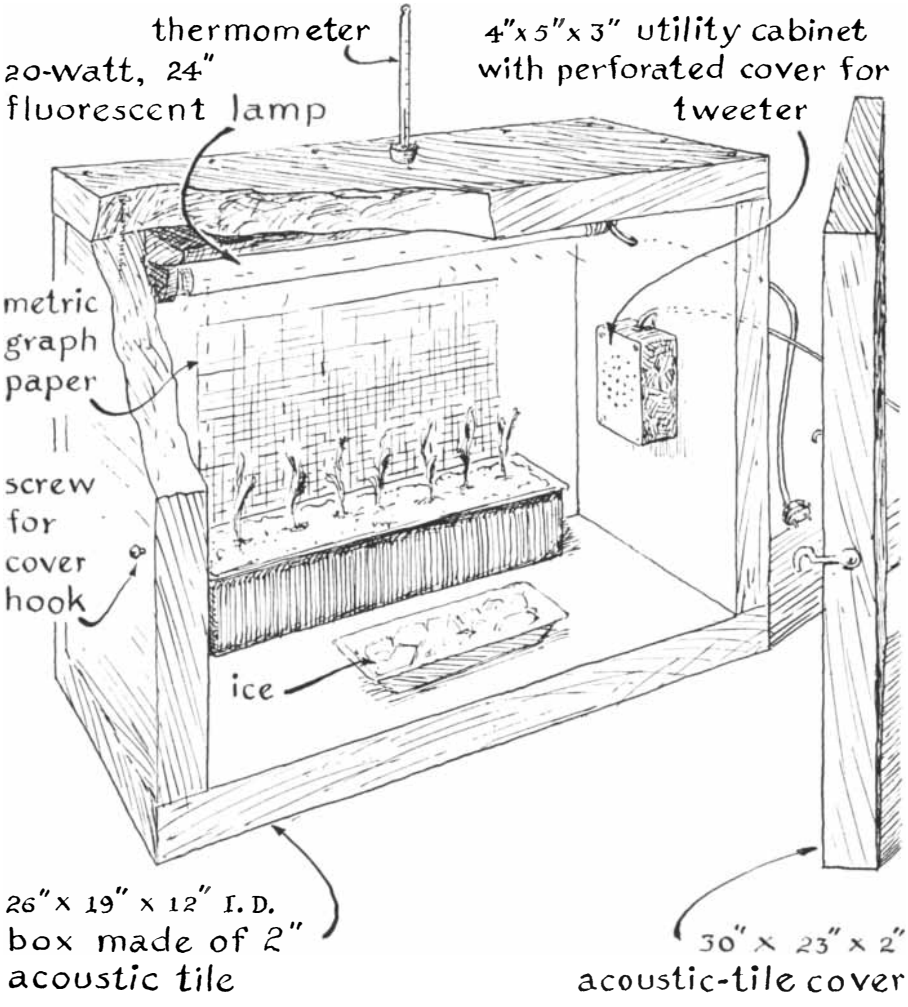
"In another experiment I compared the growth of two groups of radish seedlings: one treated with IAA and exposed to ultrasonic vibrations, the other not treated with the hormone but exposed to the vibrations. Two other groups, one treated with the hormone and one untreated, were used as controls. These plants were potted in troughs that required more room than was available in the original cabinets. Larger cabinets were built [*see illustration below*]. These were similar to the ones made first but were lighted by 20-watt fluorescent lamps. The lamps overheated the cabinets. This problem was solved by placing the ballast coils of the lamps outside the cabinets and by keeping a tray of ice inside as required. A more elegant cooling system could have been set up by installing a heat exchanger in the cabinets, but my scheme worked nicely even though it required close attention.

"One group of control plants and one group of experimental plants were watered regularly as in the first experiment. The other group of controls and the second group of experimental plants were watered with a .1 percent solution of IAA. All other conditions were identical with those of the first experiment. The IAA-treated control plants showed 91.5 percent of the growth of the untreated controls. The IAA-treated experimental plants grew 140 percent higher than the untreated controls, and the untreated experimental plants grew 150 percent higher than the untreated controls.

"Although the hormone-treated plants in both cabinets grew somewhat less than their untreated counterparts, the treated experimental plants exhibited more growth with respect to the untreated experimental plants than the treated controls did in relation to their untreated counterparts. This result does not necessarily implicate IAA in the phenomenon of growth acceleration, although in my opinion some relation is implied. The lower comparative growth rate of the treated plants may be explained by the fact that auxin can cause a plant to spend more energy 'burning' food than using it.

"As a final experiment in the series, I compared the relative growth of a group of normally lighted controls with a comparable group of experimental plants exposed to ultrasonic vibrations but deprived of light. I was curious to learn if some or all of the energy necessary to support growth could be provided by ultrasonic vibrations. Plants normally grown in darkness are tall, thin and devoid of the green pigment chlorophyll; they die of starvation soon after sprouting. Unfortunately this experiment was undertaken just prior to the science fair, when my time was limited. Even so, it produced at least one interesting result.

"The control cabinet was lighted by a single 7.5-watt incandescent lamp. The experimental plants were irradiated with ultrasonic vibrations in darkness. Both cabinets were operated 12 hours a day for 20 days. Four plants were grown in each cabinet. The average growth of the two groups is shown in the accompanying illustration [*lower illustration on preceding page*]. The control plants were small but sturdy; they had thick stems and the leaves were bright green. The experimental plants, which grew 134 percent taller than the controls, were spindly, thin-stemmed and yellowish, but they survived."



Second design for a cabinet

Nyle A. Steiner of Kaysville, Utah, submits what is perhaps the most inexpensive system that can be devised for demonstrating the many effects associated with electrical discharges in a gas at low pressure. The complete apparatus, including the gas-discharge tube and vacuum pumps, can be constructed for about $5 if the experimenter owns an induction coil and no more than $10 if he does not. Steiner writes: "My discharge tube was made from a glass straw bought at a drugstore. The tube has an inside diameter of about four millimeters and is about 25 centimeters long. The anode was prepared by wrapping enough black plastic tape snugly around a two-inch length of 14-gauge clean copper wire to make a snug fit with the inside diameter of the glass tube. The joint was made airtight with a coating of plastic cement. It could also have been sealed with paraffin or with a mixture of equal parts of rosin and beeswax applied smoking hot.

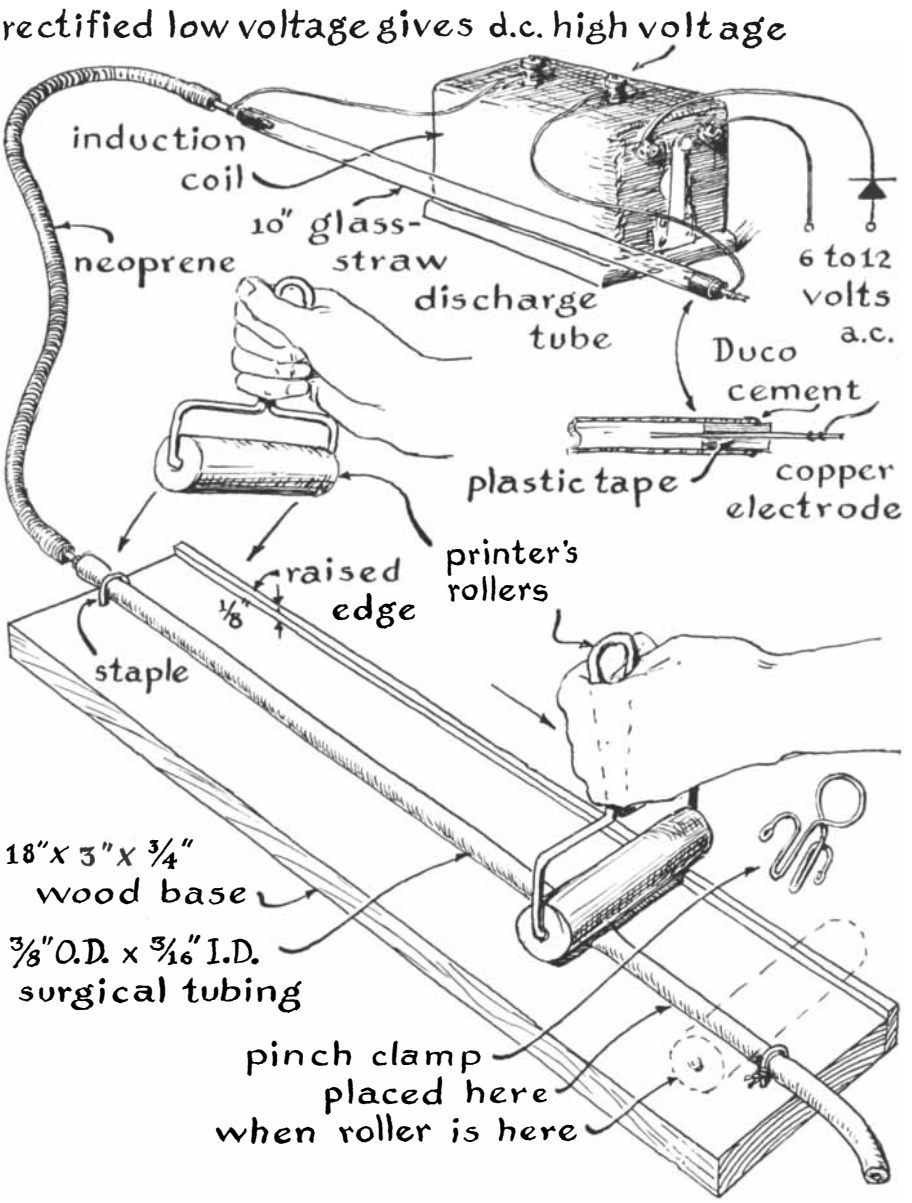
"The cathode, which is installed in the other end of the glass tube, consists of a 1½-inch length of small brass tubing removed from a ball-point pen. Traces of ink inside the tubing can be removed with carbon tetrachloride or a comparable cleaning fluid. The cathode is sealed into the glass tubing by the same method used to install the anode. The brass tube serves both as an electrode and as an outlet for exhausting the glass tube.

"The air pump consists of two parts: a length of heavy-walled rubber tubing, mounted on a flat board, and a pair of rollers equipped with handles. I take a roller in each hand, press one against the flexible tubing near one end and roll it to the opposite end. This causes a closed constriction to move down the tube, pushing the air ahead of the constriction. The second roller is then pressed against the tubing at the same initial point before the first roller is lifted. This sequence of motions is continued. The action resembles that of milking a cow. The glass tube to be exhausted is connected to the end of the rubber tubing at which the strokes originate. Care must be taken to avoid lifting both rollers simultaneously or air will rush into the vessel.

"I used a 20-inch length of surgical tubing for the pump. The tubing had an outside diameter of 3/8 inch and an inside diameter of 3/16 inch. This tube was mounted by means of staples on a board 18 inches long, three inches wide and 3/4 inch thick. A guide rail 1/4 inch thick that extended 1/8 inch above the surface of the base at one side prevented the rollers from tipping off the tubing [*see illustration at right*].

"The connection between the pump and the discharge tube was made by a six-inch length of neoprene tubing that made a tight fit with the brass tubing serving as the outlet of the discharge tube. The neoprene tubing was coupled to the larger surgical tubing by means of a reducer made by soldering a one-inch length of brass tubing from a ball-point pen into a similar length of 1/4-inch copper tubing. The small neoprene tubing was obtained from a hobby shop. Such tubing is normally used for the fuel line of miniature gasoline engines. The rollers are ink brayers and cost $1 each at a shop selling art supplies. The operation of the pump can be improved by lightly coating the inner surface of the surgical tubing with vegetable cooking oil.

"The capacity of the pump is low. For this reason small leaks can be troublesome. In some versions of the apparatus I have installed oil seals at all joints. The joints are placed inside a small container, such as the cap of a catsup bottle, and flooded with oil [*see top illustration on next page*]. A coating of the rosin-beeswax mixture is about as easy to apply and more convenient because it does not spill.

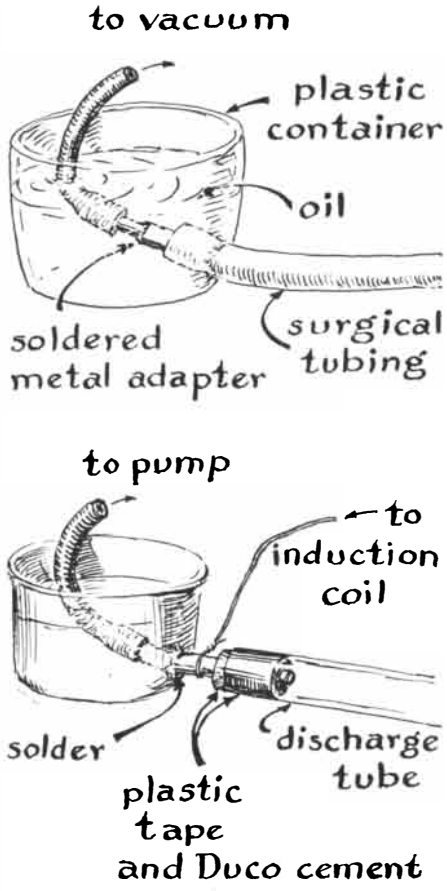


Apparatus for experiments with electrical discharges in gas

"For the high-voltage power supply I used an induction coil with a self-contained vibrator for interrupting the primary circuit. The coil produced a half-inch spark between needle points in air. Such coils are available from dealers in scientific apparatus. The high-voltage output is unidirectional and equivalent to direct current. Comparable coils were formerly used in the ignition system of Model-T Ford automobiles and can be bought for a few dollars from mail-order houses that cater to antique-car enthusiasts. The ignition coil from a modern automobile can be used but it must be equipped with a switch for rapidly closing and opening the primary circuit. This could be done by coupling a small electric motor to the camshaft of a distributor from an automobile.

"Direct current for energizing the induction coil can be provided by rectifying the alternating-current output of a 12-volt step-down transformer. For the rectifier I used a single silicon diode. The coil performs much better, however, when it is powered by a 12-volt storage battery. The high-voltage output leads of the coil connect directly to the electrodes of the discharge tube. Avoid touching the leads or electrodes when the coil is in operation or you may get an unpleasant shock.

"To operate the system, switch on the high voltage and operate the rollers. After about 10 strokes reddish streamers

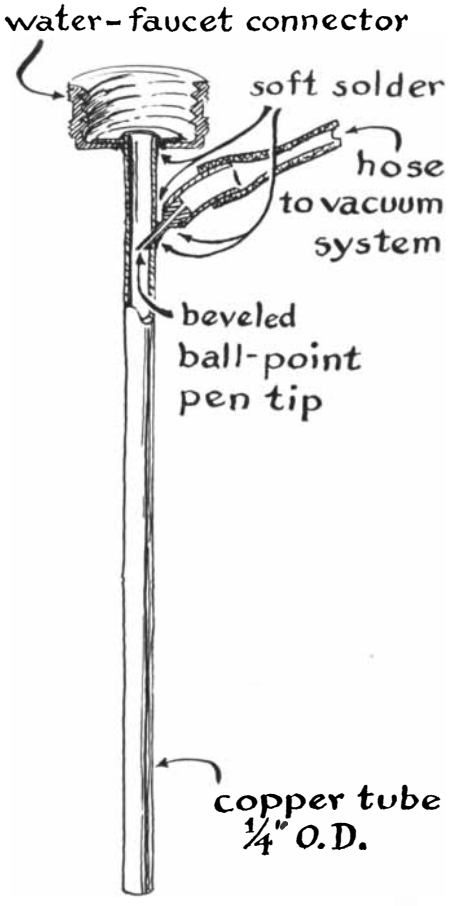


Sealing of joints

that resemble miniature bolts of lightning will appear between the electrodes. As pumping continues the streamers will be replaced by a solid bluish glow that fills the entire tube. Shortly thereafter the glow will fade at one end; the so-called Faraday dark space will appear and the remaining glow will slowly break into striations. When the pump is operated at the rate of about one stroke per second, all these phenomena will be observed in less than a minute.

"If the system is working well, the Faraday dark space may grow to a length of about a quarter of an inch. Greater length requires lower pressure. To achieve it you can convert the surgical tubing into a two-stage pump by means of a pinch clamp. First pump the system to the lowest possible pressure. Then clamp the surgical tubing on the low-pressure side of the brayer at the end of the stroke. Pumping is resumed by stroking the brayers between the hose connection and the pinch clamp. Thereafter air that is removed from the discharge tube is compressed in the short length of surgical tubing between the pinch clamp and the end of the brayer stroke. The pressure in this region, even after prolonged pumping, will remain far below that of the atmosphere. Still lower pressures can be achieved by similarly installing a second pinch clamp, thus converting the device into a three-stage pump. Continued operation will then cause the striations to fade, and within minutes a greenish glow will appear on the inner walls of the glass. This glow is fluorescence excited by X rays.

"Faster pumping speeds can be achieved at a somewhat lower cost in terms of labor by backing up the pump with a water aspirator. Such an aspirator can be made easily by inserting the brass tubing from a ball-point pen through the side of a seven-inch length of copper tubing (1/4 inch outside diameter) fitted with a hose connection [*see illustration below*]. The hose connection is screwed to a water tap. When water runs through the copper tubing, air is drawn into the stream through the brass tubing. I have also backed up the pump with the compressor unit from a discarded refrigerator. The inlet of the compressor is connected to the outlet of the surgical tubing. With this arrangement I have succeeded in pumping the tube to a pressure so low that all glow disappears, indicating a pressure of less than .001 millimeter of mercury."



A water aspirator

ALLOY STEELS

(*Advertisement*)

The interaction of solute elements, their thermodynamic relationships with each other and with iron... how these interactions control subsequent solid state transformations to produce a microconstituent which determines the properties of the alloy.

by James Smith

Alloy steel studies were once measured in terms of "the state of the art." Not so now. Steel research activity is moving forward so rapidly it now includes such sophisticated concepts as atomic scale interactions, solid state reactions and micron scale defect measurements.

This rapid advance in alloy steel development can be attributed to the interaction of physicists, chemists and engineers—often working as a team. Separately as well as together, they make careful studies of the intimate structure of metals and the mechanisms by which the structure controls engineering properties of steel, such as strength, toughness, ductility and joinability.

True, iron is the backbone of steel. But it is only that until researchers work to develop in it properties many times superior to those inherent in iron. Strength is an important example. The yield strength of iron is approximately 4,000 psi. But research has developed commercial steels with strengths two orders of magnitude greater.

Research studies begin with the periodic table. Here is where the researcher makes a finite choice of those elements that may be alloyed with iron.

The treatment the alloy then receives ultimately determines what engineering properties the steel will develop.

Alloy studies delve into the interaction of these (alloying) solute elements. Their thermodynamic relationships with each other, as well as with the iron are investigated. These interactions control subsequent solid state transformations to produce a microconstituent which can enhance the properties of steel. These transformations are also studied. The internal structure or atom array within the microconstituent is examined by electron microscopy, electron and/or X-ray diffraction and by microstraining techniques. This examination can reveal the presence of dislocation networks which determine the deformation characteristics of the alloy steel.

These tools are useful in observing the contribution made by the clustering of solute atoms. Also, the precipitation of intermetallic compounds to the strengthening by coherency binding and strain hardening mechanisms.

Through these observations, new concepts are being introduced. Concepts such as the interaction of precipitates or foreign particles with dislocation structures and vacancy concentrations. These new concepts permit the interpretation of why and how steels can be made tougher, stronger and more ductile. The way these mechanisms operate to form the microconstituents which comprise the composite microstructure determines the engineering properties of the steel.

Just as chemistry determines what is to be alloyed with the steel, the treatments which can be given to the steel are determined by the variables of pressure, temperature and time. These alter the thermodynamics and kinetics of the solid state transformations in alloy steels.

Every time steel is heated or cooled, compressed or stretched, squeezed or expanded, its properties are changed. Science and engineering are combined to exercise a control over these variables under conditions where the research investigator can examine the contribution of each variable. And where he can optimize the combination of variables to produce steels with superior properties.

Recently this type of investigation has resulted in a physical simulation of hot rolling steel through experiments in the laboratory – experiments in which the steel is not even rolled!

Greatly enhanced thermal transfer systems used in cooling steels provide an excellent example of advances in engineering. This kind of advancement has enabled steel production to make use of the thermal-mechanical treatments. Previously, this treatment could be performed only in the laboratory.

Alloy steels which take advantage of these increased capabilities are now evolving. Concepts are developing from a combination of chemistry, physics and engineering, and will produce the engineering properties required by an advancing technological age.

This article gives you a glimpse of just a few developments in alloying steels. It's only a small part of the continuing, widespread research effort that is going on 24 hours a day at Youngstown's research center. If you think our researchers might be able to help you, just give us a call or write Department 251B6.

Youngstown Steel

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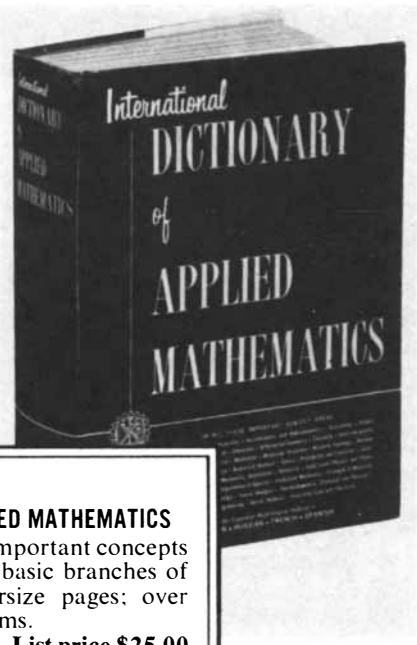

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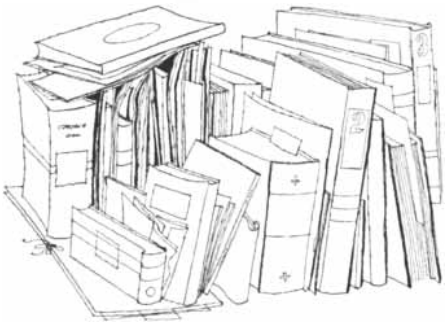

BOOKS

The Masters-Johnson study of human sexual response

by Frank A. Beach

HUMAN SEXUAL RESPONSE, by William H. Masters and Virginia E. Johnson. Little, Brown and Company ($10).

The subject and scope of the work presented in this volume are faithfully represented in its title when the proper definitions are supplied. The "response" consists exclusively of a sequential pattern of muscular, glandular and vascular changes. In the studies conducted by Masters and Johnson this pattern was evoked by touch and pressure stimuli applied to the genitalia. A more explicit title would have been "Physiological Changes Evoked in Men and Women by Genital Stimulation." In their preface the authors refer to the "massive state of ignorance" that exists with respect to the simplest details of sexual response. This lack of knowledge is not peculiar to the general public but is also characteristic of the medical profession. According to Masters and Johnson, medical schools have shown a "consistent refusal... to instruct in human sexual physiology." It was partly to provide the knowledge needed for such instruction that investigation of the details of this topic was begun in 1954. Since 1959 the strictly academic aspects of the work have been closely coordinated with a "clinical-research program" dealing with problems of sexual inadequacy. In the ensuing seven years some clinical patients have contributed to the empirical study, and conversely some of the research discoveries have proved useful in clinical therapy.

The complete sexual response actually consists of a temporal pattern, or "cycle," with four sequential phases termed excitement, plateau, orgasm and resolution. A single pattern is presented for the male since individual differences usually affect only the duration of the response. In contrast, three different patterns are diagrammed for the female, and even they "are simplifications of those most frequently observed and are only representative of the infinite variety in female sexual response." These "simplifications" were abstracted from a minimum of 7,500 complete cycles experienced by female subjects in the course of the investigation. In view of the reduced variability characterizing sexual response in men it was considered adequate to collect data on a minimum of 2,500 male cycles.

The book is organized in terms of the "response cycle," and separate chapters are devoted to the physiological manifestations that characterize each phase in women and in men. Separate treatment is given to the sexual response in 111 pregnant women, to the response of seven women with artificially constructed vaginas and to the effects of aging in 61 women and 39 men. A concluding section covers three disparate topics: male-female similarities, the role of muscular tone and individual protocols of four selected participants. The scope and general nature of the data reported can be indicated by a few selected examples, but it must be kept firmly in mind that the individuals observed were specially chosen for this study and therefore represent a highly selected population.

During the excitement phase, which begins soon after the initiation of stimulation, the nipples of the female breast become erect and the entire breast begins to increase in size as a result of increase in the local blood supply and retention of venous blood. During the plateau phase the pigmented skin immediately surrounding the nipple (the areola) becomes engorged. There is no pronounced change in the breast during orgasm, but in the resolution phase the nipples and areolae soon return to the preexcitement state and overall breast size declines gradually. Nipple erection occurs in some men, but for the most part there are no dramatic changes in the masculine breast as a result of genital stimulation.

In both sexes the excitement phase may be marked by development of a "sex flush": a measles-like rash that first appears along the midline of the chest, tends to spread laterally to cover the breasts and in extreme cases extends to the lower abdomen. This flush reaches a maximum late in the plateau phase and fades rapidly after orgasm. Early in the resolution phase some men and women exhibit a perspiration response involving the forehead, face and neck, and in some individuals larger areas of the body.

The rate of breathing increases in both sexes toward the end of the plateau phase and throughout the orgasmic phase, when it may reach a tempo of 40 per minute. Heart activity is accelerated at the same time, rates during orgasm of 110 to 180 beats per minute having been recorded. Systolic blood pressure is elevated, and increases from the resting state vary between 30 and 80 millimeters.

Masters and Johnson present detailed descriptions of the changes that take place in the reproductive organs during successive stages of the response cycle. The account of these changes in men is clear-cut and important, but the most striking, novel and clinically significant evidence pertains to the female.

During the excitement phase of the cycle the amount of blood reaching and retained by the outer lips of the vagina (labia majora) is markedly increased; as a result they become noticeably congested and swollen. At the same time these structures flatten out and pull apart, so that the inner lips (labia minora) are partially exposed. With the onset of the plateau phase the labia minora expand, thus increasing the diameter of the opening to the barrel of the vagina. As the plateau phase progresses, the coloration of the labia minora changes from pink to a bright red, and in women who have borne children the change progresses to a deep wine color. This color shift is described as a highly reliable indicator of "sexual tension" and a premonitory sign of orgasm. Once the color change has occurred a

woman is almost certain to attain orgasm if effective stimulation is continued. Conversely, the orgasmic phase never occurs unless the minor labia have undergone the pronounced change from pink to red. With the termination of orgasm and the beginning of the resolution phase the color of the inner labia fades rapidly, returning to the prestimulation base line within 10 to 15 seconds.

During the excitement phase the clitoris increases in size, but this effect is restricted to the outer end of the structure and is due entirely to the congestion of blood in it; it is not a genuine erection such as occurs in the penis. In the plateau phase the clitoris retracts—is withdrawn under the hood of skin directly above it. This organ exhibits no particular change with the occurrence of orgasm and returns to its normal resting position during the first five to 10 seconds of the resolution phase. The rapidity of the reaction is comparable to the postorgasmic loss of red coloration in the inner labia and to the initial stage of loss of erection in the male's penis. Some psychoanalytic theorists have laid considerable emphasis on supposed differences between orgasms produced by clitoral stimulation and those produced by vaginal stimulation. As far as strictly physiological measures are concerned no difference is detectable.

The earliest physiological sign of a woman's response to sexual stimulation is the appearance of droplets of a special lubricating fluid on the walls of the vagina. Beginning from 10 to 30 seconds after the onset of stimulation a "sweating" process develops, and as the numerous drops coalesce they form a smooth coating over the lining of the entire vaginal barrel. The source of this mucus-like material is not, as many authorities have believed, the cervix of the uterus; nor is it produced by the glands of Bartholin, which have been implicated by other writers. Instead the lubricating substance appears to be exuded by the vaginal lining, which contains no recognizable glandular elements.

As the excitement phase continues, the inner two-thirds of the vaginal barrel lengthens and expands. At this point the cervix, which normally projects downward into the posterior uterine cavity, is pulled upward, thus contributing to the increased size of the interior portion of the vagina. Changes taking place during the excitement phase are concentrated in the inner two-thirds of the vaginal barrel, but as the plateau phase is attained a very important modification occurs in the outer third. This portion of the organ becomes grossly engorged with venous blood, so that together with the already engorged inner labia it reduces the effective diameter of the previously distended opening by at least a third. The engorged outer third of the vagina is termed by Masters and Johnson the "orgasmic platform" because of its activity during the next phase of the response cycle.

The woman's orgasmic experience coincides with a series of powerful, localized contractions of the orgasmic platform. There may be as few as three to five such contractions or as many as 10 to 15; they occur at intervals of approximately .8 second. The psychological intensity of the orgasm is directly related to the number of vaginal spasms. It would appear a reasonable conclusion that the subjective experience depends in large measure on sensory feedback from this vaginal activity.

The resolution phase of the female response cycle is characterized by a rapid regression of the orgasmic platform and a more gradual collapse of the expanded inner two-thirds of the vaginal barrel. The latter change, as well as the return of the cervix from its elevated position, take at least three or four minutes following the termination of the orgasmic phase. One of the most noteworthy facts concerning the woman's resolution phase is that under appropriate conditions of stimulation the regressive changes of resolution can be halted at the level of the preorgasmic plateau, and continuing stimulation can in many individuals elicit one or more additional orgasms before sexual reactivity returns to the resting level. This observation is particularly important because no comparable phenomenon occurs in men. The resolution phase of the male cycle must proceed until the physiological conditions produced by stimulation have returned to the prestimulatory level. Only then is it possible, after a period of inactivity, to reinstate the excitement phase.

The details of the masculine response cycle, the effects of aging on different phases of the cycle in men and women and other topics covered in this book are as significant as the material summarized above, but that summary must suffice to establish the character of the findings reported in the book. There is much to be said about such matters as the constitution of the subject population and the methods used to obtain data.

At the beginning of the investigation 118 female and 27 male prostitutes were intensively interviewed; eight women and three men were selected for intensive anatomical and physiological study. None of the data collected from prostitutes were incorporated in the published report, but this pilot phase of the work provided a valuable opportunity for developing and standardizing the investigative techniques used later. Furthermore, the diverse experience of prostitutes provided useful information regarding a variety of methods for elevating and controlling sexual tensions.

The next step in the program was to enlist "a group of study subjects whose reproductive viscera could be related to baselines of anatomic normalcy and from whom long-range cooperation was possible." There was also the requirement "that there be a positive history of masturbatory and coital orgasmic experience before any study subject [was] accepted in the program." To achieve this end "volunteers were sought from relatively selected social, intellectual and economic backgrounds." The resulting study-subject population came primarily from the academic community associated with a large university-hospital complex and therefore included a high proportion of men and women from upper socioeconomic and intellectual levels. Other subjects were drawn into the study when they came to the clinic with problems of infertility or "sexual inadequacy." Finally, some subjects were recruited to meet specific project interests such as the geriatric program.

In sum, these various sources yielded 382 women and 312 men who actively participated in the study. The ranges in age were 18 to 78 for women and 21 to 89 for men, with the majority of individuals falling between 21 and 40. Included in the total were 276 married couples and 106 women and 36 men unmarried at the time of the study. The use of unmarried subjects "was abandoned as soon as it was established unequivocally that there is no basic difference in the anatomy and physiology of human sexual response regardless of the marital status of responding units." The men and women who participated in the study are described as "a small, arbitrarily selected segment of male and female society," and the number is regarded as too small to justify statistical presentation of the results.

Potential subjects were given a detailed interview; final selection depended on, among other things, the individual's willingness to participate, sexual

responsiveness and ability to communicate details of the sexual reaction. Thus reticent, inarticulate and sexually unresponsive men and women were weeded out, as were any individuals with anatomical abnormalities of the reproductive system. Having been selected as a subject, each person was "exposed to a controlled orientation program before assuming active participation." A detailed medical, social and sexual history was obtained by the two investigators working as a team. The subject was then shown the research setting and equipment, and the functions of the equipment were explained. In the next step "sexual activity first was encouraged in privacy in the research quarters and then continued with the investigative team present, until the study subjects were quite at ease in their artificial surroundings." Until they felt secure in their surroundings and confident of their ability to perform no recordings were made. There were 338 instances in which a subject was unable to respond fully to stimulation. These are negligible compared with the more than 10,000 instances in which complete response cycles occurred.

Sources of stimulation included manual and mechanical genital manipulation and natural and artificial coition. The last variant concerned only women and involved the use of special equipment consisting of a transparent plastic penis mechanically activated in such a way that the rate and depth of thrust could be initiated and controlled completely by the responding individual.

The investigators were aware of the possible effects of the experimental situation on the psychological attitudes and even the physiological reactions of their subjects. They write: "The investigation has underscored many examples of socially or culturally oriented situations that could influence human sexual response patterns. The possibility that the artificial atmosphere of the research laboratory might alter physiologic as well as psychologic sexual reaction patterns has been a constant concern.... In view of the artificial nature of the equipment, legitimate issue may be raised with the integrity of observed reaction patterns."

Instead of trying to overpower the reader with arguments calculated to negate criticism, the authors cite several relevant facts. All the subjects were able to perform sexually in the "research environment" and to regularly achieve orgasm in spite of the presence of the observer team and the employment of various measuring devices. It can be considered extremely unlikely that this would be true of a randomly selected population or even of one constituted entirely of volunteers, but it has already been mentioned that all the participants in the Masters and Johnson study were carefully selected from a much larger volunteer group. In addition, the initial period of orientation had a definite effect. Some subjects found themselves unresponsive during the first few sessions, but experience and greater familiarity with the setting brought progressive improvement until by their own account these men and women felt at ease and able to respond as frequently and intensely as they could in their own homes.

As far as the use of artificial stimulation for some women is concerned, the authors offer the following observation: "Suffice it to say that intravaginal physiologic response corresponds in every way with previously established reaction patterns observed and recorded during hundreds of cycles in response to automanipulation."

One passage in the book should be considered with special care because it raises fundamental questions that are certain to occur to every thoughtful reader and because it points out why no objective answers are as yet available.

"How does the sexuality of male and female study subjects differ from that of our general population, and are there significant differences? These biologic and behavioral questions are of major moment. Unfortunately, they are questions for which there are no answers, because there are no established norms for male and female sexuality in our society.... Without established norms of human sexuality, there is no scale with which to measure or evaluate the sexuality of the male and female study-subject population.... Comparisons may be drawn electively between the reported response patterns of this highly selected research population and the reader's personal experience or his concept of norms of human eroticism in today's society. From these prejudiced levels of comparison, there is no appeal at this time."

How is this extraordinary collection of evidence to be viewed, interpreted, evaluated? It appears to the reviewer that, in spite of the fact that the authors frequently use such terms as "psychologic" and "eroticism," this is clearly a research program belonging within and confined to the domain of experimental physiology. Throughout the presenta-

tion of results there are many references to "sexual tension" and its "release," but when we examine the primary data we are restricted to measurements of "superficial and/or deep vasocongestion" and "increased myotonia, both voluntary and involuntary in character," in other words, temporary changes in local blood supply and transitory muscle spasms.

Since Masters and Johnson explicitly avoid dealing with problems of motivation and of psychosexual interpretation, their approach is far removed from the realm of psychoanalysis (although their data should be of great interest to analysts and other psychiatrists). Because they make no attempt to describe a "statistically normal" population, and because they stress directly observed physical responses rather than the verbal reports of their subjects, their contribution belongs in a category different from the monumental interview studies carried out by Alfred C. Kinsey and his co-workers.

Viewed as a series of investigations into the functions of the reproductive system, the work reported in this book can be most meaningfully compared to the pioneering observations and experiments of William Beaumont, Walter B. Cannon and others in connection with the physiology of the digestive system. There are obvious similarities to Beaumont's brilliant discoveries concerning the movement of food through the stomach, which were facilitated by the opportunity to obtain samples directly through an opening in the stomach of one of his subjects. The present work is also comparable to Cannon's classic experiment demonstrating that the physical basis of hunger pangs is contraction of the stomach muscles, a demonstration made possible by recording the pressure changes in a small balloon that had been swallowed and then inflated to fill the stomach's interior. Cannon's procedure of comparing his subject's report of hunger pangs with the mechanical record of stomach activity is directly comparable to Masters and Johnson's correlations between the observed and recorded contractions of vaginal muscles and their subjects' report of sexual orgasm.

Testifying as an experimentalist with a long-standing professional interest in the scientific understanding of sexual behavior, the reviewer can confidently assert that Masters and Johnson have made a number of extremely original and significant contributions to the theoretical aspects of this very important field of investigation. Undoubtedly, however, most readers of their book will be more interested in the practical significance of the work reported in it. This aspect of their program is partially covered by chapter subdivisions entitled "Clinical Considerations." Under this heading in six chapters the authors deal specifically with the application of their findings to successful sexual adjustment in everyday life. A partial list of the questions raised and answered will indicate the scope of this material.

Women vary somewhat with respect to the size and positioning of the clitoris; does this have any influence on sexual responsiveness? What effects, if any, do individual differences in the size of the penis have on a man's ability to effectively stimulate his female partner? Do the movements of the cervix during female orgasm facilitate or impede the migration of the sperm the male deposits in the vagina? What are the physiological consequences of sexual intercouse during pregnancy and nursing? Are they harmful? What effects follow intercourse during menstruation? Does menopause alter the physiological response to sexual stimulation? What are the symptoms and causes of reduced sexual ability or impotence in men over 50, and can such symptoms be alleviated?

All of these will surely be accepted as questions of genuine importance and direct relevance to the achievement and maintenance of successful marital sexual relations. In addition to greatly increasing our factual knowledge concerning sexual physiology, Masters and Johnson have provided basic information that can be used to improve the lives of many men and women.

Short Reviews

MUSICAL INSTRUMENTS: A COMPREHENSIVE DICTIONARY, by Sibyl Marcuse. Doubleday & Company, Inc. ($17.50). Miss Marcuse tells us in her preface to this encyclopedic record of instruments from all over the world that there are more than 5,000 books and papers on non-European and folk instruments alone. Her fascinating book, with its thousands of entries, makes this seem altogether plausible. In greater or less detail, with the help of good pictures (but not, alas, enough of them), she describes different kinds of noisemaker, from "talking drums" (signaling devices) and bull-roarers to walking-stick violins, raft zithers, humming tops and pibgorns. Many of the names, par-

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ticularly the African ones, are magnificently sonorous and to our ears preposterous: the lumbamba is a small cylindrical drum of the Congo; the yurupuri, a wooden trumpet played in pairs by youths of the Amazon valley; the zuffolo, a whistle flute of Lombardy; the yan-ljin, a Tibetan instrument that is cousin to a dulcimer; the zurrumbera, a bull-roarer of northern Spain; the wani-guchi, a ritual gong hung at the entrance to Japanese shrines and struck by worshipers; the xaque-xaque, one of a number of different Brazilian rattles; the wurumbumba, a musical bow of the Congo and Angola; the bum-bum, a musical bow of Honduras; the wurstfagott, a "sausage bassoon"; the abilosen adar, a Basque horn sounded at night to frighten away wild animals; the abeng, a cane pipe of the Gabon Republic played through one nostril; the hā, a musical bow of the African bushman; the ehecacozcatl, a shell trumpet of the pre-Columbian Toltec culture; the eunuch flute, an instrument resembling the kazoo (which is also called the bazoo); the ndingi, a wooden cowbell of the Congo; the kshudrā katyayana vīnā, a small stringed instrument of Bengal with a calabash body, an almost circular soundboard and 18 steel strings.

A History of Epidemics in Great Britain, by Charles Creighton. Barnes & Noble, Inc. ($50). This two-volume work is a reprint of a noted scholarly account of infectious diseases in Britain from the middle of the seventh century, when the famine pestilences afflicted the Anglo-Saxons, to the end of the 19th century. To this edition have been added an essay by D. E. C. Eversley on epidemiology, which critically evaluates Creighton's book, and a long introduction by the medical historian E. Ashworth Underwood, which describes Creighton's life (he died in his 80th year in 1927) and also makes a careful assessment of his *History*. Creighton was a strange, quirky man with all kinds of prejudices and blind spots, among them a disbelief in the pathogenic properties of bacteria, a strong skepticism about the efficacy of vaccination and an almost paranoid hostility to Edward Jenner, whom he regarded as a thoroughgoing knave and faker. In view of these prepossessions it may be hard to believe that he could have written a useful, let alone a great, book on epidemics, and it is to these doubts that Underwood, a staunch admirer of Creighton's, addresses a good part of his introductory essay, attempting to show that Creighton was not as pigheadedly biased or as medically ignorant as many of his contemporary critics made him out to be and as some of his own writings seem to indicate. Underwood overstates his case, but he makes it clear that Creighton's book deserves its high reputation. He was a qualified physician, a skilled physiologist, a first-rate historian and a gifted writer. These strengths outweighed his prejudices. Although the history is entirely misleading when it touches on questions of pathology and vaccination, on balance it is a brilliant survey that reflects an enormous amount of research and a pioneering work in relating epidemic disease to social circumstances. The book has long been out of print and almost impossible to find; to have it once more available, even though the price is steep, is a boon to historians and medical specialists.

The Penguin Dictionary of Saints, by Donald Attwater. Penguin Books Inc ($1.45). The key word, we are told, that distinguishes the saint is not that he had visions or performed miracles or was canonized but that he had "heroism," the saint being the man or woman who gives himself or herself to God heroically. The entries in this interesting handbook of hagiology run from Aaron and Julius (put to death at Caerleon in Monmouthshire about the middle of the third century) and Abo (a Moslem perfumer who embraced Christianity and was beheaded as a renegade from Islam) to Zeta (a domestic servant born near Lucca in the 13th century who was looked on as the patroness of domestic servants and who after a life of devoutness and generosity, particularly to the sick and to prisoners in jail, died peacefully in 1278).

The Work of Frank Lloyd Wright, edited by Th. Wijdeveld. Horizon Press ($42.50). A reprint of the celebrated "Wendingen edition" first published in 1926, this book contains several hundred photographs of structures Frank Lloyd Wright built or planned, detailed architectural drawings, and articles by Wright and leading European architects and American critics. The Wendingen volume, of which this is essentially a facsimile, was produced according to Wright's specifications. It is a curious piece of bookmaking and typography. For example, it consists entirely of double-fold pages printed on one side of each sheet, which makes the volume thicker than it needs to be and clumsy to handle when turning the pages. The advantage Wright presumably envisioned from this design was that the pictorial matter would reproduce better because only one side of the sheet would be used. Whatever the quality of the reproductions in the original edition may have been, as rendered in this volume they are quite uneven; not a few of the illustrations are grayish, mottled and unattractive. The typography is heavy and not pleasing to the eye, although it fits the old-fashioned flavor of the book as a whole. Altogether the physical appearance of the book is reminiscent of the contradictions of the master's work: ahead of its time and brilliant but in some respects quite dated; imaginative and bold but in certain of its features unnecessarily original.

A Prophet in Two Countries, by Nancy Arms. Pergamon Press ($2.45). A brief life of Sir Francis Simon, a physicist who gained an early reputation in Germany for his work in low-temperature physics and considerably enhanced it in Britain, to which he migrated in 1933. He contributed also to the development of atomic energy and to the advancement of technological education in Britain.

The Theory of the Photographic Process, edited by T. H. James. The Macmillan Company ($22.50). The third edition of this standard reference work (the first and second editions were edited by the late C. E. Kenneth Mees) has been completely rewritten and includes a large amount of new material. Unfortunately the revisions have made it necessary to eliminate sections of the earlier editions that contained valuable historical information.

Climates of the U.S.S.R., by A. A. Borisov. Aldine Publishing Company ($10). After a brief history of the study of climates of the U.S.S.R., this book gives detailed descriptions of the regional climates of the vast continental expanse that covers a seventh of the land surface of the earth. Useful for climatologists, meteorologists, geographers, botanists, ecologists and other specialists on the U.S.S.R., eastern Europe and Asia. Numerous maps.

In Gardens of Hawaii, by Marie C. Neal. Bernice P. Bishop Museum ($15). This volume of more than 900 pages, a revision of a work first published in 1928 and reissued in an

enlarged version in 1948, provides detailed information about 3,000 species of ornamental and food plants, weeds and characteristic native and endemic plants found on the lush islands of Hawaii. One cannot help regretting—although the cost might have been prohibitive—the failure to include at least a few color plates of what are obviously some of the most beautiful plants and flowers in the world.

Notes

POLITICAL PARTIES, by Robert Michels. The Free Press ($2.45). A reprint in inexpensive form of a highly regarded study concerned with the oligarchic tendencies of modern democracy.

THE COLLECTED SCIENTIFIC PAPERS OF PAUL A. SAMUELSON, edited by Joseph E. Stiglitz. The M.I.T. Press ($25). These two volumes contain most of the contributions of a distinguished American theorist to the study of mathematical economics up to 1964.

THE OXFORD ECONOMIC ATLAS OF THE WORLD, prepared by the Economist Intelligence Unit and the Cartographic Department of the Clarendon Press. Oxford University Press ($15). A revised third edition of this reference compendium that contains a large number of world commodity maps and a statistical index with information ranging from the cereal production of Aden to the machinery imports of Yugoslavia.

THE COMPLEAT STRATEGYST, by J. D. Williams. McGraw-Hill Book Company ($6.95). A revised edition, completed a short time before the author's death, of a widely used primer on the theory of games of strategy, the principal revision consisting of a chapter on the pivot method, which is useful in solving matrix games.

ECONOMIC GROWTH AND STRUCTURE, by Simon Kuznets. W. W. Norton & Company, Inc. ($7.50). Selected essays by a distinguished American economist known for his contributions to the concept of gross national product and for other quantitative studies of economic level and growth.

ANCIENTS AND MODERNS, by Richard Foster Jones. University of California Press ($1.95). A reprint of Jones's able study of the rise of the scientific movement in 17th-century England. Paperbound.

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