SCIENTIFIC AMERICAN

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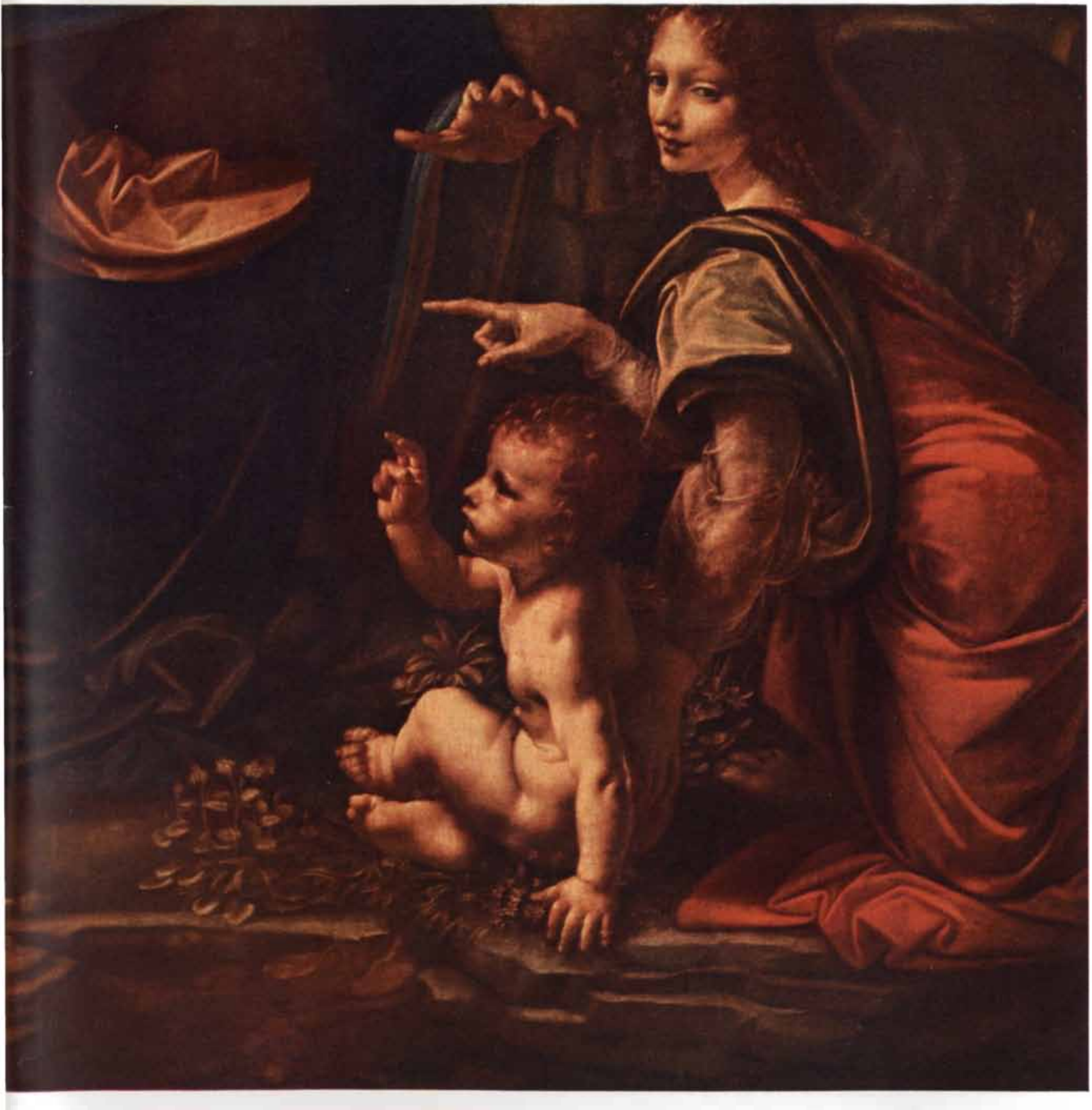
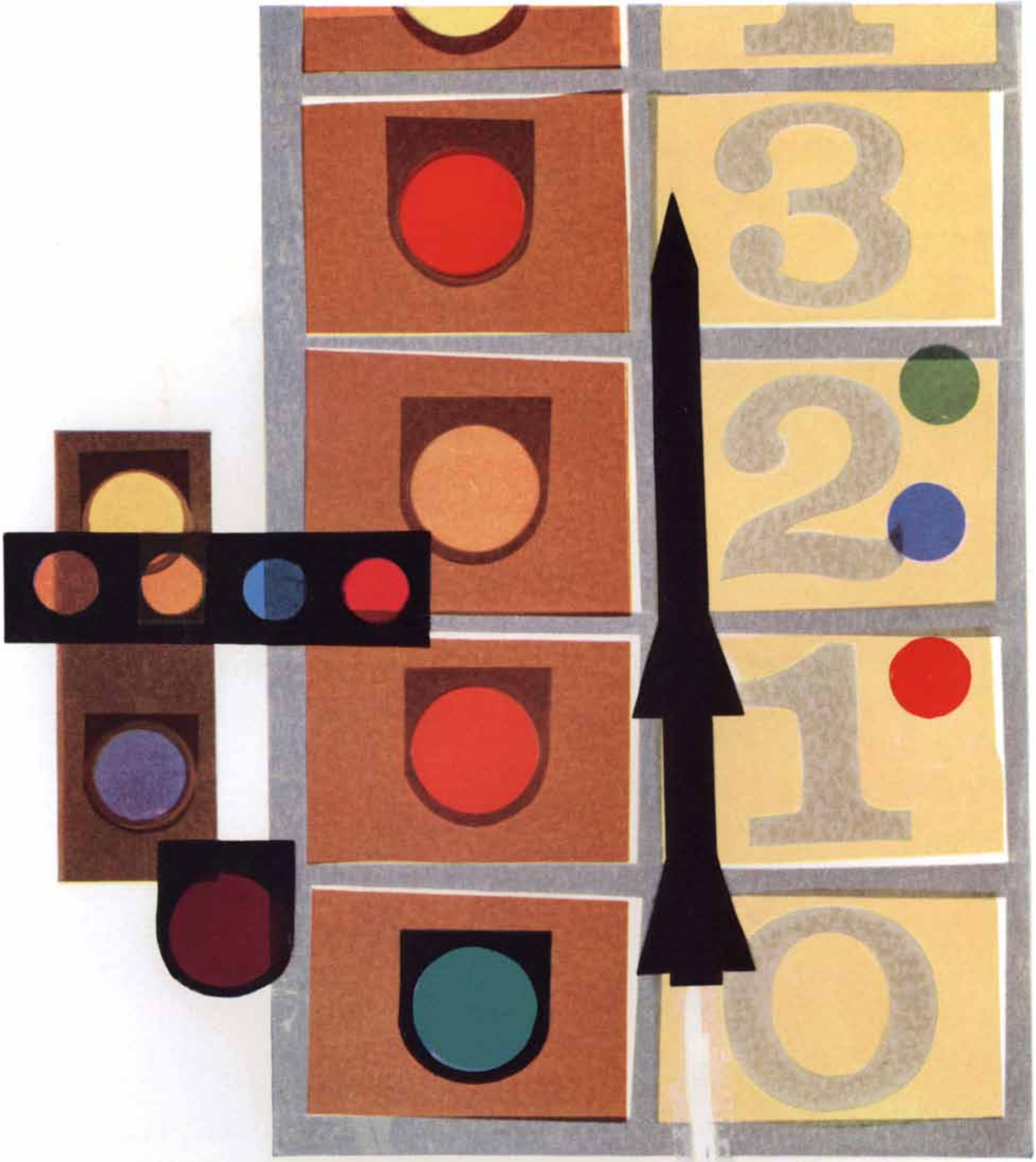


INNOVATION IN SCIENCE

FIFTY CENTS

September 1958



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Thorstein Veblen...on the place of science

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—The Place of Science in Modern Civilization, 1906

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Established 1845 **SCIENTIFIC AMERICAN** September, 1958 Volume 199 Number 3

ARTICLES

DEPARTMENTS

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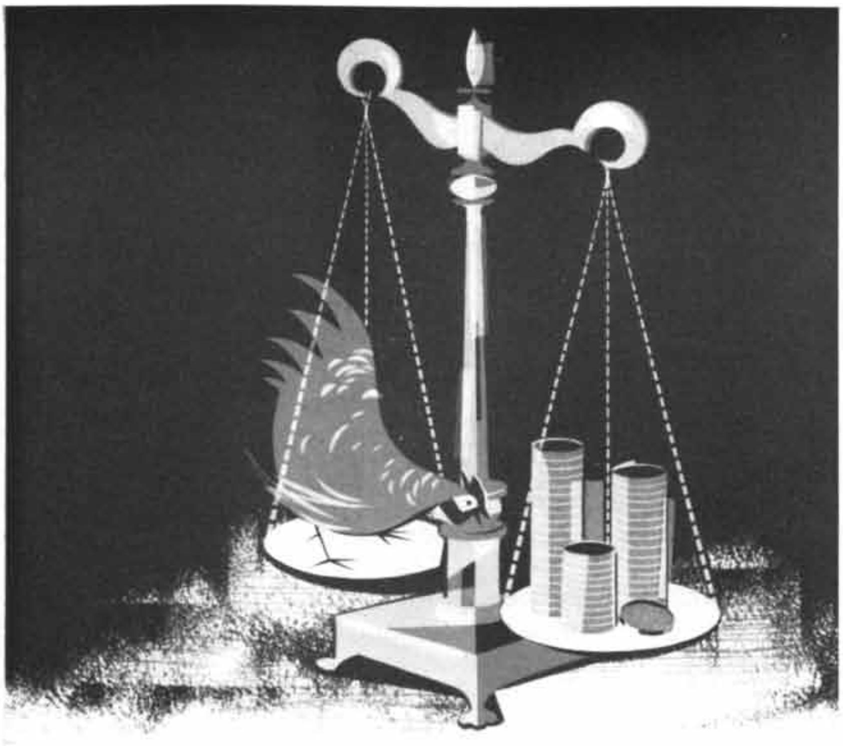

THE COVER

On the cover of this issue of SCIENTIFIC AMERICAN, which is solely concerned with the subject of innovation in science, is a detail from Leonardo da Vinci's masterpiece *Madonna of the Rocks.* In center is the Infant Jesus; at left, part of the figure of the Madonna; at right, an angel. As J. Bronowski says in the article which introduces this issue (*page 58*), the Scientific Revolution was an integral part of the Renaissance. The loving care with which Leonardo rendered natural detail had a deep kinship with the scientist's insistence that the details of nature were significant. The painting is in the Louvre, where it was photographed for this magazine by Inge Morath of Magnum Photos.

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1892—Original Strowger Switch, basis of the dial telephone and source of thousands of advances in many industries.

1958—This direct descendant today is activating many mechanical marvels of modern life, both in and outside the telephone field.

Where did automation begin?

It is hard to believe—but automation began with the crude contraption pictured on the left.

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Automation might be defined as machines run by other machines through automatic controls.

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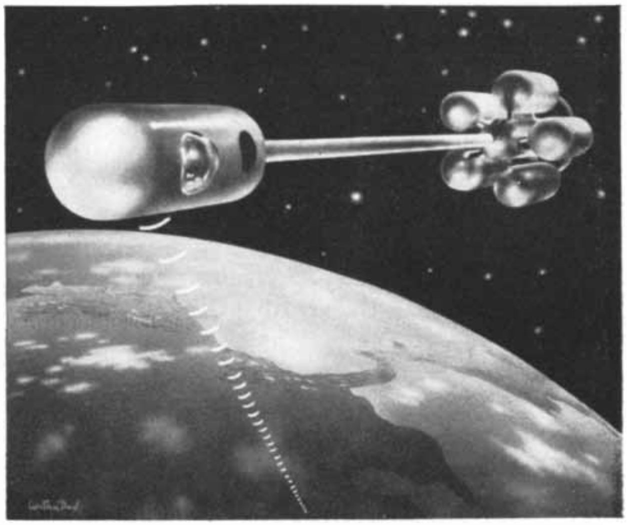

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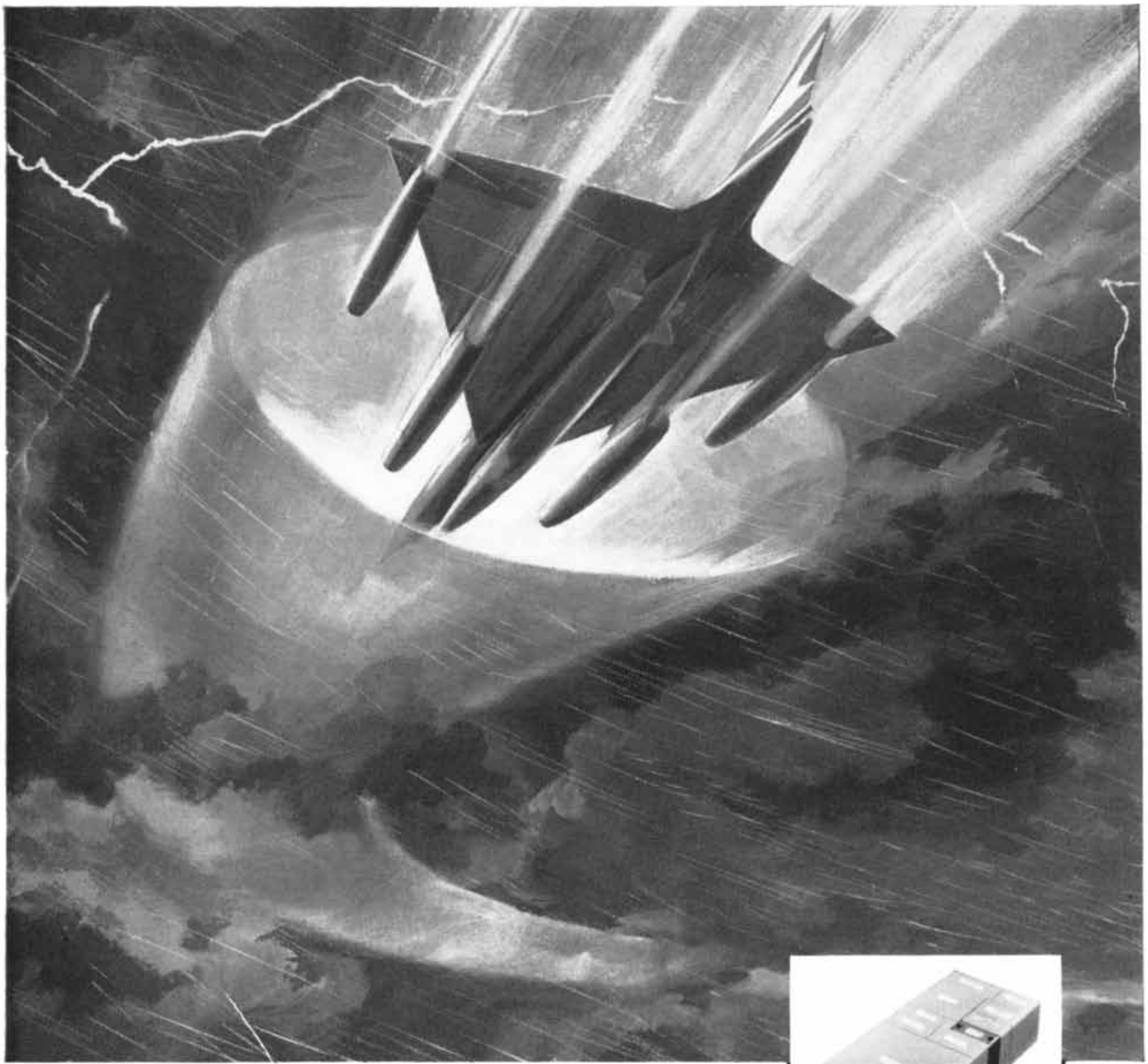

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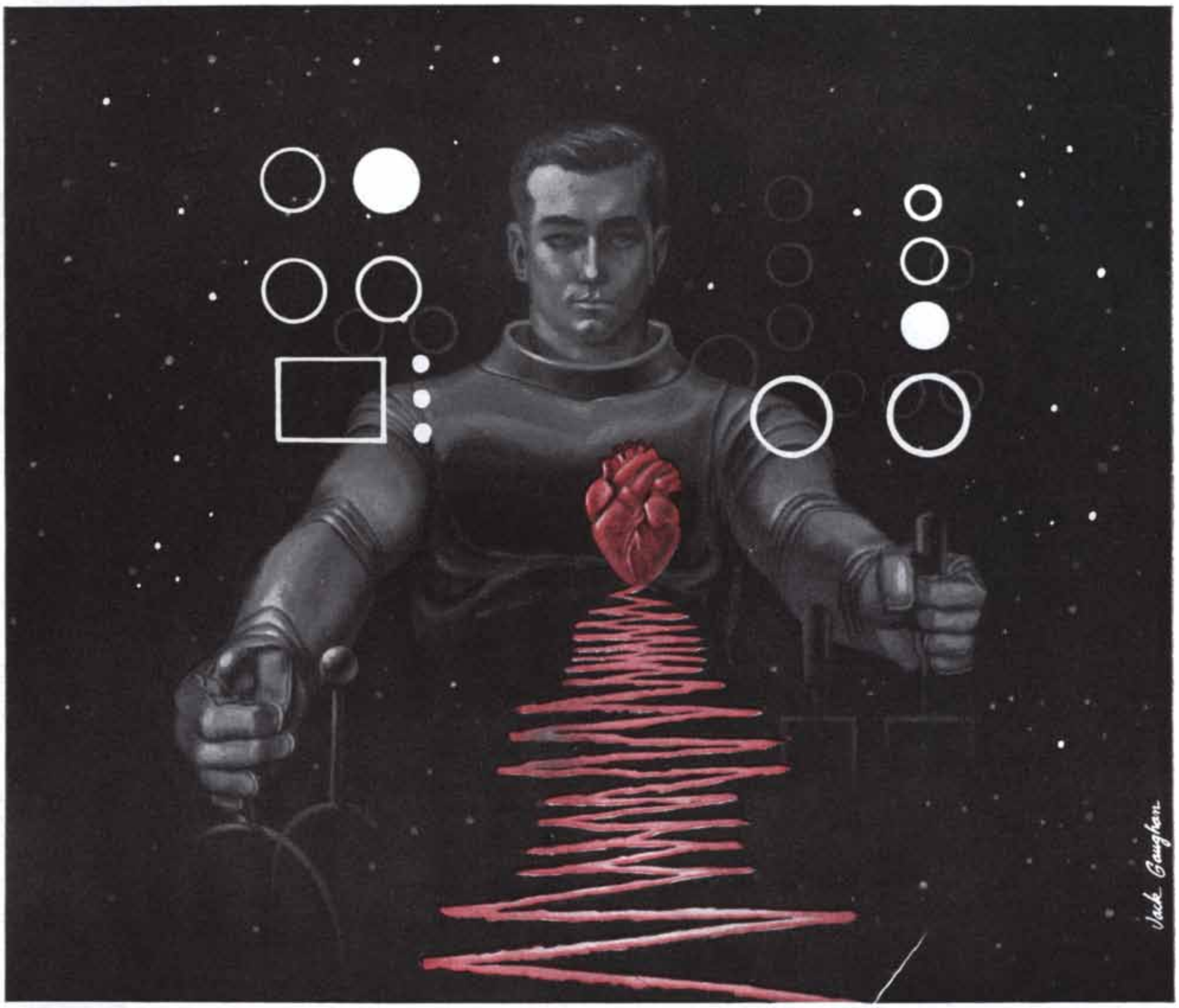
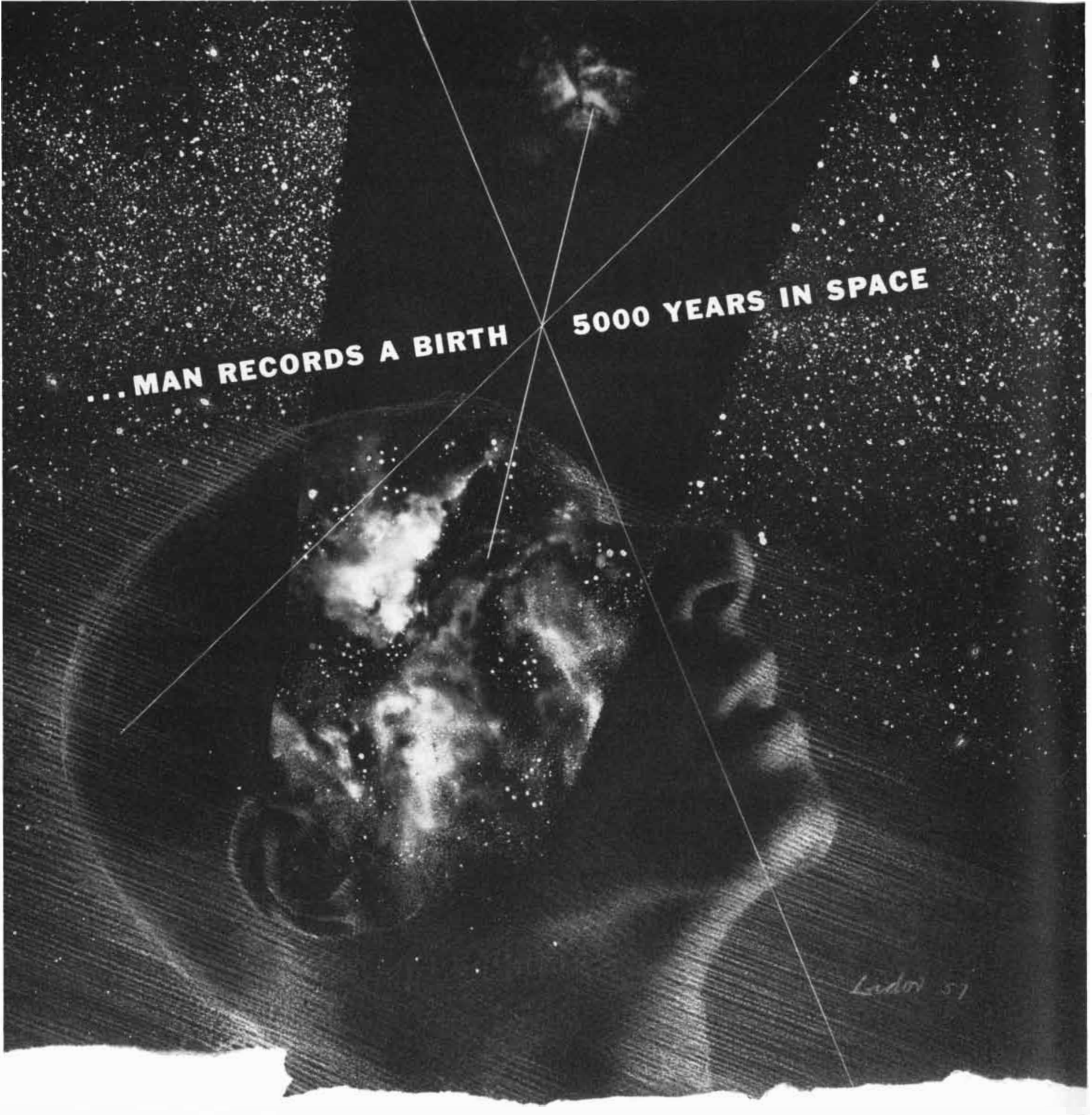

Jack Gaughan



Five thousand light years away, in one of the spiral arms of our galaxy, clouds of cosmic dust are condensing to form new stars. Through optics of the great Baker-Schmidt ADH telescope, designed and built by Perkin-Elmer, astronomers have been able to obtain the first photographic proof of the process by which these stars are being born.

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VITON

TRADEMARK

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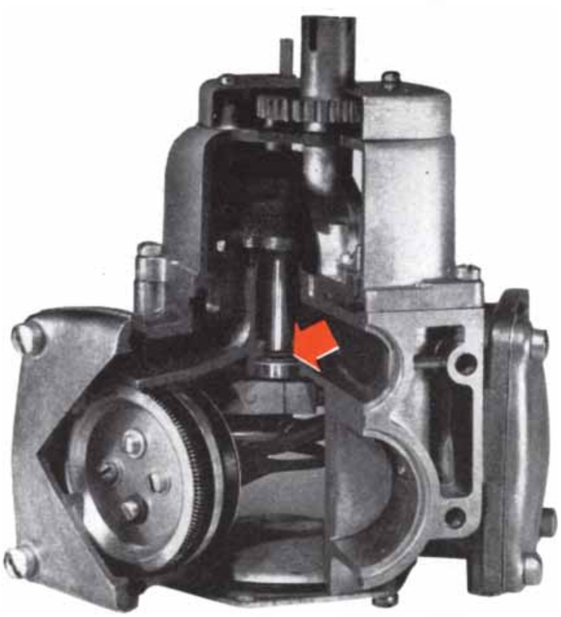

In this meter for gasoline pumps, the O-ring seal on the output shaft is exposed to aromatic components in high octane gasolines. A noted oil-resistant synthetic rubber was first used for the O-ring. It became swollen, however, and caused metering difficulties. When an O-ring of VITON was substituted, the trouble was eliminated.

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VITON is easy to process; components can therefore be made to close tolerances. This new synthetic rubber has already proved successful in precision seals (such as the one shown here), diaphragms, coated fabric and linings. To learn more about VITON, see your rubber supplier or send for our new booklet. E. I. du Pont de Nemours & Co. (Inc.), Elastomer Chemicals Dept. SA-9, Wilmington 98, Del.

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VITON vulcanizates were immersed for 7 days in a wide variety of corrosive fluids. These data show the effect of representative fluids upon the properties shown.	Tensile Strength Retained %	Hardness Change Points	Volume Increase %
Carbon tetrachloride, 75° F.	85	+ 2	1.3
Aniline, 75° F.	100	− 1	3
Tricresyl phosphate, 300° F.	93	−11	24
JP-5 petroleum aircraft fuel, 75° F.	100	+ 1	0.4
Turbo oil No. 15 diester lubricant (Mil-L-7808), 400° F.	60	− 6	19.6
Transmission fluid, Type A, 212° F.	77	− 1	1.5
OS-45 silicate ester, 400° F.	62	− 3	11.1
Sodium hydroxide, 46.5%, 75° F.	75	+ 1	2.1
Hydrofluoric acid, 48%, 75° F.	98	+ 2	4.8
Sulfuric acid, fuming, 75° F.	58	− 4	4.8

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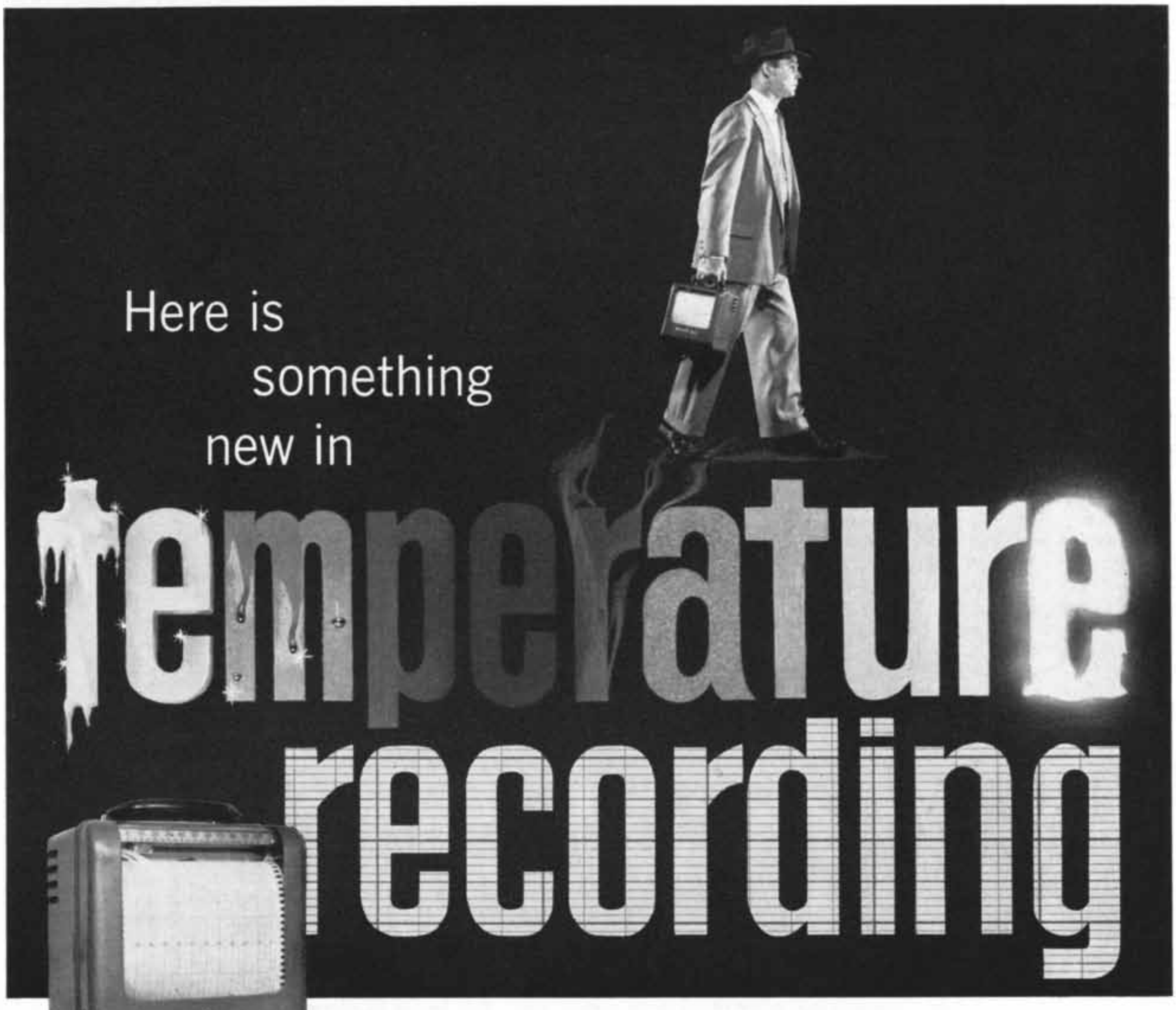
...through Chemistry



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ADDITIONAL FEATURES

- Automatic reference junction compensation eliminates need for any external temperature reference.
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- Reliable servo operated null-balance potentiometer principle as used on large panel instruments.
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LETTERS

Sirs:

In an article which appeared in the June issue of *Scientific American*, the German cipher expert T. S. Barthel claims to have deciphered the carved symbols on the ceremonial wooden tablets found in the hands of the 19th-century population on Easter Island. He says that the texts are mainly religious and ritualistic, that the stone statues are hardly mentioned, and that the tablets "contain almost no mention of historical events on Easter Island." Still his own conclusion is that: "The story told by the tablets now leaves no doubt that the settlers came from somewhere in the heart of Polynesia—perhaps Raiatea. . . ." He also says, "Archaeologists are reasonably sure that this immigration took place in the 14th or 15th century."

There is nothing new to anthropologists in this conclusion, but the author claims that it "seems to disprove conclusively the recent theory of Thor Heyerdahl that the Easter Islanders came from Peru."

It is only the latter statement which merits a comment by the present writer. One need not be a cipher expert to perceive that the validity of his claim of disproving my theory is based on two fundamental conditions: (a) that my theory really is that the 14th-15th-century Easter Islanders came from Peru and not, as he concludes, from Polynesia proper; (b) that nobody else had settled Easter Island *before* the said 14th and 15th-century Polynesians arrived.

I am able to prove that both these stipulations are wrong. In the monograph on my Polynesian migration theory (*American Indians in the Pacific: The Theory behind the Kon-Tiki Expedition;* Rand McNally, 1952) I make it very clear that I maintain that the 14th-15th-century migrants to Easter Island came from Polynesia proper, and that they had nothing whatsoever to do with the peoples or cultures of Peru. Like Dr. Barthel, I fully agree with other scientists on this point. However, the question under dispute was whether or not another culture had *preceded* this known Polynesian epoch on Easter Island. The general opinion was that the 14th-15th-century Polynesians found the island uninhabited, whereas I maintained that another people—from Peru—had discovered and settled Easter Island about a thousand years earlier.

These discussions concerning a cultural substratum on Easter Island were, until recently, highly theoretical for lack of archaeological information. Strange as it may seem, no archaeological dating and no attempt at systematic excavation had ever been attempted among the spectacular remains on Easter Island until the present writer brought a team of professional archaeologists to the island in 1955-56. Extensive excavations in various parts of the island were then organized by E. N. Ferdon, archaeologist of the Museum of New Mexico, William Mulloy of the University of Wyoming, Carlyle S. Smith of the University of Kansas, and A. Skjoelsvold, archaeologist of the University of Oslo. Our expedition discovered for the first time that two distinct culture strata preceded the commencement of the final epoch of civil wars and decadence on the island. It was disclosed that the construction of the local stone statues and Inca-like megalithic masonry antedated the final Polynesian arrival by many centuries. In fact, carbon datings revealed that by 380 A.D. ± 100 years large-scale constructions were already achieved by the earliest settlers of the island. This goes to prove that a thousand years or more before the Polynesians arrived to conquer Easter Island another people had settled as the original discoverers, and it was they who left for posterity the giant stone constructions which have made the little island so renowned.

As Barthel admits in a letter to the

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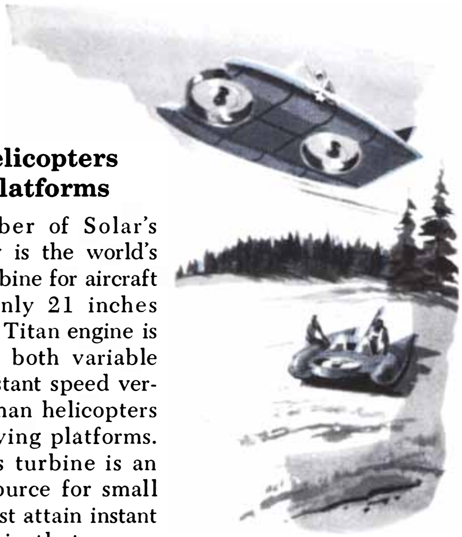

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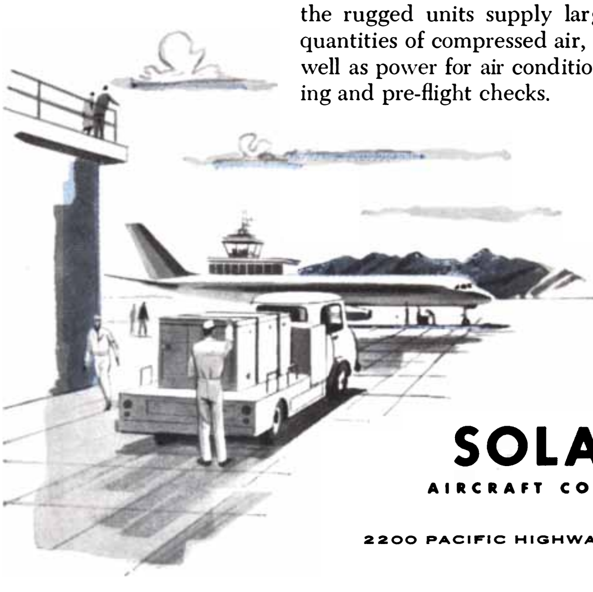

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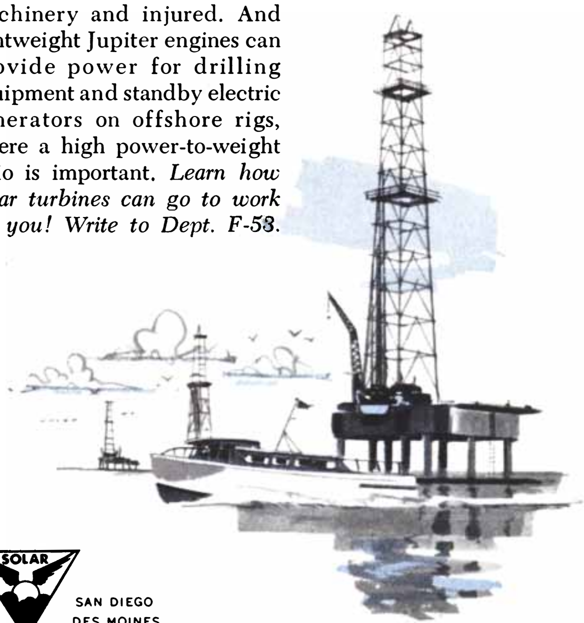

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DES MOINES

2200 PACIFIC HIGHWAY, SAN DIEGO 12, CALIFORNIA present writer dated June 13, his own view was based on the assumption that Easter Island was unpopulated when the Polynesians arrived in the 14th-15th century, and the seeming discrepancies in migratory views were to be accounted for as references to two utterly different time levels in the aboriginal history of Easter Island.

THOR HEYERDAHL

Oslo, Norway

Sirs:

Thor Heyerdahl's comment demonstrates that Easter Island's past is a highly complex problem. A whole series of specialized approaches will be necessary before a final elucidation of the island's early history can be given. So we are not engaged in a contest of "digging *v.* deciphering."

However, a scientific criticism should be limited to the subject under discussion; in this case, to pertinent arguments against my solutions of the Easter Island writings. Heyerdahl refers to his monograph *American Indians in the Pacific*. In this monograph he postulated a connection between the "talking boards" of Easter Island and a highly debatable script in the Andean area as evidence for his migration theory. I am especially gratified now to see that he does not, in the light of my results, repeat his former claims.

Turning to the field of digging, let me answer not as a decipherer but as an anthropologist. Unquestionably the future publication of the results obtained by the Norwegian archaeological expedition of 1955-56 will provoke further discussion on the nature of the early cultural substratum on Easter Island. Actually, during my own fieldwork subsequent to Heyerdahl's visit, I discovered evidence in native lore pointing also toward a pre-Hotumatua population. A carefully balanced picture, however, should not omit the following well-established facts:

The main wave of immigrants, under their chief Hotomatua (approximately 14th-15th century), not only brought the writing system from Polynesia, but also language (there is no un-Austronesian substratum in the vocabulary, grammar or place-names of Easter Island!), plus social organization and ideological patterns, the vital ecological base (from tubers and bananas to fowl), and technology, including the art of stone sculptures. The impact of this immigration cannot be described as "the final epoch of civil wars and decadence"; on the contrary, it shaped the gigantic stone busts of Rano Raraku and built the ceremonial and funeral monuments along the coastline.

Possibly this stratified society did not come first. But the ethnic affinity and the cultural level of its predecessors are still unknown factors. Only additional research can show whether such *earlier* explorers of the southeast Pacific reached Easter Island from the east or from the west.

T. S. BARTHEL

Hamburg, Germany

Sirs:

In the article "The Action of Insulin" by Rachmiel Levine and M. S. Goldstein [SCIENTIFIC AMERICAN, May] the thesis was advanced that "all of the enzyme systems involved in conversion of sugar to lactic acid were ruled out as targets of insulin's action. . . . Biochemists could find no place for it to act." These quotations run contrary to scores of well-known experimental biochemical articles and critical reviews of the past two decades. In furtherance of a more balanced presentation of existing knowledge as to how and where insulin may act chemically, we wish to call the attention of readers of *Scientific American* to certain highly pertinent facts, none of which were mentioned in the article cited, and all of which militate against the concluding inference, unsupported by direct evidence, that "insulin attaches itself to some specific point on the surface of the cell. . . . Insulin has now been identified as a gatekeeper."

For some years we have been investigating the unique characteristics of insulin:anti-insulin hormonal regulation of glucose utilization in intact cells of both normal and malignant mammalian tissues. These characteristics include stimulation of glucose utilization by exogenous insulin, inhibition by anti-insulins (*e.g.*, sex and adrenal steroids), high-temperature coefficients (two- to five-fold per 10 degrees centigrade), insulin-reversible lowering of fermentation by prior temperature stress, differential rates of utilization of glucose and fructose, and galactose inhibition of glucose and fructose utilization.

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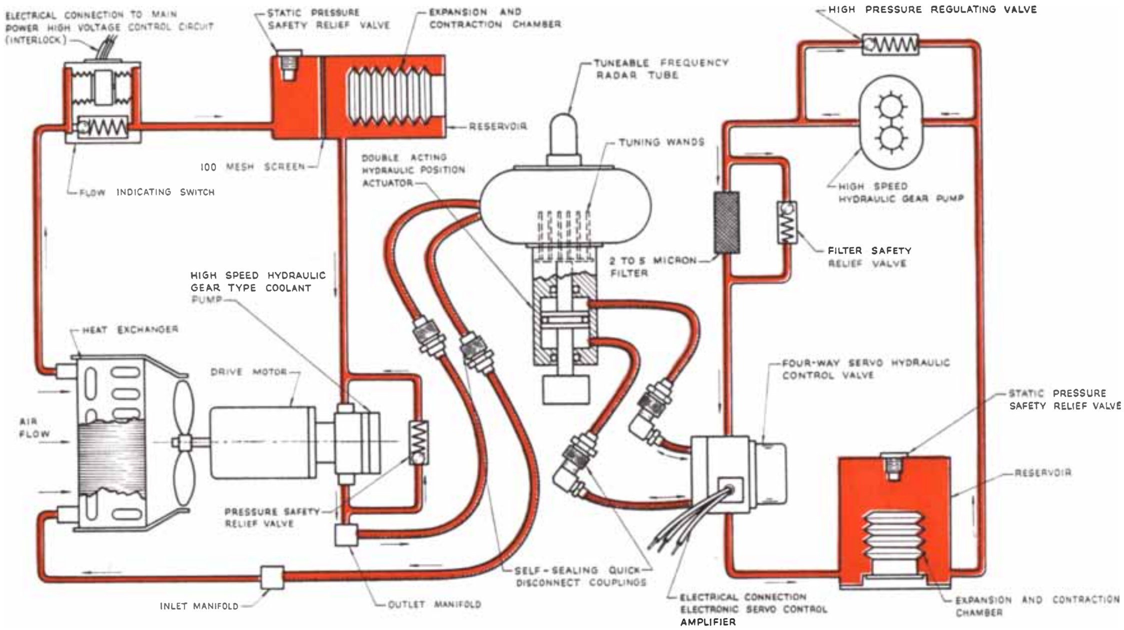


Equipment diagram: courtesy Eastern Industries, Inc., Hamden, Conn.

This new multipurpose fluid system developed by Eastern Industries, Inc., may be used for missile guidance or fire control systems and electronic countermeasures equipment. It is composed of a liquid heat-dissipating unit on the left (Model E/HT 200) and a hydraulic tuning unit on the right (Model E/HS 100). Sealed in both units, Coolanol 45 cools the magnetron tube, actuates the mechanical tuning mechanism.

LIQUID cooling with Coolanol 45 brings new performance concepts to electronic equipment by allowing engineers to build more and more power into less and less space. The liquid flows around tube units to dissipate the great heat created by miniaturization. As a result, aircraft electronic systems can operate at altitudes where air cooling is impractical . . . missiles have increased accuracy over their effective striking ranges.

Cooling and hydraulic units can be designed into packages smaller than a portable typewriter. Every pound saved, every watt of increased power contributes to a greater effective range.

Coolanol 45 operates efficiently from -65° F. to 400° F.—a remarkable temperature variation for a liquid. No longer held to the maximum temperature water imposes, engineers can design even "hotter" equipment. Coolanol 45 is one of many Monsanto fluids you see establishing new performance concepts for guidance and control systems, radar and countermeasures units and nuclear reactors.

Fifty years of fluid research places Monsanto first in the synthetic fluid field. Aside from the 25 commercial fluids now available, Monsanto has a number of base stocks that allow modification. Whatever your requirements, consult Monsanto first if you have a fluid problem.

WHEN YOU NEED A SYNTHETIC FLUID, COME TO MONSANTO—
Creator of Fluids for the Future

Send for more information

MONSANTO FLUIDS

Coolant/dielectrics for electronic equipment
Hydraulic fluids in electromechanical systems
Lubricants for high-temperature operations
Dielectrics for transformers and capacitors
Coolant/moderators for nuclear power reactors
Modifiers for special fluid properties
Heat-transfer fluids for temperature control
Coolanol 45: Monsanto T.M. (formerly OS-45)

Monsanto

MONSANTO CHEMICAL COMPANY
Organic Chemicals Division
Dept. SA-4, St. Louis 24, Missouri

Please send literature:
- ☐ Coolanol 45 Technical Bulletin
- ☐ "Fluids . . . For Specialized Engineering" (Technical Data)

Name........................*Title*.............
Company....................................
Address.....................................
City......................*Zone*.....*State*.........

anti-insulin effects on glucose metabolism with *cell-free* extracts of tumors. Paul Hochstein, working in our laboratory, has shown that insulin and anti-insulin actions occur in the cell mitochondria, but not in active solubilized systems derived by leaching from damaged mitochondria (*Science*, Vol. 125, No. 496; 1957). With our co-worker George Hobby we find the same mitochondrial localization of the other characteristics listed. That the hexokinase reaction on the mitochondria is the primary site of chemical action of insulin is demonstrated by a complete by-passing and elimination of insulin:anti-insulin action upon addition of the product of the hexokinase reaction, glucose-6-phosphate, instead of the normal substrate of the hexokinase reaction, glucose. These findings can fully account for the well-known actions of insulin and anti-insulins on permeation of sugars and related substances, since it is a long-established biological phenomenon that uptake of a wide variety of molecules and ions by living cells, plant or animal, is strongly and differentially regulated by the *internal* metabolism, involving either fermentation or oxidation energy. Increased permeation of nonutilizable sugars, induced by insulin in the absence of exogenously added glucose, has never been accompanied by adequate proof of the absence of hexokinase substrates either within the cell or as an impurity in the nonutilizable sugar employed. Drs. Levine and Goldstein note that four sugars which in the presence of insulin will enter cells have an identical aspect of structural formula. They failed to point out, however, that the uptake and utilization of fructose, which does not possess the same aspect of structure, has been shown in several laboratories, including our own, to be markedly stimulated by exogenously added insulin, under various suitable conditions.

The foregoing "bird-in-hand" evidence that the primary chemical site of insulin action is at the hexokinase reaction *localized in the mitochondria* confirms and notably extends the original findings over a decade ago of Winston H. Price, S. P. Colowick and their co-workers of the group led by Carl and Gerty Cori at Washington University in Saint Louis, who reported that insulin effects could at times be obtained with cell-free homogenates of certain tissues, and that the stimulating action of insulin was in the nature of a counteraction of pituitary and adrenal hormones that inhibit the hexokinase reaction. It should further be noted that accumulating evidence from many laboratories suggests that insulin:anti-insulin regulation of glucose metabolism is by no means limited to muscular and connective tissues, but is characteristic of a wide range of malignant and normal tissues, including adipose tissue, mouse skin, liver and even kidney and brain. The cell-membrane hypothesis should not derive its support from neglect of available data and a negative approach to the "problem of how to analyze the (living) system chemically without taking it apart."

MARK WOODS

DEAN BURK

National Cancer Institute
National Institutes of Health
Bethesda, Md.

Sirs:

We appreciate the courtesy shown by Drs. Woods and Burk in sending us their letter which concerns our article on insulin action. We were, of course, aware of their work in the field and their interpretation of the data. In addition, the recent literature on lipogenesis and other liver effects of insulin has also been interpreted to mean that insulin may act on certain intracellular systems which may or may not have anything to do with membrane transport of sugars.

It is, however, impossible (it seems to us) to present all such data and discuss them adequately in a nontechnical article. One can obtain an almost infinite variety of insulin effects, both *in vivo* and *in vitro*, without knowing which of these effects obtain physiologically in the intact animal. We were only concerned with putting down our present viewpoint, namely that the action of insulin in the intact animal is most probably due to its facilitation of glucose transport across cell membranes of certain tissues. This action, confirmed in many laboratories, seems to explain most of the observed insulin effects in the living animal. It does not account for other data obtained in the perfused liver, or on *in vitro* tissues, etc. Perhaps more work like that of Drs. Woods and Burk will in time reconcile these seemingly diverse results.

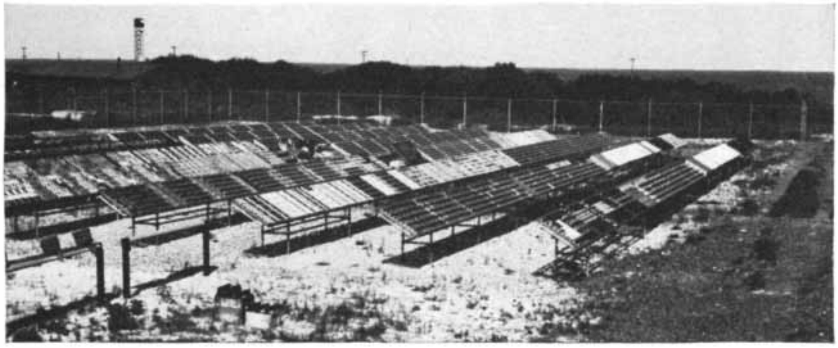
RACHMIEL LEVINE

MAURICE S. GOLDSTEIN

Michael Reese Hospital
Chicago, Ill.

THE FACTS ABOUT MAGNESIUM AND CORROSION

Once this basic law of nature is recognized, proper design and protective measures permit excellent service life.



EXPOSURE TESTS on many assembly protection methods and new finishing developments are constantly in progress on these seaside test racks (International Nickel Test Station, Kure Beach).

MAGNESIUM, the world's lightest structural metal, has a successful history of application in aircraft, missiles, military ground equipment, portable tools, and materials handling equipment.

Yet some designers and production men hesitate to use magnesium because they have heard that it "corrodes." What are the facts about this important matter?

It's quite true that magnesium corrodes under certain environmental conditions—as does every other basic structural metal. Each has its own distinct corrosion "personality" in the presence of corrosive elements. For example, magnesium has excellent resistance to corrosion in strongly alkaline surroundings and readily becomes subject to attack under acidic conditions. Conversely, aluminum is resistant to many acids but suffers attack in strongly alkaline environments.

Approximately 95% of all corrosion problems with magnesium stem from galvanic corrosion. This type of corrosion is caused by differences in the electrical potential of dissimilar metals coupled together and immersed in an electrolyte. By understanding the source of corrosion currents, metals and their environments can be controlled so as to minimize or eliminate these sources. Techniques of joining magnesium to other metals have been developed which effectively overcome the conditions causing galvanic corrosion.

NIKE GROUND GUIDANCE—Large magnesium assemblies are easily and effectively protected by standard finishing methods.

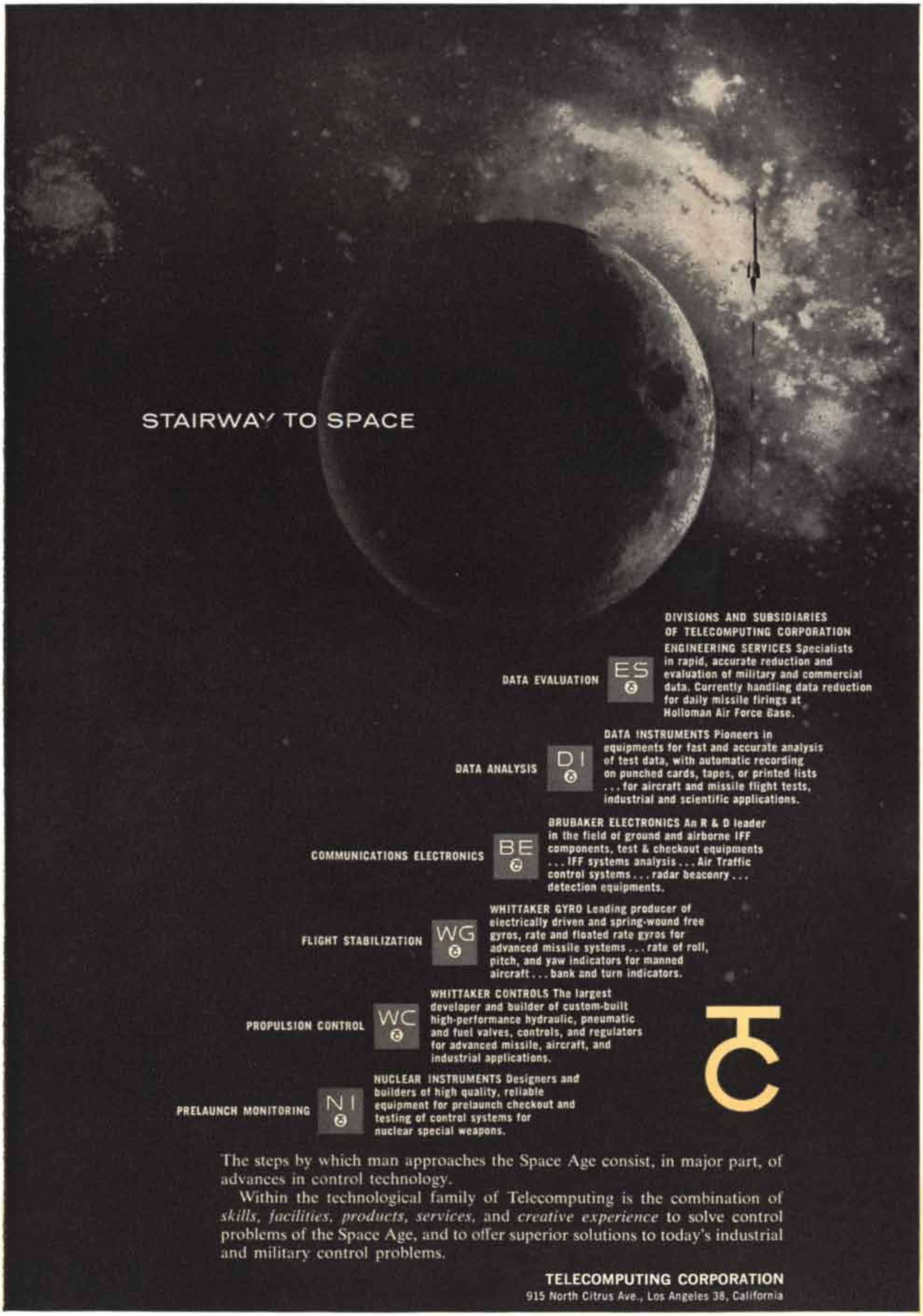
The corrosion behavior of metals is as much an inherent characteristic of materials as tensile strength, elongation and other physical properties. The laws of corrosion are well understood. Thus they can—and should be—taken into full consideration in any design analysis of a product or part. With this concept in mind, almost any corrosion problem can be "designed out" from the beginning when working with magnesium.

RYAN FIREBEE, with 75% of it's exterior surface magnesium, has withstood repeated dunkings in the ocean with no adverse effects. The reason—Ryan applied the proper protective measures.

Whenever the corrosion characteristics of magnesium are acknowledged, and preventative measures are incorporated into designs, magnesium gives outstanding performance in service. Proof of this statement is evident by the growing use of magnesium alloys for such applications as: aircraft skins, wheels and engines; missile frames, fins and skins; radar antennas; military vehicle platforms and wheels; chain saws, hand trucks and dock boards.

TO AID YOU IN APPLYING the correct design and proper protective measures for magnesium, write for your free copy of "MAGNESIUM FINISHING". Either contact your nearest Dow Sales Office or write to THE DOW CHEMICAL COMPANY, Midland, Michigan, Department MA 1483AA.

YOU CAN DEPEND ON DOW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NAVY'S POLARIS MISSILE TO REACH VIRTUALLY ANY TARGET IN WORLD

1500-mile missile will be fired underwater from sub

THE STORY BEHIND THE STORY

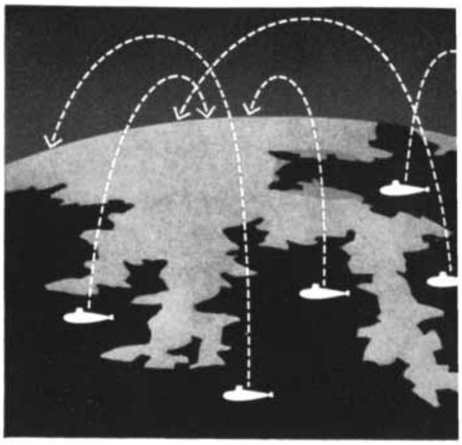
When the new Polaris weapon system becomes operational, it will give our Navy the power to deliver a decisive retaliatory blow at almost any enemy target on earth. Polaris can be launched from an atomic sub hidden in the ocean depths, and its 1500-mile range can bring virtually every major military area of potential aggressors under fire. Defense against Polaris is said to be nearly impossible since the direction of attack cannot be foreseen.

Launching a missile at a distant target from a maneuvering atomic sub presents extraordinary navigation problems. Location of the sub must be known precisely.

To provide exact navigation data, Sperry is developing for the Navy advanced electronic and gyroscopic systems that will stabilize the sub, continuously establish its precise position and true speed, and feed target data automatically into the missile's guidance system.

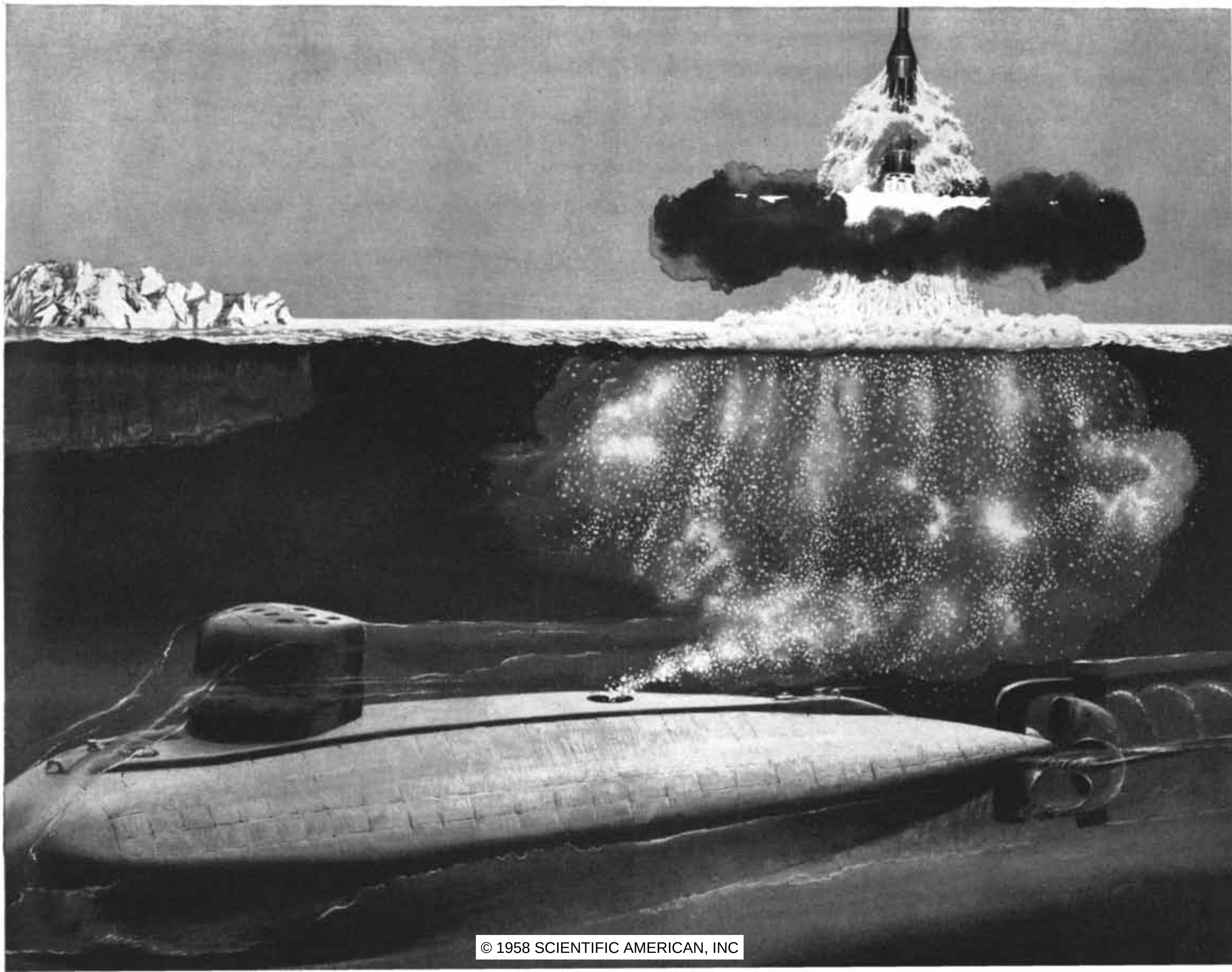
Sperry's efforts, joined with those of the missile system manager—Lockheed—and other companies involved, will make Polaris one of the most powerful deterrents in America's strategic defense arsenal.

SPERRY GYROSCOPE COMPANY
Great Neck, New York
DIVISION OF SPERRY RAND CORPORATION



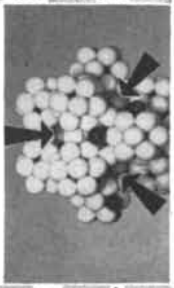
STRATEGIC IMPORTANCE of Polaris is seen in this symbolic map showing possible launching sites. Every major body of water on earth is potential site for Polaris. 1500-mile range covers most of world's land area.

ATOMIC SUBS, guided to exact launching position by Sperry navigation system, launch Polaris missiles from remote areas. Ship's Inertial Navigation System (SINS) requires no contact with shore stations to establish sub's position, speed, course, and true North.



Chemical-Loaded Molecular Sieves— Latent Curing Aids in Rubber and Plastics

Rubber and plastics fabricators need faster curing systems. The use of more active agents for rapid curing reactions has been restricted, because their use generally results in formulations difficult to process and store. This problem is serious at the high temperatures reached during the processing of rubber formulations. A novel series of latent curing aids, called LINDE Chemical-Loaded Molecular Sieves, now make it possible to use these active compounds to obtain faster, more effective curing systems, while still maintaining processing safety.



In LINDE Chemical-Loaded Molecular Sieves curing aids are "locked" within the pore structure of the Molecular Sieves by strong adsorptive forces. The active compounds, when loaded on Molecular Sieves, are effectively isolated from the rubber or resin formulation during processing and storage. However, at curing temperatures, which are generally higher than processing temperatures, the active compound is released from the Molecular Sieve to accelerate the curing reaction.

In this way, Loaded Molecular Sieves permit the use of highly active compounds to obtain fast cures, without sacrificing processing safety or pot life. Now, even vulcanization agents previously considered too active or volatile for practical use, may be used with processing safety.

Chemical-Loaded Molecular Sieves can be used as latent accelerators and curing agents in a variety of rubber and plastics formulations including styrene-butadiene rubber, natural rubber, Neoprene, nitrile rubber, epoxy resins, rigid vinyl plastisols and others. Loaded Molecular Sieve CW-2015 (di-tertiary butyl peroxide) is being used commercially in the curing of silicone elastomers and rigid vinyl plastisols. Loaded Molecular Sieves are now being investigated by many processors of rubber and plastics in such items as tires, mechanical goods, hose, belting and footwear. For further data, write to Molecular Sieves Department R-9, LINDE COMPANY, Division of Union Carbide Corporation, 30 East 42nd Street, New York 17, N. Y.

Radioactive Krypton

Krypton 85 is a radioactive isotope of the inert atmospheric gas, with a half-life of 9.4 years.

Radioisotopes such as Kr-85 are relatively inexpensive and new uses for them are being found every day.

One application is in tracer element testing of hermetically sealed encapsulated transistor devices. Another is in an "external" non-electric illuminating lamp which uses Kr-85 to activate a phosphor coating on the inside of a glass globe. Studies at the National Institutes of Health have shown that Kr-85 can be used to detect abnormal heart openings. 99 per cent of Kr-85 radiation is non-penetrating, quite safe, even for repeated exposures.

LINDE is marketing Kr-85 as an additive to non-radioactive rare gases (argon, helium, neon, krypton and xenon) individually or as mixtures. LINDE does not sell Kr-85 in pure or concentrated form. The other rare or inert gases, with Kr-85 added, will normally be available only in Atomic Energy Commission-approved, specially-marked cylinders.

Purchasers must be licensed by local or regional A.E.C. offices except for purchases of one microcurie or less. Non-licensed purchasers of one microcurie each may have 10 such cylinders on hand at a time.

LINDE's price for Kr-85 additions will be based on the radioactive level of the gas mixture expressed in millicuries of activity (N.T.P.) per liter. For additional information, write to Rare Gas Department R-9, LINDE COMPANY, Division of Union Carbide Corporation, 30 East 42nd Street, New York 17, N. Y.

Three-Level Ruby Maser

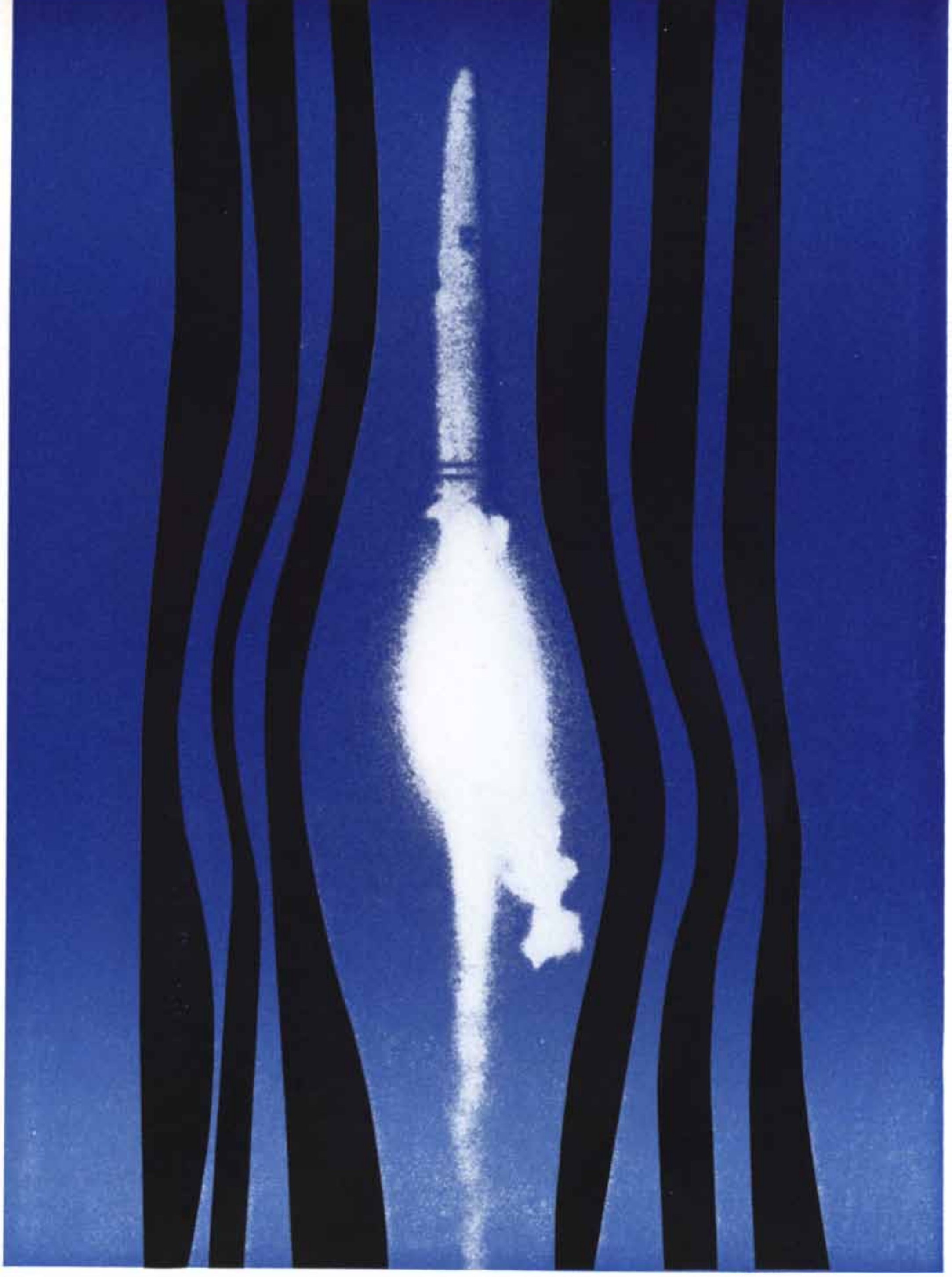
The Maser is a microwave amplifier utilizing energy stored in a molecular or atomic system. Emission of this energy is stimulated by the input signal. Masers operate at liquid helium temperatures and have incredibly low noise levels approaching zero db. Recently a University research laboratory* used LINDE single crystal synthetic ruby (Al_2O_3 with Cr_2O_3 additive) in a three-level solid state Maser. The ruby crystal was placed at the center of the Maser's tuned cavity and a magnetic field of 4200 gauss was applied. To bring electrons from a ground state into a permissible higher energy level, a pumping frequency of 24 kMc was used and the Maser successfully amplified signals at 9.3 kMc.

LINDE also supplies other crystals including rutile, spinel and sapphire (Al_2O_3). Sapphire is used in infrared optical systems, windows for high power microwave tubes, spacers and supports in vacuum tubes, radiation pipes. It has strength at elevated temperatures, melts at 2040°C, is hard, inert, nonporous and can be sealed to metals and glasses. Sapphire is currently available in the shape of domes, windows up to 4½ inches in diameter, rods and special configurations.

For further data write to Crystal Products Department R-9, LINDE COMPANY, Division of Union Carbide Corporation, 30 East 42nd Street, New York 17, New York.

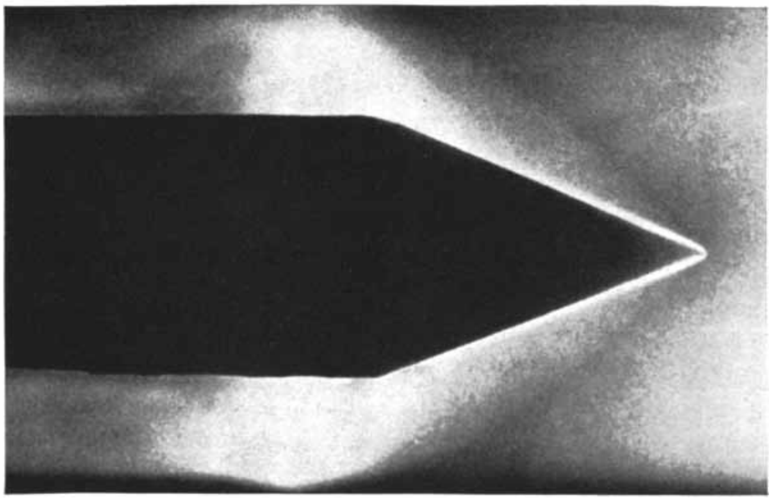
*"Maser Action in Ruby," by G. Makhov, C. Kikuchi, J. Lambe, and R. W. Terhune. "Physical Review," Volume 109, Number 4, Page 1399, Feb. 15, 1958.

PRODUCTS WITH A FUTURE Linde TRADE MARK UNION CARBIDE

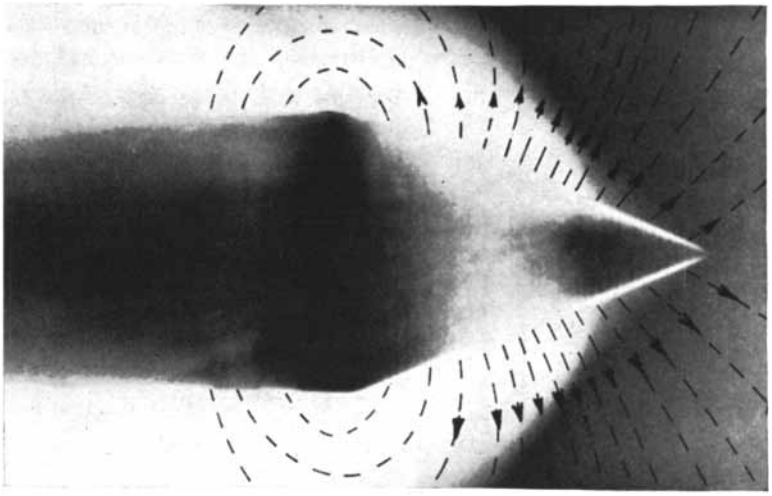


PROGRESS REPORT FROM AVCO RESEARCH LABORATORY

NEW LIGHT ON MHD*



NO MAGNETIC FIELD. This shock tube photograph, taken by emitted light only, shows the typical shock wave configuration formed by high-velocity gas flowing around a pointed cone.



WITH MAGNETIC FIELD. Here is shown the magnetohydrodynamic displacement of the shock wave. The magnetic field is caused by electric current flowing through a coil of wire within the cone. This experiment qualitatively demonstrates the interaction of a high-temperature gas with a magnetic field. This effect would be expected to produce drag and reduce heat transfer to the body.

The Avco Research Laboratory was founded a little more than three years ago for the purpose of examining high-temperature gas problems associated with ICBM re-entry. The success of this research led to the birth of a new corporate enterprise, Avco's Research and Advanced Development Division.

The Research Laboratory, now established as a separate Avco division, has expanded to embrace all aspects of physical gas dynamics. We are currently gravid with several embryonic projects which we anticipate will likewise grow into new corporate enterprises. Our work in the physics, aerodynamics and chemistry of high-temperature gases is growing in the following areas:

Magnetohydrodynamics—
Flight and industrial power-generation applications

Space flight—
Manned satellites
Electromagnetic propulsion

These developments have created a number of openings for physicists, aerodynamicists and physical chemists. If your background qualifies you to work in any of these areas, we would be pleased to hear from you.

Arthur Kantrowitz

Dr. Arthur Kantrowitz, Director
Avco Research Laboratory

P. S. A listing of laboratory research reports indicative of the scope and depth of our activities is available. Address your request: *Attention: Librarian, Avco Research Laboratory, 2385 Revere Beach Parkway, Everett, Massachusetts.*

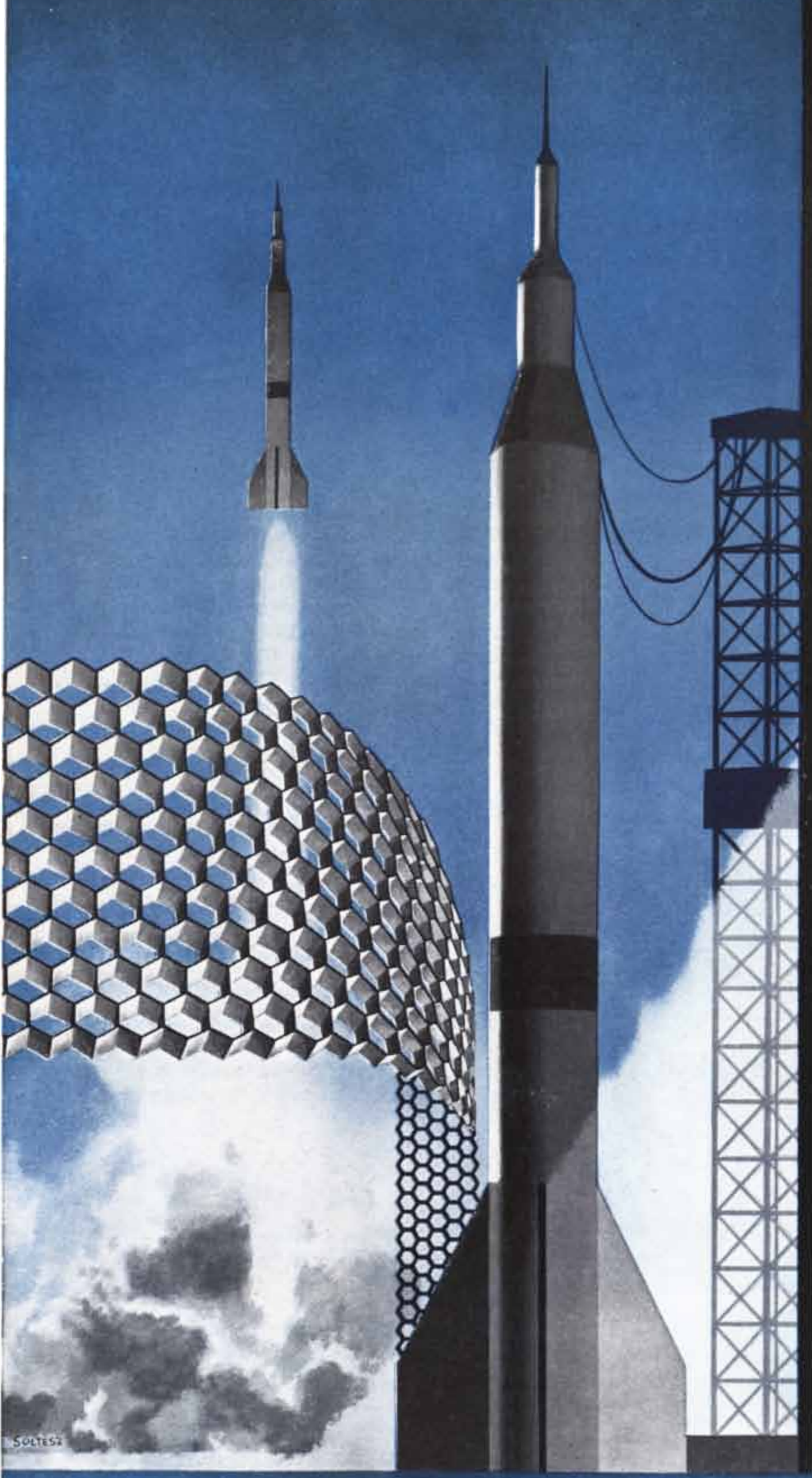
***Magnetohydrodynamics,** the study of the dynamics of electrically conducting fluids interacting with magnetic fields.

Avco
RESEARCH LABORATORY

A Division of Avco Manufacturing Corporation/Everett, Mass.

Other divisions and subsidiaries are:

AK Division
Crosley Division
Ezee Flow Division
Lycoming Division
New Idea Division
Moffats Limited
Crosley Broadcasting Corporation
Research and Advanced Development Division



Steel structures for space . . . from Crosley

Today's missiles require materials that are lighter, stronger and more heat resistant. Such requirements make Avco-Crosley a leading contender for building missile frames and structures.

Avco-Crosley is a pioneer in the development of stainless-steel honeycomb, a structural material that is cutting deep into the "thermal barrier" that so long has limited the speed at which planes and missiles travel through the air.

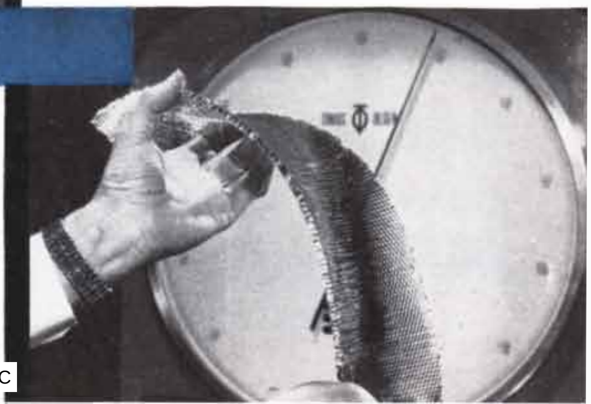
Using stainless-steel honeycomb, it is now possible to build structures with great heat tolerance and high strength/weight ratio: with the strength of solid steel, yet weighing only one-tenth as much.

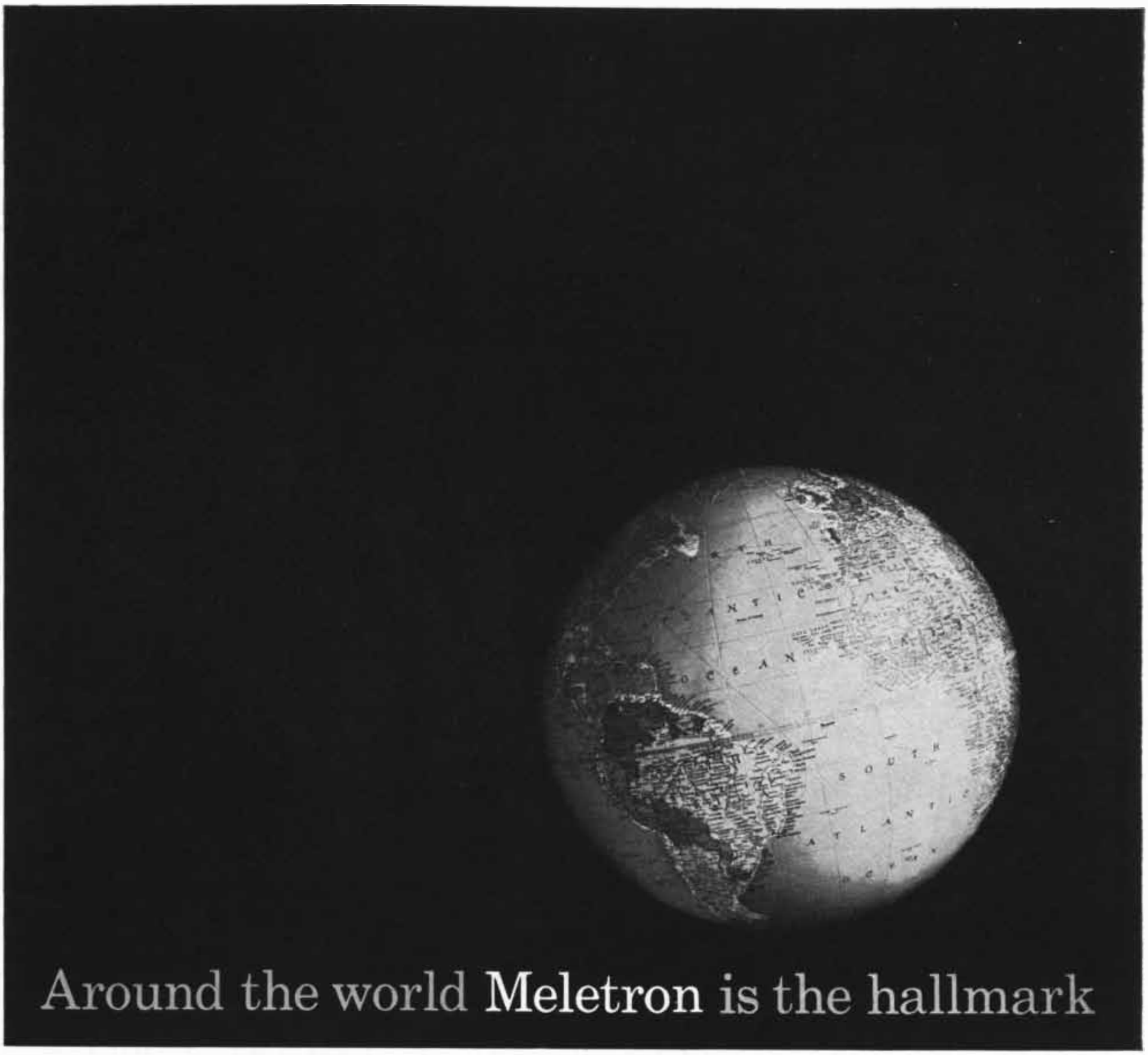
Together with its associated Avco divisions, the Crosley Division now provides facilities and personnel for:

- *Weapon systems management, from initial concept to production.*
- *Research, development and engineering design of: missile nose cones, air frames, electronics, control systems, telemetering, automatic test and support equipment, ground handling equipment and logistics.*
- *Production and manufacturing for missile and aircraft systems.*

For more information, write to: Vice President, Defense Products Marketing, Crosley Division, Avco Manufacturing Corporation, Cincinnati 25, Ohio.

Avco // Crosley





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MELETRON® Meletron Corporation, 950 No. Highland Ave., Los Angeles 38, California

50 AND 100 YEARS AGO

SEPTEMBER, 1908: "Seldom has there occurred a more pitifully tragic disaster than the sudden fall of the Wright aeroplane, involving the death of that promising young officer Lieut. Thomas E. Selfridge, and inflicting shocking injuries on the talented inventor, Orville Wright. The loss of Lieut. Selfridge will be keenly felt. The various aeroplanes built by the Aerial Experiment Association, all of which flew successfully, were designed by him, and the third of these, the *June Bug*, on July 4 last won for the first time the Scientific American trophy. Lieut. Selfridge is the first martyr to flight by a heavier-than-air flying machine. Mr. Orville Wright's broken thigh is slowly knitting, and his ultimate recovery is only a matter of time. Experts believe that after the motor was stopped the machine, which had already lost speed on the side having the broken propeller, quickly lost its momentum; and that although Mr. Wright was able to regain his equilibrium momentarily, its final downward plunge was due to the loss of speed and the forward location of the center of gravity."

"Sven Anders Hedin, the explorer, who started in 1906 from Chinese Turkestan on a journey through Tibet, and concerning whose whereabouts there was great anxiety for many months, has arrived at Simla. His work, which will rank among the great achievements of exploration, turns out to have comprised three separate journeys. In 1906 Hedin crossed the vast unexplored region of western Tibet, discovering mountain ranges, new lakes and rivers, and gold fields. The second expedition, which filled most of 1907, led him through the southern part of the unknown area, about 1,000 miles to the southwestern corner of Tibet. On this eventful expedition Hedin discovered the sources of the Brahmaputra, Indus and Sutlej rivers, and found that the Nin Chen Tangla Mountains are simply part of a chain extending, he believes, clear across Tibet east and west and at least 2,000 miles long. The third journey carried Hedin again from north to south across unknown expanses he had not seen on his route of 1906. He crossed the Nin Chen Tangla three times—he had crossed them five times on his first and second journeys—and he now reports complete proof that the mighty range is continuous to the western border of Tibet."

"We are used to thinking of gases as always less dense than liquids, and in fact we have never hitherto been able to increase the density of a gas down to the point where it becomes heavier than a liquid in contact with it. Dr. Kamerlingh Onnes has, nevertheless, accomplished this surprising feat by causing a bubble of compressed helium to descend by its own weight through liquid hydrogen, like a drop of water in oil. He compressed a mixture of hydrogen and helium in a capillary tube plunged into liquid hydrogen. The hydrogen becomes almost entirely liquefied and, beyond a pressure of 49 atmospheres, a bubble of almost pure helium, which is floating on the liquid, is seen to descend below it."

"The longest distance wireless telephone tests yet made on this side of the Atlantic have just been completed between Newark, N. J., and Philadelphia, Pa., a distance of 81 miles as wireless waves travel. The system by which this has been accomplished is due to A. Frederick Collins, who began the work in 1899. In its modified and present form it consists of an apparatus for generating continuous oscillations and an instrument for reconverting the received oscillations into audible, articulate speech."

"Antoine Henri Becquerel died in Paris on August 25. With his death there has passed away one of the world's most distinguished physicists, one of a line of distinguished men of science. Prof. Henri Becquerel was the grandson of a celebrated physicist, Antoine César Becquerel, and the son of an equally illustrious physicist, Alexandre Edmonde Becquerel. Henri Becquerel first came prominently before the public when he began the investigation of phosphorescent and fluorescent substances shortly after the discovery of the X-rays. He found that they projected emanations entirely different in character—emanations which have been fittingly named 'Becquerel rays.' Becquerel's study of invisible infrared radiations was not the least interesting work which he accomplished. Here he followed directly in the footsteps of his father, who had dis-

covered that these thermo-rays cause the phosphorescence of a substance which has previously been rendered luminous. This may be said in a measure to be the starting point of the discovery of the radioactivity of matter."

"Serum treatment, which has been so successful in diphtheria, has lately been extended to scarlet fever. The serum is obtained from horses inoculated with streptococci from the blood of scarlet fever patients. Dr. W. Pulawski has published a discussion of 117 cases of scarlet fever, occurring between 1904 and 1907. Of the 48 patients who were treated by the usual methods, 20 died, but of the 69 who received the serum treatment only 10 died. In other words, the mortality was 41.6 per cent with the old methods and only 14.5 per cent with the serum treatment."

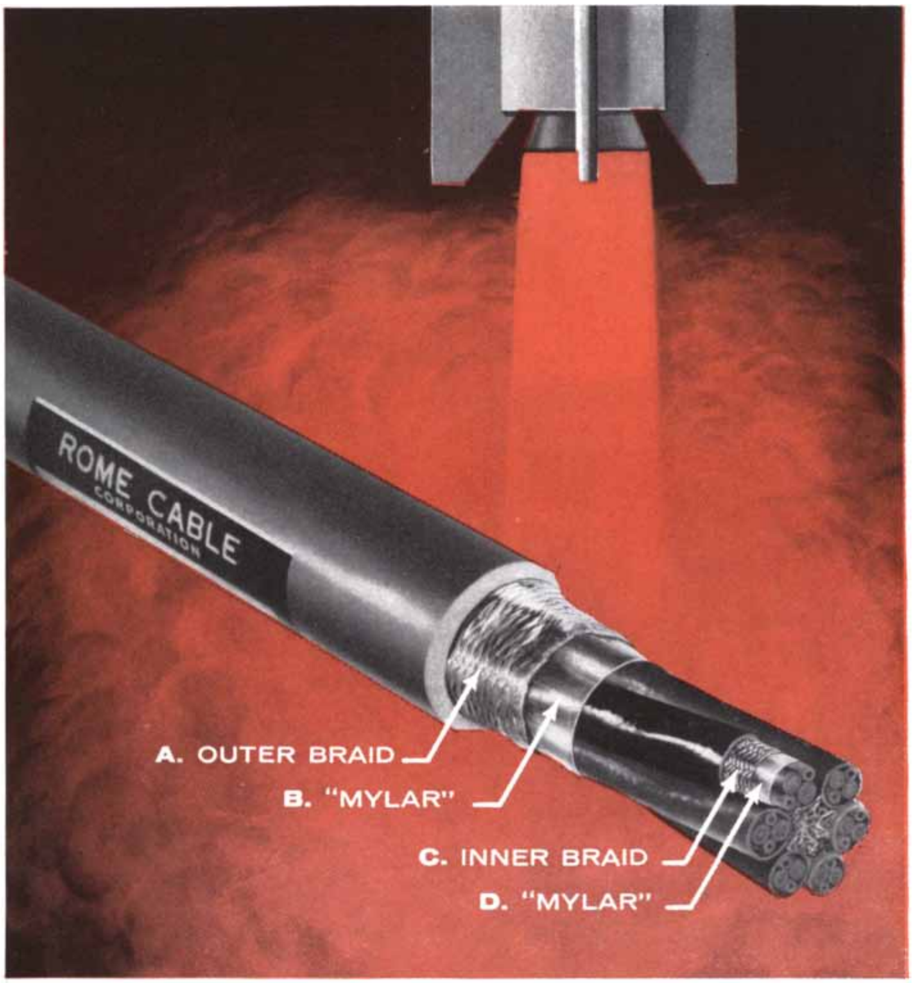
"Halley's comet is now out between the orbits of Jupiter and Saturn. It will be within the distance of Jupiter's orbit after March 1, 1909. It is possible that someone with the aid of a large telescope may catch sight of the expected visitor during the winter of 1908-09. We may begin to search for it as early as September, 1908, provided good ephemerides are at hand. Almost certainly it may be found by September or October, 1909. It will then be only a round nebula, whatever tail it has being almost directly behind it as seen from the earth. If the date of perihelion should be May 10, the comet will be lost behind the sun in the early part of April, reappearing in the morning sky about the first day of May."

"A semi-permanent wireless telegraph station has been maintained for more than a year by the French Government at the Eiffel Tower in Paris, and it is stated that spark-messages sent with a 10-kilowatt installation have been read at Morocco in the south and Nova Scotia in the west. It seems to have become necessary to bury the wireless plant at the foot of the Eiffel Tower in an underground vault, in order to preserve aesthetic appearances and to keep down the noise of the sparks in sending. The time will probably come when transmission by sparks from a large land station will be looked upon as clumsy and ineffective by comparison with the more modern sparkless methods of sustained oscillation, which have not yet come into extensive use; but almost any station, even if noiseless in operation, would be likely to mar the graceful symmetry of the Eiffel Tower, and there would doubtless be justification for going underground on the score of appearance alone."

SEPTEMBER, 1858: "Whether the Atlantic cable will ever realize all that has been expected from it by sanguine persons remains to be demonstrated—thus far it has not. Its operations have, as yet, been of a very puzzling and tedious character. With the very best known instruments messages have been very slow, and, unless some new discovery is made to remove existing obstacles, the Atlantic cable will be of very little general benefit to the commercial people of two continents. We know, by the published statement of M. de Santy, manager at Newfoundland, that the Queen's message to the President, consisting of 99 words, took about 24 hours to transmit. On page 184, Vol. XII, of SCIENTIFIC AMERICAN, the nature of the submarine cable as an electrical conductor was explained. It was there stated to be, in effect, a vast Leyden jar, and messages could not but travel very slow in it—requiring about six seconds for each signal, and therefore incapable of transmitting more than about half a column of news in 24 hours."

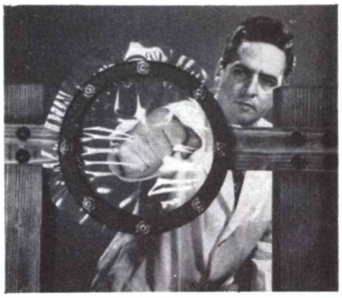
"Some time ago we remonstrated strongly against the course of Dr. Thompson and the Board of Health of New York City for the careless manner in which infected ships were treated by them; and this journal was the first to call the public's attention to the Board's official stupidity in allowing the U. S. Ship *Susquehanna* to remain for three months in the cool weather, without attempting to do anything for her restoration to usefulness, and then, when the thermometer had got to 'fever heat,' busily stirring themselves to get her disinfected, by risking the lives of stevedores and others, in a reckless and unnecessary manner. Since that time many other infected ships have been treated in the same way, and at this moment there are too many opposite the quarantine station, which is only six miles from the city. The consequence of this careless conduct is that yellow fever has broken out in three distinct parts of Staten Island."

"That amiable and talented gentleman, Edward Pease, died a few weeks

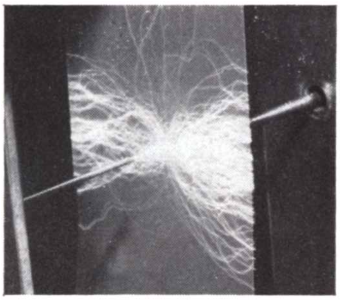


PROPERTIES OF "MYLAR"

"Mylar" offers a unique combination of properties that may help you improve performance and lower costs of *your* product. Here are two of the many important properties for evaluation.



REMARKABLE TOUGHNESS. "Mylar," the strongest plastic film ever made, is tough even in extra-thin gauges. It resists aging...heat, moisture and most chemicals.



HIGH DIELECTRIC STRENGTH. Average of 4,000 volts per mil...average power factor of 0.003 at 60 cycles . . . dielectric constant above 3.0 at 72°F., 1,000 cycles.

Rome Cable reports . . .

Du Pont Mylar® helps eliminate reject problem in manufacture of cable for "Titan" ICBM

PROBLEM: In designing its instrumentation cable for the "Titan" ICBM project, Rome Cable Corporation wanted a thin, abrasion-resistant tape to protect the insulated conductors from possible puncture by loose strands of the tin-copper braid (See C in illustration). They were also searching for a thin, heat-resistant core binder tape to prevent possible puncture from the outer braid (See A) during extrusion of the cable jacket.

SOLUTION: A tape of Du Pont "Mylar" polyester film for both applications (See B&D). Reason: "Mylar" has the desired balance of mechanical and electrical properties . . . it's tough, abrasion- and puncture-resistant, even in thin gauges. "Mylar" has a high melting point . . . runs well on existing machinery.

RESULTS: The two tapes of "Mylar" eliminated shorted cables due to puncture from loose strands of metal. Solving this problem has helped Rome Cable stabilize production, save money on time and materials and produce a cable that assures better performance and greater reliability in the ICBM.

How can "Mylar" help you? Whether you manufacture high-voltage cable or tiny components, it will pay you to evaluate the outstanding combination of properties found only in "Mylar." Figured on an area basis, this tough, thin polyester film will often *cost less* than materials you are currently using. For more detailed information, send in the coupon below.

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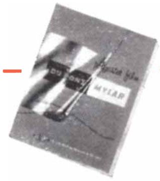


E. I. du Pont de Nemours & Co. (Inc.)
Film Dept., Room SA-9. Nemours Bldg., Wilmington 98, Del.
Please send the new booklet listing properties, applications and types of "Mylar" polyester film available (MB-11).

Application__________
Name__________ Title__________
Company__________
Address__________
City__________ State__________

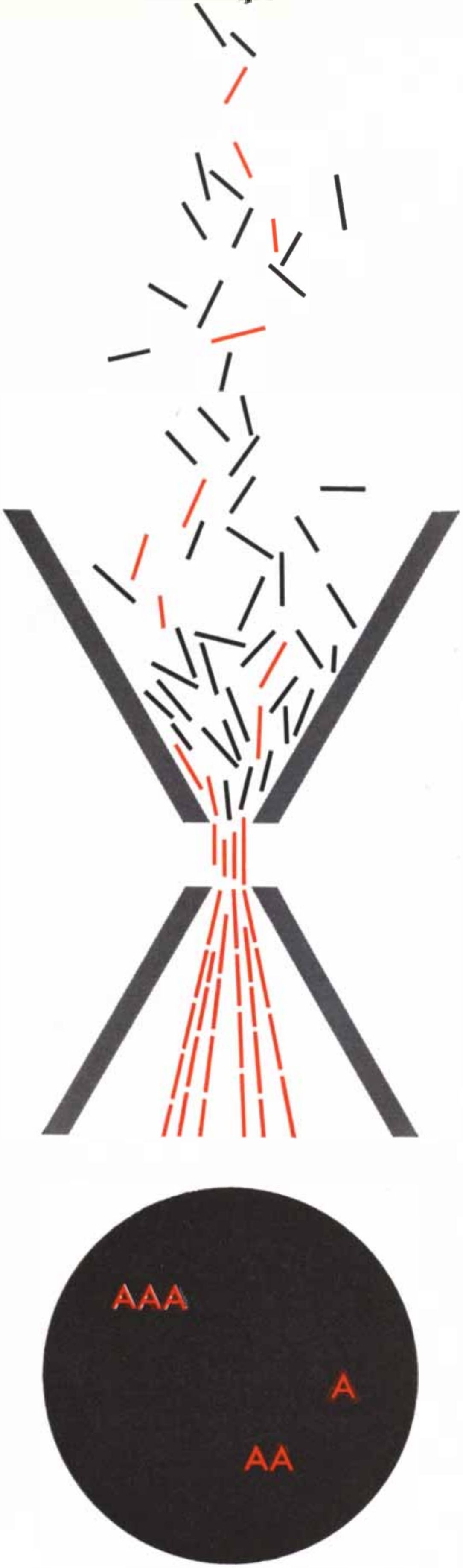
since, aged 90, at his residence in Darlington, England. He was a member of the Society of Friends and had lived a calm and peaceful life, ever doing good and encouraging humble and rising genius. He it is to whom Great Britain, in a great degree, owes her railway system, for, when George Stephenson was a humble colliery engineer, Mr. Pease believed in his ideas and advanced the capital and used his vast commercial influence to construct the first railway on which a locomotive ever traveled."

"The increasing scarcity of good oak timber for ship-building, says the London *Engineer*, induced M. Arman, the well-known ship-builder at Bordeaux, to make some experiments last year to ascertain the strength of mahogany as compared with French oak and teak. A piece about four inches square of each kind of wood was placed across the machine used for proving chain cables, and a piece of chain was attached to a ring fixed in the center of each piece. A strain being laid on, the oak broke under a force of 3,900 pounds, the teak under 7,200 pounds, and the Honduras mahogany under 7,460."

"We see it stated that the medical attendant of the Princess of Gothland asserts that hoopskirts are the cause of accouchements lately becoming so dangerous and difficult. He adds that this fashion is the source of a vast number of chills, the consequences of which are, in many cases, mortal. We have always thought that hooped skirts of reasonable bounds were not only an adornment to the persons of the fair wearers, but, on account of their ventilating character, actually beneficial to health. Ladies generally evidently think so, and as they are the actual sovereigns of creation and will wear what suits them, we doubt whether this statement will have any effect."

"Twenty-five hundred ounces of gold have been shipped from Nelson, New Zealand, to Melbourne, Australia, being the first shipment from the newly discovered gold fields of the former region."

"Cotton is our great national staple for export, and upon it foreign manufacturers are absolutely dependent. Of the total crop of last year, 2,590,455 bales were exported, Great Britain taking no less than 1,809,966 bales. The rise and progress of American cotton as an article of culture, merchandise and manufacture, is marvelous. American 'cotton is king,' and rules in the marts and cabinets of nations."



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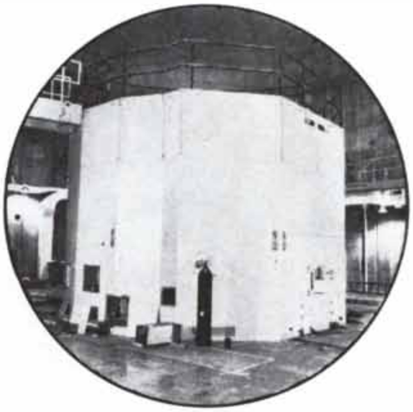
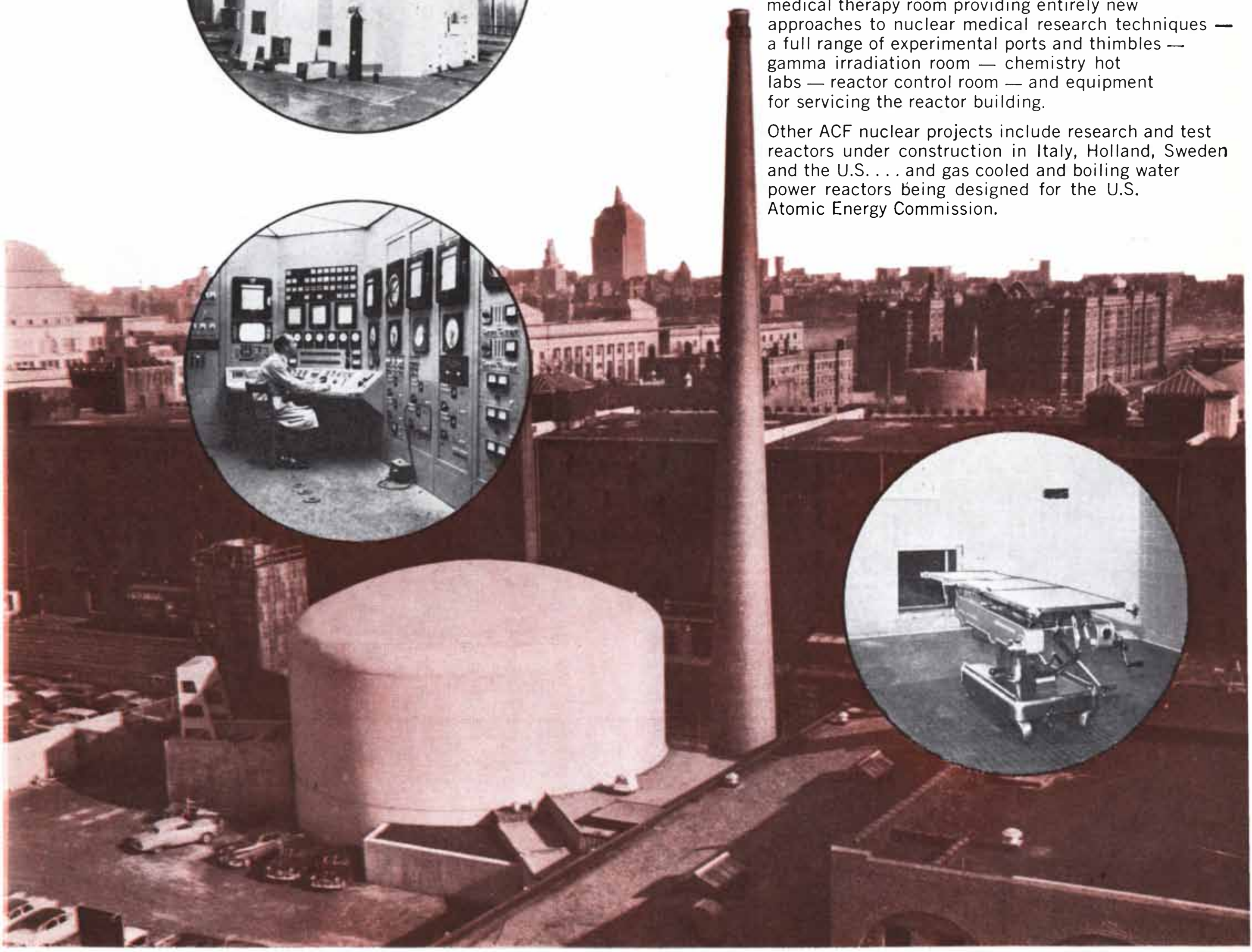


With the completion of the world's first privately owned heavy water research reactor, at the Massachusetts Institute of Technology, comes a new and powerful instrument to further man's knowledge in the peacetime use of atomic energy. As prime contractor responsible for the complete engineering design and construction of this facility, ACF Industries, Incorporated is proud to join with MIT in this achievement.

The MITR will operate at 1000KW and produce fluxes in excess of $10^{13}n/cm^2/sec$. This inherently safe facility, located near the campus, includes a unique medical therapy room providing entirely new approaches to nuclear medical research techniques — a full range of experimental ports and thimbles — gamma irradiation room — chemistry hot labs — reactor control room — and equipment for servicing the reactor building.

Other ACF nuclear projects include research and test reactors under construction in Italy, Holland, Sweden and the U.S. . . . and gas cooled and boiling water power reactors being designed for the U.S. Atomic Energy Commission.



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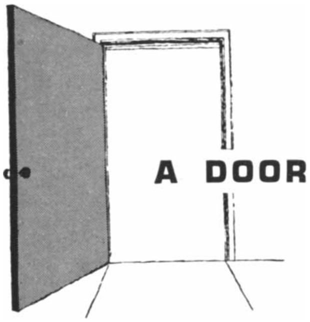

A DOOR IS OPENED... TO NEW USES FOR URETHANES

WHERE DO URETHANES STAND TODAY? A few years ago, these versatile plastics were heralded as "the next great synthetic." How have they made out? In brief—some good, some not so good, some phenomenally successful. Here we will try to give you the low-down and a quick sum-up.

First, the *dark* side of the picture: Progress is still "developmental" as far as adhesives, rubber and coatings are concerned ("developmental" being a nice word to imply that not half as much has been done in these fields as we'd like to see). Adhesives, while good, are still too expensive. Rubber—for tires, for example—is hampered by bonding and other problems. (O-rings and gaskets work fine, however.) While initial results with wire coatings and paints are favorable, there's still a lot of work to be done in those areas.

New types of urethanes. On the bright side, new combinations of isocyanates with such materials as polyethers, polyesters, dimer acids and other polyols are pushing urethanes ahead in many fields. (Our NATIONAL ANILINE DIVISION has developed some highly workable prepolymers for polyether- and polyester-type urethanes.) Excellent results are being obtained with *flexible* foams, taking advantage of their "comfort characteristics" and low compression set. This accounts for the continually increasing use of urethane foam in automobile crash pads and seats, furniture upholstery and slabbing for the better-grade mattress market. A particularly bright spot in flexible urethane applications is interlining, where the new material is described (too modestly, we would say) as "the newest textile." Perhaps a million square yards of urethane foam went into outer garments during 1957.

Egg bouncing from 12-foot drop demonstrates superior cushioning properties of flexible urethane foam.

Rigid foams, with their unique combination of properties, are moving ahead particularly fast. To wit: Refrigeration panels for trucks and railroad cars, for home refrigerators and industrial freezers; flotation chambers for boats; void-filling applications as in airplane tail fins and nuclear submarines; various as-yet-unannounced uses in the missile and satellite programs. These applications make use of one or more of the many properties of rigid urethanes: excellent thermal insulation, structural strength, and their ability to be foamed-in-place, to bond without adhesives, and be formulated in a wide weight range.

Allied Chemical

Buoy for dock has rigid urethane foam core, polyester-glass fiber surface—resists shock, marine growth.

Looking ahead. Would a look into the future be inapropos at this point? Not with versatile urethanes—especially in rigid foam form. For instance: panels for insulated freight cars; sidings for house trailers; perhaps even walls for prefabricated homes. There are dozens of household uses still untried, by the way: bath mats of flexible foam to cushion falls, for instance. Contributions to the rocket program? There's a real challenge for urethanes here—one which many alert manufacturers will doubtless meet.

WHY NOT GET MORE FACTS about urethanes and the NACCONATES that make them possible? Two new technical bulletins have just been printed: One on polyether flexible foam formulations, another on rigid foams. Write for them (or for other information) on your company letterhead, telling us about your proposed use. Address: Allied Chemical Corporation, Dept. 98-S, 61 Broadway, New York 6, N.Y.*

**Allied does not make urethane foams, but our National Aniline Division supplies isocyanates under the trademark NACCONATE. Our Barrett Division makes PLASKON polyesters.*

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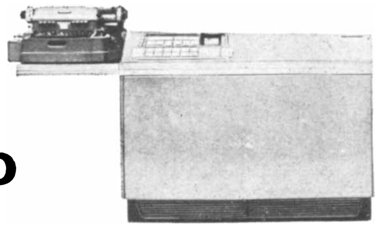

Compare it, feature by feature, with the other computers in its class

Feature	Computer A	Computer B	Computer C	Computer D	LGP-30	
Memory Size	220 words for data only	2160 words	1000 or 2000 words	84 words for data only	**4096 words for data & program (either or both)**	**LARGEST CAPACITY IN ITS CLASS**
Max. Speed Add Multiply	 20/sec. 4/sec.	 Comparable to LGP-30	 Comparable to LGP-30	 3/sec. 1/sec.	 **Over 440/sec.** **Over 50/sec.**	**SPEED EQUAL TO MANY ROOM-SIZED COMPUTERS**
Size	17 sq. ft.	6.5 sq. ft. plus table for typewriter.	45 sq. ft.	9.2 sq. ft. plus table for typewriter & control unit.	**11 sq. ft.**	**COMPACT, DESK-SIZED, COMPLETELY MOBILE**
Input-Output	Keyboard only — tape at extra cost.	Independent tape preparation at extra cost.	Extra cost peripheral equipment required.	Tape and typewriter for numerical input-output only. Independent tape preparation at extra cost.	**Tape typewriter for alpha-numeric input-output standard equipment.**	**DELIVERED COMPLETE. NO ADDITIONAL EQUIPMENT NEEDED TO PREPARE DATA, PROGRAM OR REPORTS**
No. of tubes	165	450	2,000	248	**113**	**FEWER COMPONENTS MEAN LESS MAINTENANCE, FEWER CHECKOUTS**
Voltage	220 V	110 V	220 V	110 V	**110V**	**PLUGS INTO ANY REGULAR WALL OUTLET**
Power	2.5 KW	3.0 KW	17.7 KW	1.65 KW	**1.5 KW**	**NO SPECIAL WIRING OR AIR-CONDITIONING REQUIRED**
Ease of programming & operation	Not alpha-numeric. No internal program storage.	Alpha-numeric at extra cost. 8 part instruction. Requires computer specialist.	Alpha-numeric at extra cost. Requires computer specialist.	Not alpha-numeric. No internal program storage.	**Alpha-numeric. Complete internal program storage. Standard typewriter keyboard. Simplest command structure of all.**	**EASY TO PROGRAM AND OPERATE.**
Cost Sale Rental	 $38,000 $1000/mo.	 $49,500 $1485/mo.	 $205,900 $3750/mo. up	 $55,000 $1150/mo.	 **$49,500** **$1100/mo.**	**LOWEST COST EVER FOR A COMPLETE GENERAL PURPOSE COMPUTER**

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MINIATURIZATION AWARD

THE AWARD

Miniature Precision Bearings, Inc. cordially invites you to participate in the 1958 Miniaturization Award Competition. The Miniaturization Award for 1958 will be presented during the Spring of 1959 at the 2nd Annual Award Dinner in New York. The Award will consist of a piece of original sculpture, symbolizing miniaturization, by a leading American artist, which is cast in bronze and inscribed. Certificates of Merit will also be awarded for additional outstanding contributions.

PURPOSE OF THE AWARD

To increase public knowledge of the importance of miniaturization and to stimulate further activity within industry toward the advancement of the concept of miniaturization.

CRITERIA FOR AWARD

Contributions considered for the Award should have been made in the recent past to be eligible for consideration by the Miniaturization Award Committee. Details of criteria on which awards will be based and entry blank can be obtained by writing: Miniaturization Award Committee, P. O. Box 604, Keene, N. H.

JUDGING OF ENTRIES

The entries will be judged by an independent committee comprised of members of the electronics, metalworking, research, and publishing fields.

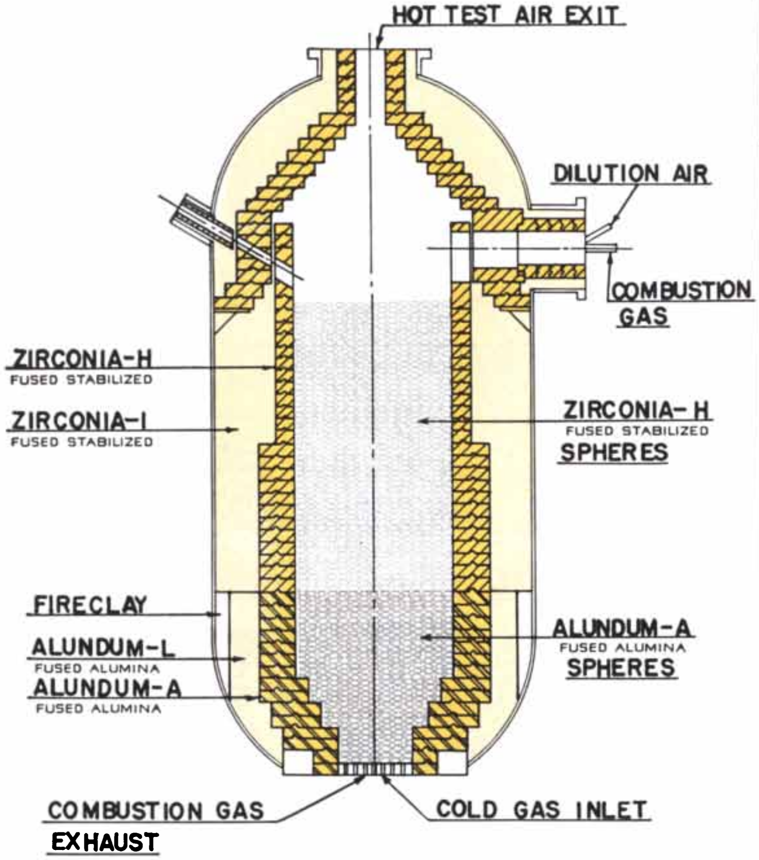
ENTRIES

Description of a specific contribution should be made in as complete a form as possible and mailed to the Miniaturization Award Committee, P. O. Box 604, Keene, N. H. Samples of the product itself, blueprints or photographs will be helpful. Descriptive information should include some of the design characteristics of the product and the problem solved by the miniaturization effort.

DEADLINE

In order to be considered for the 1958 Miniaturization Award, entries must be received by January 31, 1959.

Newly Installed Pebble Heater at the Marquardt Aircraft Company of Van Nuys, California, designed to produce hot air for testing missile materials. *Combustion Inlet* shown above is lined with Norton Fused Stabilized Zirconia.



Aiding progress in high temperature testing . . .

Norton refractories provide high temperature insulation and heat transfer — at temperatures over 4000°F.

Norton refractories were specially designed to meet the high expansion and contraction conditions encountered in this new pebble heater. ALUNDUM* Fused Alumina and Fused Stabilized Zirconia refractories used for practically 100% of the construction of this unit and for the pebble bed protect against extremely high temperatures and provide maximum efficiency in heat transfer. As shown in the diagram of the pebble heater — designed by Marquardt engineers — combustion gas, mixed with dilution air, enters at upper right. The input burner supplies 100,000 to 1,000,000 B.T.U. per hour over temperatures ranging from 200°F. to above 4000°F.

The intensely hot gas, after flowing through a pebble bed of Zirconia and ALUNDUM Fused Alumina spheres, exhausts below. Entering near this exhaust, ambient cold air passes up through the pebble bed, extracts the stored heat and leaves at the top of the heater. This hot air is used for testing the heat resistance of various missile materials.

A similar installation, using Norton-designed refractories, and operating intermittently, 2 cycles per day, has provided nine months of trouble-free service. ALUNDUM Fused Alumina and Fused Stabilized Zirconia refractories are among the very few materials with sufficient resistance to chemical, thermal and mechanical attack to be suitable for such operations.

If you have a problem involving high temperature insulation or heat transfer, or if you would like further details on Norton Refractories, write to NORTON COMPANY, Refractories Division, 548 New Bond Street, Worcester 6, Mass.

*Trade-Mark Reg. U. S. Pat. Off. and Foreign Countries

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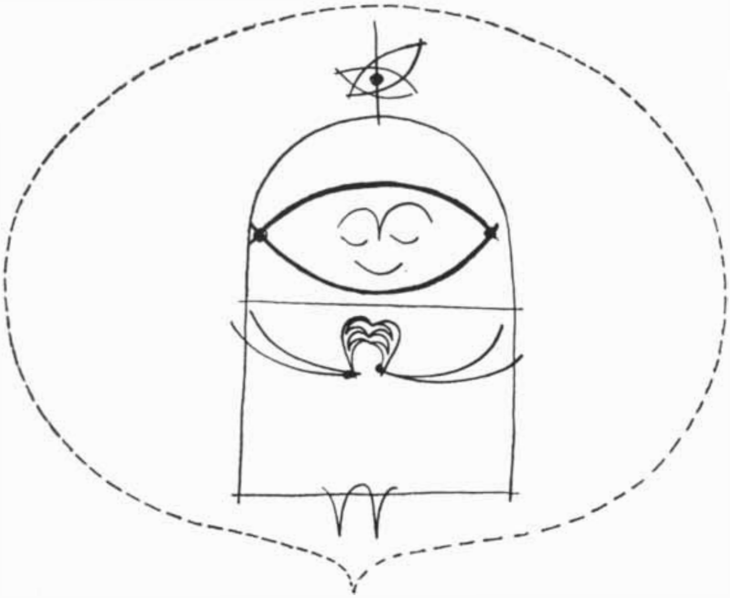

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This is one of the newest and most modern facilities of its kind in the world . . . and key opportunities are available to a select number of cream-of-the-crop, senior advanced design engineers, electronicists, aerodynamicists and many others.

Qualified applicants will be invited to visit the Martin-Orlando facility for private interviews with chief engineering staff personnel.

Immediate project requirements and the dynamic advanced design activities of this important new addition to the Martin Company facilities make this opportunity an engineer's dream!

Contact Jack Wallace, Department D, The Martin Company, Orlando, Florida.

MARTIN

ORLANDO

THE AUTHORS

J. BRONOWSKI ("The Creative Process") was born in Poland, raised in Germany and trained as a mathematician in England, where in 1933 he received his Ph.D. from the University of Cambridge. He is known not only for his work in topology and statistics but also as an administrator and man of letters. Bronowski taught mathematics at University College, Hull, until 1942. He then entered the service of the British Government, which employed him to assess bomb damage and later to work in the field of operations research. In 1945 he joined the Chiefs of Staff mission to Japan—a trip which resulted in his report on atomic-bomb damage in Nagasaki and in his radio play *The Journey to Japan*. Bronowski now heads the Coal Research Establishment of Britain's National Coal Board. In addition to many mathematical papers, he has written *The Poet's Defence*, *William Blake: A Man without a Mask*, *The Common Sense of Science*, and most recently *Science and Human Values* [see "Books"; SCIENTIFIC AMERICAN, June].

PAUL R. HALMOS ("Innovation in Mathematics") was born in Budapest, emigrated to Chicago as a boy, and, in 1934, graduated from the University of Illinois at the age of 18. The next year he became a mathematician, when, having failed the examinations for an M.A. degree in philosophy, he was given an M.S. in mathematics instead. Halmos went on to acquire a Ph.D. in mathematics at Illinois; then he worked for two years as assistant to John von Neumann at the Institute for Advanced Study in Princeton, N. J. After a year at the Radiation Laboratory of the Massachusetts Institute of Technology, he joined the University of Chicago staff in 1946, and is now an associate professor there. Halmos's honors include a Guggenheim Fellowship and the Chauvenet prize for mathematical exposition.

FREEMAN J. DYSON ("Innovation in Physics") is a professor in the School of Mathematics of the Institute for Advanced Study. He was born in England—his father is Sir George Dyson, former director of the Royal College of Music—and was educated at Winchester College and the University of Cambridge. Dyson's undergraduate career at Cam-

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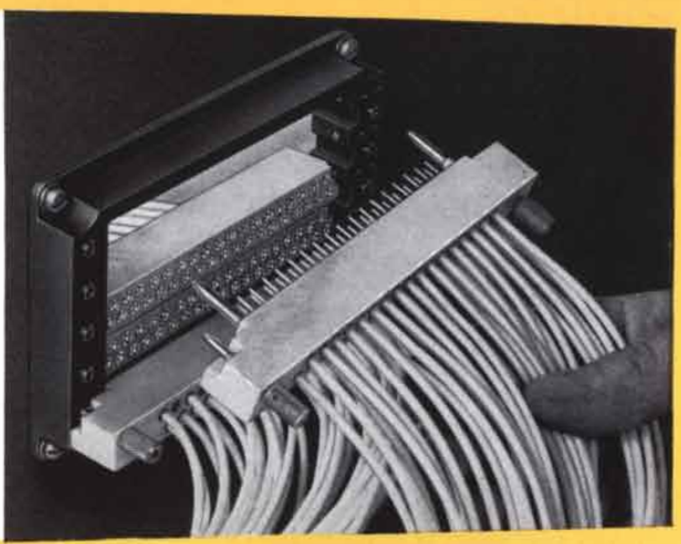

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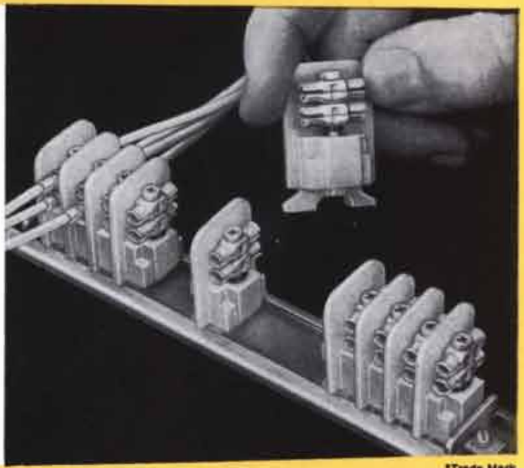

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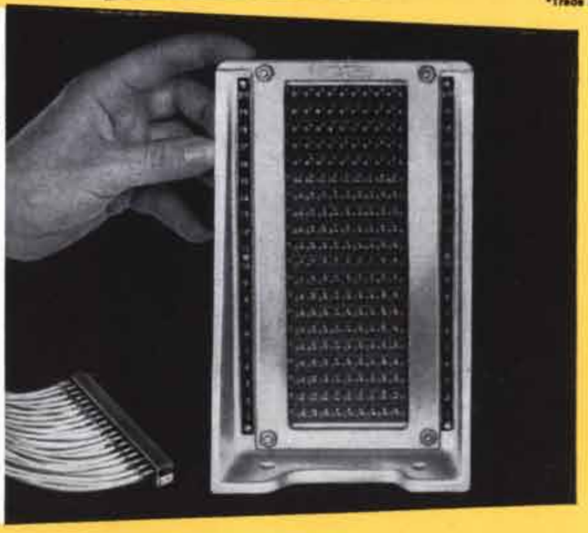


For complete information, write: **OMATON DIVISION**

BURNDY

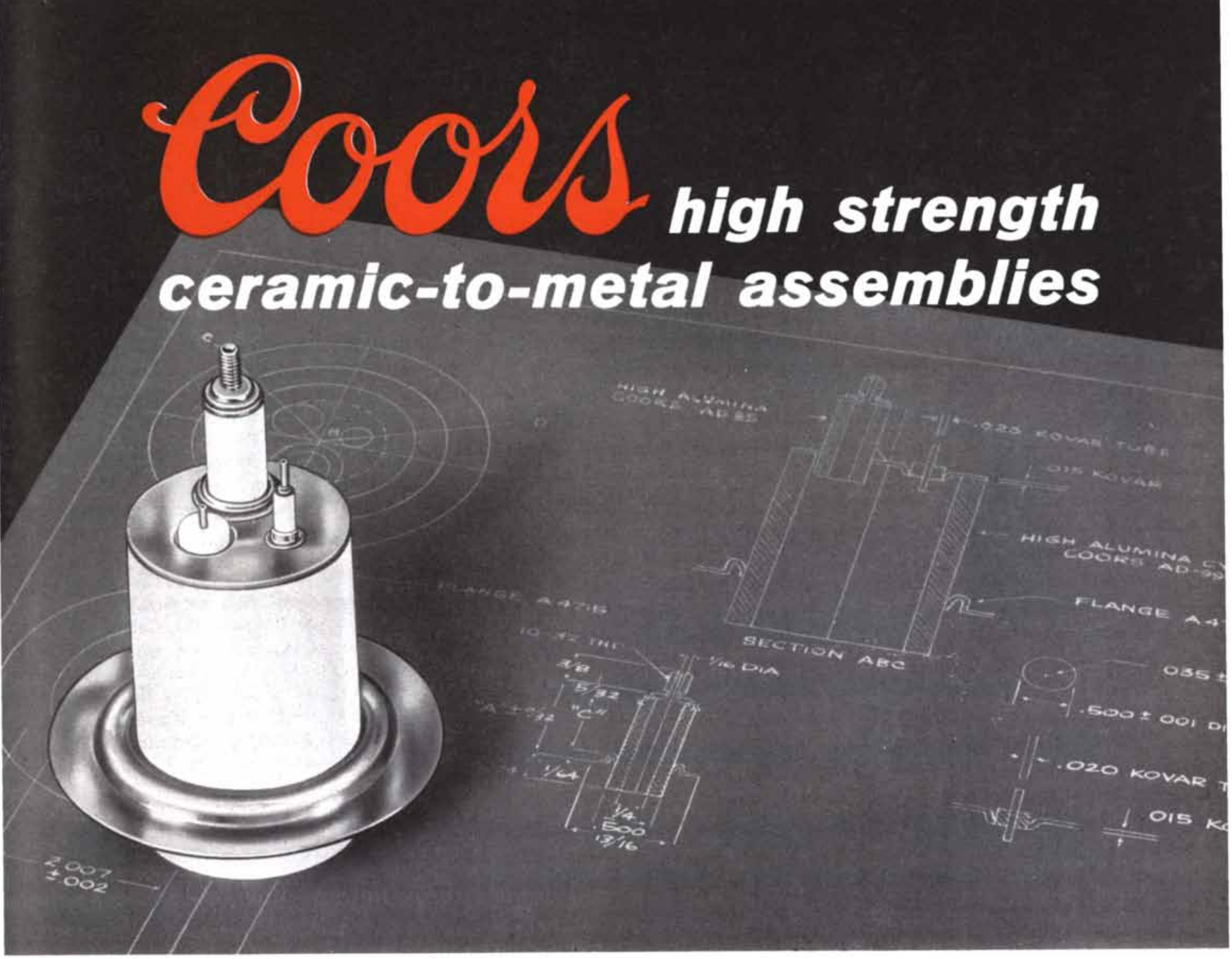
58-24

Norwalk, Connect. In Europe: Antwerp, Belgium Toronto, Canada bridge was interrupted by a wartime stint with the Royal Air Force, where his mathematical talents were employed in investigating the cause of the heavy loss of bombers on night missions. After reading the Smyth report in 1945, he decided to return to Cambridge to study physics. He was a fellow at Trinity College, Cambridge, for a year, then came to the U. S. on a Commonwealth Fund Fellowship and studied at Cornell University with Hans Bethe and Richard P. Feynman. After two years as professor of physics at Cornell, he joined the Institute for Advanced Study in 1953.

GEORGE WALD ("Innovation in Biology") is Harvard University's well-known authority on the chemistry of vision. Born in New York, he graduated from New York University in 1927, then did graduate work in zoology at Columbia University under Selig Hecht. After receiving his Ph.D. in 1932, he traveled to Germany on a National Research Council fellowship. While studying in Otto Warburg's laboratory at the Kaiser Wilhelm Institute in Berlin, Wald made his first notable contribution to knowledge of the eye–his discovery of vitamin A in the retina. After another year of postdoctoral study at the University of Chicago, he went to Harvard, where he is now professor of biology.

JOHN R. PIERCE ("Innovation in Technology") is director of research in electrical communications at Bell Telephone Laboratories. Born in Iowa, he received his B.S., M.S. and Ph.D. degrees from the California Institute of Technology, then joined Bell Laboratories in 1936. There he has conducted research on microwaves and worked on the development of electron tubes and automatic switching systems.

JOHN C. ECCLES ("The Physiology of Imagination") is professor of physiology at Australian National University and president of the Australian Academy of Sciences. "My interest in nerve physiology dates from my medical-student days in Melbourne," he says, "when I became interested in philosophical problems relating to the nature of man and the way in which brain activity was related to all of the events experienced in consciousness. I became dissatisfied with the explanations given by psychologists and philosophers and decided to try and investigate for myself the basic phenomenon of nerve action. For that purpose I went to Oxford to work under Sir Charles Sherrington, who was then the acknowledged



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Coors engineers will help you work out the mechanical design details of your metalized ceramic parts or ceramic-to-metal assemblies. Contact us at the earliest possible stage of design in order to save time.

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world leader in this field. I was fortunate enough to have the opportunity of actually collaborating with him in research from 1928 to 1931, and we published about 10 papers conjointly." Eccles was a Victorian Rhodes Scholar at Oxford. He received a D. Phil. there in 1929, then held fellowships at Oxford's Exeter and Magdalen colleges until his return to Australia in 1937 as director of the Kanematsu Research Institute of Sydney Hospital. In 1944 he became professor of physiology at the University of Otago in New Zealand. He has taught at Australian National University since 1951. He is a Fellow of the Royal Society, a former Waynflete lecturer at Oxford, and this year was created a Knight Bachelor in the Queen's Birthday Honours List.

FRANK BARRON ("The Psychology of Imagination") is a research psychologist at the University of California's Institute of Personality Assessment and Research in Berkeley. A graduate of La Salle College in Philadelphia, he did his graduate work at the University of Minnesota and at the University of California, where he received his Ph.D. in 1950.

WARREN WEAVER ("The Encouragement of Science") is well qualified to speak on problems of the support of science: he is Vice President of the Rockefeller Foundation and Director of its Division of Natural Sciences and Agriculture. Weaver was trained at the University of Wisconsin, and became chairman of its department of mathematics in 1928. He joined the Rockefeller Foundation in 1932. During World War II, while working with the National Defense Research Committee, he revolutionized the technique of anti-aircraft fire control; for this contribution he received the Medal of Merit. He was also head of the Applied Mathematics Panel of the wartime Office of Scientific Research and Development.

VICTOR F. WEISSKOPF, who reviews Werner Heisenberg's *Physics and Philosophy* in this issue, is professor of physics at the Massachusetts Institute of Technology. Born in Vienna, he received a Ph.D. from the University of Göttingen in 1931 and has since taught at the universities of Copenhagen, Berlin and Rochester and at the Swiss Federal Institute of Technology in Zurich. Weisskopf worked on the Manhattan Project at Los Alamos during World War II.

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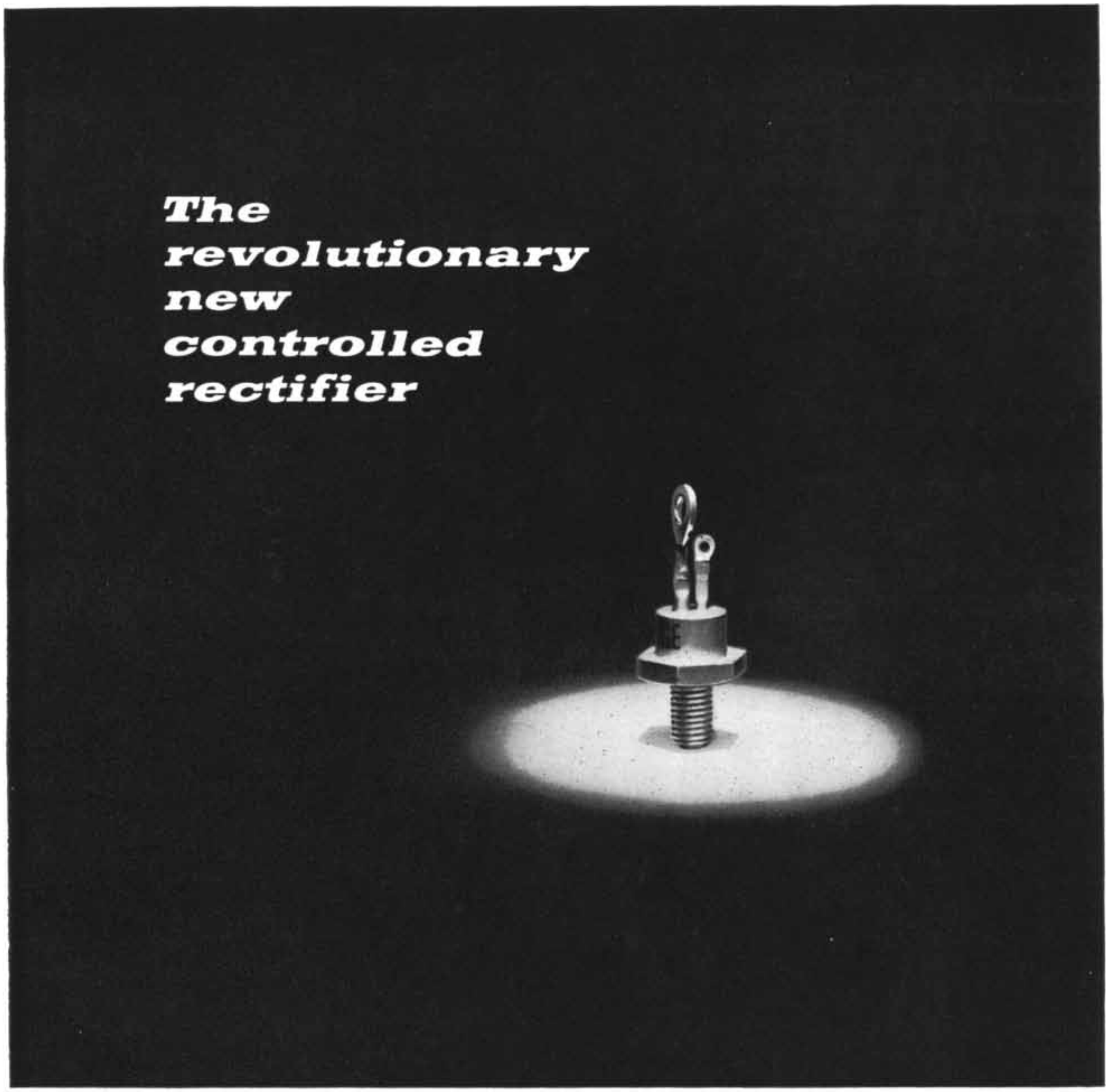

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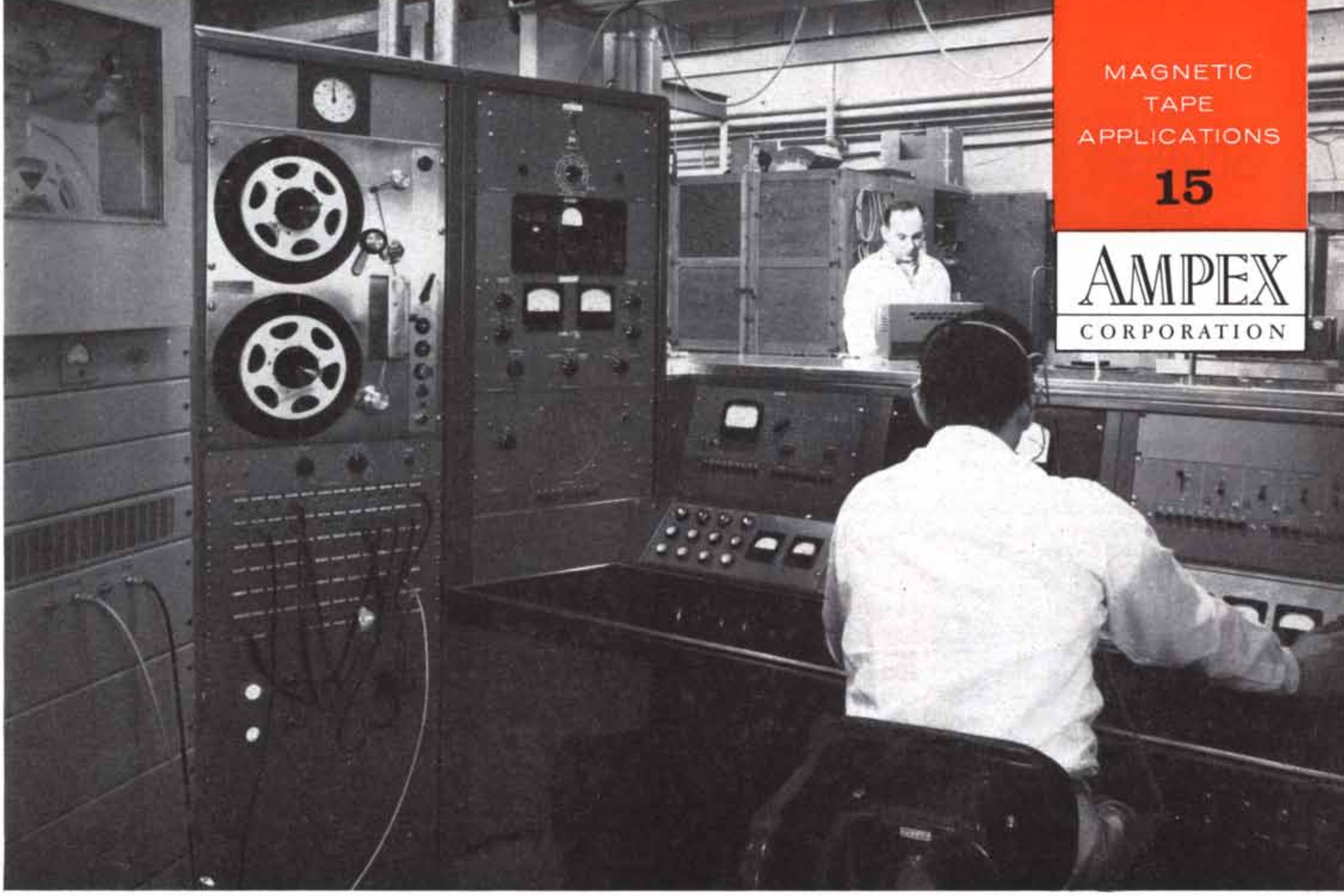

How to improve component reliability by better shake tests

Magnetic tape simplifies complex-wave testing and lessens human error

Many of the components that got their first ride on this tape-driven shaker are now circling the sky in Explorer I, our first successful earth satellite. It is highly significant that the California Institute of Technology Jet Propulsion Laboratory which led the development work on this satellite also pioneered complex-wave vibration testing. In this technique, magnetic recording plays many vital roles.

THE WAY TO OUTGUESS THE UNKNOWNS

Is simple sine-wave vibration testing sufficient? Or is a closer simulation of the missile's actual vibration environment a necessity? Results are not the same. Sinusoidal simplification often demands knowledge more complex than the complexities of a realistic test itself. Rocket components can bear neither the weight of excess safety factors nor the risks of conjecture — reasons why JPL chose random noise and complex waves.

Telemetered vibration tapes from actual missile flights are often used on shakers to assist development of test procedures. But this is not a complete answer. Different flights yield different vibration environments. A more ideal test-programming tape is a synthesized composite or envelope of the more severe conditions from many flights. This tape often combines random noise of engine vibration and complex waves from aerodynamic properties and structural resonances. And just as the missile's mass, velocity and surrounding atmosphere will change rapidly with time — so the taped program must change too.

Once on magnetic tape, any test program stays intact. It is repeatable without tedious setup and time-varying control of separate signal sources. With a properly calibrated tape, there is little chance that an operator will accidentally create destructive forces by errors in frequency or gain settings. Tape eliminates many possible sources of human error. It also leaves personnel free to concentrate on other requirements of shaker operation and test observation.

TAPE PASSES ALONG THE "IDEAL" TEST

So that co-contractors and subcontractors will run desired shake tests correctly on the components they furnish, Caltech's JPL frequently sends them program tapes. These contain calibration data in addition to the program itself. Thus a similar shake-table setup on the other side of the country can exactly duplicate the tests run in JPL's own laboratory. The tape lessens chance of misinterpretations and additive safety factors.

As quantity production of missile components gets under way, magnetic tape offers a means to run optimum shake tests on large numbers of components at widely separated manufacturers. From copy tapes, test programs of complex waves can be run almost as easily as a simple sinusoidal scan. Individual users need not have equipment to generate their own shaker-control programs. Prime contractor or research co-contractor can furnish the tapes. And since any number of duplicates can be made, a well-conceived test program can have unlimited circulation.

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Practical results are outstanding. Product contamination is eliminated, since pumping chamber is completely sealed, and no metal touches the liquid. Leakage and scoring of pump parts are eliminated; maintenance is reduced to infrequent replacement of liners. Body blocks and liners can be fabricated from a wide variety of plastic materials, to handle any corrosive, abrasive, or pharmaceutical fluid pumped in industry today.

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Original Equipment Model, with long trouble-free working life, and *no maintenance schedule needed,* styled *and priced* to meet the needs of original equipment manufacturers in all fields, from industrial to aircraft to home appliances.

Where can you use this simple, trouble-free, leak-free pump design?—or this kind of pioneering, problem-solving Cooper Alloy thinking? Inquiries welcomed, especially from Original Equipment Manufacturers. Write today, won't you?

COOPER ALLOY

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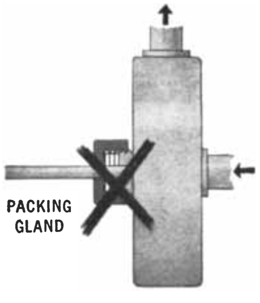
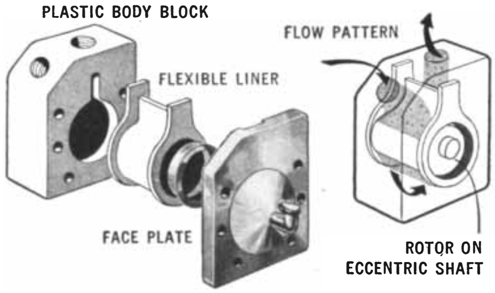
New Cooper Alloy pump design outflanks shaft seal problems by eliminating seals. Here's how:



Conventional Pump. Seals and packing are needed to seal off fluid pumping chamber where impeller shaft, powered from outside, enters casing. Seals require constant maintenance and attention, to prevent leakage, and depending on product, contamination and scoring of pump shaft. Vanton Pump, having no shaft seals, avoids these problems.



Vanton Design Is Simple. Minimizes Maintenance: Liquid flows in channel between molded plastic body and synthetic liner. No liquid touches metal. Liner flanges are secured to body block by bolted face plates. Pumping mechanism is rotor on eccentric shaft. All bearings are located outside of fluid area. At each revolution rotor pushes liner against body block and sweeps a "slug" of liquid around track from inlet to outlet. Resilient liners, replaceable in minutes, absorb "grind" of abrasive slurries. Wide choice of plastic materials gives easy handling of all industrial corrosive and abrasive liquids, with minimal maintenance. Self-priming, high vacuum, capacities ⅓-40 gpm. FOR ALL THE FACTS, WRITE FOR BULLETIN SA50.

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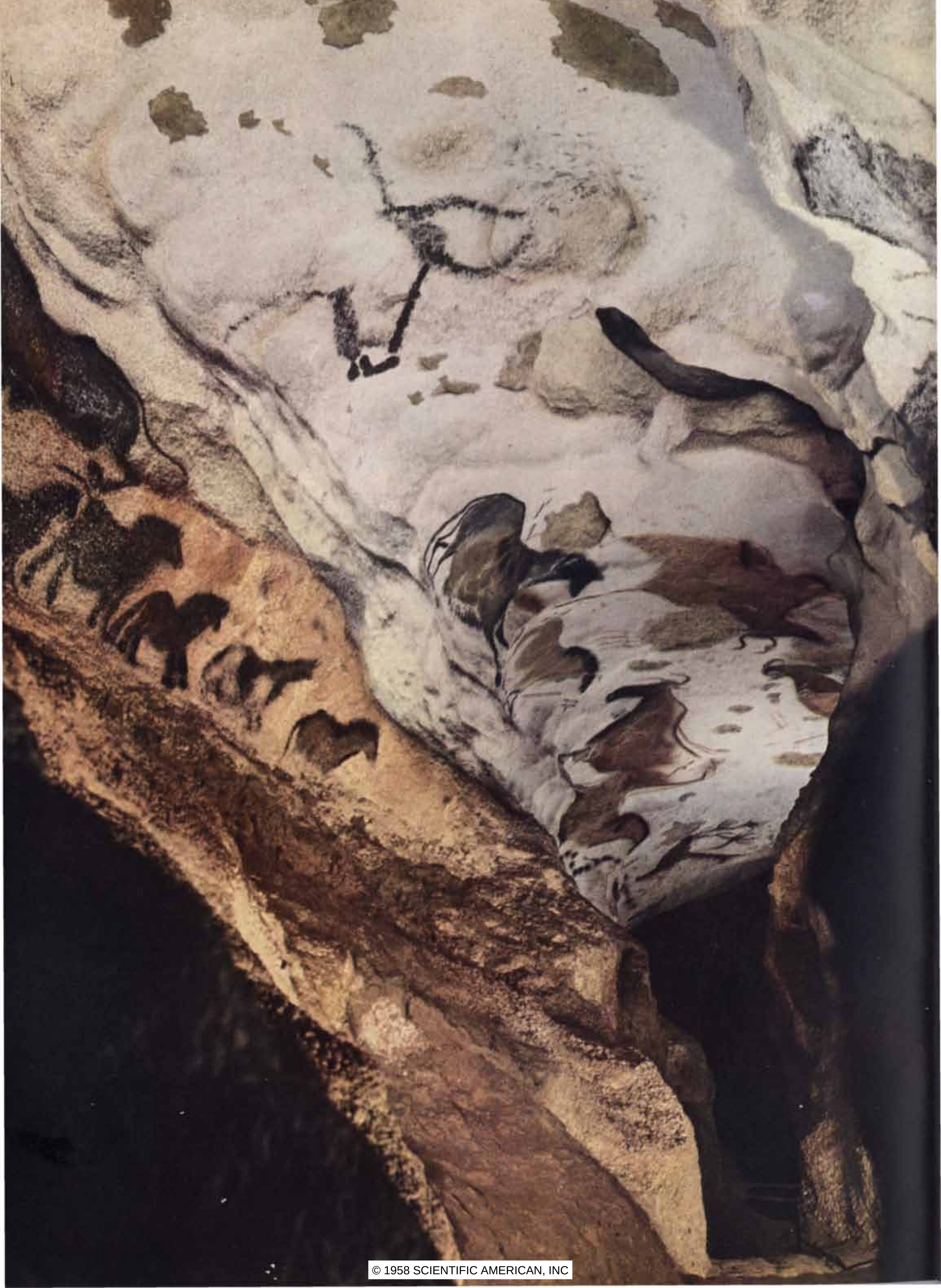

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THE CREATIVE PROCESS

Introducing an issue on innovation in science. The argument: Although science and art are social phenomena, an innovation in either field occurs only when a single mind perceives in disorder a deep new unity

by J. Bronowski

The most remarkable discovery made by scientists is science itself. The discovery must be compared in importance with the invention of cave-painting and of writing. Like these earlier human creations, science is an attempt to control our surroundings by entering into them and understanding them from inside. And like them, science has surely made a critical step in human development which cannot be reversed. We cannot conceive a future society without science.

I have used three words to describe these far-reaching changes: discovery, invention and creation. There are contexts in which one of these words is more appropriate than the others. Christopher Columbus discovered the West Indies, and Alexander Graham Bell invented the telephone. We do not call their achievements creations because they are not personal enough. The West Indies were there all the time; as for the telephone, we feel that Bell's ingenious thought was somehow not fundamental. The groundwork was there, and if not Bell then someone else would have stumbled on the telephone as casually as on the West Indies.

By contrast, we feel that *Othello* is genuinely a creation. This is not because *Othello* came out of a clear sky; it did not. There were Elizabethan dramatists before Shakespeare, and without them he could not have written as he did. Yet within their tradition *Othello* remains profoundly personal; and though every element in the play has been a theme of other poets, we know that the amalgam of these elements is Shakespeare's; we feel the presence of his single mind. The Elizabethan drama would have gone on without Shakespeare, but no one else would have written *Othello*.

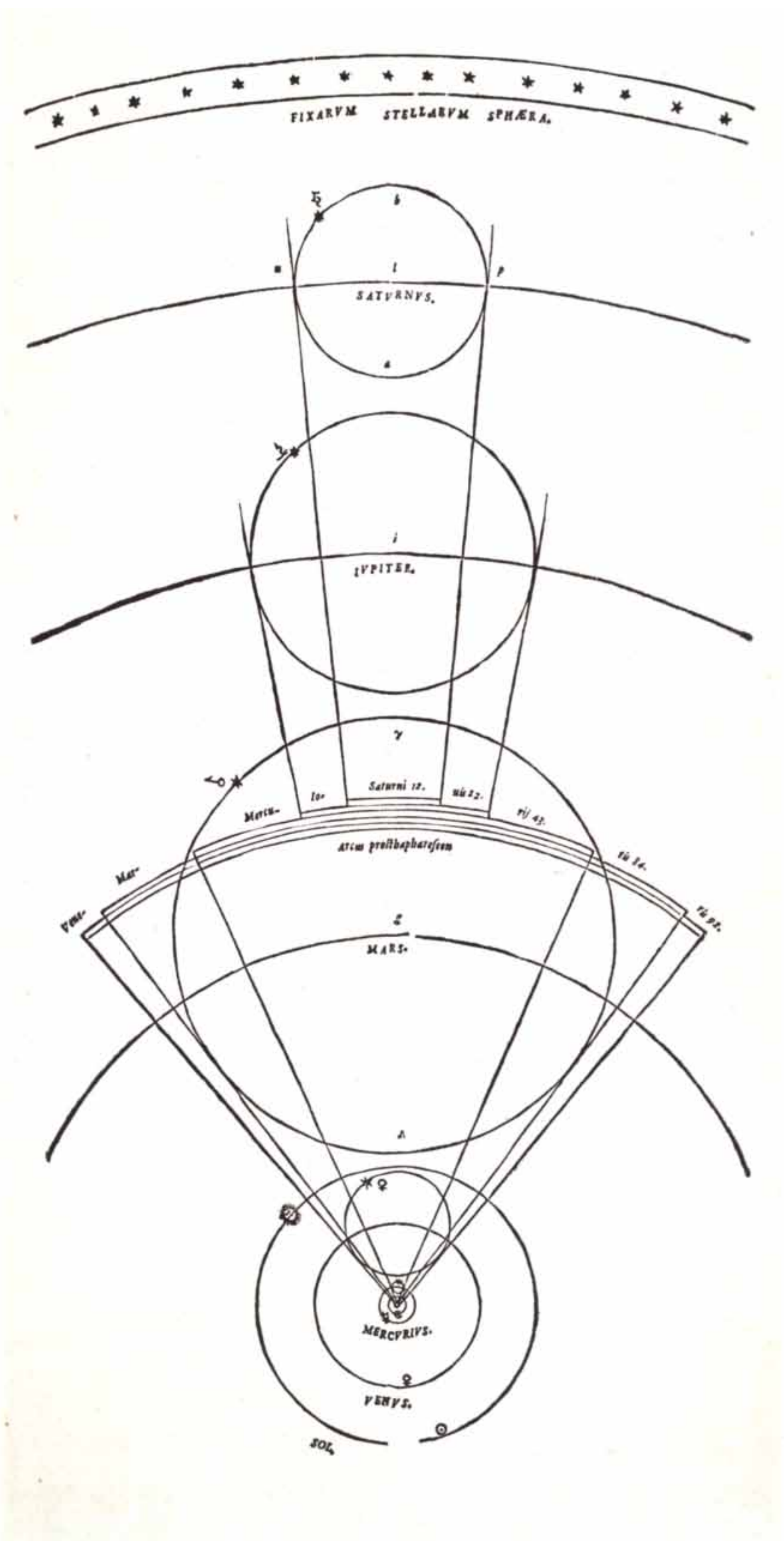
There are discoveries in science like Columbus's, of something which was always there: the discovery of sex in plants, for example. There are tidy inventions like Bell's, which combine a set of known principles: the use of a beam of electrons as a microscope, for example. In this article I ask the question: Is there anything more? Does a scientific theory, however deep, ever reach the roundness, the expression of a whole personality that we get from *Othello*?

CAVE PAINTING is a profound innovation which can be compared with the invention of writing and of science. The paintings on the opposite page adorn the roof and the walls of a cave in Montignac in south-central France. The horned bull at upper left and the troop of horses beneath it were painted at least 15,000 years ago. The animals toward the rear of the roof were painted at least 17,000 years ago. This photograph, made by *Life* photographer Ralph Morse, is published by the courtesy of *Life*.

A fact is discovered, a theory is invented; is any theory ever deep enough for it to be truly called a creation? Most nonscientists would answer: No! Science, they would say, engages only part of the mind—the rational intellect—but creation must engage the whole mind. Science demands none of that groundswell of emotion, none of that rich bottom of personality, which fills out the work of art.

This picture by the nonscientist of how a scientist works is of course mistaken. A gifted man cannot handle bacteria or equations without taking fire from what he does and having his emotions engaged. It may happen that his emotions are immature, but then so are the intellects of many poets. When Ella Wheeler Wilcox died, having published poems from the age of seven, *The Times* of London wrote that she was "the most popular poet of either sex and of any age, read by thousands who never open Shakespeare." A scientist who is emotionally immature is like a poet who is intellectually backward: both produce work which appeals to others like them, but which is second-rate.

I am not discussing the second-rate, and neither am I discussing all that useful but commonplace work which fills most of our lives, whether we are chemists or architects. There are in my laboratory of the British National Coal Board about 200 industrial scientists—pleasant, intelligent, sprightly people who thoroughly earn their pay. It is ridiculous to ask whether they are creators who produce works that could be compared with *Othello*. They are men with



PRE-COPERNICAN CONCEPTION of the solar system is depicted in this woodcut from Copernicus's successor Johannes Kepler. The earth is in the center (*bottom*). Around it move Mercury, Venus, the sun (*Sol*), Mars, Jupiter and Saturn. At top is the sphere of the fixed stars (*fixarum stellarum sphaera*). The planets moved not only in orbits but also in epicycles centered on the orbits. The straight lines show angles subtended by epicycles.

the same ambitions as other university graduates, and their work is most like the work of a college department of Greek or of English. When the Greek departments produce a Sophocles, or the English departments produce a Shakespeare, then I shall begin to look in my laboratory for a Newton.

Literature ranges from Shakespeare to Ella Wheeler Wilcox, and science ranges from relativity to market research. A comparison must be of the best with the best. We must look for what is created in the deep scientific theories: in Copernicus and Darwin, in Thomas Young's theory of light and in William Rowan Hamilton's equations, in the pioneering concepts of Freud, of Bohr and of Pavlov.

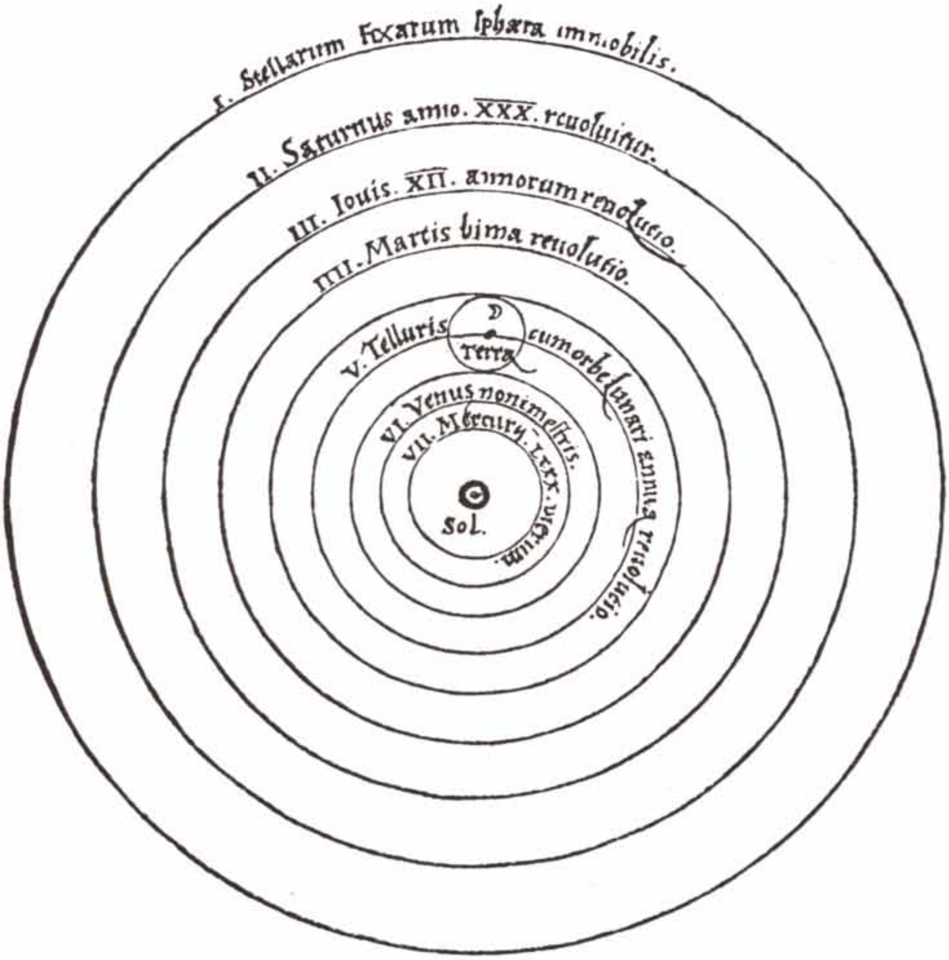
The most remarkable discovery made by scientists, I have said, is science itself. It is therefore worth considering the history of this discovery, which was not made all at once but in two periods. The first period falls in the great age of Greece, between 600 B.C. and 300 B.C. The second period begins roughly with the Renaissance, and is given impetus at several points by the rediscovery of Greek mathematics and philosophy.

When one looks at these two periods of history, it leaps to the eye that they were not specifically scientific. On the contrary: Greece between Pythagoras and Aristotle is still, in the minds of most scholars, a shining sequence of classical texts. The Renaissance is still thought of as a rebirth of art, and only specialists are uncouth enough to link it also with what is at last being called, reluctantly, the Scientific Revolution. The accepted view of Greece and of the Renaissance is that they were the great creative periods of literature and art. Now that we recognize in them also the two periods in which science was born, we must surely ask whether this conjunction is accidental. Is it a coincidence that Phidias and the Greek dramatists lived in the time of Socrates? Is it a coincidence that Galileo shared the patronage of the Venetian republic with sculptors and painters? Is it a coincidence that, when Galileo was at the height of his intellectual power, there were published in England in the span of 12 years the following three works: the Authorized Version of the Bible, the First Folio of Shakespeare and the first table of logarithms?

The sciences and the arts have flourished together. And they have been fixed together as sharply in place as in time. In some way both spring from one civilization: the civilization of the Mediter-

NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum deniq; locum Mercurius tenet, octuaginta dierum spacio circũ currens. In medio uero omnium residet Sol. Quis enim in hoc



pulcherimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentẽ omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoq; minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximã Luna cũ terra cognationẽ habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub

hac

COPERNICAN CONCEPTION of the solar system is reproduced from Copernicus's own *De Revolutionibus Orbium Coelestium.* The sun is in the center. Around it move Mercury, Venus, the earth (Telluris) and moon, Mars, Jupiter and Saturn.

ranean, which expresses itself in action. There are civilizations which have a different outlook; they express themselves in contemplation, and in them neither science nor the arts are practiced as such. For a civilization which expresses itself in contemplation values no creative activity. What it values is a mystic immersion in nature, the union with what already exists.

The contemplative civilization we know best is that of the Middle Ages. It has left its own monuments, from the Bayeux Tapestry to the cathedrals; and characteristically they are anonymous. The Middle Ages did not value the cathedrals, but only the act of worship which they served. It seems to me that the works of Asia Minor and of India (if I understand them) have the same anonymous quality of contemplation, and like the cathedrals were made by craftsmen rather than by artists. For the artist as a creator is personal; he cannot drop his work and have it taken up by another without doing it violence. It may be odd to claim the same personal engagement for the scientist; yet in this the scientist stands to the technician much as the artist stands to the craftsman. It is at least remarkable that science has not flourished either in an anonymous age, such as the age of medieval crafts, or in an anonymous place, such as the craftsmanlike countries of the East.

The change from an outlook of contemplation to one of action is striking in the long transition of the Renaissance and the Scientific Revolution. The new men, even when they are churchmen, have ideals which are flatly opposed to the monastic and withdrawn ideals of the Middle Ages. Their outlook is active, whether they are artists, humanist scholars or scientists.

The new man is represented by Leonardo da Vinci, whose achievement has never, I think, been rightly understood. There is an obvious difference between Leonardo's painting and that of his elders—between, for example, an angel painted by him and one by Verrocchio. It is usual to say that Leonardo's angel is more human and more tender; and this is true, but it misses the point. Leonardo's pictures of children and of women are human and tender; yet the evidence is powerful that Leonardo liked neither children nor women. Why then did he paint them as if he were entering their lives? Not because he saw them as people, but because he saw them as expressive parts of nature. We do not understand the luminous and transparent affection with which Leonardo lingers on a head or a hand until we look at the equal affection with which he paints the grass and the flowers in the same picture.

To call Leonardo either a human or a naturalist painter does not go to the root of his mind. He is a painter to whom the detail of nature speaks aloud; for him, nature expresses herself in the detail. This is a view which other Renaissance artists had; they lavished care on perspective and on flesh tones because these seemed to them (as they had not seemed in the Bayeux Tapestry) to carry the message of nature. But Leonardo went further; he took this artist's vision into science. He understood that science as much as painting has to find the design of nature in her detail.

When Leonardo was born in 1452, science was still Aristotle's structure of cosmic theories, and the criticism of Aristotle in Paris and Padua was equally grandiose. Leonardo distrusted all large theories, and this is one reason why his experiments and machines have been forgotten. Yet he gave science what it most needed, the artist's sense that the detail of nature is significant. Until science had this sense, no one could care—or could think that it mattered—how fast two unequal masses fall and whether the orbits of the planets are accurately circles or ellipses.

The power which the scientific method has developed has grown from a procedure which the Greeks did not discover: the procedure of induction. This procedure is useless unless it is followed into the detail of nature; its discovery therefore flows from Leonardo's vision.

Francis Bacon in 1620 and Christian Huygens in 1690 set down the intellectual bases of induction. They saw that it is not possible to reach an explanation of what happens in nature by deductive steps. Every explanation goes beyond our experience and thereby becomes a speculation. Huygens says, and philosophers have sheepishly followed him in this, that an explanation should therefore be called probable. He means that no induction is unique; there is always a set—an infinite set—of alternatives between which we must choose.

The man who proposes a theory makes a choice—an imaginative choice which outstrips the facts. The creative activity of science lies here, in the process of induction. For induction imagines more than there is ground for and creates relations which at bottom can never be verified. Every induction is a speculation and it guesses at a unity which the facts present but do not strictly imply.

To put the matter more formally: A scientific theory cannot be constructed from the facts by any procedure which can be laid down in advance, as if for a machine. To the man who makes the theory, it may seem as inevitable as the ending of *Othello* must have seemed to Shakespeare. But the theory is inevitable only to him; it is his choice, as a mind and as a person, among the alternatives which are open to everyone.

There are scientists who deny what I have said—that we are free to choose between alternative theories. They grant that there are alternative theories, but they hold that the choice between them is made mechanically. The principle of choice, in their view, is Occam's Razor: we choose, among the theories which fit the facts we know now, that one which is simplest. On this view, Newton's laws were the simplest theory which covered the facts of gravitation as they were then

EIGHT MIGHTY CREATORS mentioned in this article are depicted in this drawing

known; and general relativity is not a new conception but is the simplest theory which fits the additional facts.

This would be a plausible view if it had a meaning. Alas, it turns out to be a verbal deception, for we cannot define simplicity; we cannot even say what we mean by the simpler of two inductions. The tests which have been proposed are hopelessly artificial and, for example, can compare theories only if they can be expressed in differential equations of the same kind. Simplicity itself turns out to be a principle of choice which cannot be mechanized.

Of course every innovator has thought that his way of arranging the facts is particularly simple, but this is a delusion. Copernicus's theory in his day was not simple to others, because it demanded two rotations of the earth—a daily one and a yearly one—in place of one rotation of the sun. What made his theory seem simple to Copernicus was something else: an esthetic sense of unity. The motion of all the planets around the sun was both simple and beautiful to him, because it expressed the unity of God's design. The same thought has moved scientists ever since: that nature has a unity, and that this unity makes her laws seem beautiful in simplicity.

The scientist's demand that nature shall be lawful is a demand for unity. When he frames a new law, he links and organizes phenomena which were thought different in kind; for example, general relativity links light with gravitation. In such a law we feel that the disorder of nature has been made to reveal a pattern, and that under the colored chaos there rules a more profound unity.

A man becomes creative, whether he is an artist or a scientist, when he finds a new unity in the variety of nature. He does so by finding a likeness between things which were not thought alike before, and this gives him a sense both of richness and of understanding. The creative mind is a mind that looks for unexpected likenesses. This is not a mechanical procedure, and I believe that it engages the whole personality in science as in the arts. Certainly I cannot separate the abounding mind of Thomas Young (which all but read the Rosetta Stone) from his recovery of the wave theory of light, or the awkwardness of J. J. Thomson in experiment from his discovery of the electron. To me, William Rowan Hamilton drinking himself to death is as much part of his prodigal work as is any drunken young poet; and the childlike vision of Einstein has a poet's innocence.

When Max Planck proposed that the radiation of heat is discontinuous, he seems to us now to have been driven by nothing but the facts of experiment. But we are deceived; the facts did not go so

by Eric Mose. At left is Leonardo da Vinci. Second from left is William Blake; third, William Shakespeare; fourth, Nikolaus Copernicus; fifth, Galileo Galilei; sixth, Christian Huygens. At the upper right are Albert Einstein (*left*) and Max Planck (*right*).

BAYEUX TAPESTRY, a short section of which is shown here, exemplifies the art of the "contemplative civilizations" discussed by Bronowski. Made by anonymous French artists around 1077, the tapestry is 20 inches high and 231 feet long. It depicts scenes in the

far as this. The facts showed that the radiation is not continuous; they did not show that the only alternative is Planck's hail of quanta. This is an analogy which imagination and history brought into Planck's mind. So the later conflict in quantum physics between the behavior of matter as a wave and as a particle is a conflict between analogies, between poetic metaphors; and each metaphor enriches our understanding of the world without completing it.

In *Auguries of Innocence* William Blake wrote:

A dog starv'd at his Master's gate
Predicts the ruin of the State.

This seems to me to have the same imaginative incisiveness, the same understanding crowded into metaphor, that Planck had. And the imagery is as factual, as exact in observation, as that on which Planck built; the poetry would be meaningless if Blake used the words "dog," "master" and "state" less robustly than he does. Why does Blake say dog and not cat? Why does he say master and not mistress? Because the picture he is creating depends on our factual grasp of the relation between dog and master. Blake is saying that when the master's conscience no longer urges him to respect his dog, the whole society is in decay. This profound thought came to Blake again and again: that a morality expresses itself in what he called its Minute Particulars—that the moral detail is significant of a society. As for the emotional power of the couplet, it comes, I think, from the change of scale between the metaphor and its application: between the dog at the gate and the ruined state. This is why Blake, in writing it, seems to me to transmit the same excitement that Planck felt when he discovered, no, when he created, the quantum.

One of the values which science has made natural to us is originality; as I said earlier, in spite of appearances science is not anonymous. The growing tradition of science has now influenced the appreciation of works of art, so that we expect both to be original in the same way. We expect artists as well as scientists to be forward-looking, to fly in the face of what is established, and to create not what is acceptable but what will become accepted. One result of this prizing of originality is that the artist now shares the unpopularity of the scientist: the large public dislikes and fears the way that both of them look at the world.

As a more important result, the way in which the artist looks at the world has come close to the scientist's. For example, in what I have written science is pictured as preoccupied less with facts than with relations, less with numbers than with arrangement. This new vision, the search for structure, is marked throughout the other articles in this issue of SCIENTIFIC AMERICAN; and it is also marked in modern art. Abstract sculpture often looks like an exercise in topology, exactly because the sculptor shares the vision of the topologist.

In each of the articles which follow I find again my view, that a theory is the creation of unity in what is diverse by the discovery of unexpected likenesses. In all of them innovation is pictured as an act of imagination, a seeing of what others do not see; indeed, Dr. Pierce uses the phrase "creative observation," which would outrage many theoretical scientists, but which exactly describes the pioneer vision of Leonardo. And Dr. Eccles gives me almost a physical feeling of creation, as if the structure of a theory reproduces the pattern of interlacing paths engaged in the brain.

There is, however, one striking division in these articles, between those

life of Harold II, king of England, and his defeat by William the Conqueror. At left is the funeral procession of King Edward. At right are scenes of Edward's death. This section is reproduced from *The Bayeux Tapestry*, published by the Phaidon Press in 1957.

which treat the physical and those which treat the biological sciences. The physical scientists have more fun. Their theories are more eccentric; they live in a world in which the unexpected is everyday. This is a strange inversion of the way that we usually picture the dead and the living, and it reflects the age of these sciences. The physical sciences are old, and in that time the distance between fact and explanation has lengthened; their very concepts are unrealistic. The biological sciences are young, so that fact and theory look alike; the new entities which have been created to underlie the facts are still representational rather than abstract. One of the pleasant thoughts that these articles prompt is: How much more extravagant the biological sciences will become when they are as old as the physical sciences.

"TWO FORMS," by the British sculptor Henry Moore, is an example of experimental modern art, the attitude of which Bronowski compares with that of modern science. This sculpture, carved in pynkado wood, is in the collection of the Museum of Modern Art.

Innovation in Mathematics

The first of four articles on innovation in four central fields. The mathematician seeks a new logical relationship, a new proof of an old relationship, or a new synthesis of many relationships

by Paul R. Halmos

Everybody knows that for the past 300 years innovations in science and technology have come at a steadily increasing pace. Practically everyone is aware that mathematics has played a central role in this advance. Yet, strangely, many people think of mathematics itself as a static art—a body of eternal truth that was discovered by a few ancient, shadowy figures, and upon which engineers and scientists can draw as needed.

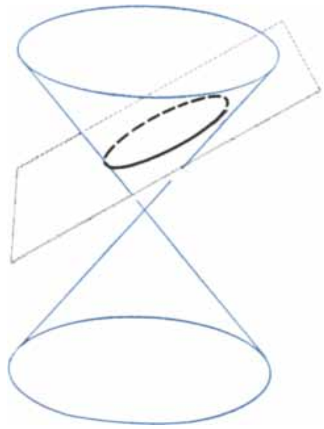
Of course nothing could be further from the truth. Mathematics is improving, changing and growing every day. On its growth depends not only progress in all the other fundamental investigations, but also progress in the crudest, bread-and-butter circumstances of our daily lives.

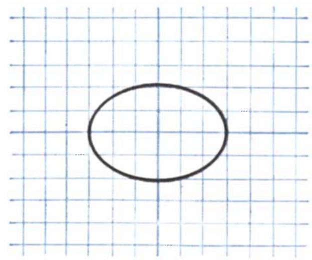
The late John von Neumann liked to cite this example of the relation between technological development and pure mathematics: A hundred and fifty years ago one of the most important problems of applied science—on which development in industry, commerce and government depended—was the problem of saving lives at sea. The statistics of the losses were frightful. The money and effort expended to solve the problem were frightful too—and sometimes ludicrous. No gadget, however complicated, was too ridiculous to consider—ocean-going passenger vessels fitted out like outrigger canoes may have looked funny, but they were worth a try. While leaders of government and industry were desperately encouraging such crank experiments, mathematicians were developing a tool that was to save more lives than all the crackpot inventors combined dared hope. That tool is what has come to be known as the theory of functions of a complex variable (a variable containing the "imaginary" number i, the square root of minus one). Among the many applications of this purely mathematical notion, one of the most fruitful is in the theory of radio communication. From the mathematician Karl Friedrich Gauss to the inventor Guglielmo Marconi it is only a few steps that almost any pair of geniuses such as James Clerk Maxwell and Heinrich Hertz can take in their stride.

The list of mathematical innovations could be continued almost endlessly. Here are just a few more. The theory of groups, for instance, was developed about 100 years ago. It probably would have seemed an ugly and useless invention to the contemporaries of Gauss. Today it is part of the mathematical repertory of every physicist. As recently as 50 years ago there was not a single professor of statistics in the U. S. Now statistical methods are an imperative tool in such sciences as genetics and experimental psychology. Von Neumann's theory of games, first published in 1928 and revived 20 years later, seems to be finding important applications in economics and operations research. Finally, lest anyone suppose that mathematical ideas spring full-blown and perfect from the brows of their creators, we may recall that Euclid's celebrated geometric proofs were found, after 2,000 years, to contain serious gaps. The holes in his reasoning were finally plugged by the great German mathematician David Hilbert, around the turn of the century.

Admitting, then, that there are innovations in mathematics, let us try to see just what they consist of, and, insofar as it is possible, how they come about. One way to classify a mathematical contribution is this: It may be a new proof of an old fact, it may be a new fact, or it may be a new approach to several facts at the same time.

A large part of the activity of professional mathematicians is a search for new proofs of old facts. One reason for this is pure pleasure: there is esthetic enjoyment in getting a fresh point of view on a familiar landmark. Another is that the original creator hardly ever





$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

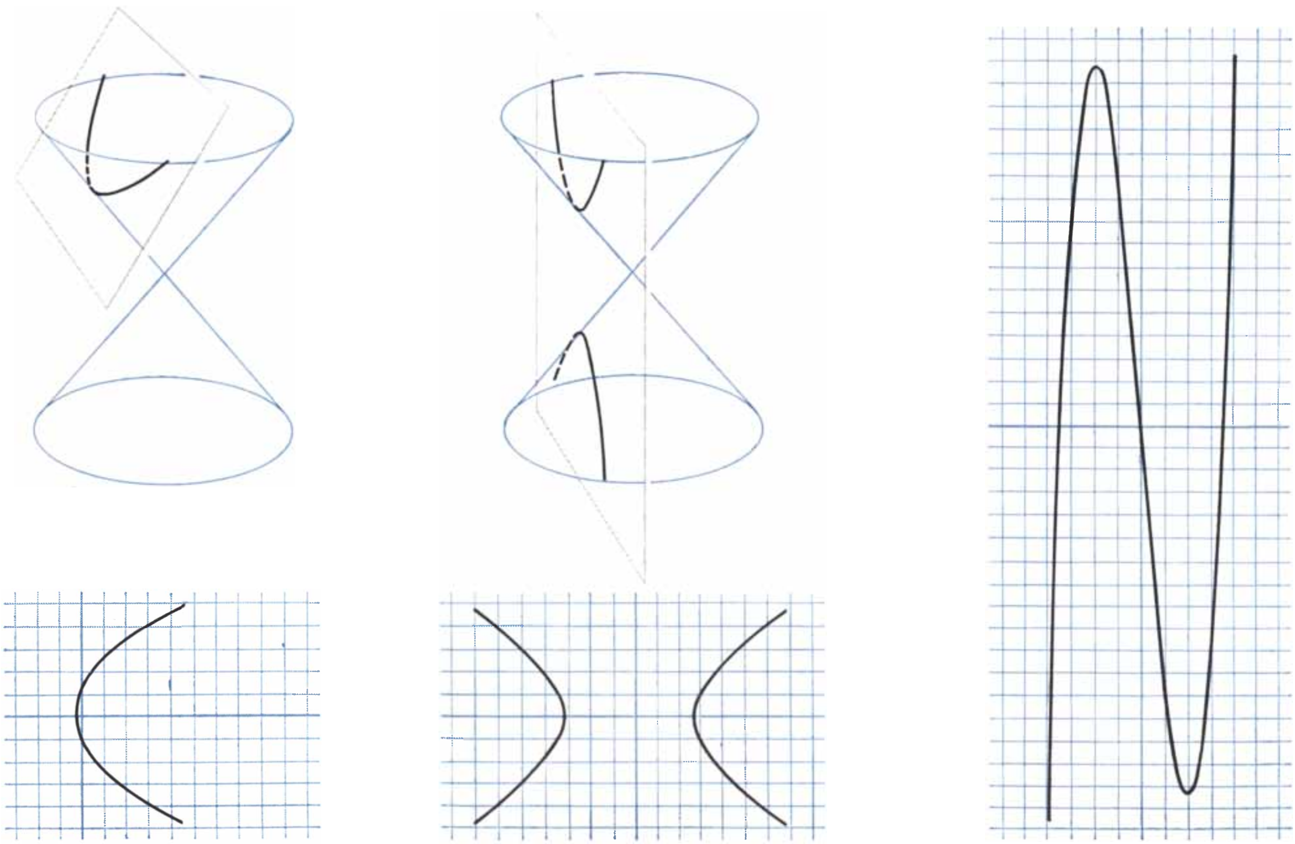
GEOMETRY AND ALGEBRA were connected by Descartes's invention of analytic geometry. The first three figures, from left

reached his goal by the shortest, neatest, most efficient route, nor fully appreciated the connections between his brain-child and all other fields of mathematics. This is connected with a third and very practical motive. Mathematics has grown so luxuriantly in the past 2,000 years that it must be continually polished, simplified, systematized, unified and condensed. Otherwise the problem of handing the torch to each new generation would become completely unmanageable. No man alive today can know, even sketchily, all the mathematics published in the last 10 years. In order to give workers in the field enough understanding so that they can move ahead intelligently, it is absolutely imperative to find ever newer, shorter and simpler proofs that at the same time are more illuminating and provide more insight than their predecessors.

Curiously, it is sometimes good to find a new proof more complicated than an old one. If the new proof establishes some previously unsuspected connections between two ideas, it often leads to a generalization that makes the task of future learners far easier than it was for their teachers. René Descartes's coordinate, or "analytic," geometry is a good example. One consequence of Descartes's innovation is that it is possible to prove every proposition in Euclid's geometry by algebraic means [*see illustrations on page 70*]. The virtues of analytic geometry are many and they are great, but the simplicity of analytic proofs, when compared with Euclidean ones, is definitely not one of them. In most cases the analytic proof of a Euclidean fact about triangles or circles is a messy calculation that teaches us nothing.

The value of analytic geometry is that it reveals a connection between two branches of mathematics—algebra and geometry—which had been thought to be entirely separate. One of the main concerns of the early geometers was conic sections, the curves that are formed by cutting a cone with a plane [*see illustrations below*]. This is obviously a purely spatial way of thinking about the figures. When the conic sections (ellipse, parabola and hyperbola) are plotted on Cartesian coordinates and their algebraic equations are written down, it turns out that all the equations contain the squares of x and y, but no higher powers. Here is a new fact that provides deeper insight into the nature of the curves. And it also suggests a new question: What about the geometric picture of curves that do involve higher powers of x and y? Now we are led to consider a whole new class of geometric figures to which spatial intuition alone would never have led us. Furthermore, by picturing the equations geometrically, we gain new insight into their algebraic structure.

Of course most new proofs represent a gain in simplicity as well as in insight. Consider, for example, the problem of finding the area of the plane region bounded by the parabolic trajectory of a projectile and the line segment joining the gun and the target. This is a problem

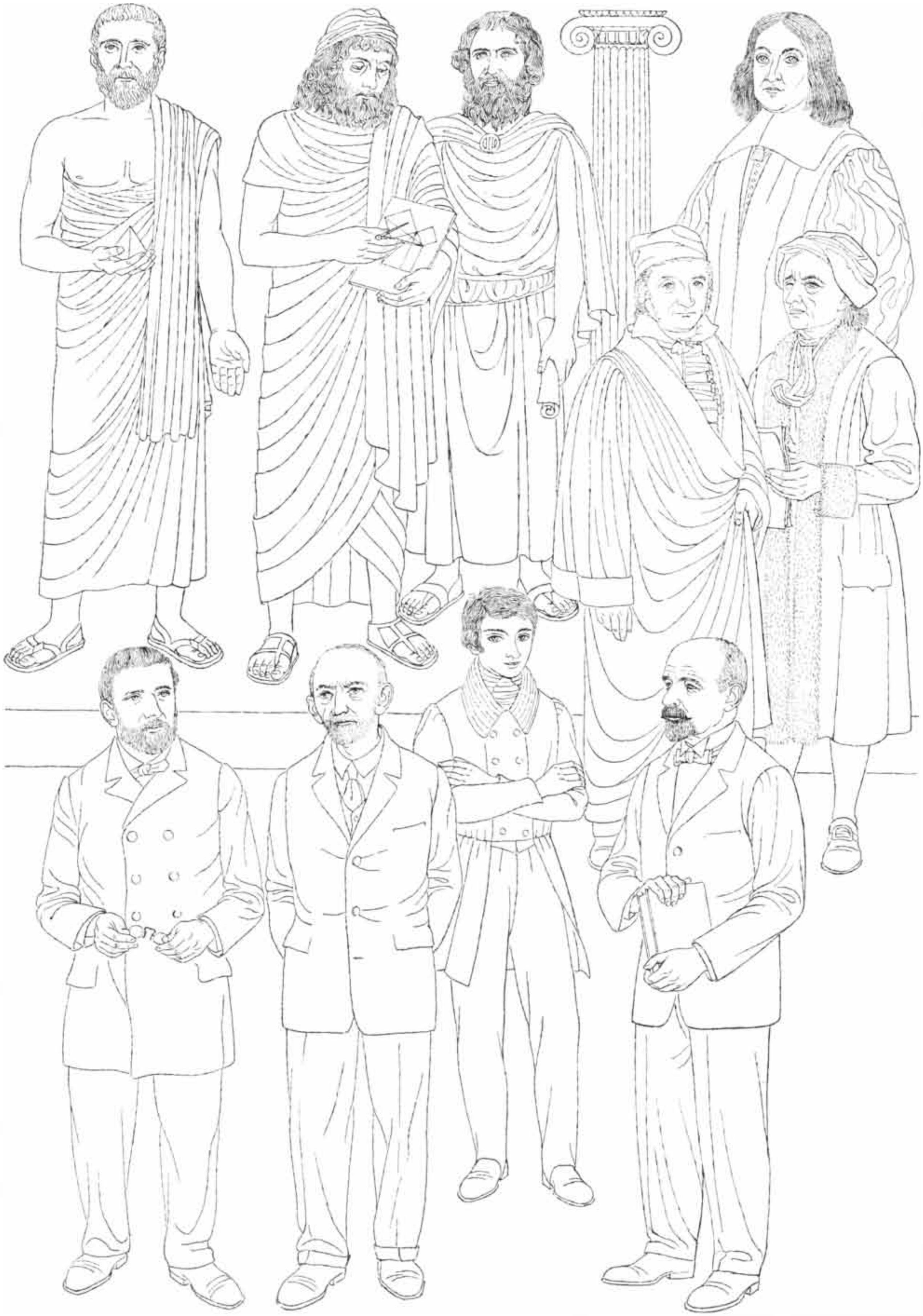


$y^2 = 2px$

$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$

$y = ax^3 + bx$

to right, show at top the curves (ellipse, parabola and hyperbola) that can be cut from a cone by a plane. At bottom the same curves are represented as graphical pictures of algebraic equations. These equations turn out to contain the squares of the variables, but no higher powers of the variables. The figure at the right on this page is the graph of an equation in which one of the variables is cubed.



that Archimedes could and did solve; his solution depends on the celebrated "method of exhaustion," a way of finding complicated areas by adding together more and more simple ones. Archimedes' solution is both ingenious and long. The problem can also be solved, in one line of writing, by any mediocre sophomore calculus student. To be sure, the sophomore's efficient solution is the product of the profound thought of many mathematicians over many years.

Individual proofs do become shorter, but only because they become embedded in larger contexts from which it is easy to pluck them. The larger contexts spread and mix with other general concepts, forming a still-larger unified whole. After a couple of centuries 10 of the greatest discoveries of the era are likely to find themselves together between the covers of a slim volume in the pocket of a graduate student who, with luck, will absorb them all in two or three months.

So much for new proofs. What about new facts? In a trivial sense we have all discovered new mathematical facts. We see one every time we add a column of figures on our tax return. The chances are that no one has ever before observed that the sum of just those figures is what it is. A really interesting new mathematical fact has much more breadth and generality. Here is an example that is not exactly brand new (it was proved by Leonhard Euler some 200 years ago), but might be new to nonmathematicians: Every positive whole number is the sum of not more than four squares. The squares are of course 1, 4, 9, 16 and so on. Between them there are larger and larger gaps [*see illustration at top left on pages 72 and 73*]. If we add the squares two at a time (repetitions such as 4 + 4 are allowed), we get a sequence with fewer gaps. If we fill in all the numbers that are sums of three squares, there will be still fewer gaps. Euler's theorem says that if we fill in all the numbers that are sums of four squares, there will be no more gaps left.

Another example of a mathematical fact, also no longer new, but which illustrates the powerful role that mathematical innovation can play, is the theory of the solvability of equations. It was created by the young French genius Evariste Galois in the early part of the 19th century. Galois's predecessors had found general formulas for solving equations up to the fourth degree—that is, equations in which the unknown is raised to no higher power than four. (One is the familiar "quadratic formula" of high-school algebra, which solves equations of the second degree.) Naturally they expected that there were also formulas that would solve equations of higher degree, and they spent an enormous amount of time and effort looking for them.

Galois dared to doubt the existence of such generalized formulas. He attacked the problem from a fresh point of view, looking not for tricks that would yield the supposedly hidden formulas, but trying to find more general properties of equations and their solutions. His work led to the important and fruitful concept of groups—sets of entities for which an operation similar to multiplication is defined. An immediate result of his beautiful and deep intellectual construction was to confirm his doubt: there are no general formulas for the solution of all algebraic equations. Thus he discovered a new fact.

The work of Galois exemplifies the third type of innovation also: the new approach. Group theory has proved an invaluable tool for attacking an extremely wide range of mathematical problems. Furthermore, Galois's ideas turned up another surprising connection between algebra and geometry. They show that the famous ancient puzzles of squaring the circle, duplicating the cube and trisecting the angle also have no general solutions. The reverberations of Galois's new approach can still be felt in modern algebra.

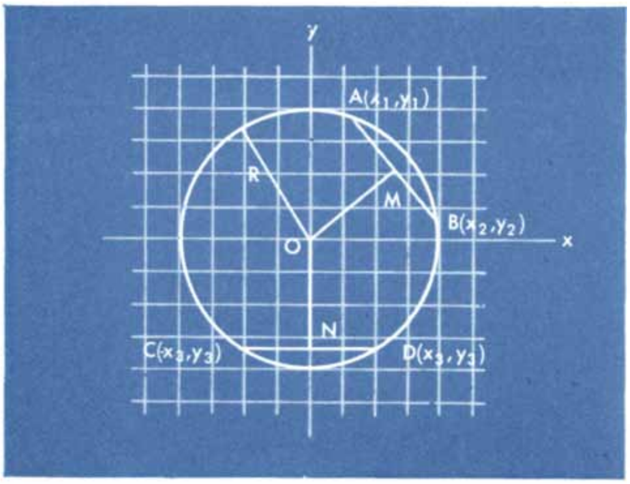
Where does a mathematical innovation come from? Sometimes, but by no means always, the source lies outside mathematics. Just as mathematics can make contributions to engineering, physics, psychology, genetics, economics and other disciplines, these other disciplines can keep mathematical creativity alive by asking stimulating questions, pointing to fresh lines of development, and, at the very least, providing suggestive language for the expression of mathematical ideas. It has happened that when a physicist needed a mathematical theory, it was already sitting there, waiting to be picked up and used. More often it happens that when something new is needed for such applications, the news percolates up to the ivory tower in a few decades (or more), and the answer comes down after a comparable time interval.

New mathematics often comes from plain curiosity. The right kind of mathematical curiosity is a precious possession that usually belongs only to professionals of the highest rank. The hardest problem of a young mathematician is to find a problem. The right question, well asked, is more than half the battle, and often the only part that requires inspiration. The answer itself may be difficult, and it may require ingenuity in the use of known techniques, but it often happens that all the thrill of creation and insight is concentrated in the question.

It should perhaps be mentioned that after the question is formulated, the mathematician does not proceed (as it is often supposed) like a scientific Sherlock Holmes. A mathematician is not a deduction machine, but a human being. New mathematics comes to him not by pure thought and deduction, but by sweat, experiment, induction and, if he is lucky, inspiration. Of course a mathematical experiment does not involve wires, tubes and bubbling liquids; it consists, rather, of a detailed examination of some particular cases or analogues of the desired result. (Example: Write down the first 10 squares, and write down systematically all the numbers that can be obtained as sums of two, or three, or four of them.) On the basis of such experiments the mathematician jumps inductively to bold conclusions. It may then be a difficult task to prove them, but often the purely deductive arrangement of the work serves more to communicate facts than to establish them.

To return to the source of innovations, it should be said that mathematicians share their curiosity, as well as their knowledge, with one another. At the beginning of his career a student often battens off the curiosity of his teachers. Great men do essentially the same thing when they decide to attack a problem that their predecessors could not solve. Galois himself was solving problems that he did not create. There will always be unsolved problems from bygone days: two famous ones that are not quite dead are the four-color map problem and Fermat's last theorem

SOME INNOVATORS whose mathematical contributions are discussed in this article are depicted on the opposite page. In the top row, from left to right, are Pythagoras, Euclid, Archimedes and Pierre de Fermat. In front of Fermat are Karl Friedrich Gauss and Leonhard Euler. The figures in the bottom row are Henri Poincaré, David Hilbert, Evariste Galois and Georg Cantor.



Given the curve $x^2 + y^2 = R^2$, AB = CD

To prove OM = ON

M is midpoint of AB and its coordinates are

$$\left(\frac{x_1 + x_2}{2}, \frac{y_1 + y_2}{2}\right)$$

$$OM = \sqrt{\left(\frac{x_1 + x_2}{2}\right)^2 + \left(\frac{y_1 + y_2}{2}\right)^2}$$

Expanding and substituting R^2 for $x_1^2 + y_1^2$ and $x_2^2 + y_2^2$

$$OM = \sqrt{\frac{R^2 + x_1x_2 + y_1y_2}{2}}$$

But ON = y_3, so we must prove

$$y_3 = \sqrt{\frac{R^2 + x_1x_2 + y_1y_2}{2}}$$

$$AB = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

Expanding and substituting as above

$$AB = \sqrt{2R^2 - 2x_1x_2 - 2y_1y_2}$$

CD = $2x_3$, and since AB = CD,

$$\sqrt{2R^2 - 2x_1x_2 - 2y_1y_2} = 2x_3$$

$$2R^2 - 2x_1x_2 - 2y_1y_2 = 4x_3^2$$

$$x_1x_2 + y_1y_2 = R^2 - 2x_3^2$$

Substituting in the expression for OM,

$$OM = \sqrt{\frac{R^2 + R^2 - 2x_3^2}{2}}$$

$$OM = \sqrt{R^2 - x_3^2}$$

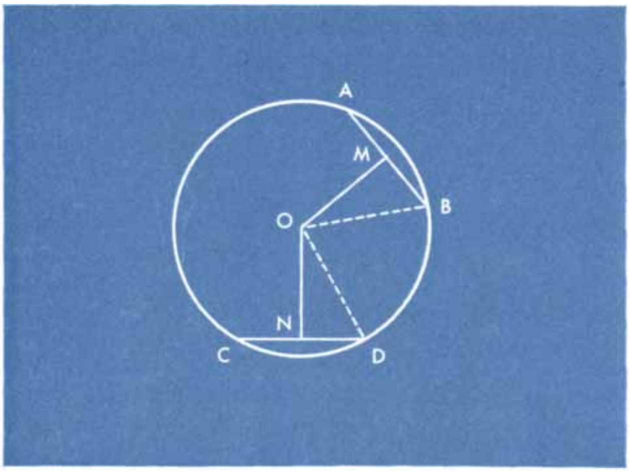
But $x_3^2 + y_3^2 = R^2$

$\therefore R^2 - x_3^2 = y_3^2$

$\therefore OM = \sqrt{y_3^2} = y_3$

$\therefore OM = ON$

ANALYTIC PROOF of a Euclidean theorem is outlined above. The theorem states that equal chords of a circle are equidistant from the center. Proving the statement requires no ingenuity, but the algebraic computations are long, tedious and unilluminating.



Draw OB and OD

OB = OD	Radii of the same ⊙ are equal
MB = ½ AB and ND = ½ CD	A perpendicular from the center of a circle to a chord bisects the chord
∴ MB = ND	Halves of equals are equal
∴ △ OND ≅ △ OMB	Hypotenuse and leg
∴ OM = ON	

Q.E.D.

EUCLIDEAN PROOF of the proposition that equal chords are equidistant from the center is much shorter and neater than the analytic proof. Analytic geometry is valuable not as a method of grinding out proofs, but as a link between algebra and geometry.

(more properly, since it has not been proved, Fermat's last conjecture). Mathematicians of this century have been singularly fortunate in having a ready-made and inspiring list of problems to work on. It consists of 23 searching questions put together by David Hilbert and presented at the International Congress of Mathematicians in Paris in 1900. Several of the problems have been solved (and have made the reputations of their solvers); many of them are still open.

Practical application, curiosity and history are the main wellsprings of innovation, but two others should also be mentioned. One is failure; the other is error. Everyone who has so far tried to prove Fermat's conjecture has failed, but some of the efforts have produced the most fruitful concepts in modern algebra and in number theory. As for error, whole books full of brilliant mathematics have been inspired by it. An oversight or a misstatement by mathematician X is often just what mathematician Y needs to find the truth; if X and Y happen to be the same person, so much the better.

Now that we have examined some of the sources of mathematical creation, let us return to the creations themselves. Perhaps the greatest single innovation in the last 100 years is set theory, invented by the German mathematician Georg Cantor. In it we find some new proofs of old facts, and we also find many, many new facts. Most important of all, we find a new approach that has completely changed the methods and the spirit of all mathematics, from the most philosophical questions about its foundations to the most intricate problems of classical algebra, geometry and analysis.

Unlike many modern scientific theories, this one is based on an extremely simple and familiar notion. The word "set" means just what it says—a collection of objects or abstract entities (such as numbers or points). The letters on this page make up a set; all odd numbers make up another. Out of this apparently trivial concept flows an astonishing stream of mathematical riches.

An old fact for which Cantor found an important new proof by means of set theory is the existence of two types of numbers, known as algebraic and transcendental. To appreciate the distinction, consider the numbers we deal with in algebra. In a standard problem we start with an equation, for example $x^3 - 2x^2 + 3 = 0$, and look for the value or values of x that satisfy it. To define an algebraic number we go in the other direction: start with a number and look for an equation. To put it more precisely, a number is called algebraic if it is a solution of an equation such as $a + bx = 0$, or $a + bx + cx^2 = 0$, or $a + bx + cx^2 + dx^3 = 0$, etc., where *a, b, c, d, etc.* stand for ordinary whole numbers (possibly negative and possibly even zero). A number that is not algebraic is called transcendental.

Now there are infinitely many equations with infinitely many different solutions. So there are infinitely many algebraic numbers. The question arises: Are there any transcendental numbers? Cantor knew the answer (it is yes). But his proof of it proceeded along completely original lines. He considered the set of all numbers and the set of algebraic numbers. He then found a way to compare the sizes of these infinitely large collections.

To compare finite sets we simply count their members. Thus there is no difficulty in showing that the set of all English consonants is larger than the set of all vowels. Cantor invented a kind of generalized counting that can be applied to infinite sets [*see illustrations at bottom left on next two pages*]. He was then able to show that the set of all numbers is unmistakably larger than the set of algebraic numbers. The matter is settled; transcendental numbers must indeed exist in profusion.

Many new facts about numbers and other mathematical systems have been uncovered by Cantor's methods. His most impressive contribution, however, was his new point of view, to which almost the entire mathematical world has now been converted. Instead of considering individual numbers or points or functions, the post-Cantor mathematician considers large sets of numbers or points or functions. These have properties that cannot be ascribed to the individual elements, but that nevertheless shed some light on the elements. A set of two (or more) people can walk arm in arm, but one person cannot. And we can learn something about a person from the company he keeps.

As a rather far-fetched example, imagine that you are a European attending the Princeton-Yale football game. Between the halves one of the bands marches out on the field. You have a pair of high-powered binoculars through which you can inspect the musicians one by one. The color of their blazers means nothing to you, so you cannot tell which college they belong to. But if you put down your glasses and notice that the entire band is forming the letter P as it

$x^n + y^n = z^n$

where

x, y, z, n

are positive integers

If n = 2

the equation reads

$x^2 + y^2 = z^2$

and there are

many solutions

For example

$3^2 + 4^2 = 5^2$

$5^2 + 12^2 = 13^2$

etc.

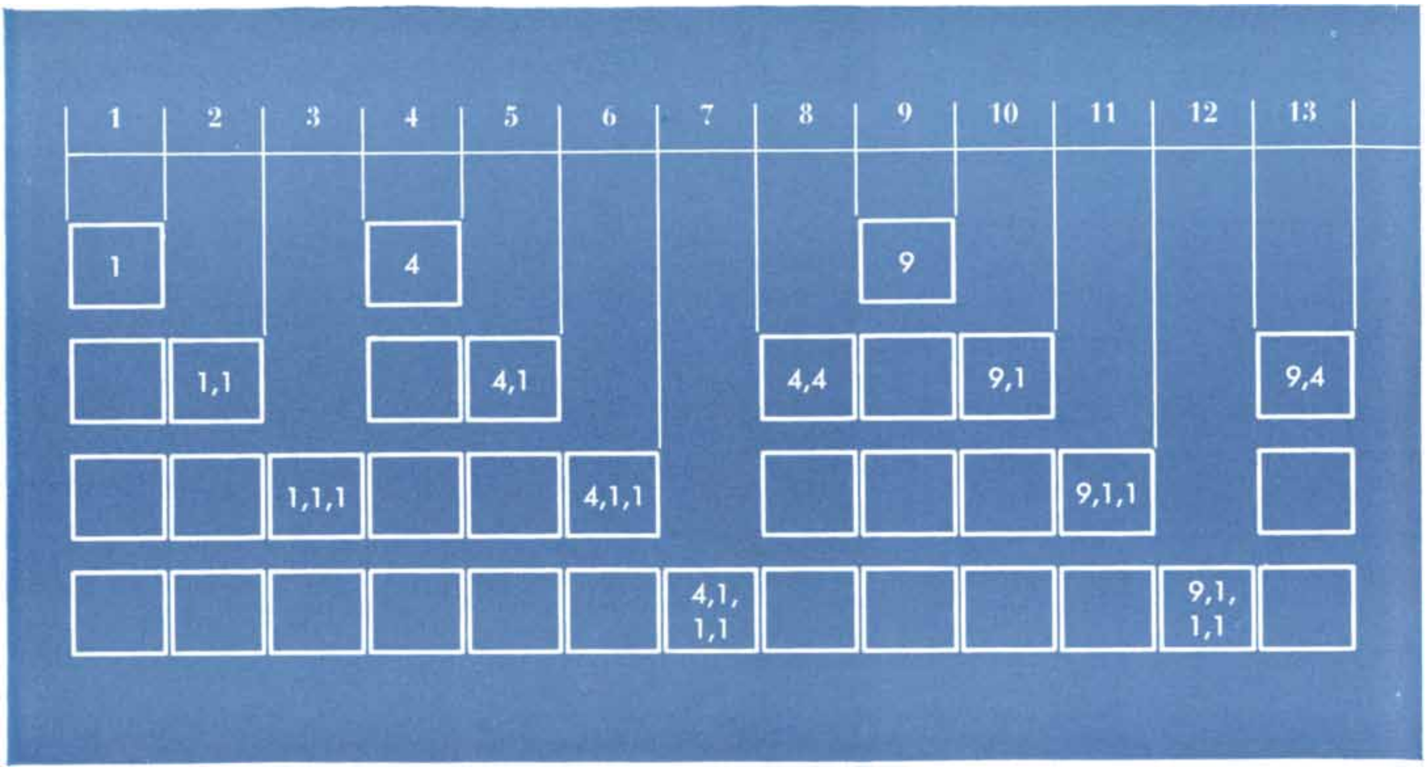
But if n > 2, as for instance in

$x^3 + y^3 = z^3$

there is no integral solution

for x, y, z

FERMAT'S LAST THEOREM states that the equation $x^n + y^n = z^n$ has no solutions in which *x*, *y* and *z* are positive whole numbers, if *n* is a whole number greater than two. Fermat noted in a book that he had "discovered a truly remarkable proof which this margin is too small to contain," but no one has been able to prove the theorem.

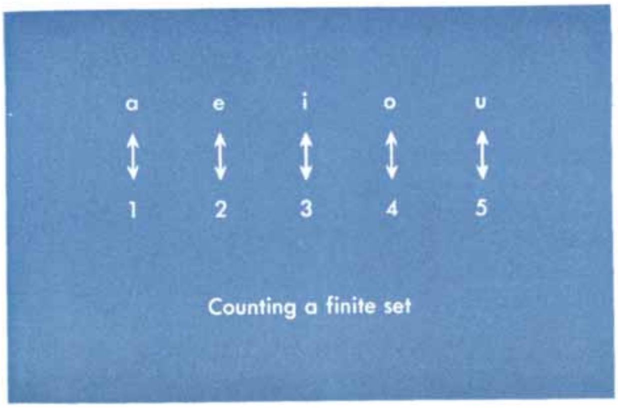


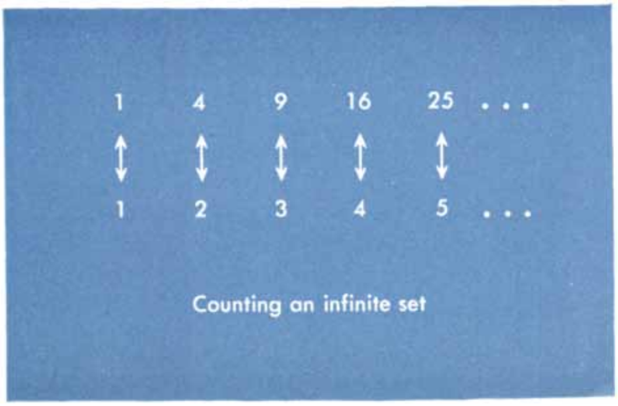
A MATHEMATICAL DISCOVERY of Euler is illustrated in this table. The theorem states that every positive whole number can be expressed as the sum of no more than four squares of other whole numbers. Rectangles in top row represent the squares themselves. Those in succeeding rows represent numbers that can be formed by adding two, three and four squares respectively. Figures

marches out, you can probably decide that they are Princetonians. Of course, it might be the Yale band making a courteous gesture, but the general idea is clear. The structure of a set can tell you something about its members.

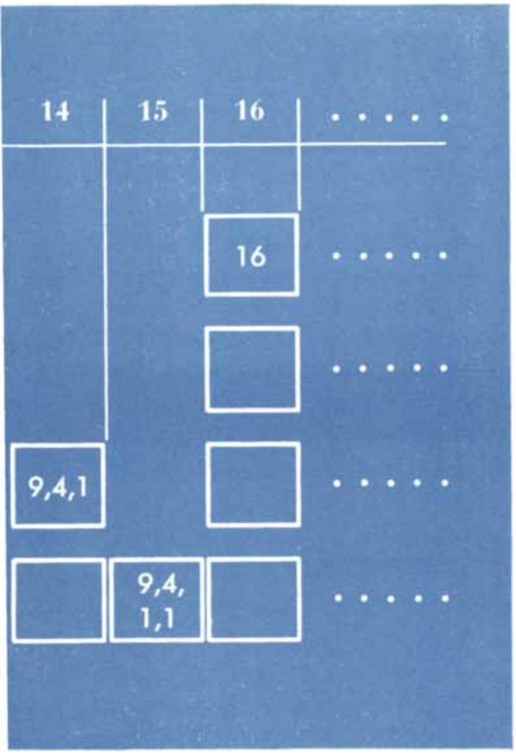
The classical mathematician was interested in individual problems. Confronted with a system of equations, he asked: Do they have solutions? If so, what does each solution look like? The modern mathematician also wants to know the answers to these questions, but he approaches the problem differently. He might begin, for instance, by asking: "Is the sum or the product of two solutions also a solution?" This is a question about the structure of the set of all possible solutions. If the answer is yes, he knows that he is dealing with a particular type of set (for instance, a group), and this gives him important information about the individual solutions.

Some problems lead to complicated and difficult sets. Consider a few sets of points that can be chosen from a particular straight line. (Assume that the line is graduated like a thermometer. There is a point marked zero, with positive numbers on one side of it and negative numbers on the other.) Let us start with some simple sets: the set of all points above zero (the positive numbers); the set of all points (we might as well say numbers) between 2 and 7; the set of all points below — 2. All these are easily conceived, everyday sets, and can be readily visualized in geometrical dia-





SETS are counted and compared by the method illustrated here. Counting a finite set, such as the vowels (*left*), means matching its members to positive integers. Counting an infinite set, such as the squares of the whole numbers (*middle*), also means matching each of its members to a positive integer. The infinite set of points in a line (*right*) is known to be larger than the infinite set of positive



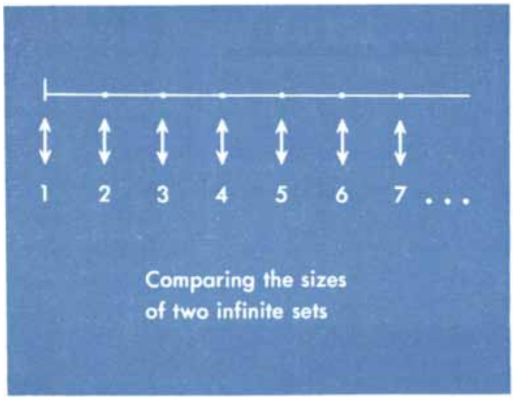
in rectangles are the squares which, when added together, give the number. The theorem is true for all of the positive integers.

grams [*see top three illustrations at right*]. Now suppose we think of the points between the whole numbers as decimals, and construct the set of all those points with a positive odd number to the left of the decimal point. This is still not too bad; with a small mental effort we can imagine it and draw its picture [*bottom illustration at right*]. But what about the set of points in whose decimal representation the digit 6 never appears? It is a perfectly reasonably defined set, and we know quite a lot about it. We know, for instance, that the point 11/20 (.55) and the point 8/7 (1.142857142857 . . .) belong to the set, and the point *pi* (3.14159265 . . .) does not. The geometric diagram of the set is probably impossible to visualize—and even so this set is much simpler than some which mathematicians are regularly forced to study. To show just one possible additional complication, consider the set of points in whose decimal representation the digit 6 may or may not occur, but never six times consecutively. Once again we know something about the set; we know, for instance, that 11/20 and 8/7 still belong to it. There is no one on the face of the earth who can decide whether *pi* belongs to the set or not.

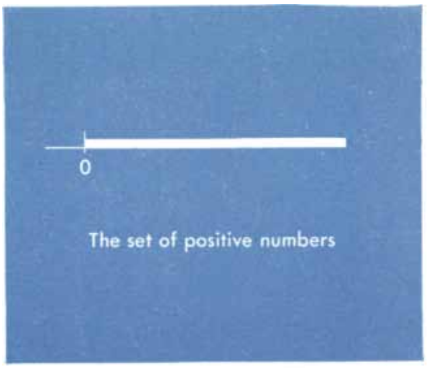
Of course mathematicians long before Cantor had been studying certain kinds of sets (for example, lines, triangles, circles and the like), even if they did not think of them in those terms. In the early days of set theory, many mathematicians took up the idea with more enthusiasm than discretion. Any set was as good as any other. The result was mathematical anarchy. A kind of inverted snobbishness even led some workers to prefer the wildest and most unruly sets to the well-behaved, coherent sets of older days. This radicalism was not welcomed in all quarters. The great French mathematician Henri Poincaré remarked on one occasion: "Later generations will regard set theory as a disease from which one has recovered."

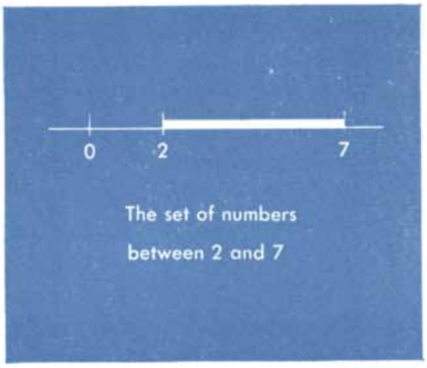
But after its youthful excesses post-Cantorian mathematics settled down to a mature and responsible evaluation of itself and its role in history. The set-theoretic approach is now instilled into young mathematicians virtually in the cradle, and, as a result, it is so much in their bloodstream as to have lost almost all its controversial character. It has proved to be one of the most powerful unifying themes in the history of mathematics, a theme which reveals connections between apparently remote regions of ideas.

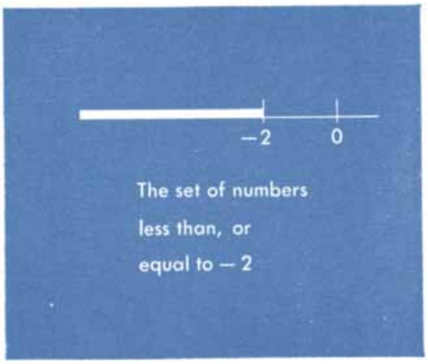
What is the mathematics of today that will precipitate the controversies of tomorrow and become the orthodoxy of the next day? No one can say. It may take a decade, or a century, to see a mathematical innovation in its proper light. But of one thing we may be certain: As long as there is a world with mathematicians in it, innovation will continue. The new ideas will be studied, sometimes applied to practical problems, and always enjoyed.

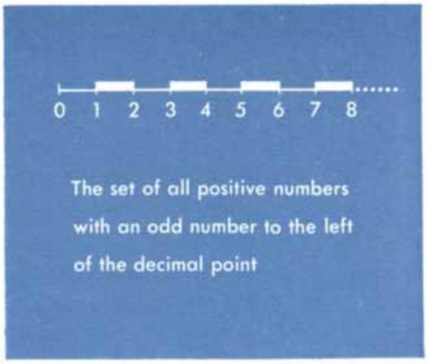


integers because, no matter how some of the points are matched up with integers, some other points will always be left unmatched.









SETS OF NUMBERS such as those in the illustrations above are easy to visualize and to represent diagrammatically. Others that are mentioned in the text are difficult to conceive and also impossible to diagram.

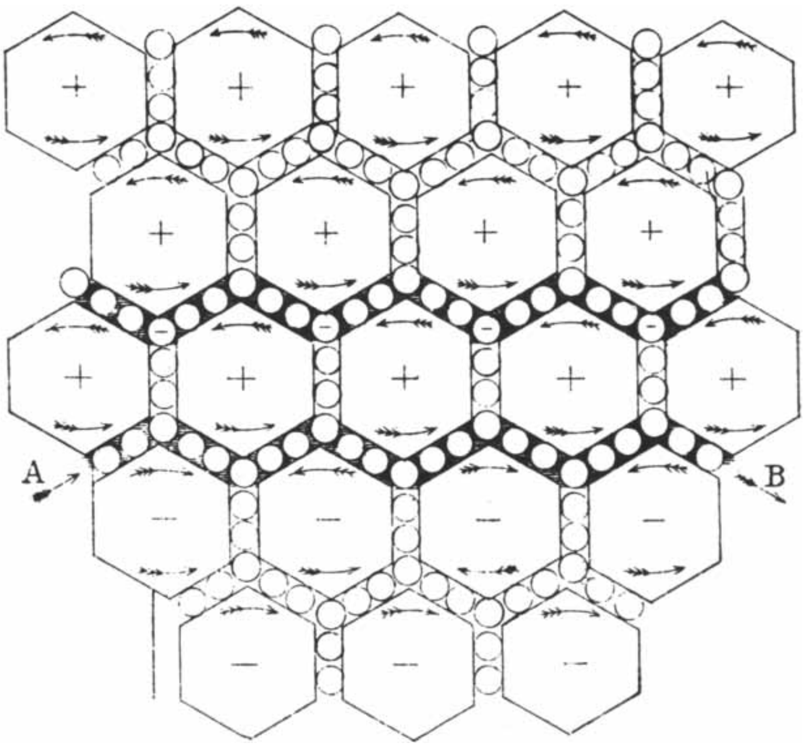
Innovation in Physics

Faced with the facts of physical observation and experiment, the theoretical physicist applies the abstract relationships of mathematics to connect these facts and predict new facts

by Freeman J. Dyson

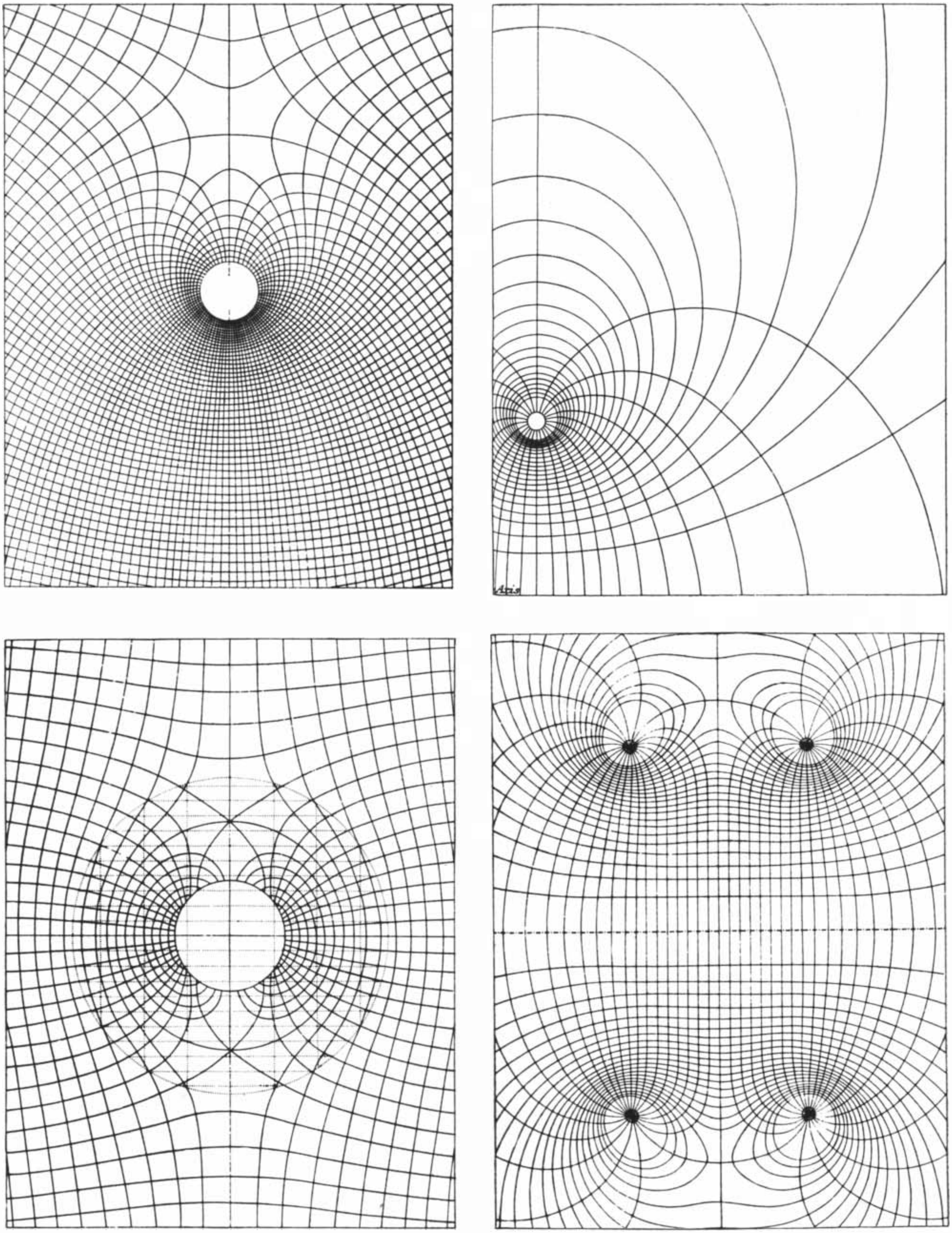
One of the most entertaining scientific autobiographies is a book called *From Immigrant to Inventor,* by Michael Pupin. The name Pupin may be seen over the door of the physics laboratory of Columbia University; for the younger physicists of today the name belongs to the building, and the man is forgotten. This is a pity, for he was a colorful as well as a great man. He arrived in America from the backwoods of Hungary at the age of 16, and after various adventures became a Columbia professor when he was 34. He was born with a restless curiosity and a fixed determination to master the science of his time.

His book is interesting in two ways. It gives a vivid picture of U. S. society in the 1870s, seen from the point of view of the penniless immigrant. It also describes, with well-observed detail, the physics and the physicists of that time. Physics then was dominated by one transcendent innovation, James Clerk Maxwell's theory of the electromagnetic field. Pupin set out to understand the Maxwell theory like a knight in quest of the Holy Grail. First he went to Columbia, but found nobody there who could explain Maxwell. Then he went to Cambridge, where Maxwell had worked; but Maxwell was dead, and Pupin's tutors were mainly interested in getting him good marks in the mathematical tripos. Finally he went to Berlin, and there he found Ludwig Boltzmann; Boltzmann had understood the Maxwell theory, and he taught Pupin what he knew. Pupin was amazed to find out, as he says, "how few were the physicists who had caught the meaning of the theory, even 20 years after it was stated by Maxwell in 1865."



MECHANICAL MODEL of an electromagnetic field appears in James Clerk Maxwell's *Selected Papers.* The hexagons are "molecular vortices"; the circles, "idle wheels." When the wheels are moved from A toward B, adjacent vortices rotate in opposite directions. The model reflects efforts of 19th-century physicists to visualize field in terms of older concepts.

The features of the theory which seem most significant to us now are not those which seemed particularly important to Maxwell. In the broadest sense one may say that the basic idea of the theory is that nature has a double-layered structure. In the lower layer there exist electric and magnetic fields, which satisfy simple wave-equations and travel freely through space in the form of light or radio waves. In the upper layer there are material objects, energies and forces. Only the upper layer is directly accessible to our observation. A lower-layer object such as an electric field can only be observed by looking at the energies and forces which it produces in the upper layer. And these energies and forces are always proportional to the square of the field-strength. Thus the field-strength itself is a pure mathematical abstraction. The fact that a field-strength is not directly measurable can

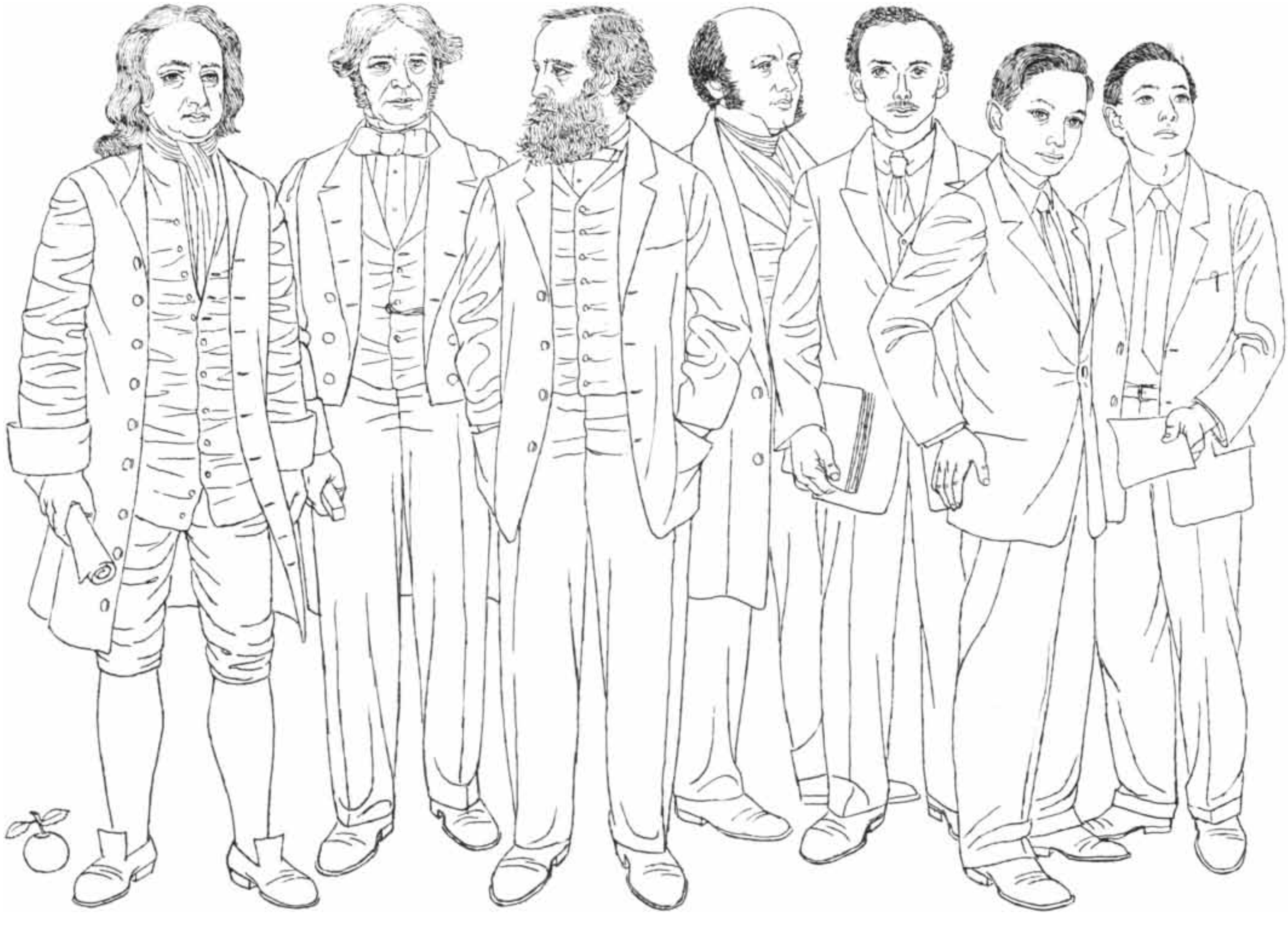


LINES OF FORCE in electromagnetic fields appear in Maxwell's *Treatise on Electricity and Magnetism*. These pictures are more in keeping with the view of the modern physicist, who regards the field as a concept in its own right which does not have to be explained in terms of older concepts. At top left are the lines of force in a field disturbed by an electric current in a straight conductor; at bottom left, in a field around a magnetized cylinder. At top right is a circular current; at bottom right, two circular currents.

be seen very simply by looking at the unit in which it is conventionally supposed to be measured. The unit is the square root of an erg per cubic centimeter. An erg is an ordinary unit of energy and can be measured with ordinary instruments such as thermometers and calorimeters. But nobody has ever imagined an instrument which will measure directly the square root of an erg, or the square root of a cubic centimeter. So the field-strengths, the basic quantities with which the Maxwell theory deals, are in their nature abstract and not simply related to things which we can see and touch.

The reason why new concepts in any branch of science are hard to grasp is always the same; contemporary scientists try to picture the new concept in terms of ideas which existed before. The discoverer himself suffers especially from this difficulty; he arrived at the new concept by struggling with the old ideas, and the old ideas remain the language of his thinking for a long time afterward. In the preface to his *Treatise on Electricity and Magnetism* Maxwell writes: "I shall endeavour to place in as clear a light as I can the relations between the mathematical form of this theory and that of the fundamental science of Dynamics, in order that we may be in some degree prepared to determine the kind of dynamical phenomena among which we are to look for illustrations or explanations of the electromagnetic phenomena." This was written seven years after the original publication of Maxwell's theory. It still did not occur to him that he had created a new science having an equal claim with Newtonian dynamics to the adjective fundamental.

The basic difficulty of the Maxwell theory in those days was that no one could conceive an electric field except in terms of a mechanical model; Maxwell himself was an ingenious inventor of such models [*see illustration on page 74*]. The previously existing physical ideas were material particles, fluids and elastic solids, all obeying the laws of Newton's dynamics. So the physicists of that time had no other way to think of an electric field; they were forced to start from some complicated picture of mechanical objects in motion, and in these terms the Maxwell equations appeared neither simple nor natural. Only very slowly did it become possible to forget the mechanical models and to picture an electric field as something basic and indivisible, a physical object which exists in its own right and does not need to be "explained" in terms of something else. It took about 30 years for physicists to make this change in their way of thinking. Once the change was made, the sim-



PHYSICISTS AND MATHEMATICIANS mentioned in this article are arrayed in a fanciful grouping. At the far left on the page at the left is Isaac Newton. Second from the left is Michael Faraday. Third is Maxwell; fourth, William Rowan Hamilton; fifth, P. A. M.

plicity and beauty of the Maxwell equations were no longer hidden, and it was hard to understand what all the fuss had been about.

We stand today in relation to quantum mechanics just as Pupin stood in relation to the Maxwell theory. Quantum mechanics has a reputation for being strange, difficult and incomprehensible to ordinary mortals. Yet I believe it is not more difficult to understand quantum mechanics now than it was to understand Maxwell in 1885.

Again in the broadest sense one may say that the fundamental idea of quantum mechanics is merely the extension to matter of the two-layered view of nature already inherent in Maxwell's treatment of electricity and magnetism. Quantum mechanics ultimately makes no distinction between matter and electricity. The two-layered view of nature thus becomes consistent and universal. In the lower layer are put electric and magnetic fields, together with mathematical abstractions of a similar kind called wave-functions which describe the behavior of matter. In the upper layer are now only energies, forces and probabilities. The wave-functions are also not directly accessible to measurement, and it is only the squares of wave-functions that are seen in observations at the upper level. There are of course many differences in detail between quantum mechanics and Maxwell's theory, between the behavior of matter and of electromagnetism. But in the broad view the picture is the same. The reason why quantum mechanics seems to us now so much the more difficult to grasp is that our intuitions of the solid nature of matter are more deep-rooted than our intuitions about electricity.

There is hope that quantum mechanics will gradually lose its baffling quality. The Maxwell theory is not easy to explain to nonspecialists, but the difficulties now are in the details and not in the basic conceptions. Today we may find it hard to remember the various terms in Maxwell's equations with the correct plus and minus signs, but the general physical picture of an electric and magnetic field in empty space is not conceptually difficult. We do not suffer the agonizing bafflement which the scientists of the 1880s felt in trying to imagine an electric field. It is even difficult for us to understand precisely what the difficulty was; that is why Pupin's book is valuable. So it seems that the essential ideas of quantum mechanics (though not the details) may in time be taught to school children and become familiar to the general public.

I have observed in teaching quantum mechanics (and also in learning it) that students go through an experience which

Dirac; sixth, C. N. Yang; seventh, T. D. Lee. At the left on the page at the right is Louis de Broglie. Second from the left is Erwin Schrödinger. Third is Enrico Fermi; fourth, Werner Heisenberg; fifth, Niels Bohr. At the far right in the drawing is Ernest Rutherford.

PARTICLE	SYMBOL	MASS	LIFETIME
1. PHOTON	γ	0	STABLE
2. NEUTRINO	ν°	0	STABLE
3. ANTINEUTRINO	$\bar{\nu}^{\circ}$	0	STABLE
4. ELECTRON	e^-	1	STABLE
5. POSITRON	e^+	1	STABLE
6. NEGATIVE MU MESON	μ^-	206.2	2.2×10^{-6}
7. POSITIVE MU MESON	μ^+	206.2	2.2×10^{-6}
8. NEGATIVE PI MESON	π^-	273.2	2.56×10^{-8}
9. POSITIVE PI MESON	π^+	273.2	2.56×10^{-8}
10. NEUTRAL PI MESON	π°	263	$< 4 \times 10^{-16}$
11. NEGATIVE K MESON	K^-	966.5	1.22×10^{-2}
12. POSITIVE K MESON	K^+	966.5	1.22×10^{-2}
13. NEUTRAL K MESON	K°	966	
14. NEUTRAL ANTI K MESON	$\bar{K}^{\circ}$	966	
15. NEUTRAL K MESON (1)	K_1°	966	$.95 \times 10^{-10}$
16. NEUTRAL K MESON (2)	K_2°	?	9×10^{-8}
17. PROTON	p^+	1836.1	STABLE
18. ANTIPROTON	$\bar{p}^-$	1836.1	STABLE
19. NEUTRON	n°	1838.6	1.04×10^{3}
20. ANTINEUTRON	$\bar{n}^{\circ}$	1838.6	1.04×10^{3}
21. LAMBDA PARTICLE	Λ°	2182	2.77×10^{-10}
22. ANTI LAMBDA PARTICLE	$\bar{\Lambda}^{\circ}$	2182	2.77×10^{-10}
23. NEGATIVE SIGMA PARTICLE	Σ^-	2341.4	1.67×10^{-10}
24. POSITIVE ANTI SIGMA PARTICLE	$\bar{\Sigma}^+$	2341.4	1.67×10^{-10}
25. POSITIVE SIGMA PARTICLE	Σ^+	2327.6	$.83 \times 10^{-10}$
26. NEGATIVE ANTI SIGMA PARTICLE	$\bar{\Sigma}^-$	2327.6	$.83 \times 10^{-10}$
27. NEUTRAL SIGMA PARTICLE	Σ°	2331.7	$< 10^{-11}$
28. NEUTRAL ANTI SIGMA PARTICLE	$\bar{\Sigma}^{\circ}$	2331.7	$< 10^{-11}$
29. NEGATIVE XI PARTICLE	Ξ^-	2570	$5-200 \times 10^{-10}$
30. POSITIVE ANTI XI PARTICLE	$\bar{\Xi}^+$	2570	$5-200 \times 10^{-10}$
31. NEUTRAL XI PARTICLE	Ξ°	?	?
32. NEUTRAL ANTI XI PARTICLE	$\bar{\Xi}^{\circ}$	?	?

FUNDAMENTAL PARTICLES of matter and energy that are presently known to physicists are listed in this chart. The mass of each particle is given in terms of the mass of the electron. The lifetimes of unstable particles are listed in seconds or fractions of a second. No lifetime is given for the neutral K meson and the neutral anti K meson because they decay immediately into the particles listed as neutral K meson (1) and neutral K meson (2).

is very similar to the one that Pupin describes. The student begins by learning the tricks of his trade. He learns how to make calculations in quantum mechanics and get the right answers, how to calculate the scattering of neutrons by protons and so forth. To learn the mathematics of the subject and to learn how to use it takes about six months. This is the first stage in learning quantum mechanics, and it is comparatively easy and painless. The second stage comes when the student begins to worry because he does not understand what he has been doing. He worries because he has no clear physical picture in his head. He gets confused in trying to arrive at a physical explanation for each of the mathematical tricks he has been taught. He works very hard and gets discouraged because he does not seem able to think clearly. This second stage often lasts six months or longer, and it is strenuous and unpleasant. Then, quite unexpectedly, the third stage begins. The student suddenly says to himself, "I understand quantum mechanics," or rather he says, "I understand now that there isn't anything to be understood." The difficulties which seemed so formidable have mysteriously vanished. What has happened is that he has learned to think directly and unconsciously in quantum-mechanical language and is no longer trying to explain everything in terms of pre-quantum conceptions.

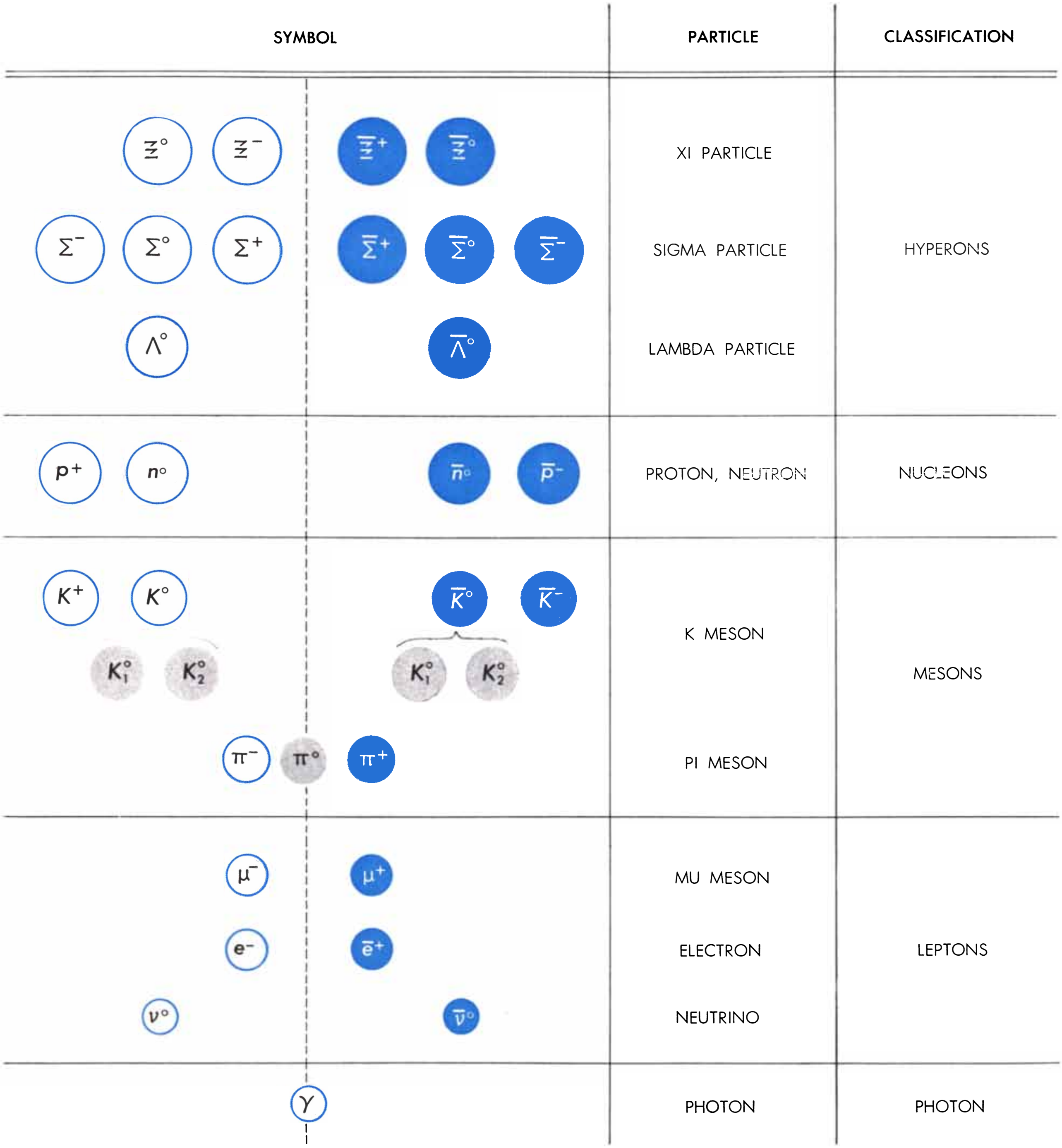
It seems that the duration and severity of the second stage are decreasing as the years go by. Each new generation of students learns quantum mechanics more easily than their teachers learned it. The students are growing more detached from the pre-quantum pictures; there is less resistance to be broken down before they feel at home with quantum ideas. Eventually the second stage will disappear entirely; quantum mechanics will be accepted by students from the beginning as a simple and natural way of thinking, just because we shall all have grown used to it. By that time, if science progresses as we hope, we shall be ready for the next big jump into the unknown.

The Maxwell theory and quantum mechanics are examples of physical innovation at its deepest level. Such innovations occur when experimental facts are seen to be incomprehensible within the bounds of earlier conceptions. A new style of reasoning and imagining has to be groped for, slowly and painfully, in the dark.

For the last 10 years it has been

clear to most physicists that a basic conceptual innovation will be needed in order to come to grips with the properties of elementary particles. A great part of our present effort in experimental physics is devoted to the study of these particles. The justification for studying them so intensively is the belief that here more than elsewhere in physics we have a situation ripe for radical innovations. It is worthwhile, then, to look at the historical perspectives and to inquire how and when a radical innovation is likely to occur.

A few months ago Werner Heisenberg and Wolfgang Pauli believed that they had made an essential step forward in the direction of a theory of elementary particles. Pauli happened to be passing through New York, and was prevailed upon to give a lecture explaining the new ideas to an audience which included Niels Bohr. Pauli spoke for an hour, and then there was a general discussion during which he was criticized rather sharply by the younger generation. Finally Bohr was called on to make a speech



PARTICLES ARE CLASSIFIED as photon, leptons, mesons, nucleons and hyperons. The mu meson, despite its name, is placed with the leptons. To right of broken line are anti particles; to left, the corresponding particles. The photon and the neutral pi meson may be considered their own anti particles. The neutral K meson and the neutral anti K decay into the same daughter particles.

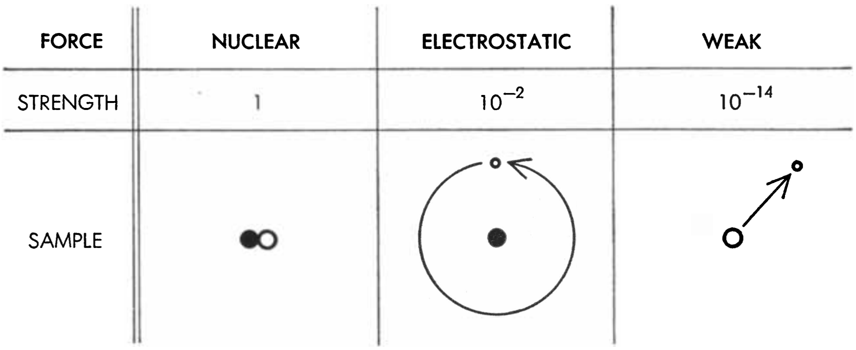
summing up the argument. "We are all agreed," he said, "that your theory is crazy. The question which divides us is whether it is crazy enough to have a chance of being correct. My own feeling is that it is not crazy enough."

The objection that they are not crazy enough applies to all the attempts which have so far been launched at a radically new theory of elementary particles. It applies especially to crackpots. Most of the crackpot papers which are submitted to *The Physical Review* are rejected, not because it is impossible to understand them, but because it is possible. Those which are impossible to understand are usually published. When the great innovation appears, it will almost certainly be in a muddled, incomplete and confusing form. To the discoverer himself it will be only half-understood; to everybody else it will be a mystery. For any speculation which does not at first glance look crazy, there is no hope.

The pace of fundamental advance in physics is set by human stupidity. The pace is, and has always been, very slow. The rapid expansion of experimental work in the last 10 years has had the consequence that experimental knowledge is now far ahead of theory. This is a healthy situation. But fundamental understanding will not be hurried. It could easily happen that all conceivable experiments that can be done with accelerators by bashing elementary particles together will be done, and the results will be accurately recorded, and still we will have no understanding of what is happening. Then we will have to sit and wait for ideas or for radically new kinds of experiments. Somehow, sometime, we believe the log-jam will be broken. But we can push at only one log at a time, and few of them move when we push them.

There have been many innovations in physics, some of supreme importance, which did not involve any radically new ways of thinking. One of these was the discovery of the atomic nucleus by Ernest Rutherford. Another was the recent proposal by C. N. Yang and T. D. Lee that left-right symmetry might be violated in subatomic processes. The history of both these innovations shows again the incapacity of even the best of us to see very far beyond the end of his nose.

Rutherford discovered the nucleus in 1911. He deduced, from the fact that alpha particles passing through a thin metal foil are deflected at large angles, that the entire mass and positive charge of an atom must be concentrated within a sphere of radius less than a thousandth part of the radius of the atom. This work was published in May, 1911. One might have expected that it would create some stir in the world of physics. But in a recent lecture E. N. da C. Andrade has said of this event: "At the time, I was working in Lenard's laboratory in Heidelberg, a very active center of research on electronic physics. I have no recollection of any attention aroused by Rutherford's atom." In 1913 Rutherford published a book *Radioactive Substances and Their Radiations,* in which the structure of the atom, consisting of a nucleus with surrounding electrons, is for the first time clearly spelled out. This book was reviewed in *Nature* by Lord Rayleigh, surely as broad-minded and versatile a physicist as one could find. The review does not mention the subject of atomic structure.



THREE FORCES OF PHYSICS are compared. The strongest force is the nuclear, here represented as the force binding a proton (*black ball*) and a neutron (*white ball*). One hundred times weaker than the nuclear force is the electrostatic, represented as the attraction between a proton and an electron moving around it. One hundred million million times weaker is the weak-interaction force. This is involved in the decay of a nucleon (*larger white ball*) by emission of a beta particle (*smaller white ball*). Not shown is a still weaker force: gravity.

It is perhaps not surprising that the clear evidence for an atomic nucleus should have been so long ignored by Rutherford's contemporaries. They had been accustomed to regard speculations about the insides of atoms as belonging to metaphysics rather than to physics. They naturally closed their minds to any information concerning a field which had for centuries been the domain of charlatans and philosophers. What is more surprising is that it took Rutherford himself several years to wake up to the importance of what he had done. When he first announced his discovery in a letter to Otto Hahn in April, 1911, he said, "I have been working recently on scattering of alpha and beta particles and have devised a new atom to explain the results, and also a special theory of scattering." It seems he was then more intrigued by his ability to calculate the deflection of a particle acted on by a force varying as the inverse square of the distance from a fixed center than by the mystery of what this massive fixed center might really be. In his 1913 book the nucleus still occupies a very minor place. Otherwise it could hardly have been overlooked by Lord Rayleigh. In fact one could almost say it was Niels Bohr who first called Rutherford's attention to the importance of what he had done.

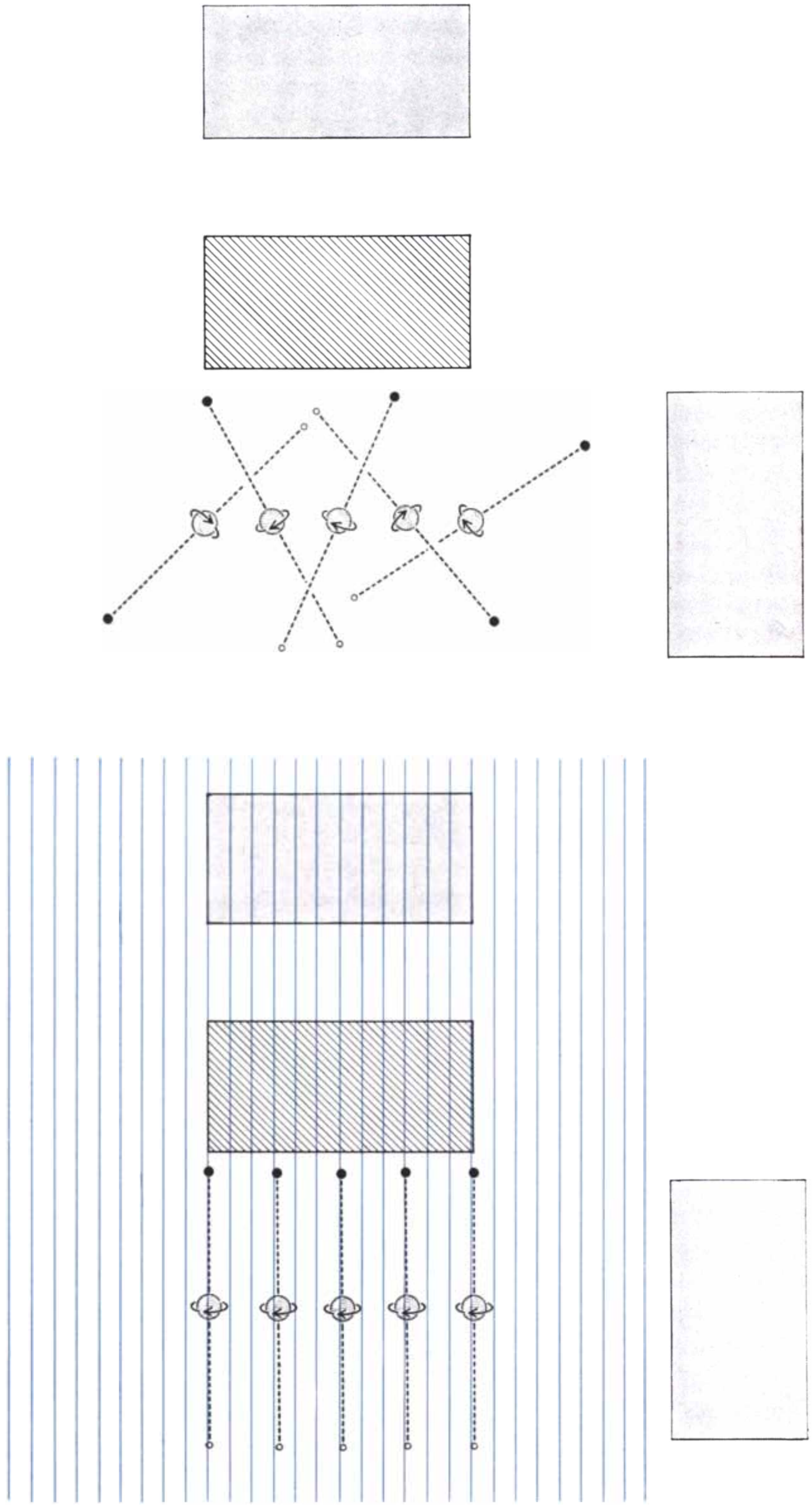
The work of Yang and Lee has revealed similar blindness in the physicists of a younger generation. This I know from personal experience. Yang and Lee wrote their paper entitled "Question of Parity Conservation in Weak Interactions" in June, 1956. A copy of it was sent to me, and I read it. I read it twice. I said, "This is very interesting," or words to that effect. But I had not the imagination to say, "By golly, if this is true it opens up a whole new branch of physics." And I think other physicists, with very few exceptions, at that time were as unimaginative as I.

In their paper Yang and Lee proposed several specific experiments by which the question of parity conservation could be tested. One might suppose that every experimentalist who heard of these proposals was itching to go to work on them. Here was the long-awaited chance to do a crucial experiment which would unambiguously reveal a new law of nature. But the experimentalists, with a very few exceptions, calmly went on doing what they had been doing before. Chien Shiung Wu, with her collaborators at the National Bureau of Standards, had the courage to spend six months in preparing the decisive experiment. Her positive results were announced in January, 1957. By that time there were altogether three other groups who were preparing similar experiments: in Chicago, in Leiden and in Moscow. Four groups of people, among all the experimental physicists in the world, were ready to lay aside their regular work and gamble on a new idea.

I remember in October, 1956, I met Yang and said: "It will be exciting if this Wu experiment shows up something." "Yes," he said, "it will be exciting," and he went on to talk about his calculations in the theory of imperfect gases. I believe even he at that time had no clear idea of how exciting it would be. In this respect he was no better and no worse than Rutherford.

It may be said as a general rule, to which there are some notable exceptions, that every great innovation in physics is merely the decisive moment in a gradual growth of understanding which extends over about 60 years. Thirty years commonly pass between the recognition of a puzzling phenomenon and the birth of the new idea that will explain it. Another 30 years pass between the birth of the idea and the working out of its major consequences. The first 30 years are a time of struggle and searching for a solution, the second 30 a time of readjustment and assimilation of strange conceptions. From Michael Faraday's discovery of electromagnetic induction to Maxwell's theory was 30 years. From Maxwell's theory to Heinrich Hertz's demonstration of electromagetic waves, or to Pupin's transmission lines, was another 30. It took 30 years to go from Rutherford's nucleus to a rough understanding of nuclear structure and nuclear reactions. It took 30 years from Heisenberg's quantum mechanics to John Bardeen's new theory of superconductivity, although most physicists have long believed what Bardeen has now brilliantly demonstrated, that superconductivity is merely a spectacular large-scale manifestation of quantum-mechanical principles.

In the case of the work of Lee and Yang, we can see the past but not the future. Thirty years ago Enrico Fermi gave the first general description of the weak interactions responsible for the decay of a radioactive nucleus by the emission of a beta particle and formulated the problem of describing these interactions precisely. This problem remained unsolved for 30 years, although



PARITY EXPERIMENT performed by Chien Shiung Wu and her collaborators is depicted in simplified form. The spinning balls at top are the radioactive nuclei in a thin film of cobalt 60. The nuclei decay by emitting a beta particle (*black dot*) and a neutrino (*white dot*). The beta particles are detected by a crystal of anthracene (*hatched rectangle*). Crystals of sodium iodide (*gray rectangles*) detect gamma rays as a measure of the disorder, and hence of the temperature, of the cobalt 60. When the cobalt 60 is cooled by liquid helium and a magnetic field (*colored lines*) is applied to it, the cobalt nuclei are lined up so that the beta particles are preferentially emitted in one direction. This indicated that the direction in which the beta particles were emitted, which had been thought to be independent of the direction in which the nuclei spun (*curved arrows*), was actually related to the direction of spin.

an enormous number of experiments, becoming more and more ingenious and exact as the years went by, was devoted to its elucidation. Then came the breaking of the log-jam by the suggestion of Lee and Yang that a violation of left-right symmetry might be an essential feature of weak interactions. Within a year of the first experimental confirmation of the Lee-Yang idea, new experiments came in a flood—experiments measuring and exploiting the left-right asymmetries. These experiments have finally solved the problem posed by Fermi. We now know, at least for the case of nuclear beta-decay, what the weak interactions are. But it is clear to everybody that we are only halfway through the story. The existence of left-right asymmetry in weak, but not in strong, interactions is not in any basic sense understood. It is now for the first time possible to begin thinking in a realistic and coherent way about the fundamental properties of weak interactions. We can confidently predict that thinking on this subject will go on and on and never stop until the full meaning of the discovery of Lee and Yang is brought to light. If historical precedents are followed, the task will keep us busy for the next 30 years or more.

I have given a brief and fragmentary survey of some of the main innovations in physical theory during the last hundred years. I do not mean to overstress the similarities and regularities which these examples show. There are no historical laws in science, so far as I can see. What I have wanted to emphasize is the slower and wider process of enlargement of human understanding which precedes and follows every significant innovation. The work which must be done by scientists great and small, to absorb and assimilate an innovation after it has occurred, is as long, as hard and as important as the work which pushed and groped along the way to the innovation's birth. The best description of the whole process is to be found in the words which Sir Arthur Eddington wrote in 1934: "When we see these new developments in perspective they appear as the natural unfolding of a flower."

Finally, what of the future? Can we predict or in any way influence the course of future innovations? The answer is clearly no, except in the vaguest and most conjectural sense. Nevertheless I shall hazard a few random guesses about the shape of things to come.

There are two points of view commonly held about the present situation in elementary-particle physics. One view, which may be called the optimistic view, holds that we are in a situation comparable to that of 1925, when classical and atomic physics were in glaring conflict. At that time the heroic intellectual struggles of Bohr, H. A. Kramers, Louis de Broglie, Erwin Schrödinger, P. A. M. Dirac and Heisenberg brought order out of chaos by giving birth to quantum mechanics. The optimistic view is that a similarly epoch-making innovation, which will put an end to the present confusions of particle physics, is just around the corner. The opposing view is often called pessimistic, but I prefer to call it skeptical, since I hold it myself and I do not admit my joy in the works of nature to be any less than that of the optimists. The skeptical view believes in a longer time-scale; it assigns a more modest place to the problems and capabilities of the present generation of physicists, and it has more faith in the inexhaustible richness of nature.

The skeptical view places our generation in somewhat the same position as the 18th-century successors of Newton. After Newton had completed the framework of dynamics, his successors had two great tasks. One task was to work out and fully understand the mathematical consequences of Newton's ideas. This task was the lifework of the great applied mathematicians of the 18th and 19th centuries: Leonhard Euler, Joseph Louis Lagrange, Pierre Simon de Laplace, Karl Jacobi and William Rowan Hamilton. It was not finished until 150 years after Newton's *Principia*. The second task was to study and reduce to order those physical phenomena which Newton well knew lay outside the scope of his dynamics, especially light, electricity and magnetism. This task occupied the efforts of the leading physicists for some 200 years after Newton, and was accomplished only with the work of Michael Faraday and Maxwell.

It seems to me incontestable that quantum mechanics could not have been discovered by anybody, no matter how great his genius, until after Hamilton and Maxwell had completed their work. If somebody had said 30 years after Newton, "It is clear that we need a radical innovation in dynamics in order to explain the behavior of light and electricity," and had sat down and tried to invent quantum mechanics, he would have been wasting his time. Without Hamilton's deep mathematical analysis of Newtonian dynamics to suggest the form of the new theory, and without Maxwell's detailed theory of electrical forces to suggest its physical content, nobody could have had any inkling of the kind of innovation that would prove necessary.

My view, the skeptical one, holds that we may be as far away from an understanding of elementary particles as Newton's successors were from quantum mechanics. Like them, we have two tremendous tasks ahead of us. One is to study and explore the mathematics of the existing theories. The existing quantum field-theories may or may not be correct, but they certainly conceal mathematical depths which will take the genius of an Euler or a Hamilton to plumb. It may well be that the approach to a new theory cannot begin until the mathematical nature of the old ones is clearly understood. Our second task is to press on with the exploration of the wide range of physical phenomena of which the existing theories take no account. This means pressing on with experiments in the fashionable area of particle physics, but it also means much more. Outstanding among the areas of physics which have been left out of recent theories of elementary particles are gravitation and cosmology. Einstein's theory of gravitation is an outstanding innovation which has still after 40 years not begun to be absorbed into the mainstream of physics. Cosmology is to most physicists, like the insides of atoms to the contemporaries of Rutherford, not a respectable subject to think about. It is quite probable that a satisfactory theory of elementary particles will demand as an essential ingredient a description of the "boundary conditions" which the universe had to satisfy at its beginning. If this is so, then we can expect no final clarification of particle physics until the great open questions of cosmology have been answered by observation.

My guess, then, is that important innovations will occur in physics as they have in the past, at intervals of 25 or 50 years, approximately the length of time it takes for one innovation to be digested before the next can be gestated. I guess that an innovation of the magnitude of Newtonian dynamics or quantum mechanics is not likely within 100 years from now. And I guess that the next important innovation will arise, within 25 years, out of gravitational or astronomical observations made possible by elaborate equipment assembled in interplanetary space.

Kodak reports on:

the rose arbor, the finch, or the chondrosarcoma in color on paper . . . a ceramic magnet, a coil, a capacitor, a germanium diode, and some nylon bearings...an organic too versatile to lie down and die

Be creative, if you insist

Persons who deplore photography as mechanistic submergence of the human spirit may, if they wish, go on sketching anatomical specimens with a charcoal pencil and then retire to the library to enjoy their personal collections of authenticated original Botticellis. But here's the dope on the new *Kodacolor 135 Film* for miniature cameras—in case you prefer photography. It is the first Kodak color film expressly made for obtaining color prints with a 35mm camera.

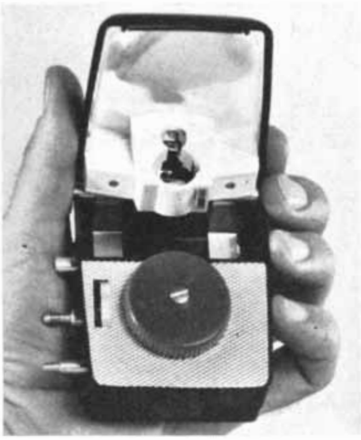
You bring your exposed film to your dealer. He sends it to a color processor—of which gentry Kodak is one. Kodak provides 2½ x 3½-inch enlargements (2X from the 35mm negative) at 23¢ each list, or 3½ x 5's (3X) at 32¢ list. To compensate for numerous unknowns along the way, we have to exercise (electronically) for each negative an individual judgment of the color balance you would like. By dint of intensive studies employing techniques of experimental psychology and statistical analysis and by further dint of having made quite a pile of satisfactory prints already, we generally hit it right.

If your subject is a rare tropical finch or a chondrosarcoma instead of someone's blond granddaughter in front of a rose arbor and you're going to a color lab for a custom job, it wouldn't be a bad idea to include a neutral grey card outside the area of interest in the original picture. If you ask to have the grey card rendered as grey and then cropped off, no color processor can go far off faithful color rendition of your subject.

You have an alternative to color lab processing, of course. For 75¢ a Kodak dealer will sell you a copy of the brand new Kodak Data Book, "Printing Color Negatives." You can study that and then make your own prints and your own decisions, using the right Kodak chemicals and *Kodak Ektacolor Paper* (formerly called Kodak Color Print Material, Type C).

Try it. During that first night in the darkroom the human spirit will find plenty to keep it occupied.

4 twirls for 1/5 joule



Here is a new Kodak device, obtainable for only $13.95 (list). It converts a twirl of your fingers into a half-million-erg jolt of d-c energy, four twirls for 200 watt-milliseconds. With a thousand ohms of load resistance, 63% of the four twirlsworth of energy is discharged within 150 milliseconds, in a surge that starts at 50 volts. The energy can be taken off from the socket in the hinged cover. To trip, you close circuit between the projecting screw at the left and the lower stud, first having wedged the knurled nut firmly to the left in its slot.

Don't complain that the device could be designed for better mechanical convenience. We are merely trying to be helpful. For commercial practicability, we have had to design the *Kodak Generator Flasholder* to the convenience of those who want to snap it onto a camera —almost any camera—for photoflash pictures that will never miss synchronization because of aged batteries.

For your part, you ought to be willing to put in a few minutes of junkbox-inspired inventiveness in adapting the gimmick to your own high scientific purpose. There is no need to write, wire, or phone. Just march down to the nearest camera counter.

Spectrography is nice too

Is $3 too much to ask for one gram of *Toluene-3,4-dithiol* (Eastman 4508)? We'll tell you why we ask.

In 1937, within a year after a British chemist announced that this compound is a reagent for tin and nicknamed it "dithiol," we tried to make some. Our luck was poor. Yield was 8%, and quality was dubious. We decided to forget about it.

Yet dithiol refused to lie down and die. Chemists have persisted in writing papers about it—"most promising colorimetric reagent for tin"; molybdenum determination in soils, metals, and rocks; precipitant for metals of the H_2S group; simultaneous determination of molybdenum and tungsten in biological materials; the zinc-dithiol complex as a reagent for arsenic and germanium; semi-microanalysis for bismuth; and on and on. There was a market there, all right.

Once we came close to doing something about it. A paper in the Indian literature, though it discussed another compound, struck us as offering a sound route to dithiol. We talked ourselves out of trying it on the grounds that dithiol had a short shelf life.

Eight more years slipped by before the break came. An inquirer so goaded us with his scoffing at our pessimism about dithiol and with his taunt about what a cinch it was that we lost our head a little and bought the right to use his method. We don't react that way very often.

His method seems to have worked. We find ourselves in possession of a large stock bottle full of dithiol. Over the dithiol there is nitrogen, just to be surer. It is to be hoped that all who have inquired about dithiol over the past 21 years are still alive and well and interested in analytical chemistry.

Procedural abstracts on the more promising applications of dithiol are obtainable without charge from Distillation Products Industries, Rochester 3, N. Y. (Division of Eastman Kodak Company). Likewise obtainable is the new List No. 41 of some 3700 Eastman Organic Chemicals, out of which, happily, dithiol is but one.

Prices stated are subject to change without notice.

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

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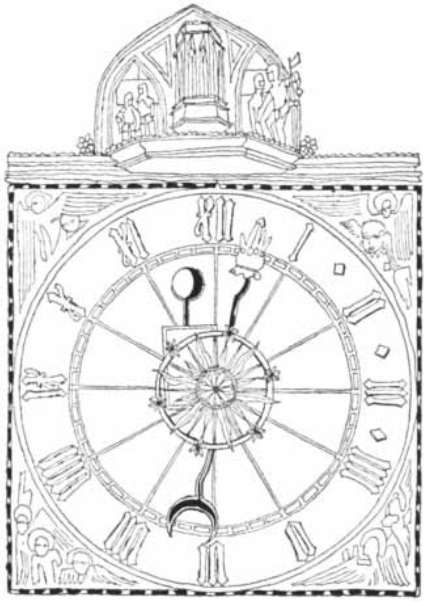


U. N. Radiation Report

"All steps designed to minimize the irradiation of human populations will act to the benefit of human health." So concluded the United Nations Scientific Committee on the Effects of Atomic Radiation last month after a three-year study. The steps it recommended were "avoidance of unnecessary exposure resulting from medical, industrial and other procedures for peaceful uses," and "cessation of contamination of the environment by explosions of nuclear weapons." The Committee added, however, that the "control of all these sources of radiation involves national and international decisions which lie outside the scope of its work."

The findings of the Committee did not differ substantially from those of earlier studies, such as the one published in 1956 by the U. S. National Academy of Sciences. The U.N. group stressed the need for research in fundamental radiobiology, particularly on the effects of small doses of radiation. It concurred in the virtually unanimous opinion that there is no lower limit on genetic effects; any dose, however small, causes mutations, and the number of mutations is proportional to the amount of radiation. As to other effects, such as leukemia and bone cancer, the question of a threshold is still open. The Committee could not decide whether a small exposure of the general population increases the frequency of these diseases, or whether some minimum dose is necessary to produce any additional cases.

Estimates of present and future levels of exposure were obtained in a world-wide survey. Natural background radiation delivers an average of three rem (a unit measuring radiant energy absorbed by tissue) to the gonads of each person in the world in a period of 30 years. (This period is taken as the average reproductive lifetime.) It delivers seven rem to the bone marrow in 70 years. Medical X-rays and other controllable man-made sources contribute a 30-year gonad dose of from .5 to five rem and a 70-year dose to the marrow of more than seven rem.

The exposure due to weapons tests was estimated on three different assumptions: (1) that tests will be stopped now; (2) that present levels of contamination will be maintained; (3) that testing will continue at the rate of the past four years, and thus gradually increase the contamination. Under the first assumption the 30-year-gonad dose will be .01 rem; under the second, .06; under the third, .12. The bone marrow exposure differs sharply in countries where most of the calcium in the diet is supplied by milk and those where it comes from rice. For milk-drinking countries the 70-year marrow doses are .16, 1.3 and 2.8 rem; for those in which rice is the staple diet, .96, 7.5 and 17.

Assessing the genetic risk, the Committee pointed out that at present about 4 per cent of all newborn babies suffer from some recognizable hereditary disorder. If the natural mutation rate were doubled (which would require a 30-year exposure of 10 to 100 rem) the number of hereditary defects would increase to somewhere between 5 and 8 per cent. Although the present and expected levels of exposure are far less than the doubling dose, they will presumably contribute a proportionate share of genetic defects. In addition to clearly hereditary traits, other characteristics of the population as a whole, such as intelligence and longevity, are probably determined genetically. These are also expected to be adversely affected by an increase in mutation rate.

On the assumption that there is no lower limit in other radiation effects, the Committee calculated that each additional rem of exposure above the natural background could cause a maximum of eight cases of bone cancer and 52 cases of leukemia per million persons over a 70-year period.

THE CITIZEN

The most dangerous components of fallout from weapons tests were stated to be the long-lived isotopes strontium 90 and cesium 137. Both are carried to the stratosphere in powerful nuclear explosions and return to the earth gradually over many years. Strontium, because of its chemical resemblance to calcium, is stored in bone tissue. Cesium is taken up by all the tissues and contributes the major share of gonad exposure from fallout.

In preparing its conclusions the Committee voted down a draft proposed by the U.S.S.R. which stated in part: "The physical and biological data presented in the report enable the Committee to draw the conclusion that there should be an immediate cessation of test explosions of nuclear weapons."

The Committee is made up of scientists from Argentina, Australia, Belgium, Brazil, Canada, Czechoslovakia, the United Arab Republic, France, India, Japan, Mexico, Sweden, the U.S.S.R., the United Kingdom and the U. S.

Science and the 85th Congress

Expectations that the post-sputnik furor would lead to a radical increase in federal aid to science and education have been cooled by the session of Congress just concluded. Some of the results:

The National Science Foundation got $130 million of the $140 million requested in the President's Budget Message. Some $30 million of this amount is earmarked for supplementary training of high-school science and mathematics teachers. The Foundation received almost all the basic-research funds it had asked for, but its request for $25 million to construct research facilities was cut by more than two thirds. However, Congress voted substantial supplemental appropriations for the National Radio Astronomy Observatory at Green Bank, W. Va., and for the U. S. International Geophysical Year program.

Senate and House committees approved omnibus education bills which include provisions for federal scholarships and loans for college students, fellowships for graduate students, and grants to the states for science, mathematics and language-teaching equipment. At this writing, however, it was uncertain whether the bills would be passed before adjournment. Proposals for federal aid for school construction were killed outright.

Congress acted to convert the National Advisory Committee for Aeronautics into the National Advisory Committee for Aeronautics and Space Administration. The revamped body will superintend the peaceful aspects of space research and exploration; space activities involving weapons or defense will remain under Department of Defense jurisdiction.

Also passed was a bill authorizing the Atomic Energy Commission to supply to allies of the U. S. information and material for the fabrication of nuclear weapons. In its original form this measure had alarmed many scientists and other citizens (one Senator called it a bill to pass out atomic bomb do-it-yourself kits). As the measure was finally passed, its application was restricted to nations which have made "substantial progress" in developing nuclear weapons. What constitutes substantial progress was not defined, but Senate debate on the measure indicated that only Great Britain is now qualified.

To Be Continued

The International Geophysical Year will end as scheduled on December 31, but the international scientific cooperation which it initiated will go on. The governing body of the I.G.Y., meeting in Moscow, has resolved to continue many I.G.Y. projects in a less intensive form at least through 1959. The resolution also endorses permanent worldwide scientific cooperation and calls upon the International Council of Scientific Unions to determine what form this should take after 1959.

Soviet delegates had urged that the entire I.G.Y. program be continued for another year. Other delegations opposed this for financial reasons or because they wanted time to study the vast amounts of data collected so far. The final resolution was a compromise between the two viewpoints.

Still Larger and Still Older

Estimates of the size and age of the universe continue to expand more rapidly than the universe itself. In 1953 previous estimates were doubled; two years later they were increased again. Now Allan R. Sandage of the Mount Wilson and Palomar Observatories suggests that even these estimates may be too small. Sandage questions the reliability of the fundamental yardstick used to measure intergalactic distances.

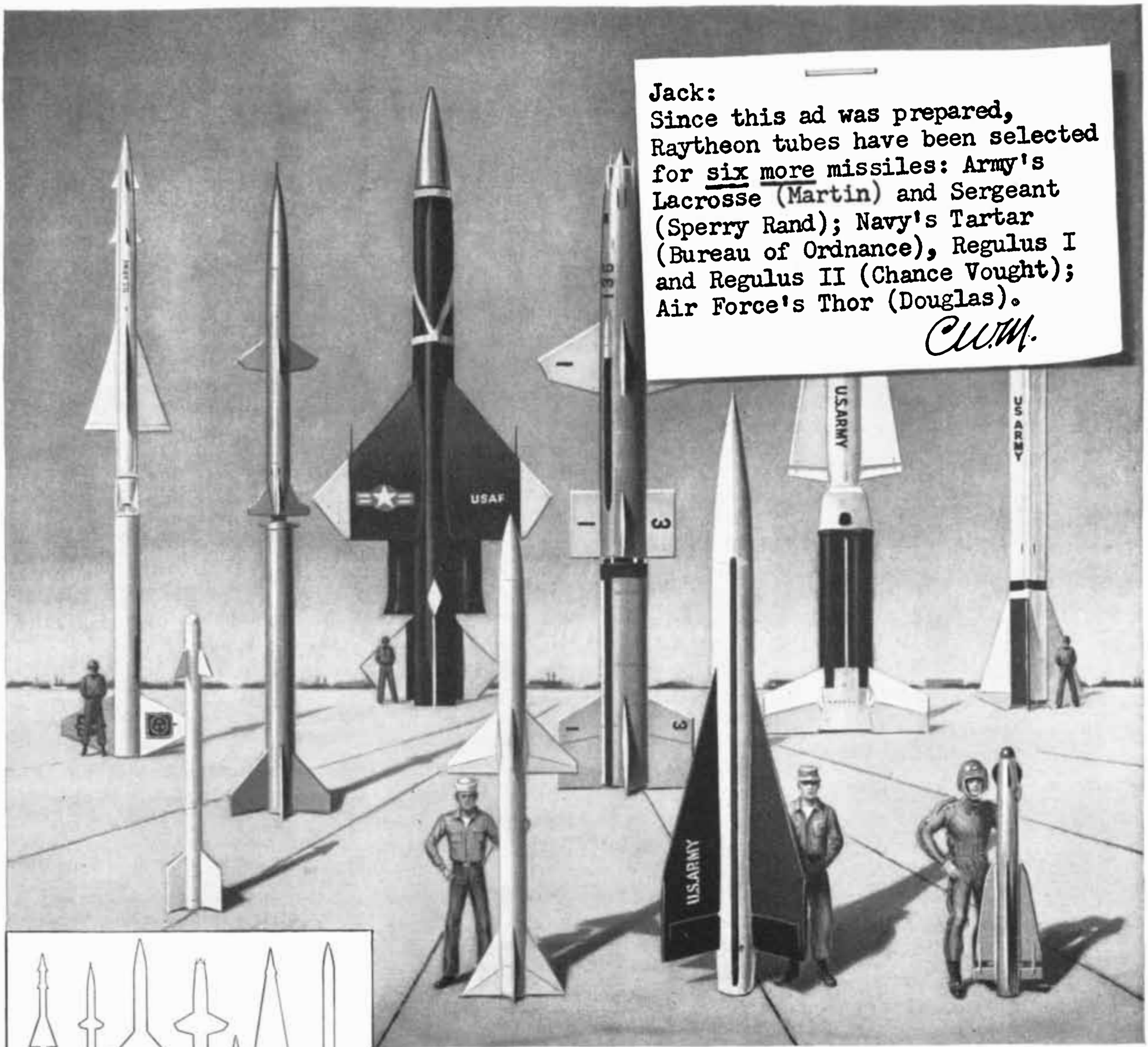
Measurements of these distances all derive ultimately from observations of the Cepheid variables, a class of stars whose brightness waxes and wanes at regular intervals. For many years astronomers believed that the length of this interval for a particular star gave a fairly accurate measure of its intrinsic brightness. The first big jump in estimates of the size of the universe came when Walter Baade of Mount Wilson and Palomar reported observations indicating that there were two kinds of Cepheids, one of which was intrinsically much brighter than the other [see "A Larger and Older Universe," by George W. Gray, SCIENTIFIC AMERICAN, June, 1953].

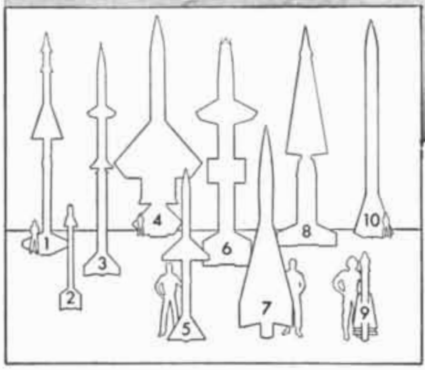
In a recent issue of *The Astrophysical Journal* Sandage reports that recent observations of Cepheids with the 200-inch Hale telescope indicate that their brightness depends on their color as well as their period. There are indications, moreover, that they do not fall neatly into the two types which Baade described. Instead, the two types may be merely extreme cases, with many Cepheids falling between them. As an intergalactic yardstick the Cepheids are for the present almost useless. Determining the exact relationship between their color, period and intrinsic brightness will require more precise measurements.

From observations of novae in nearby galaxies, Sandage concludes that they (as well as more distant galaxies) may be twice as far away as the Cepheid measuring rod had indicated. Since intergalactic distances provide a measure of the age of the universe (according to the hypothesis, accepted by most astronomers, that the universe originated in an enormous explosion of super-dense matter), its former estimated age of between 3.5 and 7 billion years must be revised upward to between 6.6 and 13.2 billion. These new figures are consistent with estimates based on studies of radioactive elements in rocks and meteorites.

The Medical Needs of 1970

The U. S. should have 14 to 20 new medical schools to maintain the ratio of 132 physicians per 100,000 persons which it has had for the past 30 years. But even if the $500 million to $1 billion needed were made available immediately, the ratio of physicians would decline between now and 1970 because of the lag before the first class graduates, warns a committee of prominent medical educators and industrial research ex-





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4. **Bomarc.** Air Force. Ground-to-air. Prime contractor: Boeing.
5. **Sparrow III.** Navy. Air-to-air. Prime contractor: Raytheon.
6. **Talos.** Navy. Surface-to-air. Prime contractor: Bendix.
7. **Hawk.** Army and Marine Corps. Ground-to-air. Prime contractor: Raytheon.
8. **Nike Hercules.** Army. Ground-to-air. Prime contractor: Western Electric.
9. **Falcon.** Air Force. Air-to-air. Prime contractor: Hughes Aircraft.
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10 MAJOR U. S. MISSILES RELY ON RAYTHEON TUBES

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ecutives. The group, headed by Stanhope Bayne-Jones, formerly dean of the Yale University School of Medicine, was appointed last year by Marion B. Folsom, Secretary of Health, Education and Welfare, to advise him on long-term needs in medical research and education.

According to the committee's report, national expenditures for medical research should be increased from the $330 million spent in 1957 to about $900 million by 1970, and research personnel should be more than doubled in that time. They base the figure on the expectation that expenditures for research and development of all kinds will rise from 2.3 per cent of the gross national product to 4 per cent, and that the proportion devoted to medical research will remain at 3.8 per cent. As at present, half the funds will have to come from the Federal Government "unless there is a marked change in social philosophy leading to private gifts or state appropriations on an unprecedented scale." Industry's share of the bill will rise from $90 million to more than $300 million, and private philanthropy, which provided $35 million last year, will have to triple its contribution by 1970.

The committee recommends increases for virtually all programs of medical research and training now sponsored by the Department of Health, Education and Welfare, especially for the Public Health Service's Communicable Disease Center in Atlanta, the Robert A. Taft Sanitary Engineering Center in Cincinnati, and the Office of Vocational Rehabilitation. They note that the National Institutes of Health at Bethesda, Md., have been expanding rapidly, and are now "the largest group of medical research laboratories in the world." The NIH, they suggest, should now consolidate and go slow on internal expansion.

The report generally praises the grant system now in use but recommends that support to educational institutions be made more general and less limited to research in specific diseases. However, it suggests extension of research on radiation injury, accidents, and air and water pollution.

"Self-teaching" Machine

A new computer that can learn to read letters, translate a speech in a foreign language and recognize faces at sight is being planned for the Navy by the Cornell Aeronautical Laboratory, Inc. While a pilot model of the machine has not yet been built, its working principles have been demonstrated on a specially-programmed International Business Machines 704 computer.

The new machine, called "Perceptron," is the brain-child of Frank Rosenblatt, a psychologist. Rosenblatt has designed the machine to be a close analogue of the human central nervous system. Existing computers "know" only what their operators tell them in a code, such as digital arithmetic or symbolic logic. The Perceptron, however, will have no code. Instead it will have elementary sense organs—such as microphones and batteries of photoelectric cells—which will report their own sensations directly to banks of "association cells" resembling a cerebral cortex. The pilot Perceptron will have only 1,000 association cells (compared to some 10 billion in the human brain). With these, however, it will be able to learn, generalize and remember. Its cells, like brain cells, will be wired together in largely random patterns. If a single connection is cut, it will make no difference in the Perceptron's behavior, for its responses will consist of statistically probable reactions of large groups of cells. The Perceptron will condition itself to respond to certain objects by developing pathways of lowered resistance through its cell network, very much as the brain is believed to do.

Equipped with an "eye" of photoelectric cells, the U. S. Weather Bureau's IBM 704, programmed to simulate a Perceptron, has already proved capable of elementary learning. When presented with squares on one side or the other of a visual field, it learned after about 30 tries to distinguish right from left with 97 per cent accuracy.

Cells in Russia

Two Soviet biologists have administered the *coup de grâce* to the "dialectic-materialist cell theory" of Olga B. Lepeshinskaya, another Soviet worker. Lepeshinskaya had won acclaim in the U.S.S.R. for her theory that cells could arise from "acellular forms of life" such as egg white, blood plasma and disintegrated cells. Trofim D. Lysenko and other Soviet figures had praised her work when it first was presented in 1950, and she subsequently received a Stalin prize for it. Lepeshinskaya and her co-workers claimed to have seen crystal-like structures form in various types of acellular material and eventually develop into complete cells. Attempts to repeat her work were unsuccessful.

L. N. Zhinkin and V. P. Mikhaĭlov also failed to duplicate the experiments; they finally concluded that there was "an error on the part of O. B. Lepeshinskaya." In an article recently translated and reprinted in *Science,* they cited evidence to demolish the "new cell theory" point by point. They summed up with a blunt denunciation: "The 'new cell theory' is not founded on solid, firmly established facts and, consequently, does not reflect any laws actually existing in nature. . . . Some . . . works have been executed at an unusually low technical level. The authors, starting with a preconception, arbitrarily treat the various visible stages in the process of cell breakdown in fixed and stained preparations as stages in their new formation. . . . O. B. Lepeshinskaya has postulated [her theory] not on grounds of firmly established facts, but on speculative hypotheses, linked with a quite primitive understanding of biogenetic law."

The Stuff of Dreams

The theory that dreams mainly reflect the dreamer's inner world rather than his outer environment has received new support. External stimuli during sleep do not, it appears, induce the sleeper to dream. If he is dreaming already, they seldom influence the dream's content.

William Dement and Edward A. Wolpert of the University of Chicago stimulated sleeping subjects with a 1,000-cycle tone, light flashes and a spray of cold water. Subjects whose brain waves and eye movements indicated that they were not dreaming showed no change in these indicators, nor did they recall any dreams when awakened soon afterward. Subjects who were dreaming incorporated the external stimulus into their dream only about one time in four. The more unpleasant the stimulus, the more likely it was to be woven into the dream. Even the cold-water spray, however, influenced the dream less than half the time.

Reporting their results in *Journal of Experimental Psychology,* Dement and Wolpert note that the movements of the eyes behind closed lids are especially useful indicators for studying dreams. Not only do these motions distinguish periods of dreaming from those of dreamless sleep, but also their character shows a close relationship to the content of the dream. Dreams in which the dreamer was an active participant were marked by many large eye movements, and the direction in which his eyes moved was generally the same as it would have been if the dream actions had occurred in real life. Where the dreamer was observing events from a

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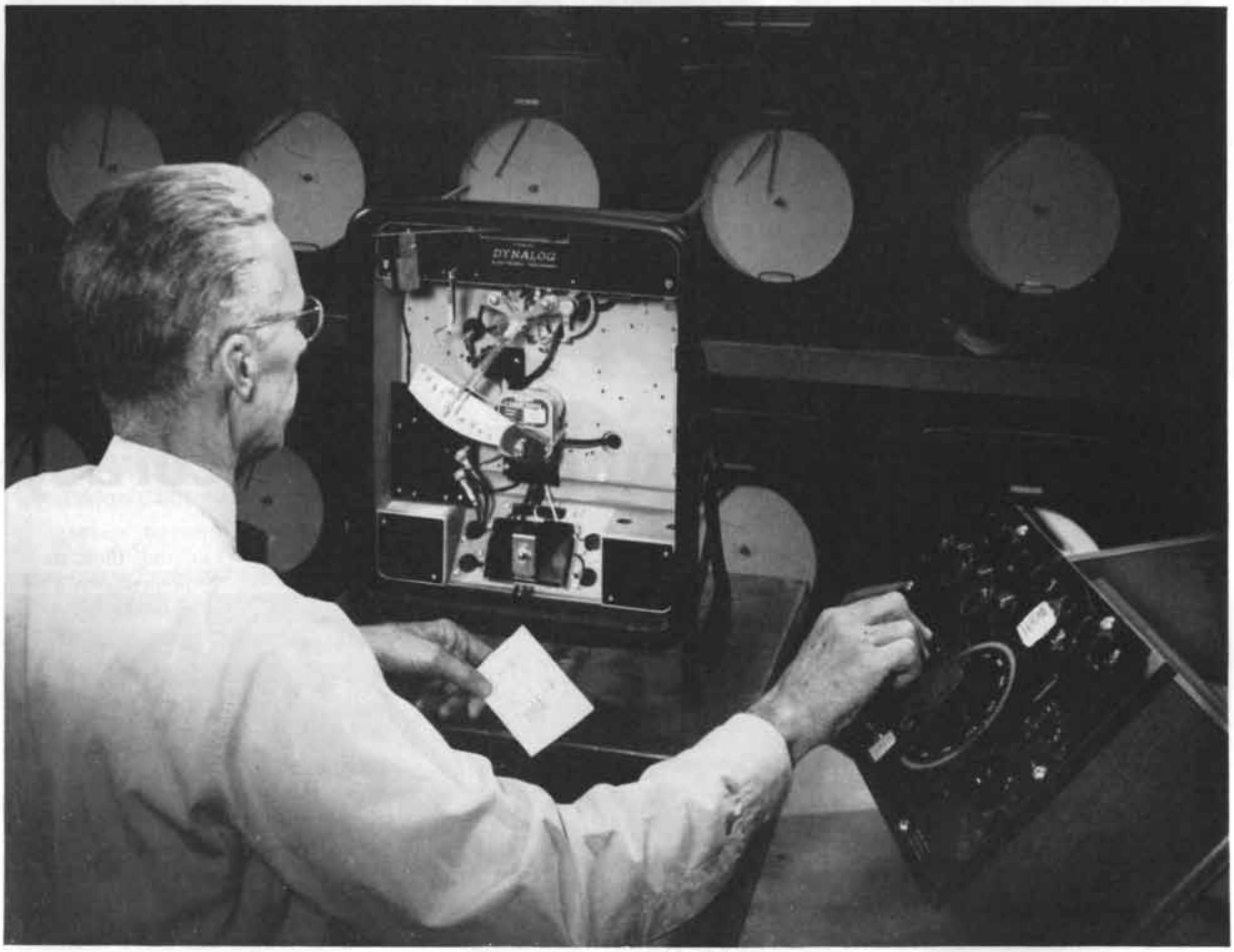

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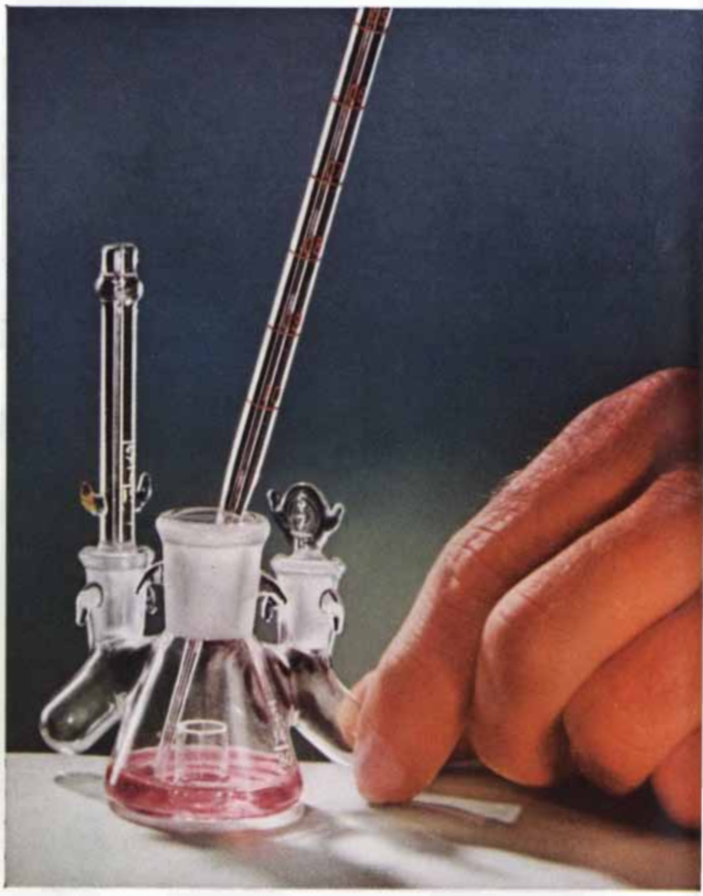

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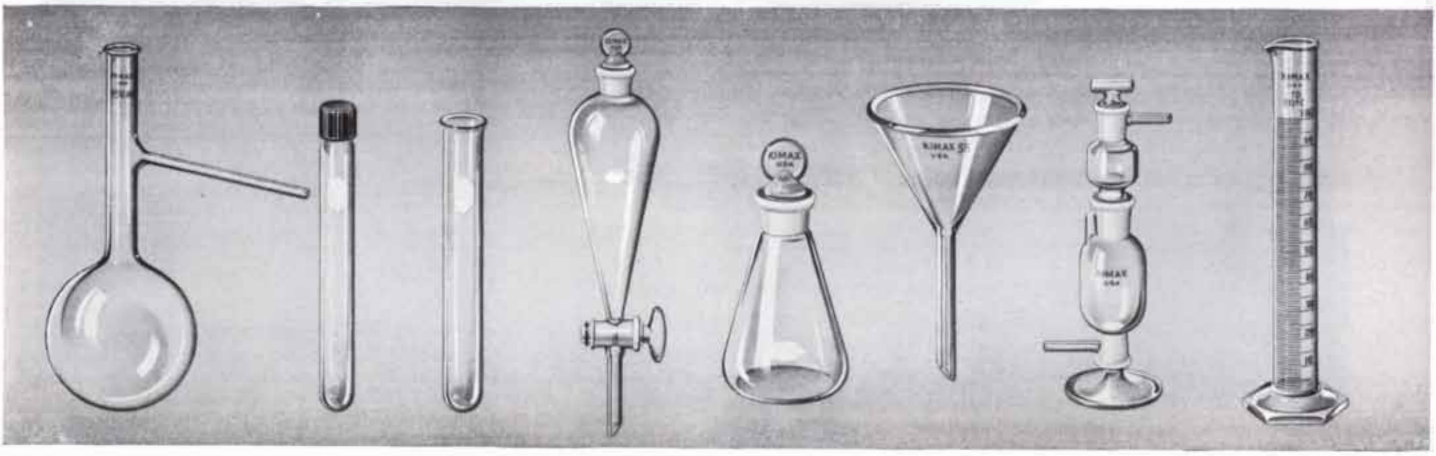

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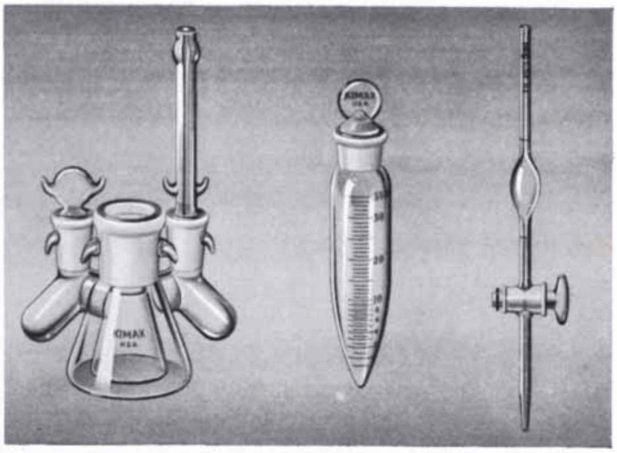

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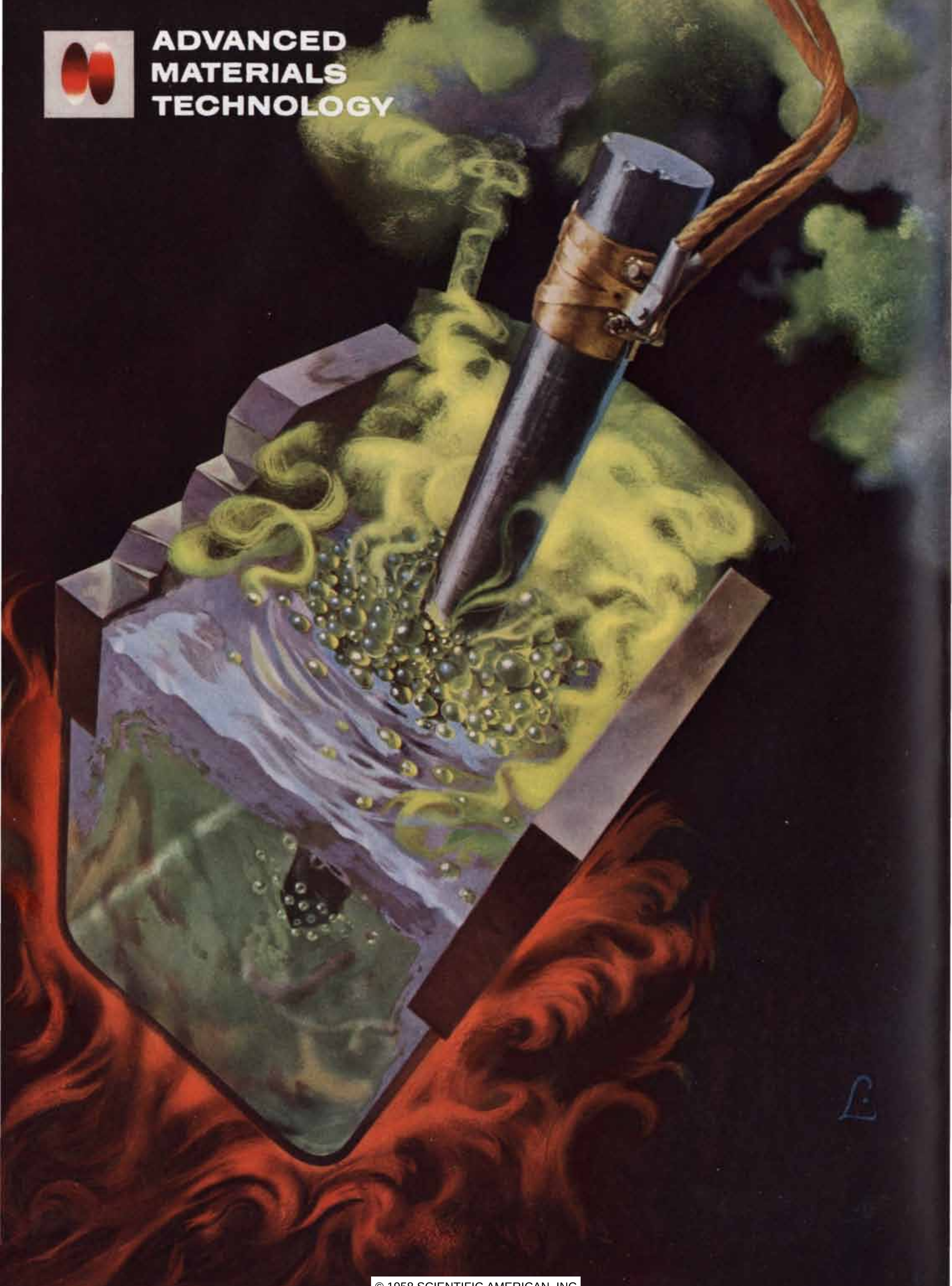
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distance or quietly conversing, however, his eye movements were few and small.

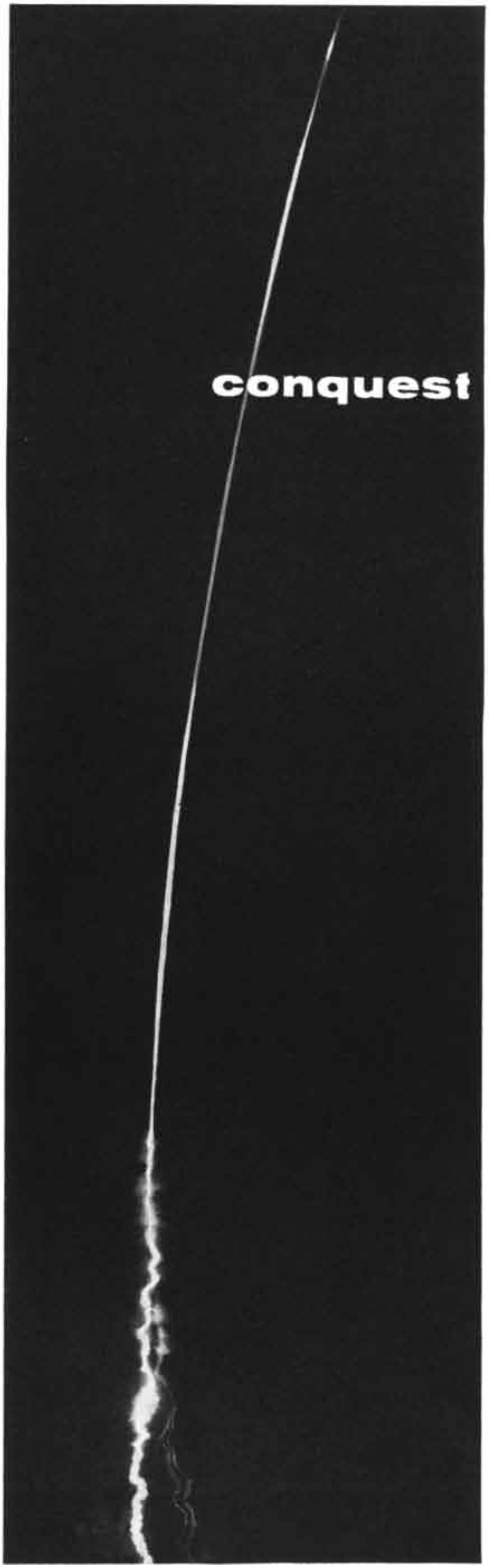
While the eyes may be busy in dreams, other parts of the body remain still, even in dreams involving running or fighting. Body movements tend to be suppressed during dreams, appearing as a sort of punctuation at the end of a dream period or between one dream sequence and another. The authors suggest that eye movements differ from other movements because they are controlled by a different part of the cerebral cortex.

Isaac Newton, Detective

A recent study explores the fact that, in his later years, Isaac Newton had turned his powerful intellect from the discovery of natural laws to the enforcement of man-made laws. While Newton was warden of the Mint from 1696 to 1700, he was a key figure in tracking down counterfeiters and clippers (men who shaved metal from coins) and securing their prosecution. Since in Newton's time there was no such thing as a police force, he had to interview informers and testify himself. Sir John Craig, a biographer of Newton, describes in *Nature* the great scientist's activities as a "crime investigator," and credits him with the imprisonment of more than 100 criminals in London alone. At least 20 of these were hanged for coinage offenses.

One man, William Chaloner, seems to have aroused special hostility in Newton. Chaloner had been accused of stealing dies from the Mint, but was pardoned; he even impressed a committee investigating corruption in the Mint by his suggestions for changing the coinage to prevent counterfeiting. Newton, however, tested Chaloner's ideas and was not impressed. Instead he spent two years tracking down evidence to convict Chaloner of counterfeiting, forging and bribing witnesses. He successively employed three criminals to gain Chaloner's confidence and obtain information from him. Despite these tactics, Newton's final case against Chaloner was far from conclusive. All the witnesses were criminals, but "common sense triumphed over the niceties of the law," and Chaloner was hanged.

Newton found the investigative work too big a task for one man and proposed setting up a special staff to handle it. In 1715, when he was assistant master of the Mint, he appointed a solicitor to do the job. From this a country-wide system eventually developed which enforced the laws with respect to coinage.



conquest of the thought barrier

Over the years, we have been hearing of many "barriers" in science . . . the sound barrier, the water barrier, the thermal barrier.

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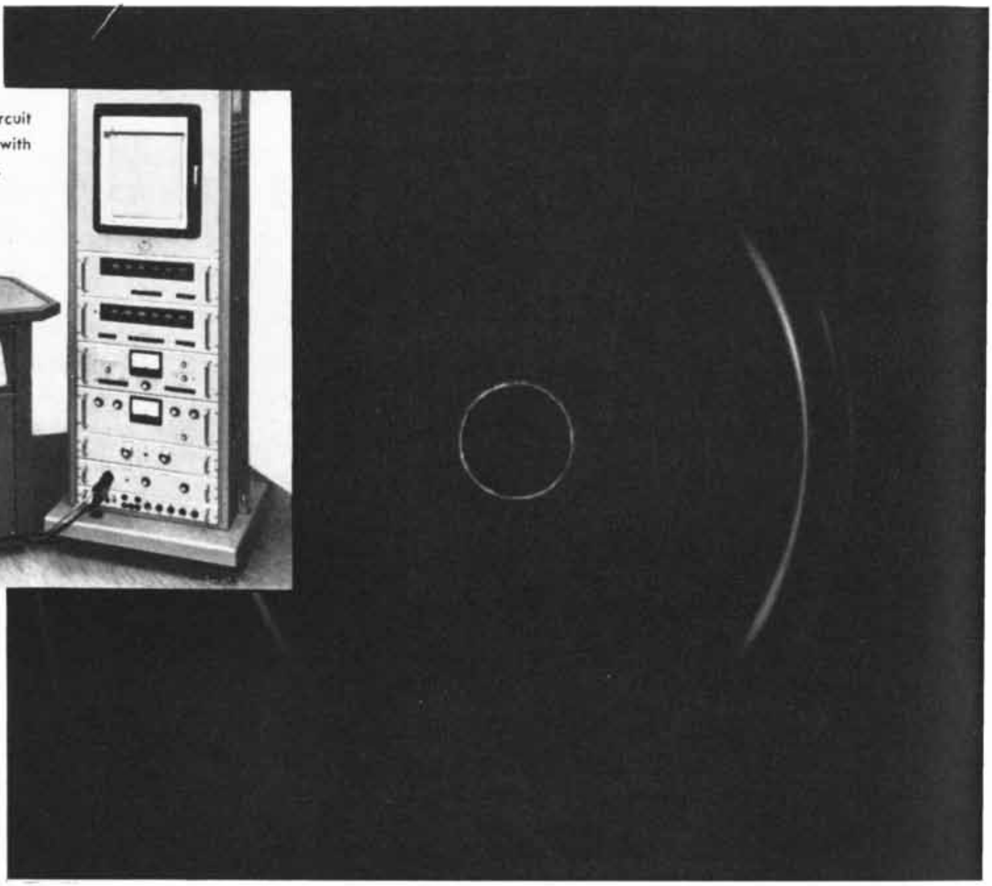

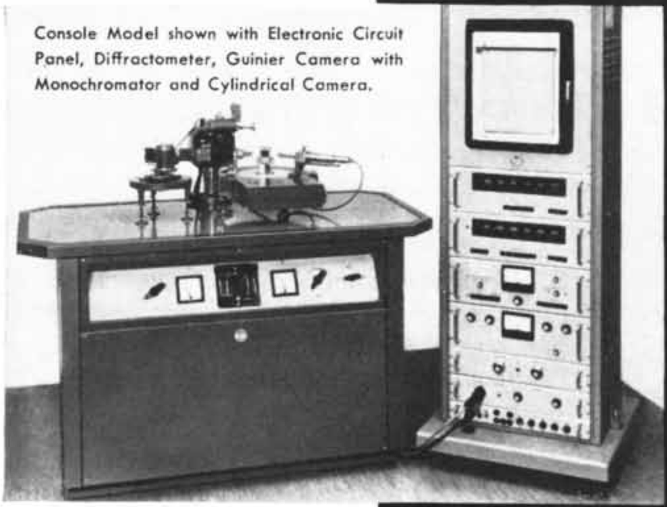

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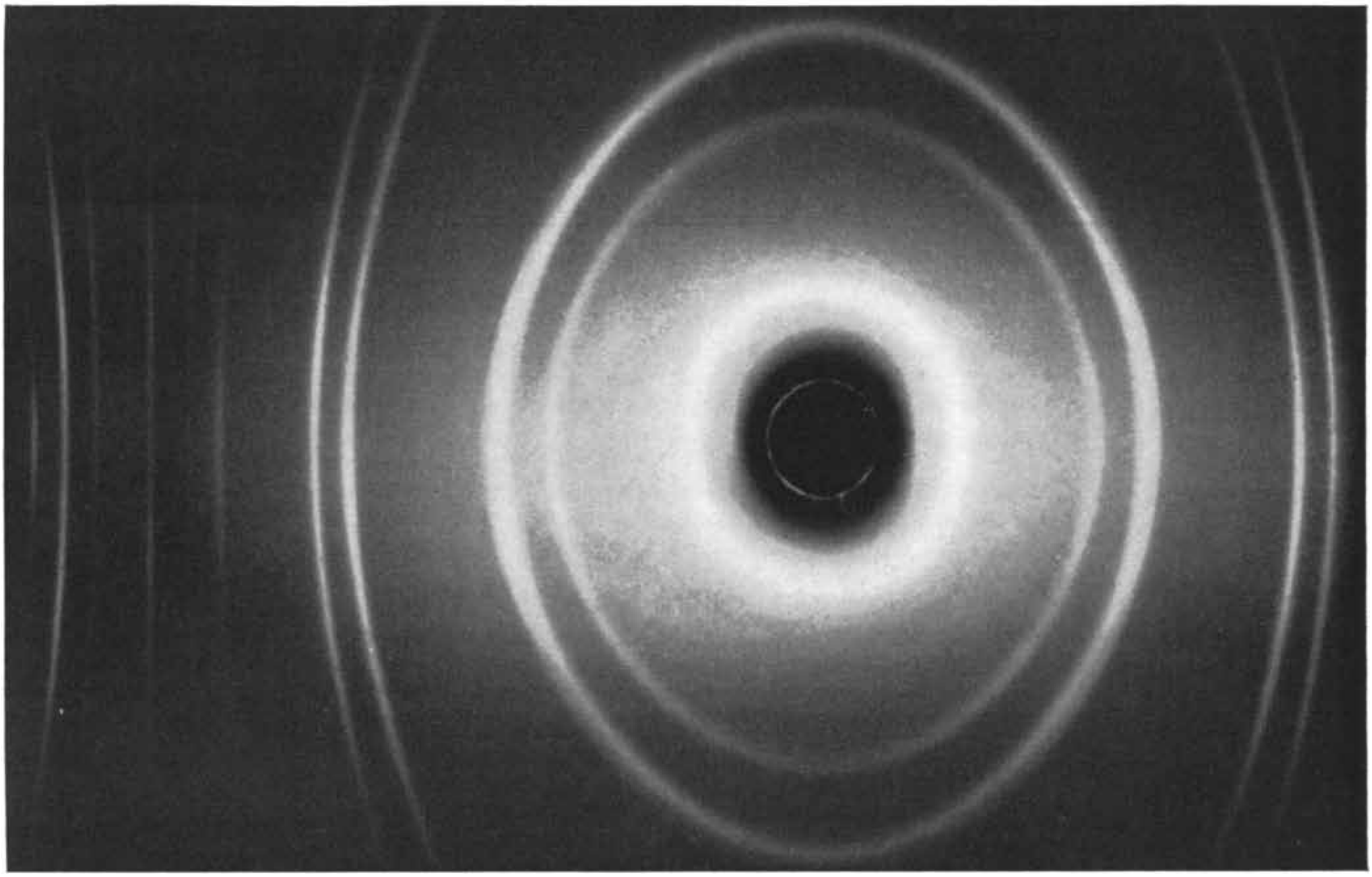

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Innovation in Biology

The biologist seeks to explain life in terms of the physical sciences, but the explanation will require physical sciences adequate to cope with the unique behavior of living systems

by George Wald

No great idea is ever lost. Like Antaeus, it is overthrown only to rise again with renewed vigor. It is dismissed only to return, yet never quite the same. Its rejection is only a step in its further development.

One could say better that all great ideas come in pairs, the one the negation of the other, and both containing elements of truth. Each generation has the satisfaction of overthrowing the idea in one of its forms, each succeeding generation the triumph of rediscovering it. The onlooker, watching this vacillation, has the illusion that no progress is made. Yet this is the very mechanism of progress. It is the progress of a screw, which advances as it rotates. Science turns the idea about and about, now accepting it, now rejecting it, giving it always fuller, more detailed and exact meaning.

The great idea emerges originally in the consciousness of the race as a vague intuition; and this is the form it keeps, rude and imposing, in myth, tradition and poetry. This is its core, its enduring aspect. In this form science finds it, clothes it with fact, analyzes its content, develops its detail, rejects it, and finds it ever again. In achieving the scientific view, we do not ever wholly lose the intuitive, the mythological. Both have meaning for us, and neither is complete without the other. The Book of Genesis contains still our poem of the Creation; and when God questions Job out of the whirlwind, He questions us.

Let me cite an example. Throughout our history we have entertained two kinds of views of the origin of life: one that life was created supernaturally, the other that it arose "spontaneously" from nonliving material. In the 17th to 19th centuries these opinions provided the ground of a great and bitter controversy. There came a curious point, toward the end of the 18th century, when each side of this controversy was represented by a Roman Catholic priest. The principal opponent of the theory of spontaneous generation was then the Abbé Lazzaro Spallanzani, an Italian priest; and its principal champion was John Turberville Needham, an English Jesuit.

Since the only alternative to some form of spontaneous generation is a belief in supernatural creation, and since the latter view seems firmly implanted in the Judaeo-Christian theology, I wondered for a time how a priest could support the theory of spontaneous generation. Needham tells one plainly. The opening paragraphs of the Book of Genesis can in fact be reconciled with either view. In its first account of the Creation, it says not quite that God made living things, but that He commanded the earth and waters to produce them. The language used is: "Let the waters bring forth abundantly the moving creature that hath life. . . . Let the earth bring forth the living creature after his kind." In the second version of the Creation, the language is different and suggests a direct creative act: "And out of the ground the Lord God formed every beast of the field, and every fowl of the air. . . ." In both accounts man himself—and woman—are made by God's direct intervention. The myth itself therefore offers justification for either view. Needham took the position that the earth and waters, having once been ordered to bring forth life, remained ever after free to do so; and this is what we mean by spontaneous generation.

This great controversy ended in the mid-19th century with the experiments of Louis Pasteur, which seemed to dispose finally of the possibility of spontaneous generation. For almost a century afterward biologists proudly taught their students this history and the firm conclusion that spontaneous generation had been scientifically refuted and could not possibly occur. Does this mean that they accepted the alternative view, a supernatural creation of life? Not at all. They had no theory of the origin of life, and if pressed were likely to explain that questions involving such unique events as origins and endings have no place in science.

A few years ago, however, this question re-emerged in a new form. Conceding that spontaneous generation does not occur on the earth under present circumstances, it asks how, under circumstances that prevailed earlier upon this planet, spontaneous generation did occur and was the source of the earliest living organisms. Within the past 10 years this has gone from a remote and patchwork argument spun by a few venturesome persons—A. I. Oparin in Russia, J. B. S. Haldane in England—to a favored position, proclaimed with enthusiasm by many biologists.

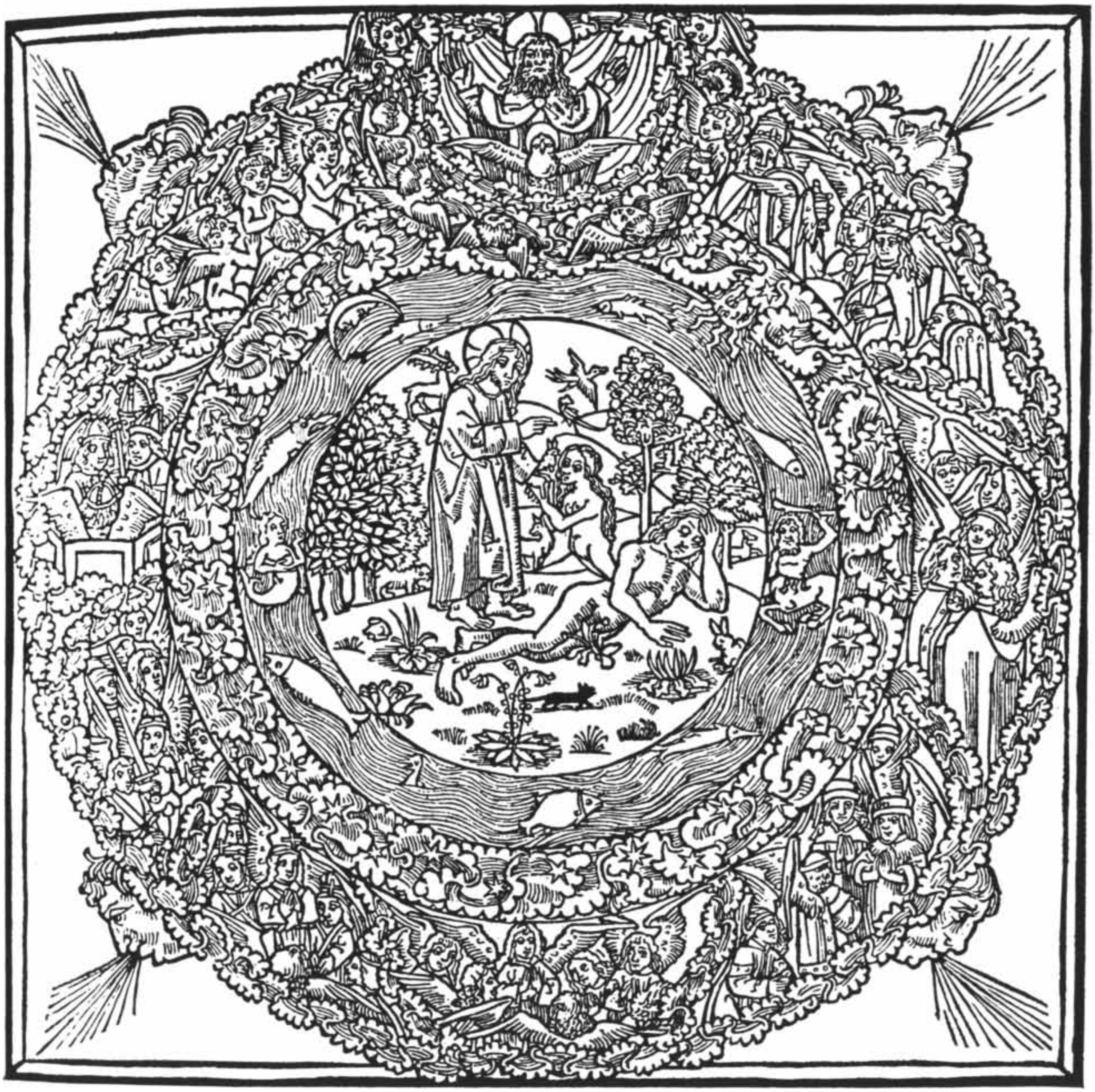
Have I cited here a good instance of my thesis? I had said that in these great questions one finds two opposed views, each of which is periodically espoused by science. In my example I seem to have presented a supernatural and a naturalistic view, which were indeed opposed to each other, but only one of which was ever defended scientifically. In this case it would seem that science has vacillated, not between two theories, but between one theory and no theory.

That, however, is not the end of the matter. Our present concept of the origin of life leads to the position that, in a universe composed as ours is, life inevitably arises wherever conditions permit. We look upon life as part of the order of nature. It does not emerge immediately with the establishment of that order; long ages must pass before it appears. Yet given enough time, it is an inevitable consequence of that order.

When speaking for myself, I do not tend to make sentences containing the word God; but what do those persons mean who make such sentences? They mean a great many different things; indeed I would be happy to know what they mean much better than I have yet been able to discover. I have asked as opportunity offered, and intend to go on asking. What I have learned is that many educated persons now tend to equate their concept of God with their concept of the order of nature. This is not a new idea; I think it is firmly grounded in the philosophy of Spinoza. When we as scientists say then that life originated inevitably as part of the order of our universe, we are using different words but do not necessarily mean a different thing from what some others mean who say that God created life. It is not only in science that great ideas come to encompass their own negation. That is true in religion also; and man's concept of God changes as he changes.

Let me go to another example. There are two great views of the animal kingdom: that of Darwin, and that of Goethe. The first view treats of evolution and its ways, the second of contemporary organisms. Darwin tells us how animals became as they are; Goethe how they are.

(Many biologists will regard this coupling of names as a species of sacrilege. Darwin represented well-nigh the perfection, Goethe the frustration, of biology as we conceive it. In Goethe's biology the poetic insight prevailed: observation entered only to stimulate and then to bolster intuition. All fruitful science contains both these ingredients; it is the proportion in which Goethe mixed them that we now reject. Goethe esteemed some of his scientific writings



THE CREATION is depicted in this woodcut from the Lübeck Bible, published in 1494. In the center God creates Eve out of Adam's rib. In the circle around this scene are the waters; in the next circle, the heavens. In the outermost circle are the angels.

SIX HISTORIC FIGURES mentioned by Wald are depicted. At left is Johann Wolfgang von Goethe. Second from left is Louis Pasteur; third, Charles Darwin; fourth, Georg Wilhelm Friedrich Hegel; fifth, Benedict Spinoza. At right is Lazzaro Spallanzani.

more than his poetry; we vastly prefer his poetry. All this conceded, Goethe stressed an idea that states a genuine biological problem. In his theory of archetypes he attempted to define the ideal forms which fit animals for the various ways in which they live upon the earth—the ideal swimming animal, the ideal flying animal, the ideal insect, the ideal mammal.)

Students of biology tend frequently to confuse the problem of origins with that of contemporary organisms. They speak at times as though a modern protozoon were the ancestor of a modern fish, and that in turn of a salamander, and that of a bird or man. But of course no contemporary animal is the ancestor of any other; each is the end-product of its own evolution. Each has been tempered in the fire of natural selection, each selected over the ages as the choicest representative of its kind. A present-day protozoon expresses whatever has best been achieved in the fashioning of protozoa; just as modern man is as much as evolution has yet been able to do with men. In this sense each contemporary animal is an approach to one of Goethe's archetypes, a creature fitted meticulously by natural selection for one possible mode of earthly existence.

Generations of biologists have rejected Goethe's position with scorn; indeed, Goethe stated it badly, and with nonsensical accretions. Nevertheless, here are two views, both true, and both necessary to understand living organisms. Now that the Darwinian position is firm, biologists are finding an awakened interest in the way in which contemporary organisms fill all the niches open to them. Wherever and however on our planet organisms can live, one finds them; and whatever peculiarities of structure and function their environment demands of them they fulfill. Virtually every chemical process that can yield free energy on the surface of the earth has associated with it living organisms particularly adapted to take advantage of that process, and to use that energy to live by. We believe that organisms achieved this diversity and their present capacities by the Darwinian mechanisms of evolution; but the end result, the design of the present product relative to its way of life—the contemporary as opposed to the historical problem—these come close to the essential ideas with which Goethe struggled and which he tried to express.

This opposition of ideas within an essential, eventual unity is not peculiar to biology. Much of the recent history of physics has involved such resolutions of conflicting viewpoints. In a recent discussion by Niels Bohr of the fundamental implications of the indeterminacy principle, on which Einstein and he held opposed views, Bohr said:

"Surely, in a situation like this, where it has been difficult to reach mutual understanding not only between philosophers and physicists but even between physicists of different schools, the difficulties have their root not seldom in the preference for a certain use of language suggesting itself from the different lines of approach. In the Institute in Copenhagen, where through those years a number of young physicists from various countries came together for discussions, we used, when in trouble, often to comfort ourselves with jokes, among them the old saying of the two kinds of truth. To the one kind belong statements so

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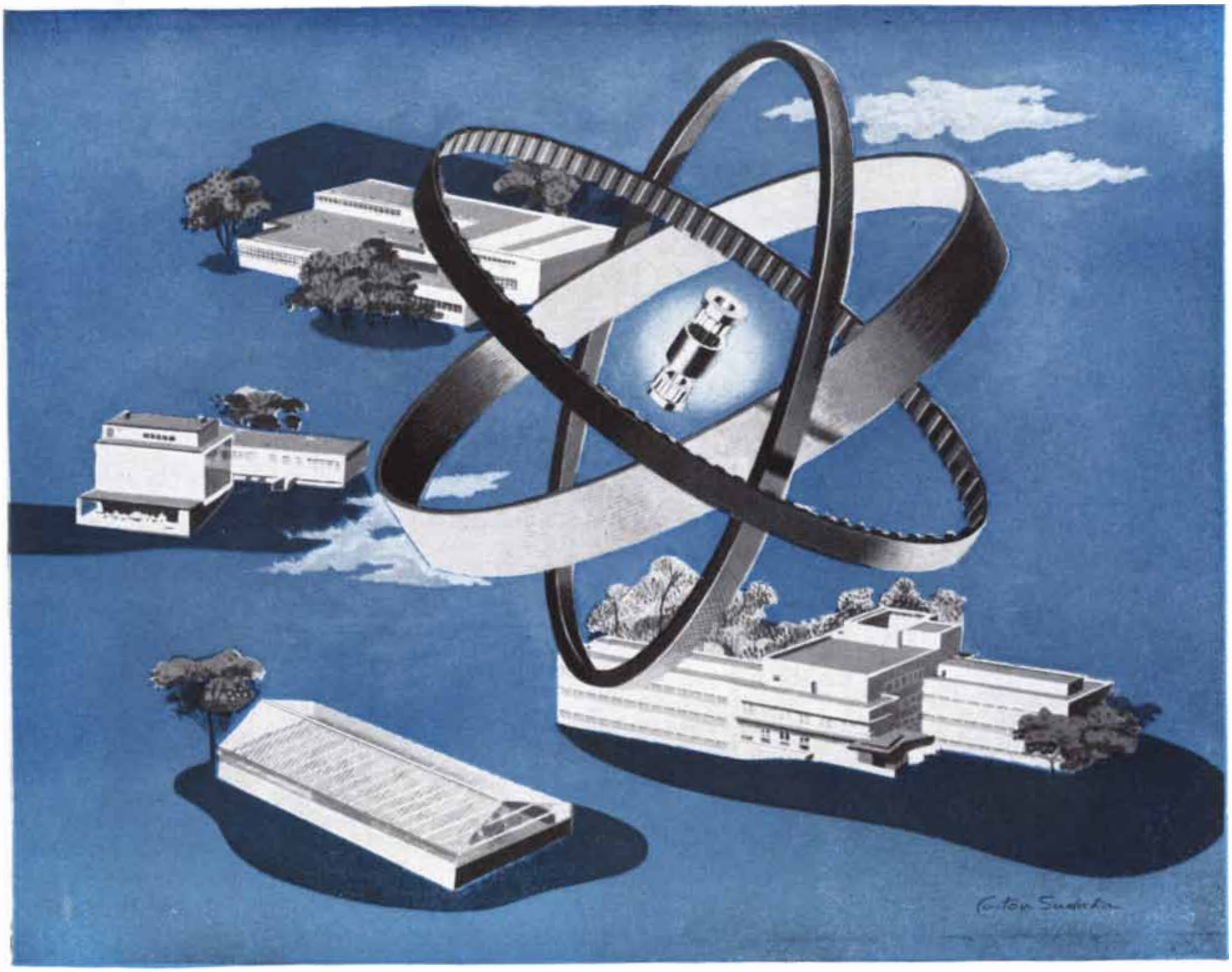

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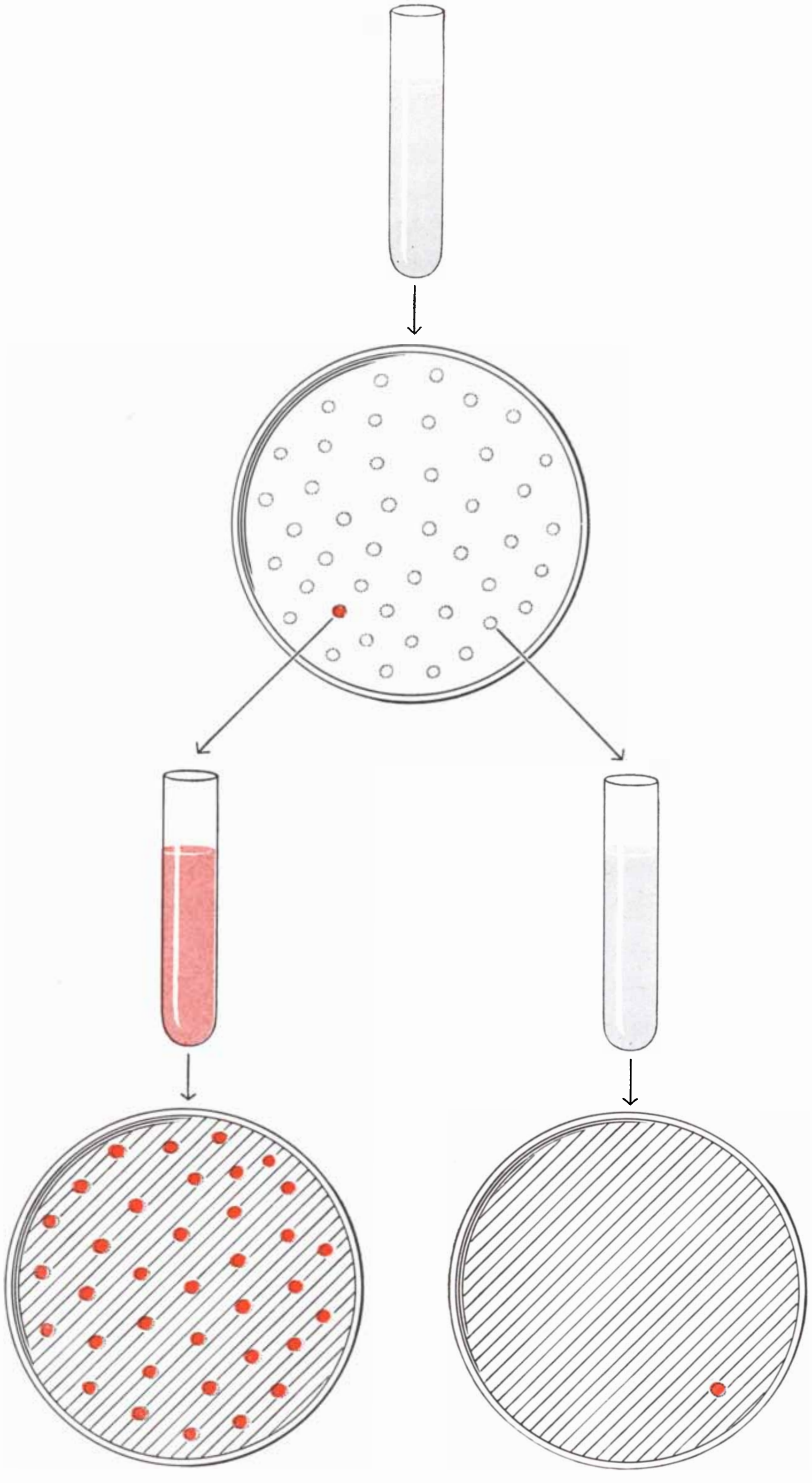


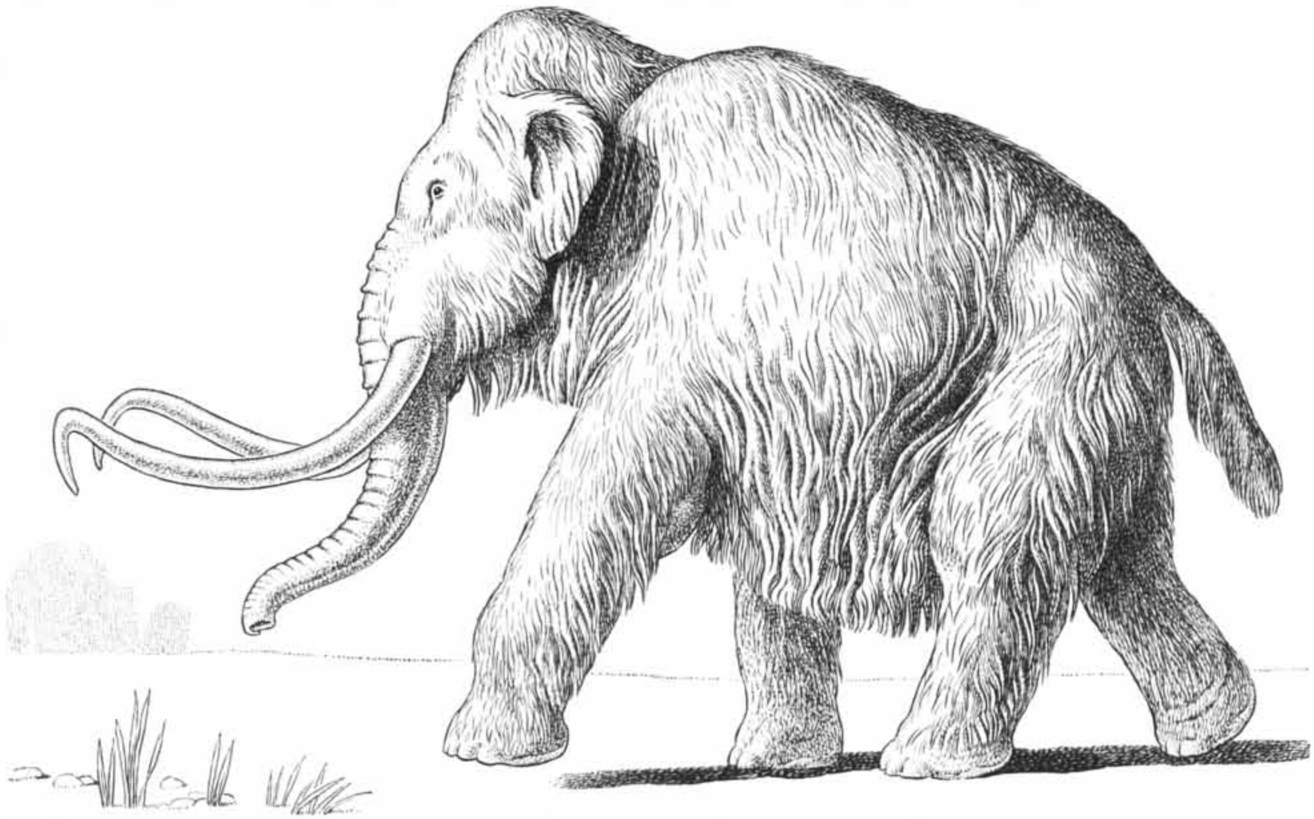
PROBLEM OF BIOLOGICAL "FITNESS" is suggested by the microbiological experiment outlined in this chart. The test tube at the top contains highly diluted bacteria. When the bacteria are poured over a nutrient medium at the bottom of a dish (*second row from top*), individual bacteria divide and ultimately form small round colonies. One of the bacteria is a mutant which can survive on a medium containing streptomycin, which kills the normal bacteria. This bacterium gives rise to a colony of mutants (*color*). Bacteria of this strain are again diluted (*test tube at left in third row*), and poured over a medium containing streptomycin (*dish at left in bottom row*). The mutant bacteria form colonies. When normal bacteria (*test tube at right*) are poured over a medium containing streptomycin, they fail to multiply (*dish at right*). One of them, however, may be a new mutant which gives rise to a colony. Thus the relative "fitness" of the two strains depends upon their environment.

simple and clear that the opposite assertion obviously could not be defended. The other kind, the so-called 'deep truths,' are statements in which the opposite also contains deep truth. Now, the development in a new field will usually pass through stages in which chaos becomes gradually replaced by order; but it is not least in the intermediate stage where deep truth prevails that the work is really exciting and inspires the imagination to search for a firmer hold."

What I have been trying to say is that biology is filled with such "deep truths." In this it is by no means unique among the sciences; nor, as I have already indicated, in other realms of thought. Indeed the further one departs from the natural sciences, with their special effort to achieve rigorousness of thinking, the more deep truths abound. It is amusing in this regard to see how difficult it is to make genuinely meaningless sentences involving large general concepts. One might think, for example, to achieve the ultimate in meaninglessness by stating something to be its exact opposite. George Orwell tried this in constructing the corrupt slogans of his book *1984:* War is Peace; Freedom is Slavery; Ignorance is Strength. There is a point at which all such paradoxes fail; for these words involve the deep truths, and one must concede with sorrow that however bitterly one repudiates such sentences, one can find meaning in them.

Indeed, such aphorisms have at times been uttered solemnly, and received with veneration. One has only to recall Hegel's famous dictum, "Freedom is the recognition of necessity," which holds a high place in the Marxian lexicon. (What does it mean? Is that society freest that forces the most complete recognition of the most wide-ranging necessity? How judge what is necessary without testing it by denial? Yet one can impart meaning to this as to all such sentences.) Much of the force of the Sermon on the Mount derives from the shock of paradox conveyed in such statements as "Blessed are the poor in spirit. . . . Blessed are they that mourn. . . ."

To return to science: From what has been said one might draw the conclusion that an alert biologist should deal habitually in antitheses; should recognize beforehand that not only his general statements but their opposite are good biology; and so turn what has heretofore been mere historical vacillation into a positive technique. The technique does not need to be invented; it is the dialectical method formulated by Hegel and



TWO EXTINCT MAMMALS also illustrate the problem of "fitness." At top is the "Irish elk," a huge member of the deer family which flourished in western Europe contemporaneously with early man. At bottom is the hairy mammoth, which lived in Europe, Asia and North America in the same period. Both animals were presumably "fit" in their original environment, and, since they are extinct, it is assumed that a change in their environment made them "unfit." But no biologist would have been able to predict this result.

summarized in the triad: thesis, antithesis, synthesis. Marx and Engels, appreciating the method but disapproving Hegel's content, "corrected" this to construct what they called the materialist—*i.e.*, "scientific"—dialectic, which formulated much that we have discussed above in such phrases as "negation of the negation," "the unity of opposites," and a third phrase that raises an issue we have not discussed, "the transformation of quantity into quality."

In the 1920s a book appeared called *Science at the Crossroads,* containing a series of papers given by Russian scientists in commemoration of Isaac Newton, which laid claim to revolutionizing the technique of science by deliberate application of the principles of dialectical materialism. The claim is still urged by scientists within the Soviet orbit, and by certain others outside, though of recent years fewer of the latter than formerly, and with much less assurance.

I did what I could to examine this view as a young student, for I thought that if this was to be the new way of science, I had better know about it. It was an interesting but on the whole disappointing venture. For one thing, modern expositions of this point of view seem to me to have an obsessive quality that I think derives in part from inverting the true order of the argument. Science *is* dialectical, and of course materialist. Marx and Engels, recognizing this, attempted to formulate these qualities in the natural sciences so as to impress them upon philosophers, economists, sociologists and historians. To preach dialectical materialism to scientists is carrying coals to Newcastle.

It might be urged, however, that the dialectic of science is mainly unconscious, and would be more effective if made explicit. It seems to me that there is some point in this for the history and philosophy of science, and very little for the scientific enterprise, for science as an activity. In the latter regard I think the materialist dialectic has fatal weaknesses. It provides an interesting way to look backward but no guide for going ahead. It is easy, for example, to pick striking instances of the unity of opposites out of the past—I have already cited several—but to assert such unity as a working hypothesis seems to me a discouraging kind of exercise. It tends to lead into sterile intellectual constructions rather than to stimulate one to act—to do the experiments that need doing, to state the unifying hypothesis, fragmentary, usually biased, but thereby sharp and provocative, that needs to be defended or attacked. The dialectical approach has too much of strategy and too little of tactics. It neglects too greatly the scientist's own motivations, which are greatly stimulated by stating and working out one point of view, while neglecting and even appearing to demolish opposed attitudes. What is St. George without his dragon? This may be a weakness, but it is a powerful one. In a sense the scientist is willing to plunge blindly, the better to plunge. His primary goal—in Francis Bacon's phrase—is "to command nature in action." The logic is left to be repaired later.

Nevertheless I think that the rubrics of the materialist dialectic are useful aids to thought, and helpful formulations of the dynamics of development, in and out of science. They are not alone in their retrospective quality. This is shared by certain great scientific hypotheses and is a weakness in them as it is in dialectical materialism. I think particularly of the hypothesis that Marx and Engels hailed as the monumental expression of all that the materialist dialectic attempts to convey: the hypothesis of evolution by natural selection.

The theory of natural selection rests upon three phenomena: the continuous production in animals and plants of heritable variations ("mutations"); the struggle for existence, owing to the fact that over long periods of time animals always overreach their means of subsistence, a concept Darwin borrowed from Malthus; and, as a result of the latter working upon the former, the survival of the fittest. The first two of these are matters of direct observation and experiment; the third is a concept circular in construction and entirely retrospective in outlook.

What do we mean by biological "fitness"? Biologists use this term frequently, and even analyze it to a degree in terms of heritable characters to which they assign positive or negative survival value, *i.e.*, characters which promote or hinder survival. How do we judge fitness, and estimate survival value? Only in retrospect, by observing what has survived; and so long as there are survivors at all, the final issue remains in doubt. Faced with a new mutation in an organism, or a fundamental change in its living conditions, the biologist is frequently in no position whatever to predict its future prospects. He has to wait and see. The species may seem to prosper; it may begin to decline, eventually to extinction; it may decline for a time, and then, perhaps through a change in conditions or by the realization of possibilities implicit in the first mutation by the addition of others which develop its potentialities, may rise to a position of dominance. The point at which a forelimb began to be modified into a wing may have represented a considerable temporary embarrassment, yet an ultimate advantage, for it opened the way to achieving through further mutations a wing. The hairy mammoth seems to have been an admirable animal, intelligent and well-accoutered. Now that it is extinct, we try to understand why it failed. I doubt that any biologist thinks he could have predicted that failure. Fitness and survival are by nature estimates of past performance. The interrelationships within a living organism, among diverse organisms, and between organisms and their physical environments are much too complex to offer firm ground for prediction.

For this reason our evolutionary constructions are formulations of past history and have little to say about the future. This is an important consideration, because in our technological culture one is tempted frequently to try to supplant processes of organic development by deliberate design, to substitute technological plan for natural selection. Societies and governments, as Darwin recognized, are subject to much the same laws of adaptation, competition and survival as are living organisms; and they are perhaps even more complex in their interrelationships. How is one to know whether a change in social institutions or ethics will in the long run prove advantageous or catastrophic? Only by watching and waiting; and again one cannot be sure so long as anything is left. As with living species, a human society might adopt some course that almost extinguishes it yet, on further development, leads to its ultimate dominance. We cannot predict better here than in organic evolution; probably not as well. The concept of a planned society rests on much shakier foundations than would the concept of a planned organism; but biologists are much too wary to attempt to plan organisms.

This is only one of the essential complexities of biology. The biologist who does not accept complexity as being at the very heart of his enterprise is a poor biologist. The biologist who does not occasionally assert simplicity as an analytical tactic is also a poor biologist.

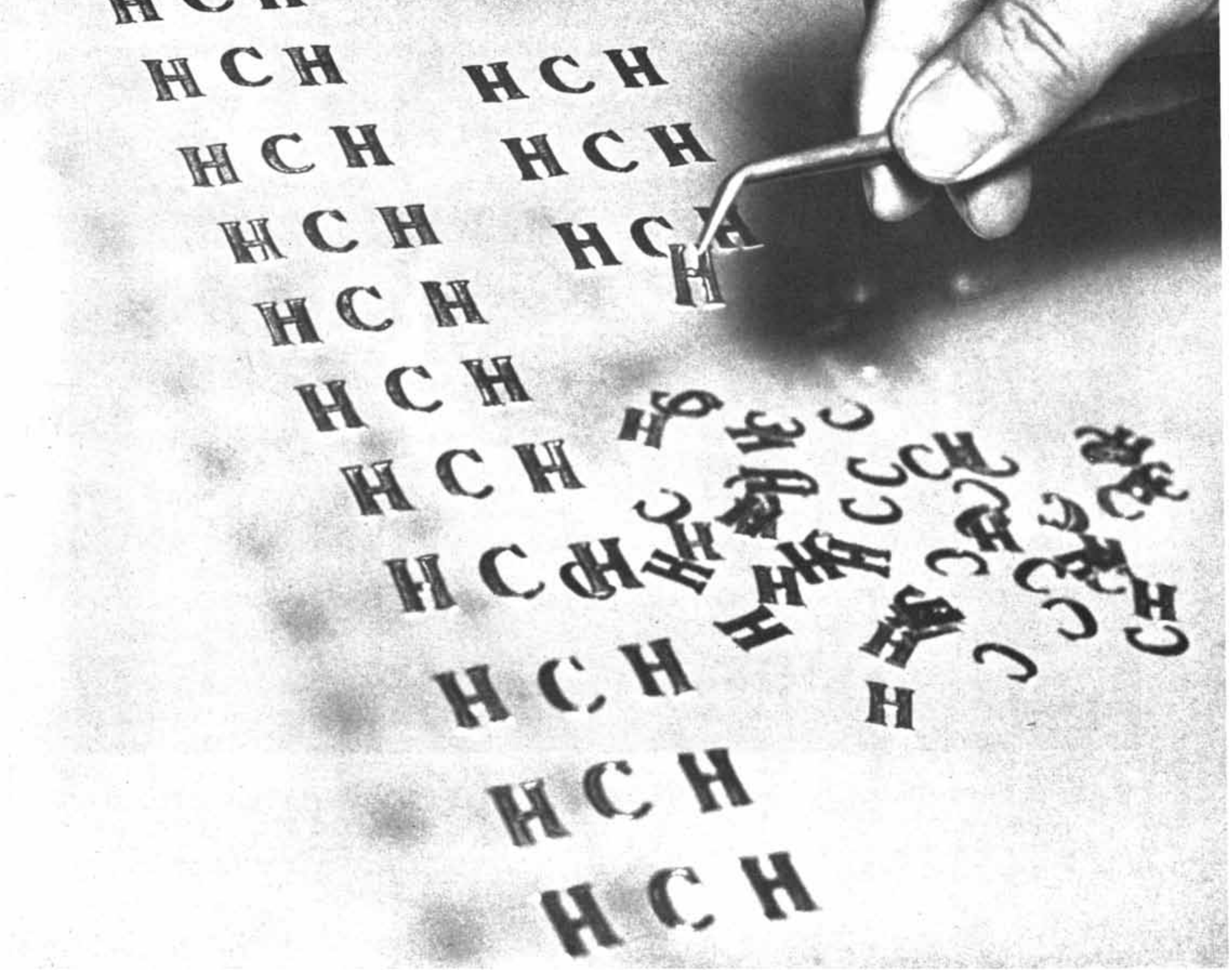
Yet one kind of complication permeates the whole structure of biology. Niels Bohr has proposed a point of view that he calls "complementarity," worked out primarily in association with problems raised in physics by the indeterminacy principle, but which Bohr suggests should find much wider application, perhaps particularly in biology. There is of course a kind of complementarity in biology that biologists have long recognized and accepted. Confronting any phenomenon in living organisms, the biologist has always to ask three kinds of questions, each independent of the others: the question of mechanism (how does it work?), the question of adaptation (what does it do for the organism?), the twin questions of embryogeny and evolution (how did it come about?). These things must be worked out one by one, for they are quite separate questions, and one goes about answering them in very different ways. Yet one really understands only when all three have been answered.

It is interesting to realize that of these fundamental questions, only the first has a substantial place in physics or chemistry. It is only the biologist who habitually asks whence and wherefore. These questions are for the most part meaningless, except when asked of living organisms.

A curious thing about biology is that it flourishes as the science of life without attempting to define life. We are often told that the beginning step in any science is to define its terms, indeed to give them *operational* definitions, by which one usually means, to describe the operations by which they can be measured. It is a gross overstatement.

Once years ago I was asked to attend a conference entitled "Fatigue in the Reading of Microfilm." For the first two days we all gave papers; they were about everything to do with vision except fatigue. A round-table conference on the third day was opened by a psychologist with a paper on fatigue. He began by defining fatigue as a deterioration in performance. He then described giving experimental subjects a battery of about a dozen different tests of performance, then keeping them awake for two or three days and retesting them. None showed any demonstrable deterioration in performance. The psychologist kept assuring us that nevertheless he was certain that these persons were fatigued.

I learned then that this familiar concept, fatigue, cannot be adequately defined. The most rigorous operation for determining fatigue seems to be to ask a person whether he feels tired. For a long period there was a Fatigue Laboratory in operation at Harvard University. At one time its director, reviewing the subject of industrial fatigue, con-



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FORTIFLEX B, the second of the series, is now in production. Field reports of a number of formulations indicate a wide area of usefulness for this new group: monofilaments of outstanding strength and break resistance . . . feather light, tough, blown bottles . . . economical wire insulation with superior aging characteristics . . . low cost transparent film with excellent crispness and two-directional tear strength . . . molded pipe and fittings . . . fabricated industrial ducting and equipment.

If you're interested in the possibilities and economies of the new Fortiflex B, get in touch with us. New field data at hand may provide your engineers with some right answers to product performance problems. Use coupon. Celanese Corporation of America, Plastics Division, Dept. 192-S, 744 Broad Street, Newark 2, New Jersey.

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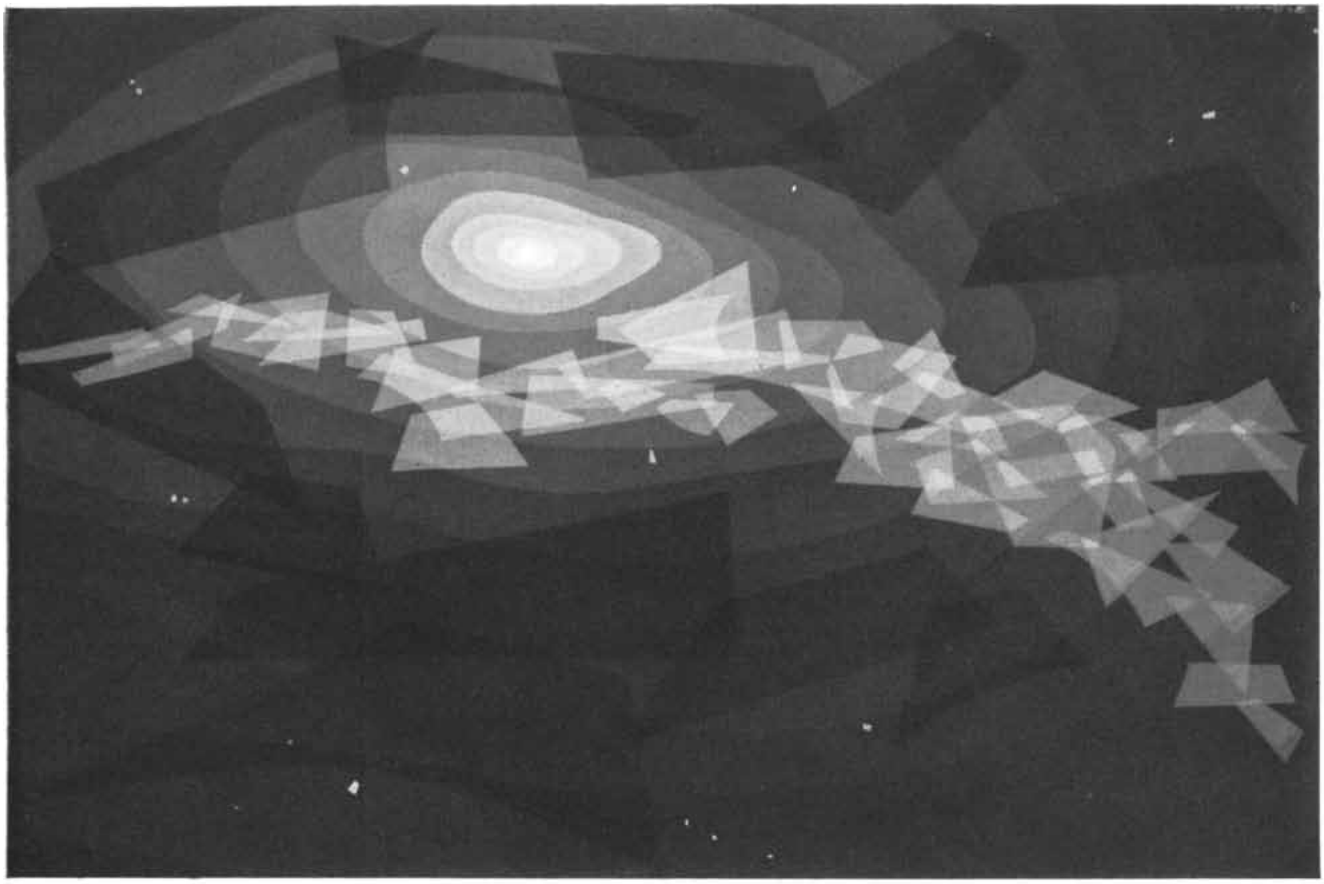

"CYGNUS," another inspiration by Simpson-Middleman, painters of the meanings of science. "Knowledge of the Universe," say these artist-scientists, "is not a matter of man's sight, but of his imagination's vision. Our eyes show us Cygnus. But creations of our genius, such as the radio-telescope, reveal unexplored, unexplained sources of energy that man may someday master. They lie amidst and even beyond those mysterious, drifting clouds of cosmic matter, lit by the stars they do not obscure." Painting courtesy John Heller Gallery, Inc.

Space-age research at Boeing

Creative scientists find at Boeing a research environment planned to help them reach and stay at the top in their special fields. Pure research along the very frontiers of knowledge is the sole concern of members of the Boeing Scientific Research Laboratories. Problems associated with man's conquest of air and space are high on the agenda, supplemented by investigations in other, equally advanced areas.

Aerodynamicists and mathematicians participate in these programs, along with nuclear physicists, physical chemists, theoretical metallurgists and physicists specializing in electronics and solid state physics. Scientists interested in imaginative, creative research are invited to communicate with Boeing.

Other Boeing openings are available to mathematicians and to engineers of all categories. Assignments are open in the fields of research, design, production and support engineering. For complete details, drop a note now to Mr. Stanley M. Little, Department B-79, Boeing Airplane Company, Seattle 24, Washington.

BOEING

cluded that it is largely boredom. And how does one define boredom?

Biologists long ago became convinced that it is not useful to define life. The trouble with any such definition is that one can always construct a model that satisfies the definition, yet clearly is not alive. And of course we do not ever measure life. We can measure many of its manifestations accurately; and we combine those with others that we observe, but perhaps cannot measure, to make up our concept of what it means to be alive. The life itself is neither observed nor measured. It is a summary of and judgment upon our measurements and observations.

What biologists do about life is to *recognize* it. If that seems a slipshod procedure, I beg the reader, try to define your wife. You have no trouble recognizing her; I think you will grant the operation to be accurate and unequivocal. But define her? Well, that's the way it is with biologists and life.

I should like to speak of a last peculiarity of biology among the sciences. The fundamental task of science is to state the minimum number of general laws needed to encompass all verifiable observations. The biologist regularly observes classes of phenomena that are unique to living organisms, and cannot be observed elsewhere. Matter exists in a hierarchy of states of organization: ultimate particles, atoms, molecules, formed molecular aggregates, living organisms, plant and animal societies. Each step in this ascending scale of complexity introduces new phenomena, not to be observed at lower levels; and ordinarily such new phenomena demand the formulation of new laws.

Yet biologists have been content to accept the laws of chemistry and physics, and have exercised great restraint about stating new laws. Indeed many of them hold that the task of biology is to "reduce" its phenomena to the level of chemistry and physics. Some of the most fundamental and stubborn problems of biology could be disposed of, at least semantically, if biologists only permitted themselves a few new laws. They prefer, however, to let their problems stand as problems. I think this is not diffidence, but wisdom. We can afford to wait; though I am sure that no amount of waiting will "reduce" the most characteristic problems of biology to present-day chemistry and physics. If biology ever is "reduced" to chemistry and physics, it will be only because the latter have grown up to biology. At that point it will be hard to say which is which.

Life on the Chemical Newsfront

SPLASHES DON'T MATTER! High water-spotting resistance is developed after only 24 hours by interior flat wall paints formulated with CYAQUA® *alkyd emulsion.* This unique water-dispersed emulsion makes it possible to formulate paints with the beauty and durability of an alkyd combined with the ease of application and cleanup of a latex. Paints dry quickly, adhere well to all surfaces, develop high scrub resistance, clean up easily with water and have no odor. Processing advantages rival its application benefits. **(Plastics and Resins Division)**

RADIOACTIVE TRACERS are among modern research tools being used at the new Cyanamid Research Center at Bound Brook, N. J., to measure efficiency of pigment dispersions in new vehicles. Basic studies are being aimed at a better understanding of the theoretical aspects of pigment vehicle interfaces and at developing new areas of interest to Cyanamid's Pigments Division. In the broad pigment research activities at Bound Brook, major emphasis is being placed on finding new chemical structures with the high degree of durability desired for coloring plastics and exterior finishes. **(Research Division)**

DURABILITY OF MODERN LAMINATED SCHOOL DESK TOPS is tremendously improved by the use of urea-formaldehyde resin adhesives. These adhesives are used to hot- or cold-press the plywood cores and also to bond the decorative surfacing laminates to the cores. Adhesives, coating resins and molding compounds are only a few of the end products that have made urea a basic raw material of industry. As the list of such products grows, so does the need for greater and greater quantities of urea. To help meet the growing demand, Cyanamid is now offering AERO* *crystal urea.* Details and technical assistance are available on request. **(Industrial Chemicals Division)**
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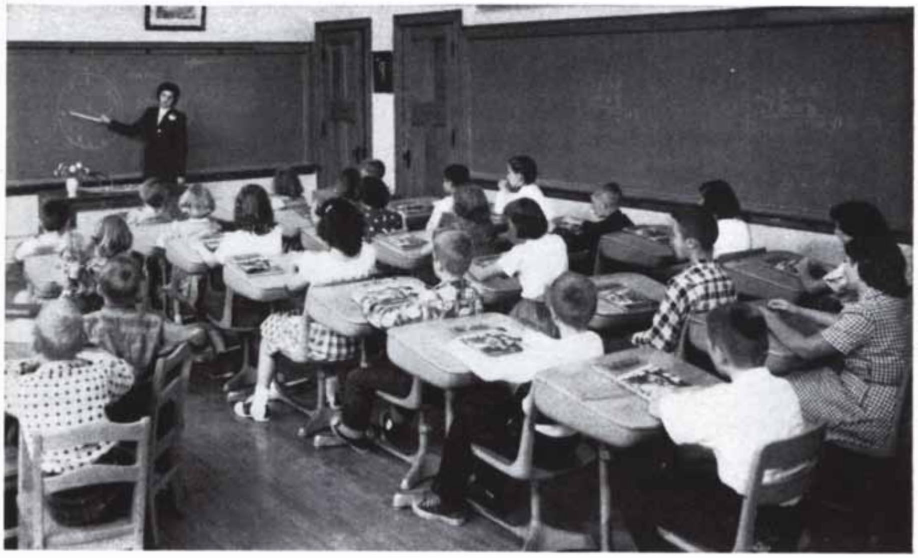
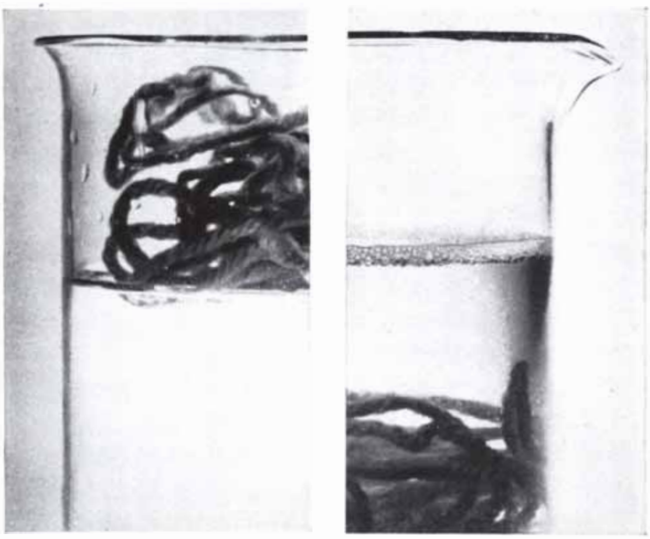


A NEW DISPLAY, illustrating the history of papermaking, has just been added to American Cyanamid Company's exhibit hall at Rockefeller Center, 40 West 49th Street, in New York City. This display also gives particular emphasis to many new and unusual uses for paper made possible by the progress of the Paper Industry. Cyanamid's permanent exhibit hall has created widespread interest, drawing more than a quarter-million visitors so far this year.

TO ACCENT A LOVELY LADY'S CHARM with the exotic orange blossom fragrance of Yara Yara—or to compound a spray that will kill carpet beetles—takes only the versatile intermediate, *beta*-naphthol, and the ingenuity of the chemist in reacting it with other compounds. *Beta*-naphthol combines the economy of a bulk chemical with an excellent reaction potential. Some of its derivatives are staples in today's chemical technology; others are still laboratory curiosities. They range from artificial fragrances and flavorings to dyes and polyethylene antioxidants. Research chemists wishing to evaluate this economical intermediate may find data accumulated by Cyanamid of value. **(Organic Chemicals Division)**



HIGH WETTING POWER of DECERESOL® *wetting agents,* important in many textile-treating operations, is demonstrated above. Yarn floats on plain water in the tumbler on the left, but sinks rapidly in water containing 0.025% DECERSOL wetting agent OT in tumbler on the right. This high wetting action promotes rapid wetting out of fabrics in scouring, desizing, bleaching, dyeing, finishing and other processes. Other DECERESOL wetting agents offer unusual combinations of solubility, emulsifying, detergent, salt-tolerance and wetting properties. **(Organic Chemicals Division)**

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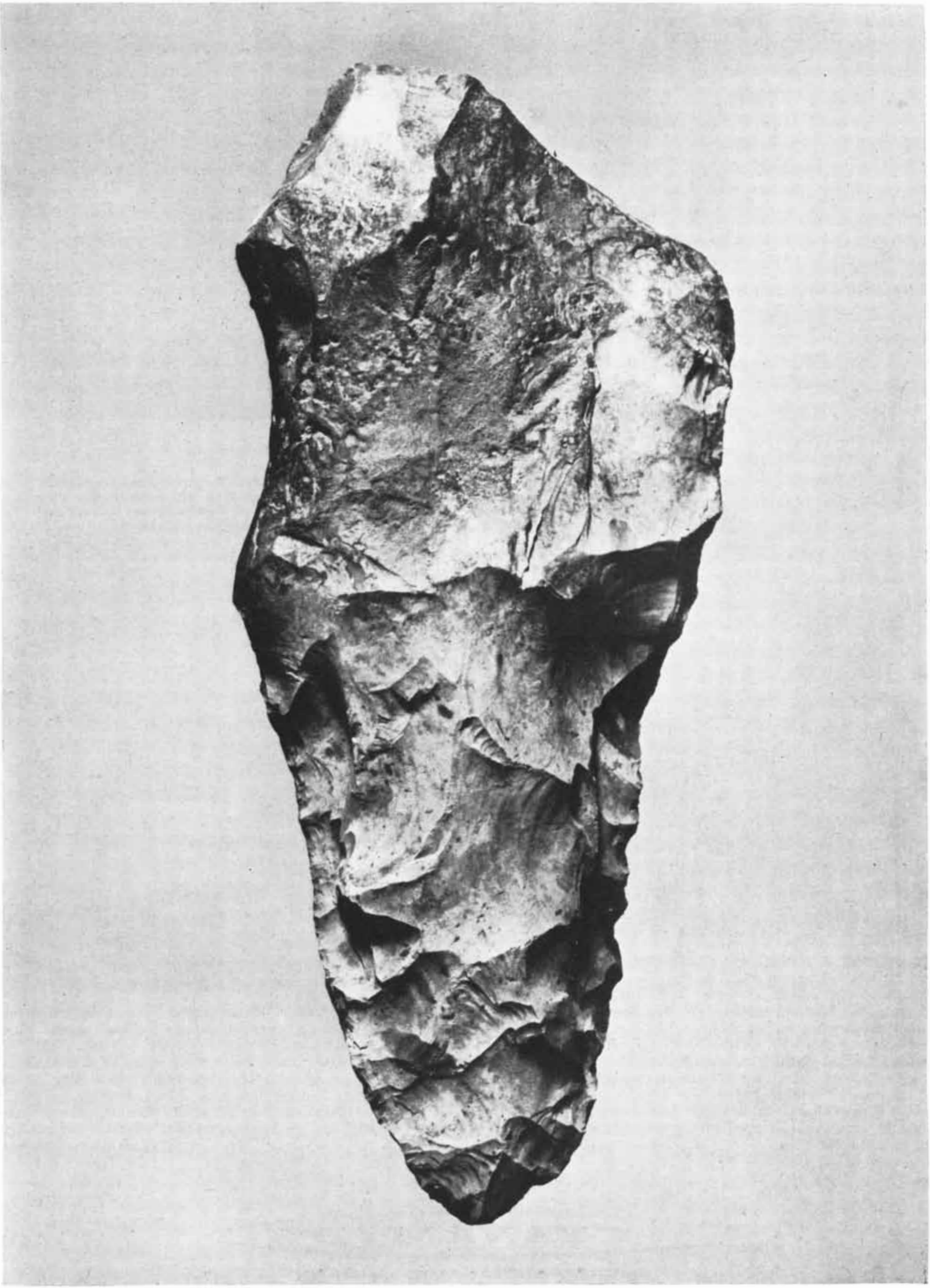


HAND-AX was one of the earliest technological innovations. This specimen, shown slightly larger than actual size, was found at Saint-Acheul in France. It is approximately 200,000 years old. The hand-ax was photographed at the American Museum of Natural History.

Innovation in Technology

It is through technological innovations that science is brought to bear upon man's material existence. The difference between creative science and creative technology is chiefly one of motive

by John R. Pierce

Technological innovations have been as important as language, art and science in distinguishing man from beast. And although technological innovation antedates our species, it has never before occupied so great a share of man's energies.

Our works are built on old foundations—on obsolete inventions such as the hand-ax and the bow no less than on inventions that have survived, such as agriculture and the wheel. But during most of human history technological art accumulated gradually. Up to a few hundred years ago the techniques of civilized life had scarcely advanced beyond the best achievements of the ancients. Then our control over the forces of nature began to increase at an explosive rate.

We usually think of our contemporary world as the product of science. The relationship between science and technology is certainly very close, and neither could have attained its present state without the other. But it is technology that affects us directly. Some of the greatest scientific innovations, for example, the discoveries of astronomy and the theory of evolution, have had little influence on our material existence. Even electromagnetic theory and atomic physics had no impact until they were brought to bear on technology by people who were not content with understanding, but who wanted to change our way of living and of doing things.

In this article we shall examine some recent advances to see what light they throw on the creative process in the complex technology of today. What do we mean by a technological innovation? Surely not the tail fins on this year's automobile, nor a new catch on a refrigerator door. A true innovation must perform some important function. It may do a wholly new job or do an old job far better or far more cheaply than it was done before.

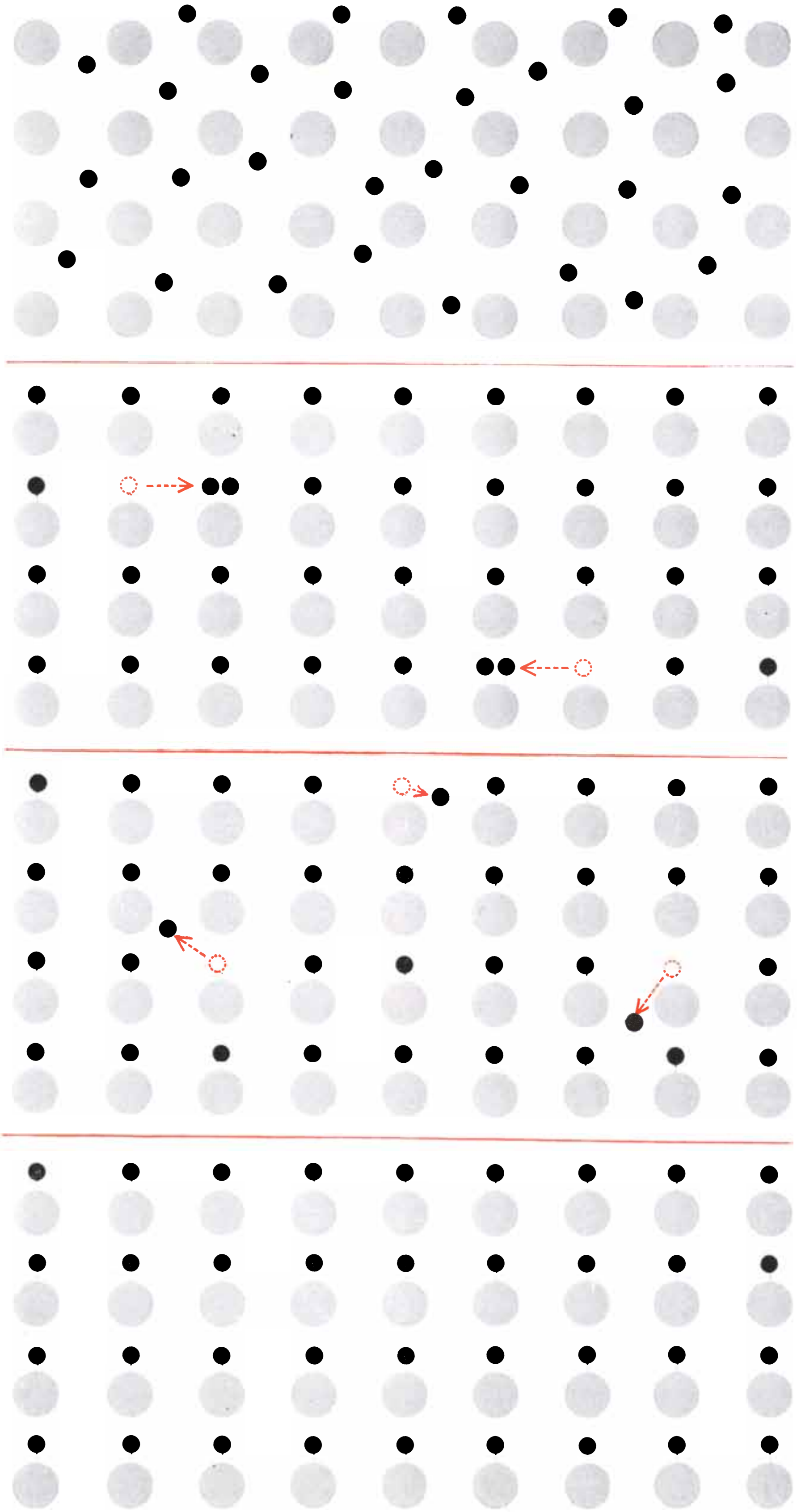
Clearly there are many examples of such innovation. An aeronautical engineer might cite the turbojet engine or the "area rule" for designing supersonic aircraft. A chemist could speak of polyethylene and other useful materials that are made by linking small molecules together into giant ones. A nuclear engineer might mention the breeder reactor. I shall talk about the things I know best: electronic devices. The specific examples are not important. From the facts surrounding a particular innovation we may hope to derive some general lessons about the character of innovation itself.

To get at the facts in the field of technology is usually difficult. Whereas the scientist must publish his results if his contribution is to be recognized, the technologist must get the job done. He may be careless about publication; he may even withhold information. Furthermore, there are probably more people working competitively on technological than on scientific problems. Thus the chance of simultaneous discovery is perhaps greater in technology than in science. An innovation is no less legitimate for having two fathers, but it is troublesome for the historian. For these reasons I shall discuss some reasonably noncontroversial innovations made at the Bell Telephone Laboratories, where I am employed, under circumstances which I believe I understand.

I have chosen my examples to illustrate different aspects of the interaction between science and technology. In one case the technological problem helped open a wide field of physical research, and the invention itself depended on a great advance in fundamental knowledge. In another the underlying physical laws were already known. The innovation lay in finding a new way to apply known physical phenomena. Finally I shall describe the origin of a complex system which combined existing techniques, new scientific knowledge and new devices.

The first example, which has probably already occurred to the reader, is the transistor. Let us sketch in its background. To begin with there was a need, an important function to perform. The vacuum tube, through its ability to amplify minute signals, had made possible the wonderful arts of radio and long-distance telephone transmission. But even before World War II Ralph Bown, then director of radio research at Bell Laboratories, had pointed out two weaknesses of ordinary vacuum tubes. First, they cannot amplify a very broad band of frequencies. This defect was later remedied by the device known as the traveling-wave tube. Second, they waste energy: the power needed to operate a vacuum tube is often thousands or millions of times greater than the power of the signals it amplifies. It is this weakness that the transistor finally overcame.

The invention of the transistor turned out to require new physical principles, new knowledge of nature. Nowadays *The Physical Review* is full of contributions to solid-state physics, but in the pre-transistor period the field was largely neglected. However, a few men at Bell Laboratories decided to take it up. For one thing, solid-state devices such as copper-oxide rectifiers and crystal diodes (the detector in the old "crystal" radio set), were important in telephony. For another, the tools of quantum mechanics had been sharpened to the point at which they could be usefully brought to bear on the properties of sol-



ELECTRICAL CONDUCTORS contain movable charges. In a metallic conductor (*top*) atoms (*gray circles*) have loosely held electrons (*black dots*) which can move through crystal. In *p*-type semiconductor (*second from top*) some atoms capture electrons from their neighbors leaving movable positive "holes" (*dashed circles*). In *n*-type material (*third from top*) some atoms have loose electrons. Insulator (*bottom*) contains no loosely held electrons.

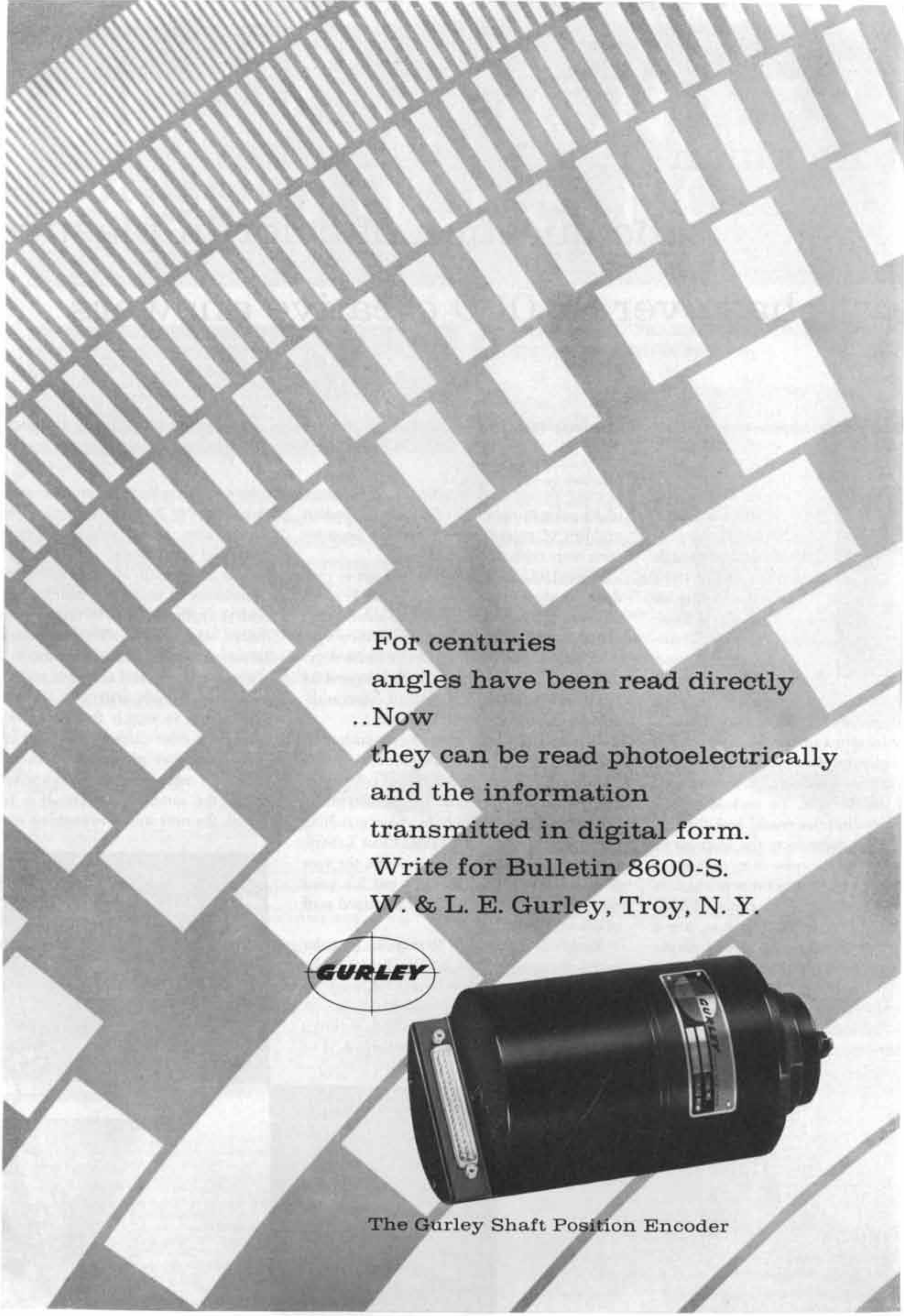
ids. Various capable men were attracted to the field, among them William Shockley and Walter Brattain.

Their early studies were interrupted by the war, but were taken up again afterward with new vigor and by more people. Among the newcomers was John Bardeen, who, with Shockley and Brattain, was to share the Nobel prize for contributions to solid-state physics in connection with the transistor.

The group concentrated much of its attention on semiconducting materials. These are crystals containing a small fraction of impurities. The impurity atoms have one more electron than they need to satisfy the requirements of crystal structure, or one less. In the first case the extra electrons are easily detached, and move through the crystal when acted on by electric forces. Such a crystal is known as an *n*-type semiconductor. In the second case a vacancy may be filled when an electron from a neighboring atom moves over, transferring the deficiency or "hole" to the atom it left. The hole may move again by the transfer of an electron from a second neighboring atom, and so on. This kind of material is called *p*-type. Both kinds conduct electricity, but not in the way that ordinary conductors do [*see illustrations at left*].

At a series of conferences in 1946 it was decided to make a thorough study of silicon and germanium, the simplest of semiconductors, under the general direction of Shockley. Altogether as many as 13 physicists, chemists and engineers in various departments of Bell Laboratories participated in the work in some essential way. They prepared highly purified samples of the materials and studied their bulk and surface properties. The investigators were not a closely organized and firmly directed "team"; they were talented individuals working on matters of great personal, as well as mutual, interest.

Shockley was not only interested in the general behavior of silicon and germanium; he also wanted to make a semiconductor amplifier. He had an idea of how it might be done. If one can vary the resistance of a material, one can control the current flowing through it, and so produce an amplified electric signal. Now the resistance of a material such as silicon or germanium decreases as its content of free electrons increases. Shockley reasoned that the number of electrons in a very thin film of silicon could be substantially changed by applying strong electric fields which would either attract electrons into the film or repel them. If so, varying the field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At Eastman

the question of color in plastics

has over 39,000 creative answers

Eastman's Leadership in Color Creativity Has Produced Tenite Plastics in a Range of More than 39,000 Colors

To get an answer, you have to ask a question.

Users of Tenite plastics have asked enough questions since 1932 to make it necessary for Eastman color technologists to create formulations that will soon total 40,000 different olors and color effects.

While an untrained person may think of olors only in terms of the basic spectrum, is eyes usually are perceptive enough to de-ect even a minute variation when two colors re placed side by side. To such an eye, a ew automobile interior would look disturb-ngly "wrong" if there were the least bit of ifference between the color of its upholstery nd its matched plastic appointments such as eering wheels, arm rests or control knobs.

Accurate color matches, therefore, are a ital concern to all manufacturers of plastic roducts that must be used in harmony with ther colored materials of different surface exture, density or reflectivity such as painted ood, enameled metal, colored tiles or textiles. nd, as color becomes more important in product design and merchandising because of its sales-stimulating effect, the attendant problem of proper color matching becomes even more critical.

Since 1932, when Eastman began to produce plastics, it has developed and kept on file, formulations for over 39,000 colors. This experience, plus Eastman's pre-eminence in color photography and textile dye technology, makes it possible for customers to depend on Eastman for the broadest range of colors available in the entire plastics industry.

In many instances, of course, customers can solve their color selection problems merely by consulting the extensive files of color chips available at every regional Tenite sales office. More extensive research in color matching can be carried out at the Tenite Color Laboratory in Kingsport, Tennessee. Here, the user of plastics is invited to work out his color problems in cooperation with a trained staff of color technicians.

Every day, some 15 to 20 requests for color matching are received by the Tenite Color Laboratory. These are submitted through regional Tenite sales representatives in the United States and Canada and through numerous Eastman affiliates abroad. The color samples submitted for matching include almost every known material—textiles, metals, tiles, wood, rubber, other plastics, paint and many more.

Four days usually are sufficient for the color technicians to make the match. For highly critical applications, as in the automotive industry, where there are many complicating factors of texture and density, the technician often submits several tentative matches.

When a sample arrives at Kingsport, the first step is to search for a possible match among the color chips in the Laboratory file. Frequently, one of the more than 39,000 chips of Tenite colors already developed may match the sample perfectly. If a match is found, the next step is to supply a trial batch

Thousands of colors on file

Accelerated weather testing

Milling the trial color

Color creativity depends on color research

of colored Tenite pellets to the customer.

When no formulation on file permits a match, the Laboratory proceeds to create a new color formulation. The technician first takes advantage of Eastman's 26 years of past color creativity—by selecting existing color chips of the nearest color matches and noting their colorant formulations. These provide him with helpful references for which there is no substitute. Drawing on the performance of colorants in many previous tests and in their actual finished or processed state, the technician avoids time-consuming delays of trial and error. He is assured that the colorants are easy to disperse, are compatible with the plastic mass and the plasticizer, and that they possess the maximum resistance to migration and the attacks of time, light, weather and temperature that limitations of availability will permit.

As he weighs out the colorants to make the new match, the technician varies the formulations of the nearest matches, adjusting them to approximate the exact color needed. When variegated, pearlescent or metallic effects are wanted, the technician must deal with the result of combining the components as well as with the color match. Often, he relies on intuition—disciplined by years of experience—to create a totally new and striking effect for the customer.

In the next operation, components of the formulation are blended together on milling rolls to insure homogeneous dispersion. Color chips are then molded from this test batch, and evaluation begins.

If surface coloration is the only critical factor, visual or "eyeball" inspection usually suffices to confirm the match. But even here, the technician must bring his highly specialized judgment into play. He must consider the visual implications of the two textures and their psychological effect in determining acceptance of the color in plastic as the proper match for the color in another material. In addition, over-all size and shape as well as contour of the original sample complicate his color matching efforts.

When light transmission is to play an important role in the end-product, the technician turns for conclusive guidance to the spectrophotometer. This precision instrument measures the length of light rays, and its findings permit formulation of properly translucent colors when transmission ratings must be held within limits dictated by the end-use.

If the color fails to duplicate the sample either by "eyeball" or spectrophotometer testing, the matching process starts all over again.

Finally, when the color technician is satisfied that the color match is accurate and that it can be supplied in commercial quantities within the prescribed limits of commercial acceptability, he makes a detailed record of the new formulation in the Tenite Color Laboratory file.

Careful detailing of the formulation is one of the most important steps in the color matching operation—for the success of full-scale production depends upon the accuracy with which the formulation has been recorded.

With the writing and filing of the formulation, another customer has had his color question answered—*and another color has been created by Eastman.*

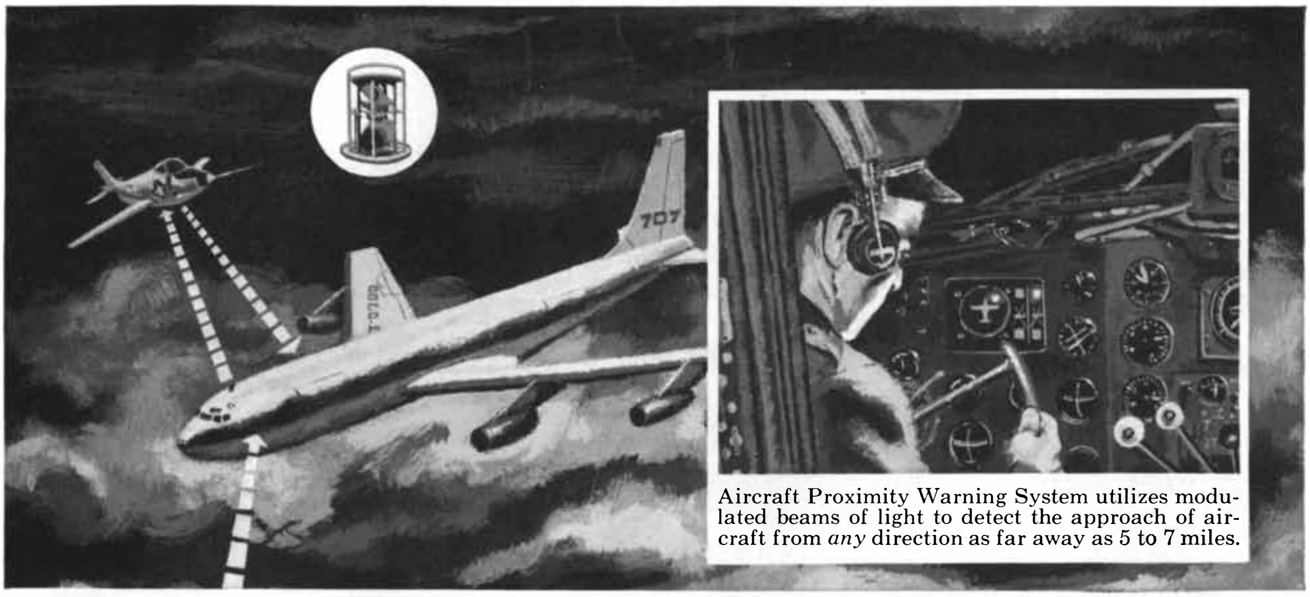
The full story of the color resources that back up the Eastman plastics—Tenite Butyrate, Tenite Polyethylene and Tenite Acetate—is told in a 20-page booklet, "COLOR." For your free copy or more information on these plastics, write to EASTMAN CHEMICAL PRODUCTS, INC., subsidiary of Eastman Kodak Company, KINGSPORT, TENNESSEE.

Judging the match

TENITE

BUTYRATE • POLYETHYLENE • ACETATE

Colorful plastics by Eastman



Aircraft Proximity Warning System utilizes modulated beams of light to detect the approach of aircraft from *any* direction as far away as 5 to 7 miles.

Voice Messages ride "silent" beams of light between control tower and aircraft.

COMMUNICATIONS
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The light that makes these words readable is brother to a new kind of light — *modulated light*. But modulated light is no ordinary brother by any measure. It can't be jammed or intercepted by any known means. Invisible, if desired, it can transmit "silent" words . . . reach out into miles of sky to give warning . . . trigger a bomb . . . give jam-free guidance to supersonic missiles . . . you name it!

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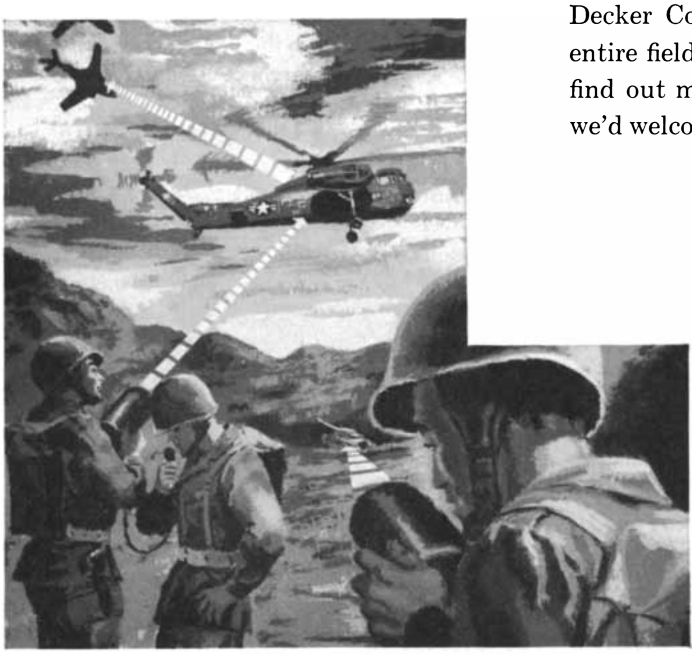


Interception-proof Military Communication System employs invisible, jam-proof light to transmit vital voice messages in air-to-air, air-to-ground, and ground-to-ground communications.

Jam-proof Missile Guidance attains new accuracy and reliability through control by modulated light.

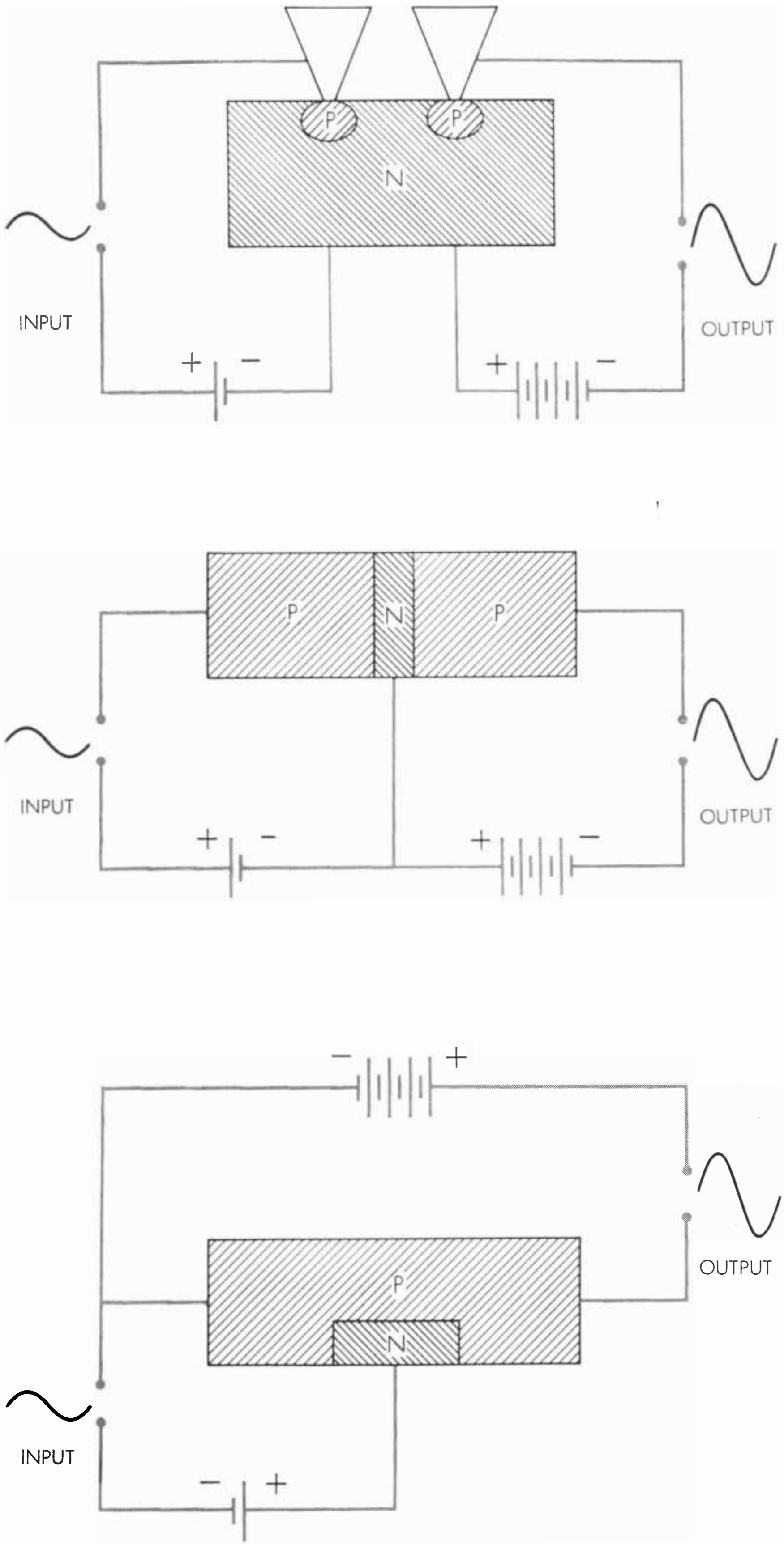
should vary the resistance of the film and hence the current flowing through it.

Efforts to make such a device did indeed lead to a solid-state amplifier, but one of a quite different sort. In the first experiments it turned out that a strong electric field had no effect on the resistance of a silicon film. Bardeen then proposed that the electrons affected by the field were not free inside the silicon, but were trapped at the surface of the material in what he called "surface states." Here was not only a practical difficulty but a new and important physical phenomenon. There followed a great variety of fundamental experiments on surface states. In some of them solid blocks of silicon were immersed in a conducting liquid to which various voltages were applied. This method actually produced some amplification of the sort predicted by Shockley, but it also led to the discovery of another and even more important fact.

In experiments on the immersed surface of a block of *n*-type germanium (in which conduction is mediated by electrons) there appeared to be a flow of holes near the surface. While following up this unexpected result, Bardeen suggested using germanium with metallic electrodes rather than liquids. Experimenting with such an arrangement, Brattain discovered a new effect: When two pieces of *p*-type material are separated by a body of *n*-type, and the proper voltages are applied to the three sections, holes will flow from one *p*-type layer to the other, passing completely through the *n*-type material. This effect, now called transistor action, was a new and important physical phenomenon. It also provided the key to the solid-state amplifier, for by varying the voltage of the *n*-type layer it is possible to control the flow of holes from a *p*-type "emitter" region into and through the *n*-type "base" region and on to a *p*-type "collector" region.

Thus was born the point-contact transistor. It filled the original need: it consumes very little power. Furthermore, it is smaller than the vacuum tube. Point-contact and later types of transistors have given us not only pocket radios and eyeglass hearing-aids, but complex electronic computers and other electronic gear that can be carried in airplanes or stowed in a manhole rather than in a telephone building.

In the history of the transistor we have the happiest combination of fundamental physical investigation and technological innovation. A group of men with related interests were working in a new field of science—the physics of the solid



TYPES OF TRANSISTORS are diagrammed schematically. Point-contact transistor (*top*) and junction transistor (*middle*) shown here are called "*p-n-p*" because they are made of two pieces of *p*-type material separated by a layer of *n*-type. There is also an "*n-p-n*" version of each type. Field-effect transistor (*bottom*) is a more recent development, although it was this kind of device that the inventors of the transistor were at first trying to discover.

state. They had two motives: to learn something, and to make a new and better amplifier. The need for the amplifier helped to stimulate the work. The theoretical tools of quantum mechanics were available to make it possible. But the irreplaceable element was the men themselves. Yet, while insight and invention are the products of individual minds, individuals are most effective when they work together in a field that is neither so narrow as to preclude adventure nor so broad as to scatter energies and prevent a fruitful interchange of ideas.

Finally we should note that the transistor work has given a still-increasing impetus to both science and technology. We now have more semiconductor devices, such as junction diodes, junction transistors, and field-effect transistors somewhat different from those which Shockley originally envisioned. Interest in solids has extended to other types, including photoconducting, ferromagnetic and ferroelectric materials. These too are finding important applications in electronics. And solid-state physics itself has become highly attractive to able physicists in universities as well as in industrial laboratories.

The second innovation I shall discuss is the negative-feedback amplifier, whose functions or principles are hidden away in almost all electronic devices and equipment. The principle of negative feedback underlies all electronic control. We shall see how we owe to it the high quality and low cost of modern long-distance telephone transmission.

Like the transistor, the idea of negative feedback was a response to a need for better amplifiers. In this case, however, the invention did not require new physical knowledge. A single creative effort showed how to apply known devices in a new and superior way.

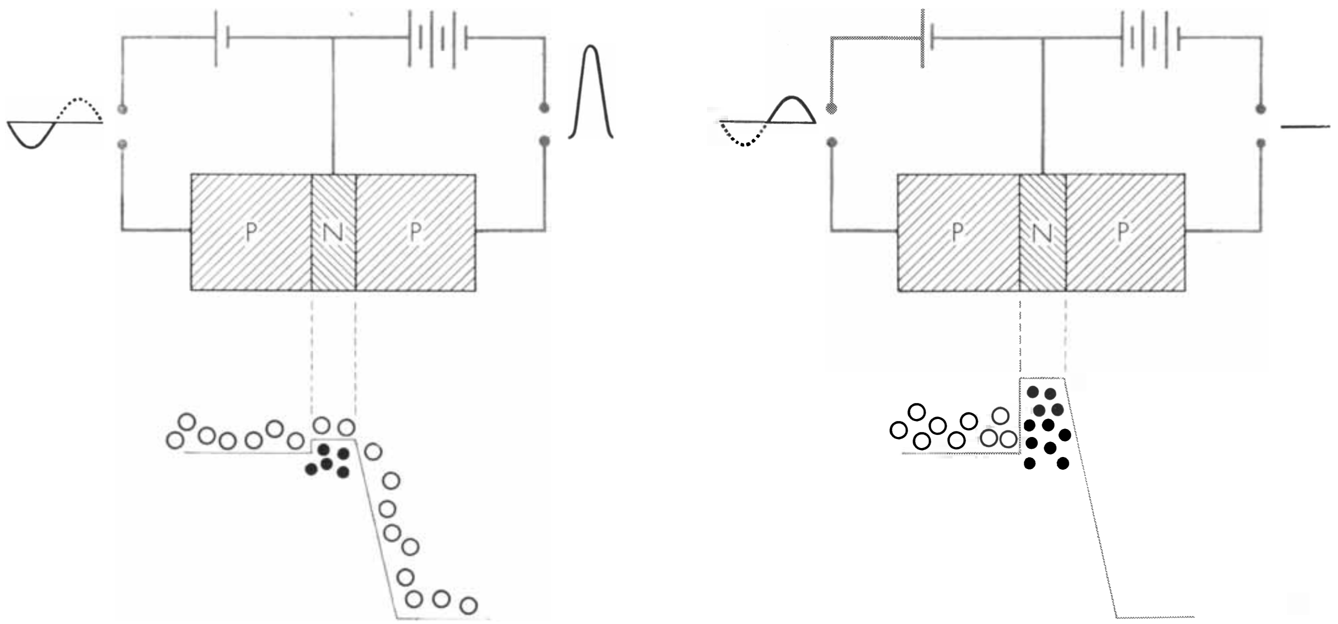
The story again goes back to the first vacuum-tube amplifiers. Inserted at intervals along a telephone line to boost the power of weakened signals, they made it possible to send messages over really long distances. In the beginning a pair of wires and a series of amplifiers could accommodate only one conversation at a time. Then, in the 1920s, telephone engineers learned to put several simultaneous messages on the same pair of wires and through the same amplifiers by sending them at different frequencies. This is the method used to transmit different radio programs through the same space at the same time. However, in radio broadcasting only one program at a time goes through a given transmitter or receiver. In today's telephone circuits hundreds of conversations go through one amplifier at a time.

To keep the signals from mixing with each other and becoming distorted, we need an extremely good amplifier. It must be linear; that is, the strength of the output signal must be strictly proportional to the strength of the input signal. Also it must be stable, maintaining the same amplification at all times. Vacuum tubes are inherently neither linear nor stable. In the 1920s engineers had all they could do to make amplifiers good enough to amplify a few telephone conversations a few times. Today we can send 1,800 separate messages through more than 1,000 successive amplifiers without noticeable distortion. It is negative feedback that is responsible for this improvement.

The principle is simple: Feedback means just what the word implies. A part of the output of an amplifier is fed back to the input side and mixed with the incoming signal before it is amplified. If the two are mixed in such a way that the portion fed back adds to the incoming signal, we have positive feedback. It increases the net input to the amplifier and thus increases the over-all gain. With enough positive feedback the amplifier can supply all the necessary input, and becomes an oscillator which generates its own signal.

If the mixing subtracts the energy fed back from the incoming signal, the net input decreases and the over-all gain is reduced. All the advantages that have come from the innovation depend on this seemingly unpromising fact.

It turns out that if the proportions are chosen properly, the actual gain of the arrangement depends almost entirely on the fraction of the output signal fed



TRANSISTOR ACTION, which is responsible for the amplifying ability of transistors, involves the flow of positive holes (*open circles*) through a layer of *n*-type material containing movable electrons (*black dots*). At left the input signal, shown as a sine wave, charges the layers so that the *n*-type material allows the passage of many holes. This results in a large output (*tall wave at other side of circuit*). At right the signal reverses and the *n*-type layer forms an impassable barrier to holes. There is no output on this half-cycle.

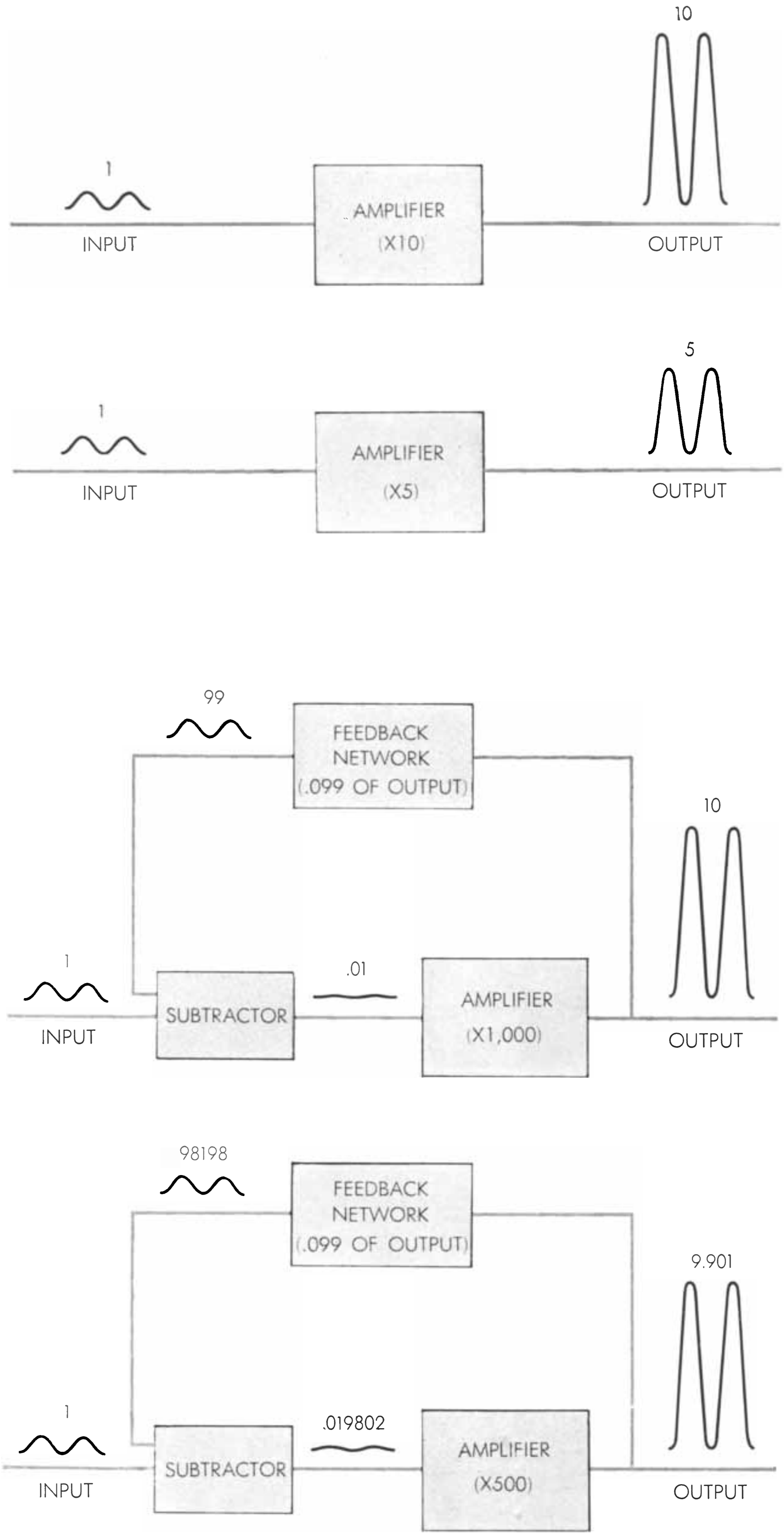
back, and not on the intrinsic gain of the amplifier. For example, suppose the gain without feedback is 1,000 times, and a fraction of the output just under one tenth is fed back and subtracted. Then the net gain will be 10 [*see illustration at right*]. Now if the intrinsic gain drops to as low as 500, but the same fraction of the output is fed back, the net gain is still almost exactly 10. Thus the gain is set not by nonlinear vacuum tubes, but by linear and stable elements—resistances, condensers and coils—which determine the fraction of the output that is fed back and subtracted from the input signal.

How did this innovation come about? A number of Bell Laboratories engineers, among them Harold S. Black, had been trying for several years to make amplifiers capable of handling many messages at once. The physical ingredients and mathematical tools needed for the invention were all at hand. All that was lacking was the idea. One day in 1927 it came to Black while he was going to work on the Lackawanna Ferry. He immediately began to work out the details on the margin of his morning newspaper.

This, of course, was only the beginning of the story. The full exploitation of Black's idea required many years of research by a number of workers. And like the transistor it opened the field for important discoveries by others and for applications ranging from hi-fi to missiles. It also provided a popular field of study in universities and industrial laboratories. But essentially the negative-feedback amplifier was the creation of a single mind.

As our final example of innovation in technology let us consider briefly the microwave-relay system which carries telephone conversations and television programs across the country without the use of cables. The key word here is "system." The problem was not to make a particular device, but to weld a great number of devices into a complex whole. Some of the devices were available at the start; others had to be developed. But the chief innovation was the choice, among the many alternative methods and devices, of the best combination of methods and devices—the system as a whole, and not merely its separate parts.

Work on the microwave relay was begun at Bell Laboratories shortly after World War II, under the direction of Harald T. Friis. Research before the war and radar work during the war had pro-



NEGATIVE FEEDBACK stabilizes the gain of an amplifier. Without feedback (*top diagrams*) the output of an amplifier changes in the same proportion as its gain. With negative feedback (*bottom diagrams*) a decrease in gain is compensated by an increase in the net signal fed to the amplifier proper so that over-all gain of system remains essentially constant.

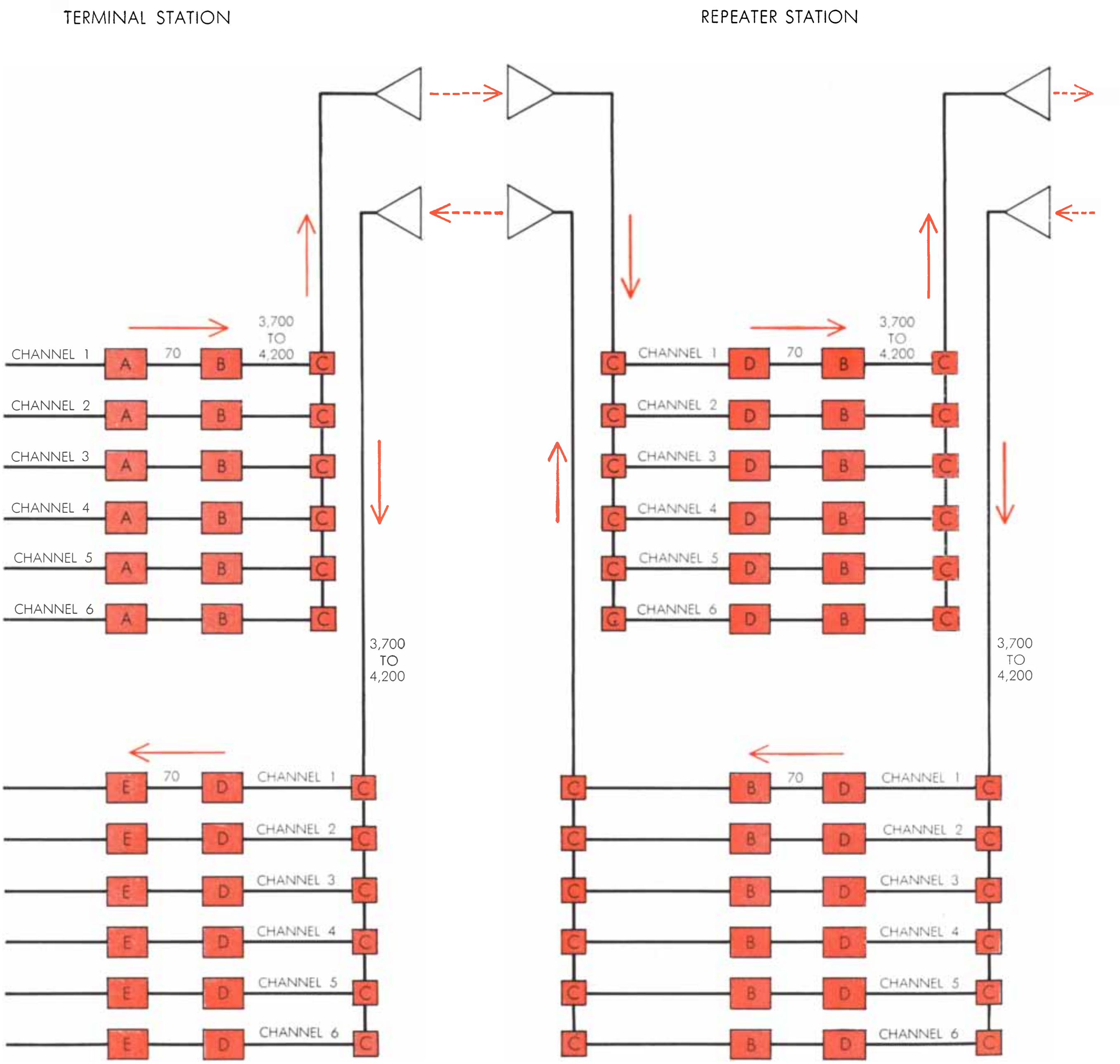
vided a considerable fund of knowledge about microwaves, and a good deal of sophisticated equipment. But more knowledge and better equipment were needed for the job.

For instance, it was known that microwaves, like light, travel in straight lines, so that each relay point must be on a line of sight to the next. But by how much must the line-of-sight path clear the ground? And how would atmospheric disturbances affect the beam?

While some engineers investigated such questions, others were busy designing new devices: microwave amplifiers capable of handling hundreds of telephone signals, a new type of antenna, filters to sort out signals of different frequencies, and many others.

Friis and his colleagues had dozens of important decisions to make. To name only one, what frequency should be used? At a high frequency, say 4,000 megacycles, antennas have narrow beams, so that a large fraction of the power transmitted from one relay station would reach the receiver of the next. At 2,000 megacycles the beams are much broader and more power would be wasted. On the other hand, tubes that operated satisfactorily at 2,000 megacycles were already available. If the higher frequency were decided on, new tubes would have to be designed and manufactured.

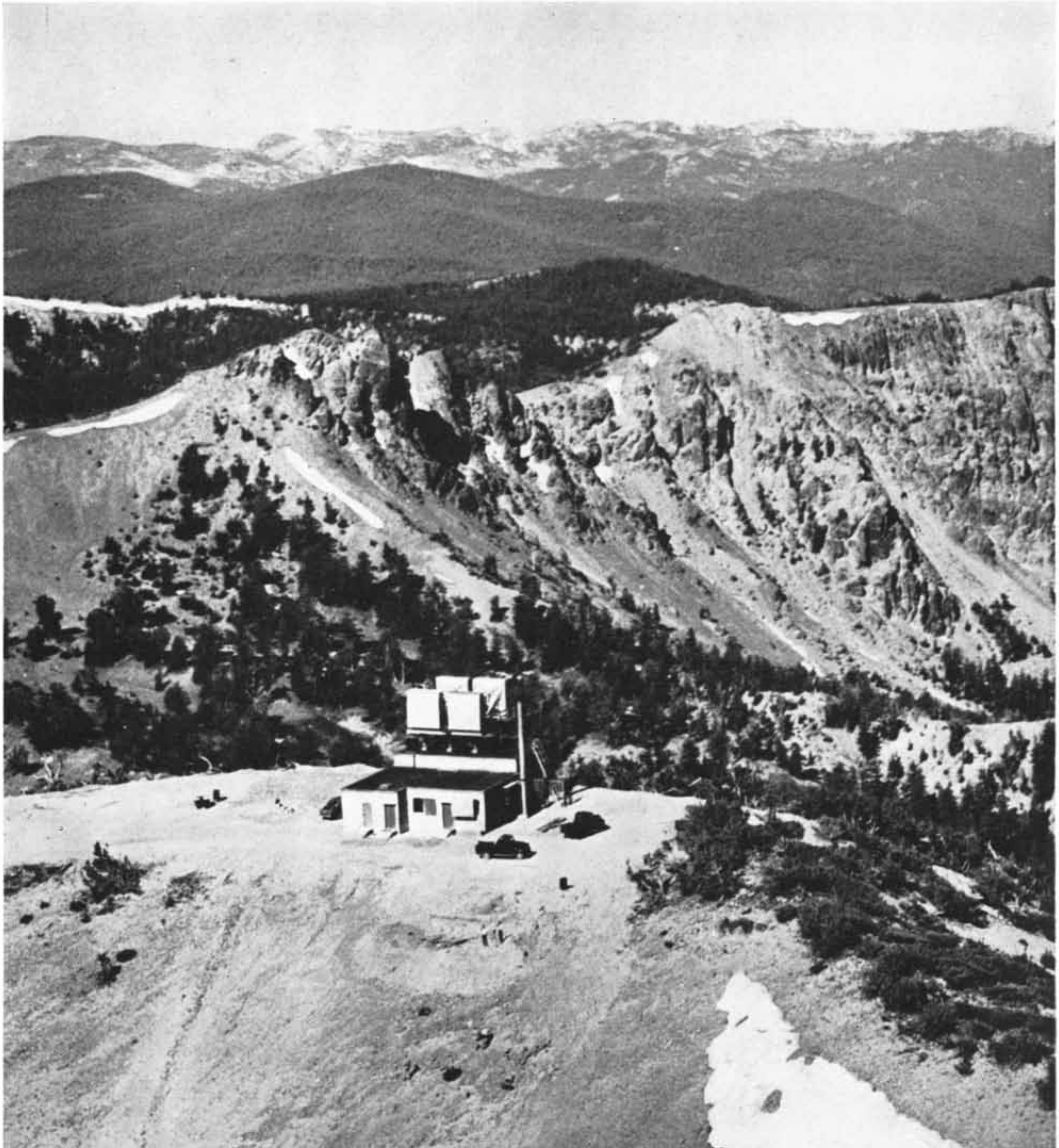
Friis's main problem, then, was not to



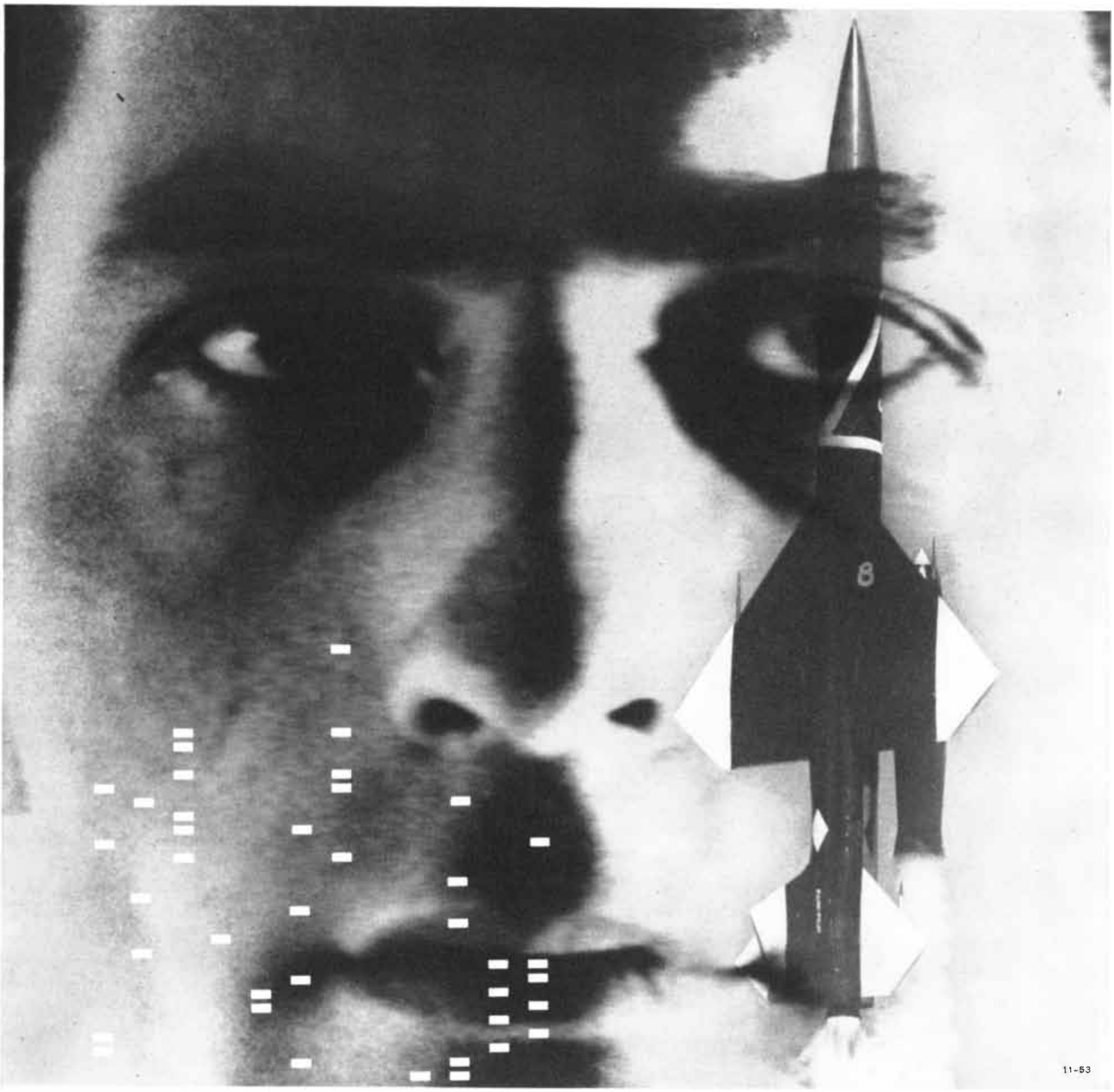
MICROWAVE TRANSMISSION SYSTEM for television programs is diagrammed schematically. Terminal station (*left*) feeds signals to and from local TV transmitters. Repeater station (*right*) boosts power as signals travel across the country. Output of a local transmitter is converted to 70 megacycles in circuits A, amplified and converted to carrier frequency between 3,700 and 4,200 megacycles in B and fed to antenna through filters C, each of which passes the frequency of a single channel. Relayed signal is converted to 70 megacycles for re-amplification in D. Circuits E convert signal to the appropriate frequency for the local transmitter.

invent this gadget or that, but to choose the best course, technically and economically, among a bewildering array of possibilities. The art of making such a choice is usually called systems engineering when the alternative means and the required knowledge are all at hand. When they are not, I suppose it should be called systems research. By 1948 the results of the research of Friis and his colleagues had been embodied in an experimental system which was installed between New York and Boston. This was the prototype of the transcontinental microwave system, which was put into service in 1951.

What can we learn from these examples? First, that in technology, as in science, the individual act of creation is the essential ingredient of innovation. It



RELAY STATION at Mount Rose in Nevada is photographed from the air. At an elevation of 10,076 feet this station is the highest in the national network. On the roof of the building can be seen the specially shaped antennas developed for use in the relay system.



may be an act of creative imagination, as in the case of the negative-feedback amplifier, or an act of creative observation of nature, as in the case of the transistor.

We may, however, observe that, while great innovations in mathematics and science are overwhelmingly more important than small innovations, a small but apt technological innovation may bring widespread and important rewards, not only to the innovator, but to all men.

The creative process in technology certainly seems to take talent, preparation, good judgment in sorting the valuable from the elaborate, incubation, inspiration and verification. Henri Poincaré has cited these elements in connection with mathematical creativity; they are clearly not unique to technology. Certainly the chief difference between scientific and technological innovation is one of motive. Scientists seek new knowledge; technologists seek to do something useful.

This difference in motive is reflected in the source of innovation. The direction of a scientist's work is likely to be determined by current fashion, and this assures the required association with and stimulation from others working on related problems. The broad goals of the technologist are usually set by the objectives of an organization rather than by fashion.

Without a clear and understandable goal, effort will be diffuse and pointless, for without a goal there is no telling success from failure. But, if the exact course or approach as well as the goal is specified, there is no real room for technological innovation. The attack on scientific or technological problems must be led with full freedom by men who are both professionally competent and creative themselves.

Useful innovations are made in small and specialized organizations as well as in large ones. But the broad yet clear objectives of a large organization, however, allow the support of the sort of mathematical and scientific research which can form the basis of major technological innovations. Indeed, such support of mathematics and science is absolutely essential if we are to escape from the narrow range of that which is currently fashionable in science and explore equally rewarding areas toward which our attention is directed by human needs.

We need both creative scientists who are broad enough to look beyond the current fashions and creative engineers who can appreciate scientific discoveries and incorporate them into technology.

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The U.S.S. Independence, newest Navy super carrier, recently christened and soon to be commissioned.

Fifty-five gallon drums of Cellulube 220 . . . part of a six-car trainload . . . being put aboard the new Independence. These hydraulic fluids will operate deck-edge elevators between hangar and flight decks.

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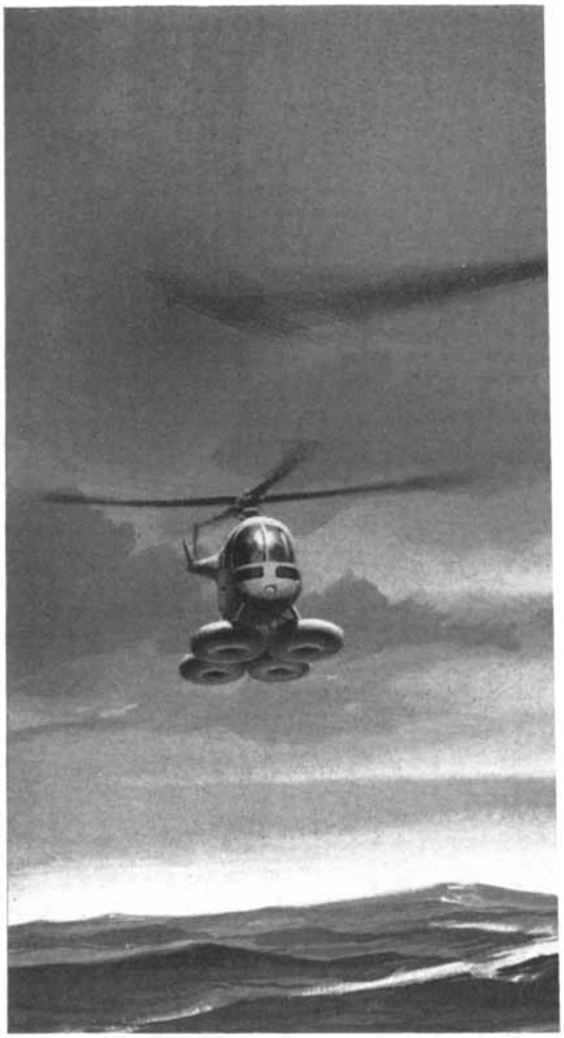
How Du Pont Fibers Help Solve the Problems of Modern Industry



Man-made fibers occupy an important place in the growing family of industrial raw materials. Laboratories throughout the country are evaluating them for tough industrial assignments. The main reason: Manufactured fibers can be engineered to meet specific design needs. Nylon offers strength and stretchability. DACRON has strength with low stretch. TEFLON TFE-fluorocarbon fiber provides extreme chemical resistance and low coefficient of friction. But these Du Pont fibers can also be made to perform differently, depending upon the way they are processed—knitted, braided, felted or twisted. And when you combine them with other materials—plastics, elastomers, wood pulp, mineral fibers—you get new materials with an almost limitless range of properties. You see some examples on these pages. And many more are under development right now.

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Write for your copy of "Du Pont Fibers in Industry". This publication gives technical and performance data on all Du Pont fibers and details on their applications. E. I. du Pont de Nemours & Co. (Inc.), Textile Fibers Dept., 5518-D Nemours Bldg., Wilmington 98, Delaware.

MASTERS OF THE STORM are mooring lines made of Du Pont nylon. This 12,000-ton vessel rode out violent swells and raging winds at dockside. To quote the captain: "For 3½ hours that nylon line fought a strain that I've never seen a natural-fiber line take without breaking. It kept the ship from being damaged, yet showed not a sign of chafing where it passed through the chocks."

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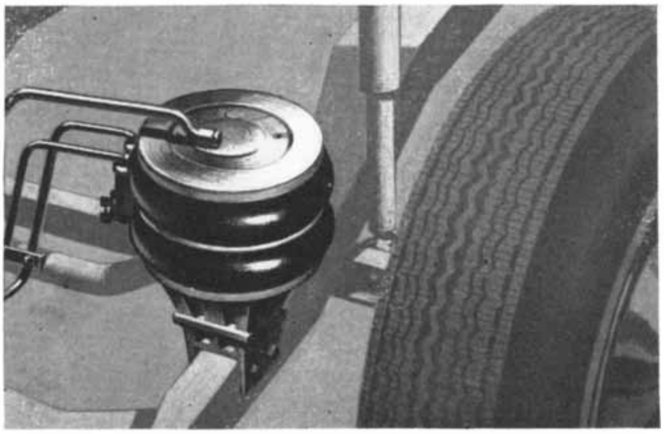
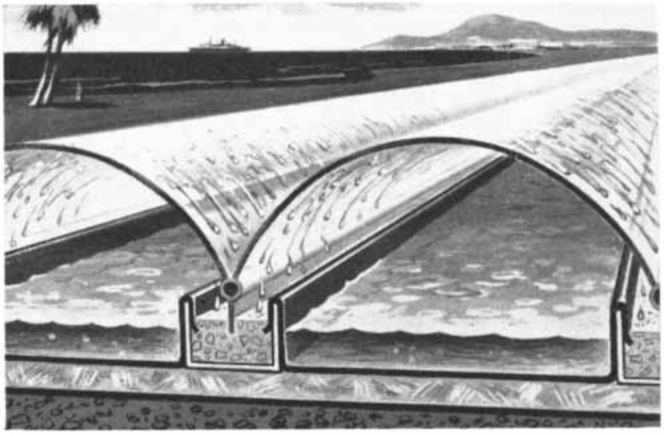
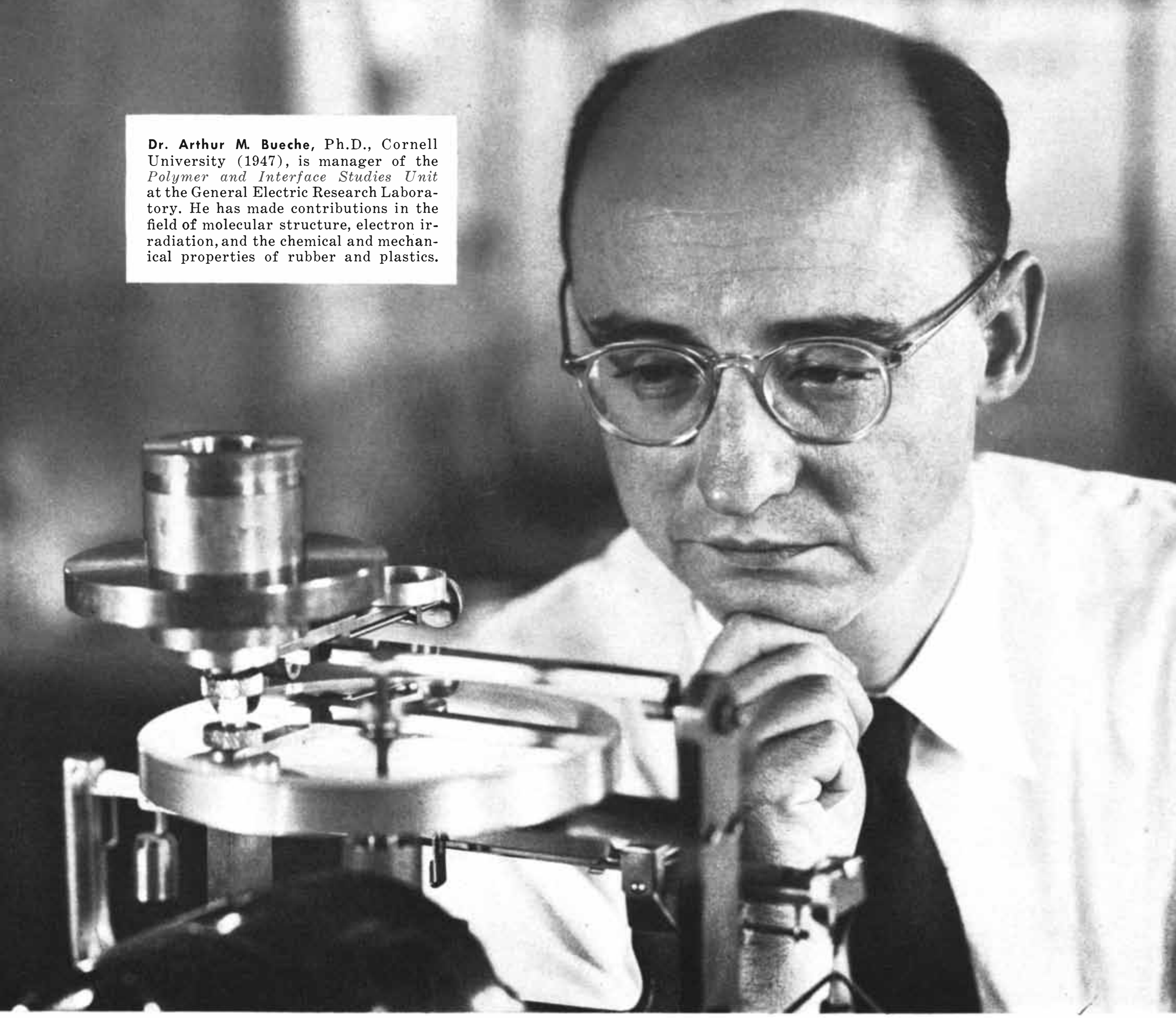


NEW AIR SPRINGS IN YOUR CAR give you a better ride than conventional springs, thanks in part to strong nylon fibers. Fabric made from nylon tire cord is used as the reinforcing material of rubber bellows which form the body of the air spring. Nylon fibers are unaffected by the heat of broiling summer roads. They have excellent abrasion resistance . . . are unharmed by oils, lubricants, grease and tar. The new springs give you a level ride, constant car height with different passenger loads, better damping.



FRESH WATER FROM SALT WATER to make the deserts bloom! That's the promise of solar stills which are—literally—*based* on a Du Pont fiber. The units are heat-insulated from the ground by batts of DACRON polyester fiber. These will not deteriorate under damp conditions. They resist mildew, salts, fungus, heat. Spread over vast areas under the hot sun, these salt-water distillation units bring an economical system for desert irrigation and municipal water supply closer to reality.



Dr. Arthur M. Bueche, Ph.D., Cornell University (1947), is manager of the *Polymer and Interface Studies Unit* at the General Electric Research Laboratory. He has made contributions in the field of molecular structure, electron irradiation, and the chemical and mechanical properties of rubber and plastics.

A deep look at friction

General Electric's Dr. A. M. Bueche explains basic facts about materials in moving contact

Scientists recently have observed substantial differences in the rolling speed of steel balls on materials that have essentially identical surfaces but are dissimilar in their internal structure. Thus *friction,* which usually has been considered to be purely a *surface phenomenon,* is now known to be dependent also on the *bulk mechanical properties* observed "beneath the surface" of the materials involved.

Dr. Arthur M. Bueche and his associates at the General Electric Research Laboratory have developed new fundamental theories explaining these surprising friction effects. Their work, which also includes basic studies in surface chemistry, is giving new insight into a problem that has harassed designers and engineers ever since men first began making machines with moving parts.

Imaginative research programs, like these led by Dr. Bueche, are making progress toward new and improved products that will not only help raise our level of living, but also will contribute to a stronger defense for the nation.

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GENERAL ELECTRIC

The Physiology of Imagination

What activity of the brain underlies the creative process? The evidence indicates that electrical waves, traveling on multilane pathways among the 10 billion cells of the cortex, correspond to the experience of mind

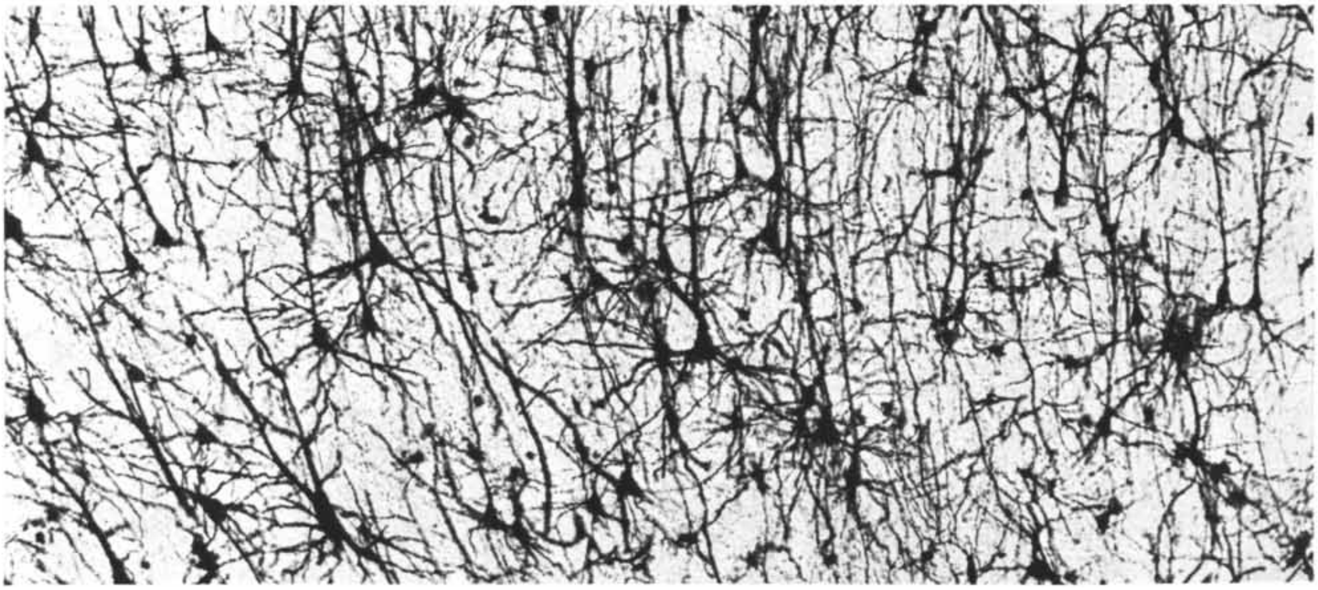
by John C. Eccles

Each of the preceding articles in this issue of SCIENTIFIC AMERICAN is concerned in its way with a process that goes on in the sheet of gray matter, .1 inch thick and 400 square inches in area, which forms the deeply folded surface of the two great hemispheres of the brain. This statement contains a premise that is best made explicit. It says all mental activity, including the supreme activity of creative imagination, arises somehow from the activity of the brain. Few would deny this premise, though a wealth of philosophical disputation lies concealed in that noncommittal word "somehow." Our task here is to see how far our present ideas on the working of the brain can be related to the experiences of mind. The way to the imagination, the highest level of mental experience, lies through the lower levels of sensory experience, imagery, hallucination and memory, and that is the path we shall traverse. All that we shall learn must itself, of course, be the product of perceiving, reasoning and imagining by our brains!

By the early part of this century, investigators had established the still-reasonable likeness of the brain to a complex telephone exchange, with lines of communication bringing electrical impulses in from sense organs and carrying impulses out to effector organs such as muscles or glands. They showed that the lines from the different sense organs ended in well-defined regions of the cerebral cortex: those from the eye at the back of the brain, those from the ear low down on each side, and those from the skin to a band running downwards from the midline over the side of the cerebral hemispheres. Just in front of the area associated with skin sensation they located a band for the control of movement: the motor cortex. Since then workers with more refined techniques have confirmed the outlines of the map and filled in significant detail.

The switchboard analogy is further supported by the nature of the working units of the cortex, the individual nerve cells, or neurons. Functionally they are similar to simple relays in man-made circuits. Just as the relay has two states, either off or on, so the neuron fires an impulse or remains quiescent.

Beyond this point, however, the analogy fails. Study of the densely packed fine structure of the cortex has generated an immense literature on the various neuron types and their arrangement and interconnection in the half-dozen layers in which the cortex is divided [*see illustration below*]. We do not even begin to comprehend the functional significance of this richly com-



CEREBRAL CORTEX, a layer of cells .1 inch thick, appears in cross-section photomicrograph by D. A. Sholl of University College London. Only 1.5 per cent of the neurons are made visible by staining; their fibers make rich interconnection among them.

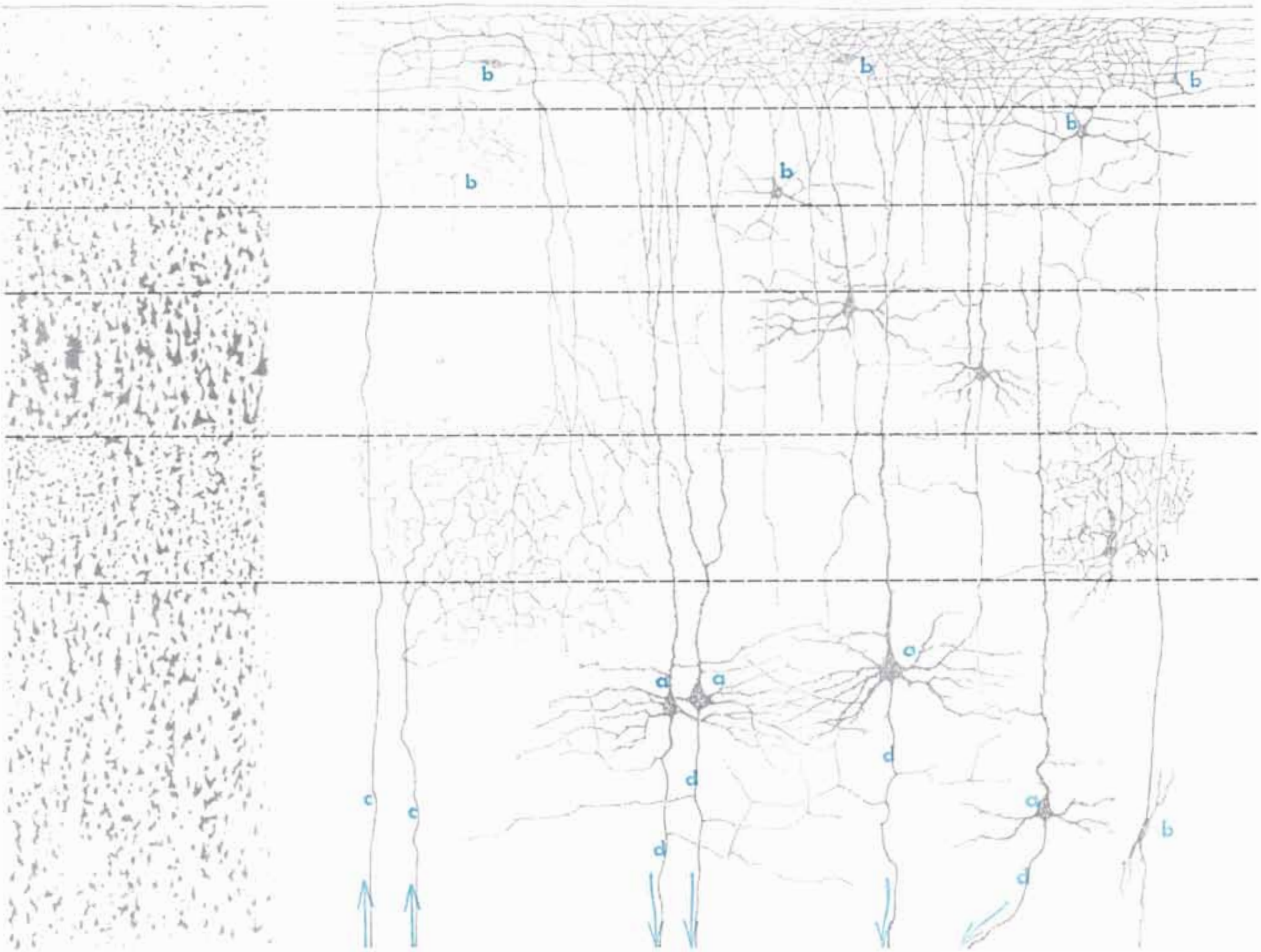
plex design. It is enough, however, to count the number of neurons—some 10 billion—and to see that each receives connections from perhaps 100 other neurons and connects to still 100 more. The profusion of interconnections among the cells of the gray matter is beyond all imagination; it is ultimately so comprehensive that the whole cortex can be thought of as one great unit of integrated activity. If we now persist in regarding the brain as a machine, then we must say that it is by far the most complicated machine in existence. We are tempted to say that it is infinitely more complicated than the most complex man-made machines: the electrical computers.

For the purposes of this consideration of brain activity in relation to imagination we may regard the cortex simply as a sheet of richly interconnected neurons. We must, however, consider briefly the design and behavior of the individual cell and the character of its interconnection with others.

Each neuron is an independent living unit. It receives impulses from other cells through intricately branching dendrite fibers which sprout from its central body; it discharges impulses to other cells via a single slender fiber, the axon, which branches profusely to make contact with numerous receiving cells via their dendrites or directly to their central bodies.

Connections between cells are established by the synapses, specialized junctions where the cell membranes are separated by a cleft only 200 angstrom units across. At these synapses the transmitting cell secretes highly specific chemical substances whose high-speed reaction carries the signal from one cell to the next. The whole of this all-important life process occurs on an exquisitely small scale. A neuron operates on a power of about a thousand-millionth of a watt (hence the entire brain operates on about 10 watts). At some synapses the transmitter substance is liberated in quanta of a few thousand molecules. The vesicles on the axon side of the synapse which apparently contain the transmitter substance are so tiny that, in accordance with the Heisenberg uncertainty principle, there is a relatively large uncertainty as to their location over a period as brief as a millisecond.

The neuron is characteristically an "all-or-nothing" relay. An impulse arriving across a synapse produces a very small and transient electrical effect, equivalent to .001 volt and lasting .01 to .02 second. It requires an excitation of about 10 times this voltage to cause the neuron to fire its discharge [*see illustration on page 146*]. Some of the incoming impulses on the surface of a neuron, however, come from a special inhibitory system of nerve cells and generate the reverse electrical change. Thus, under a



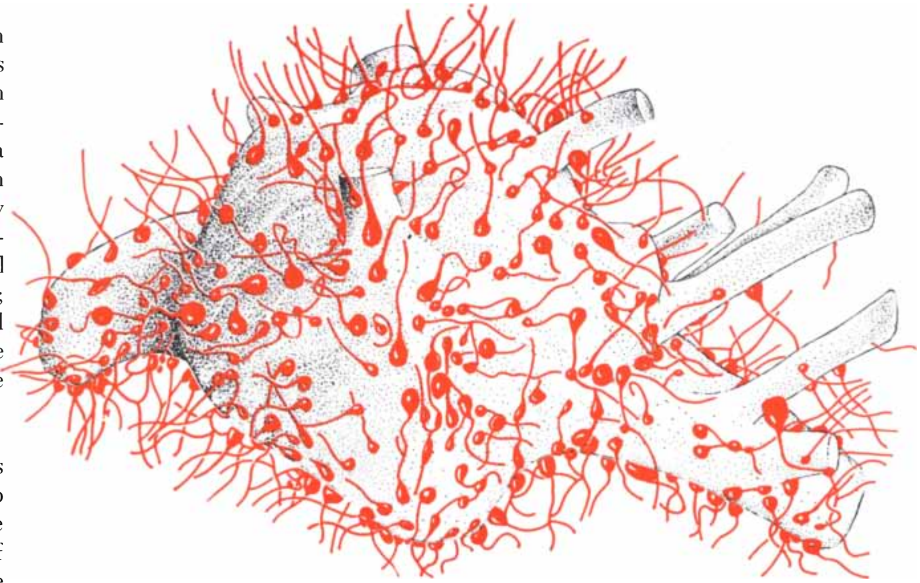
CORTICAL NEURONS and their interconnections are shown in this schematic diagram. At left the diagram indicates the relative density of the various types of cells in the six layers of the cortex. At right the diagram suggests the interconnections between cells established by their fibers. Input fibers (c) deliver impulses from elsewhere in the brain and nervous system. The large pyramidal cells (a), which are outnumbered by smaller cells (b), provide the axonal fibers (d) that carry the outgoing impulses from the cortex.

barrage of incoming impulses, a neuron must sum the opposing synaptic effects and can fire only when its net excitation exceeds the critical level. The time interval between the synaptic activation of a neuron and its own synaptic activation of the neuron next in sequence may nonetheless be no more than a millisecond. After firing, however, a neuron will resist activation for several milliseconds; its alternate states of refractoriness and excitability are probably reflected in the brain as a whole in the rhythm of the brain waves.

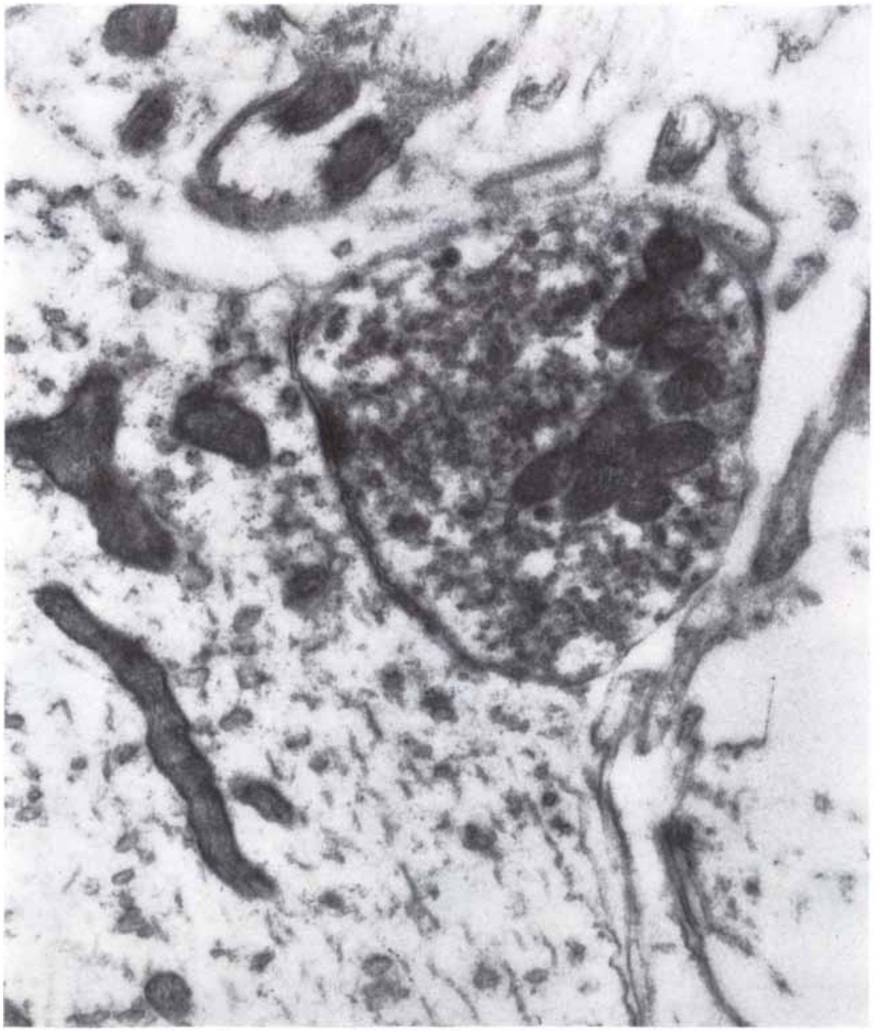
Since convergence of many impulses on any one neuron is required to make it discharge, chains of single neurons cannot propagate a wave of activity through the cortex. Rather the propagation resembles an advancing front of multilane traffic, with many cells activated in parallel at each synaptic linkage in the chain. Since it is difficult to visualize the operation of such a chain, let us study the properties of a much simpler network [*see illustration on page 138*]. Here simplification has been achieved by neglecting inhibitory action, by reducing the number of excitatory synapses made by each axon to no more than three, and by requiring the activation of only two synapses to excite a cell to discharge. By tracing the pathways of waves through this scheme we can get a faint glimpse of the way in which actual neuronal networks develop their virtuosity and plasticity.

We can see immediately the explanation for one remarkable property of a neuronal network: how two completely different inputs (one to cells A_1 and A_2, the other to A_3 and A_4) can be transmitted through the same pattern of cell connections, crossing each other and emerging as completely different outputs (D_3-D_4 and D_1-D_2). Naturally there would have to be an interval of at least several milliseconds between the two wavefronts, else there would be interference at the crossing by summation of synaptic excitations or by the postsynaptic refractoriness of the cells. Note that cells C_2 and C_3 each receive an excess of excitation (by three synapses); this helps the wave to withstand the effects of inhibition or the extinction of an excitatory line. Note also that some neurons along the fringe of an advancing wavefront receive a less than critical single excitation; such subliminally excited neurons give opportunity for growth of a wave should fringe impulses flow in from other sources.

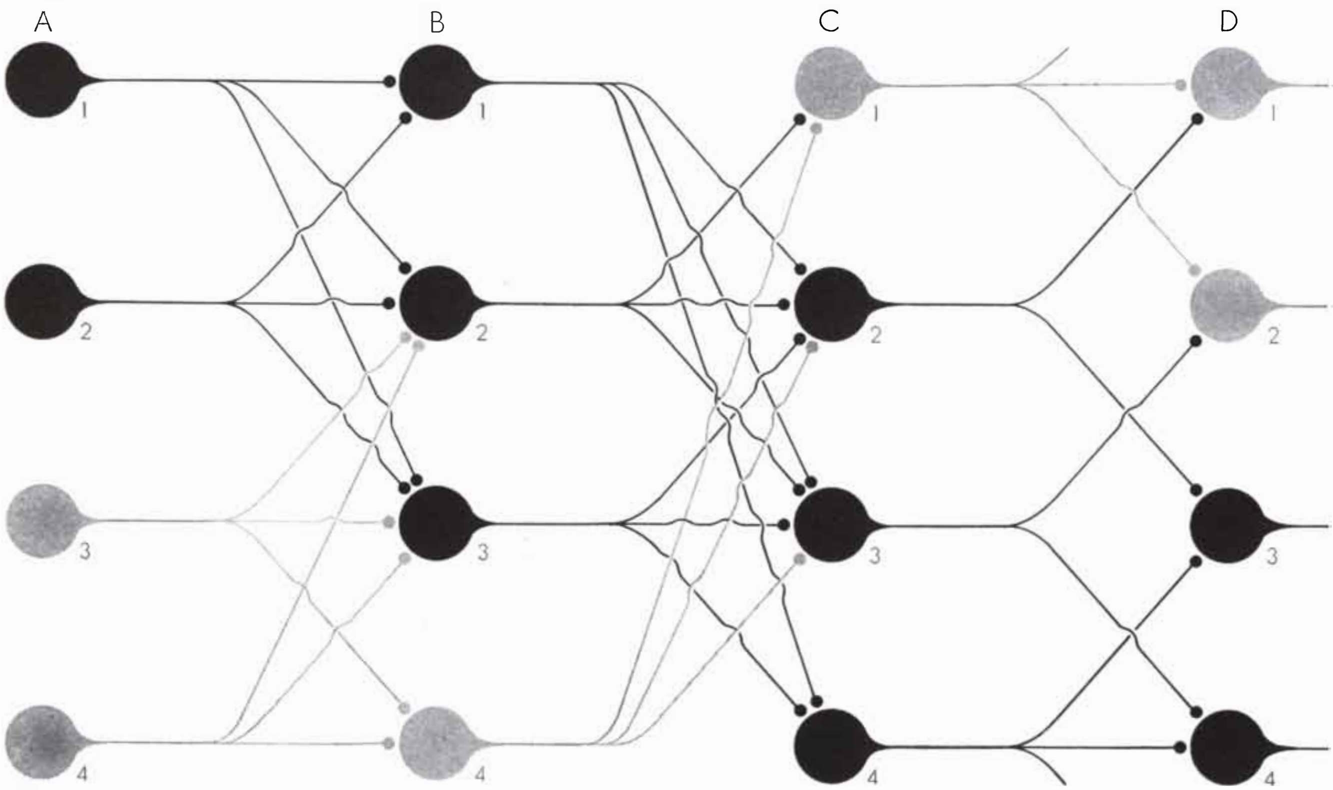
On closer inspection we can see how

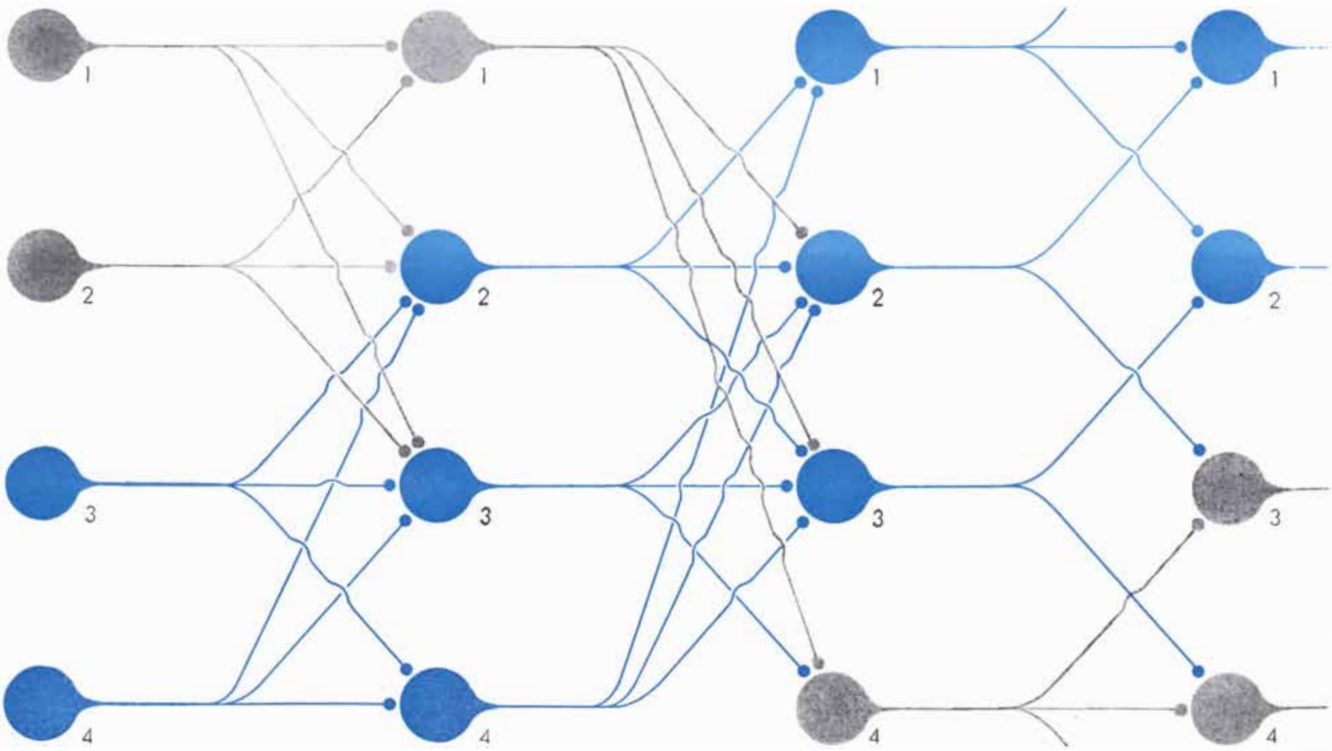


SINGLE NEURON, the working unit of the cortex, is diagrammed to suggest the multitude of interconnections with other cells. Axon fibers from other cells (*in color*) make synaptic junctions with the cell body and with its dendrites, of which only truncated stumps are shown. Impulses go out from the neuron via its axon, the stump of which appears at left.



SYNAPTIC JUNCTION is shown in electron micrograph by George E. Palade and Sanford L. Palay of the Rockefeller Institute. A portion of the receiving cell fills the lower left quadrant, and the synaptic ending of the transmitting cell forms the rough triangle at center. In synaptic ending can be seen vesicles which may contain "transmitter substance."





NEURONAL NETWORK, in highly schematic representation, shows how waves may be propagated along multilane pathways in cerebral cortex. In this scheme each cell body puts out an axon to the right, with as many as three branches, which carry impulses to the cell bodies in the next column; activation of at least two synapses is necessary to cause a cell to fire and relay the impulse. Activated cells and fibers are shown in black at top and in color at bottom; inactive cells and fibers are shown in gray. The diagram shows how two different incoming waves (*A1-A2 in the black pattern and A3-A4 in the colored pattern*) can propagate through the same cell connections, emerging as two different outputs (*D3-D4 in the black pattern and D1-D2 in the colored pattern*). The reader may trace out other patterns of operation. For example, it can be seen that a wave entering at A1 and A3 would fade out at column C.

a wave may be extinguished when there is inadequate convergence of impulses at any stage of the advancing wavefront; for example, a wave starting at cells A_1 and A_3 or A_2 and A_4, would necessarily fade out at the stage of synaptic relay from C to D. Our simple model suggests further that two wavefronts propagating at the same time into the same pool of neurons may coalesce and give an onwardly propagating wave having features derived from both, with additional features due to the summation. Thus activation of the two pathways leading to A_1-A_2 and to A_3-A_4 would cause all four neurons at the D stage to discharge. In addition neurons outside the diagram fringing C_1 and C_4 would be activated, creating opportunities for further interaction beyond the D neurons. Conversely we can visualize how a wavefront moving into neuronal pathways of suitable configuration may bifurcate into two waves propagating independently.

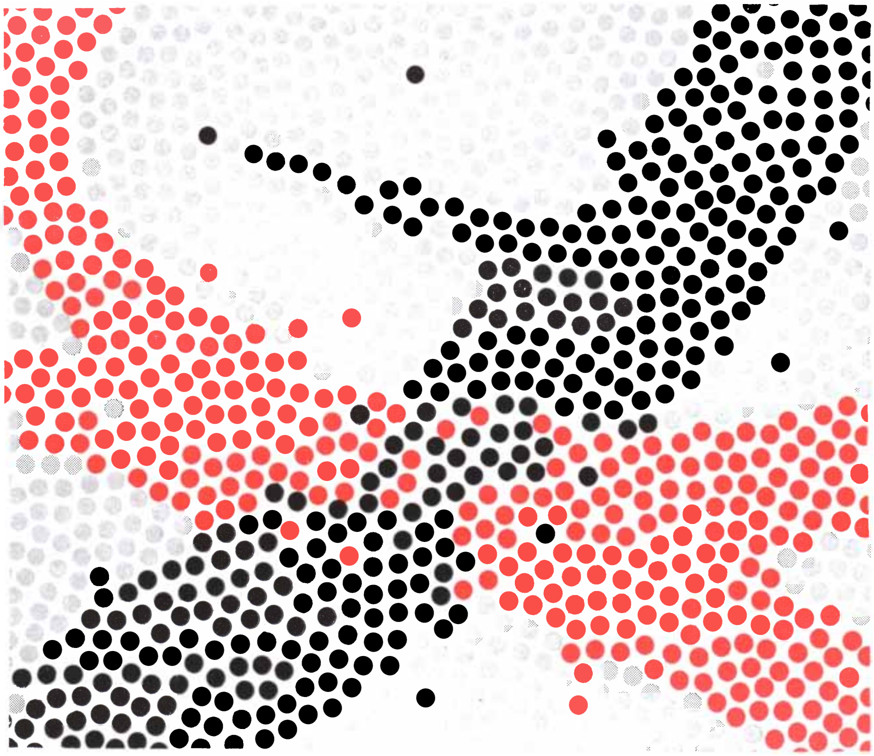
The transmission of a wavefront in the cortex is, of course, a much more complicated matter. With as many as 100 neurons involved at each relay stage, an advancing wave may sweep over 100,000 neurons in a single second. Such a wave has much richer potentiality than the simple case we have been considering. The diagram on the opposite page suggests a few of the configurations it may exhibit, branching at intervals, often abortively, reconverging, and coalescing with other waves.

Of particular interest are the closed loops that appear along the main pathways of the waves. Delisle Burns of McGill University and other investigators working with isolated slabs of cortex have found that rhythmical waves of several seconds' duration may be evoked by brief electrical stimulation. Such reverberatory activity implies the existence of closed self–re-exciting chains, in which waves recirculate again and again. These reverberatory waves need not follow stereotyped paths through the neuronal multilane channels, but may open new paths in the same vicinity on each rhythmic cycle, depending upon the convergence of excitatory impulses on each neuron.

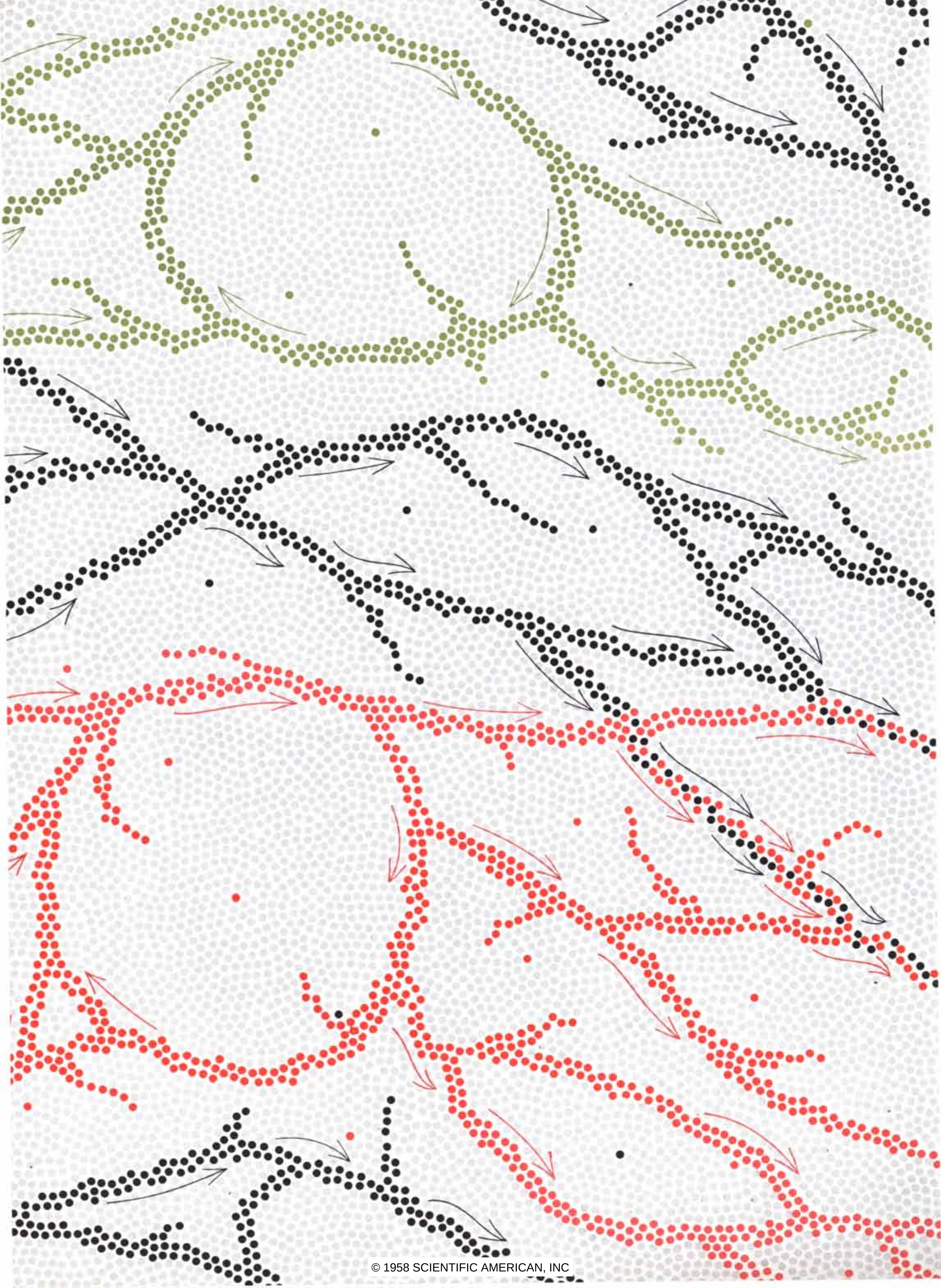
It is important to realize that a wave is not restricted to advance through immediately adjacent neurons. The key pyramidal cells of the cortex operate not only on nearby cells, reached by short branches from their axons, but also upon cells in remote parts of the cortex. Via their very long branches which pass through the massive bridge of nerve fibers in the corpus callosum, the pyramidal cells in one hemisphere of the brain may activate the symmetrical region of the other hemisphere. Thus part of an advancing wavefront may dip through the white matter to start up a new excitatory focus at a distant point in the cortex, or even perhaps in the thalamus or other large masses of nerve cells at the base of the brain. It may even return to reinforce the activity close to its zone of origin, so completing an immense reverberatory circuit.

Here we have come upon a mechanism to explain the brain waves made familiar by electroencephalography. During inattentive, but waking, states the predominating wave is that of the 10-a-second "alpha" rhythm. Its frequency is readily explained by the circulation of impulses in reverberatory circuits with a circuit time of about .1 second, which corresponds approximately to the post-synaptic refractory time of the pyramidal cell. To maintain even the low activity giving rise to the alpha rhythm the cortex must be subjected to continuous excitation by impulses from lower centers. Otherwise the activity of the cortex virtually ceases, and it lapses into deep sleep.

When the brain is active, the alpha wave gives way to fast, small irregular waves. Visual experience, for example, brings an immense barrage of impulses into the cortical neurons which disrupts their tendency to settle into the phased activation of the alpha rhythm; concentration on a problem or on a task involving skill stirs up similarly heightened neuronal activity over a large area of the cortex. At such times the massive synaptic bombardment of the neurons must evoke discharges at intervals much shorter than the .1 second needed for a virtually full recovery of excitability. It is apparent, moreover, that specific local patterns of activity replace the diffuse random activation indicated by the alpha rhythm. The relatively high voltage of the alpha waves is evidence that large numbers of neurons are activated in phase, while the negligibly small potential of the fast waves suggests an intense and finely patterned activity. This interpretation is supported by an interesting experiment: A flickering light on the retina will drive



INTERSECTION OF PATHWAYS in schematic neuronal network corresponds to the intersection diagrammed in larger scale on the opposite page. Each dot represents a neuron, the black and colored dots being activated and the gray dots inactive. The two pathways utilize the same group of neurons, each entering the group from a different direction and leaving it in a different direction. The waves may have to be separated by an interval of time in order not to lose or merge their identity; the black wave occupies most of the intersection at the moment shown. Isolated black and colored dots represent "fringe" neurons excited by waves.



large-amplitude brain waves at frequencies up to 20 a second. Here the powerful visual pathway becomes a channel for the input of synchronous bursts of discharges rather than the fine pattern of activation of ordinary visual experience.

We are now ready to attempt a picture of the patterns in the cortex that attend simple sensory experience, the raw material on which in the end the imagination acts. As will be seen, our picture must be largely speculative. But it is based upon secure evidence which answers the primary question of how it is that information is conveyed to the cortex with a sufficient degree of specificity to make subsequent interpretation possible. As the well-established map of the cortex shows, each of the sense organs reports on its own lines to specific regions in the cortex. Vernon Mountcastle of Johns Hopkins University has found, moreover, that the sensory receptors of each different type, *e.g.*, touch, pressure or joint movement, initially activate neurons in narrow vertical columns that are arranged as an interdigitated mosaic in the cortical map. At the receptors the intensity of stimulus from instant to instant is encoded in impulses of varying frequency, like a Morse system of dots only. This specificity of discharge is preserved through the sensory pathways up to the cortex, where it can be observed in the responses of single neurons. Sensory information thus comes into the brain as a specific signal to a sharply defined point in the cortex.

Beyond this stage virtually nothing is known about the evolving patterns of cortical activity. But we may speculate that a wavefront initiated by the arrival of a sensory signal in the cortex preserves the specificity of that signal as it propagates through the neuronal network. We may further assume that the interaction of wavefronts originating at different sites in the cortex effects the integration and synthesis of the information relayed from different sensory receptors. For example, a wavefront initiated by the sensation of pressure on a certain area of skin, interacting with wavefronts signaling muscle sensation and cold, would integrate in an assembled wave form characteristic of a smooth, cold object of a certain shape and mass—perhaps a stone. If this line of speculation is valid, then integration must occur between wavefronts generated by the most diverse receptor-organ discharges from eye and hand, or from eye and ear, or, to take the more complicated example of the interpretation of the visual field, discharges from the retina, the eye muscles, the neck and body musculature, and the apparatus of the inner ear which signals the orientation of the head. In fact, information from any sense organ must potentially be capable of integration with that from any other.

In the light of these speculations it is significant that electrical stimuli applied to the sensory zones of the cortex evoke only chaotic sensations: tingling or numbness in the skin zones; lights and colors in the visual zone; noises in the auditory zone. Such chaotic responses are to be expected, since electrical stimulation of the cortex must directly excite tens of thousands of neurons regardless of their functional relationships, and so initiate a widely spreading amorphous field of neuronal activation quite unlike the fine and specific patterns that must be set up by input to the cortex from the sensory organs. A familiar chaotic sensation, involving elements of touch, heat, cold and pain, arises for similar reasons when a sensory nerve is directly stimulated, as when the ulnar nerve in the elbow (the "funny bone") is injured.

From the cortical patterns that mirror sensory experience we proceed next to consider what mechanism may account for the recall of some sensory experience. Here we come to imagery or memory and so to the simplest level of imagination. Memory must be dependent on some enduring change that has been produced in the cortex by its previous activation. Theory and even some experimental evidence favor the hypothesis that the initial activation of the synapses in a network brings about a lasting improvement in the efficacy of these junctions. As yet no one knows just how. One suggestion is that the synaptic knobs grow in size, another is that the synaptic transmitter substance becomes available in increased volume. For the present it is sufficient to consider the increased synaptic function as giving a "congealed" neuronal pattern or "engram" ready to be replayed by an appropriate input.

NEURONAL PATHWAYS in this schematic diagram suggest the variety of configurations made possible by the rich interconnection of neurons in the cortex. Here a number of waves (shown in black, red and green dots, respectively) are shown traveling through a neuronal field, branching and coalescing and putting out abortive channels. An important feature in both the red and the green pathways is the reverberatory circuit, in which the wave travels repeatedly around the same closed loop of cells, as indicated by the arrows; such a reverberatory circuit can presumably maintain the excitation of the entire system of pathways in the direction of the arrows beyond. The abortive branches in a reverberatory circuit may develop into new functional pathways. In the black and red pathways at bottom two different waves are shown to propagate through the same chains of cells over portions of their lengths.

Experiments on the synapses at simpler levels of the nervous system lend considerable support to this postulate; they suggest that usage enhances synaptic efficacy for periods of days or weeks. Investigators have also found that the conditioned reflex is attended by changes in the electroencephalogram of experimental animals, indicating that specific patterns of neuronal activation are laid down during the conditioning. D. O. Hebb of McGill University has surmised that significant synaptic change requires reverberatory circulation of impulses many times around the pattern that is to be "remembered." In this connection it is relevant that an experience may not be remembered if a cerebral trauma (concussion or electric shock) is sustained as long as 20 minutes later. Such amnesia is much less pronounced, however, when cerebral activity is blocked by rapid anesthesia, suggesting that something other than recirculation of the impulses helps to establish the engram in the cortex.

The engram postulate accords well with the experience of remembered imagery. By far the most vivid memories are evoked by some closely similar experience. Here the new, evolving spatiotemporal pattern must tend to correspond closely to the old, congealed pattern; the impulses of the new pattern flow into a channel of the old and trigger its replaying. Such an intersection of patterns is suggested by the diagram on page 140. In less favorable situations we call upon various devices or tricks of memory, deliberately choosing specific sensory inputs (trains of thought) that may trigger the memory.

Language, whether spoken or written, is overwhelmingly important to the function of memory and becomes increasingly so with education and cultural development. Thus we learn to experience vicariously the imagery of writers and artists. Poetry is a particularly effective medium for the transmission of imagery, transcending time and place and appealing to all who have educated themselves to have in their cortex engrams ready to be evoked by the reading—or better still the hearing—of some "pregnant" lines of poetry. The word "pregnant" is significant of our experience of the wealth of evoked imagery.

Karl S. Lashley, former director of the Yerkes Laboratories of Primate Biology, has convincingly argued that "the activity of literally millions of neurons" is involved in the recall of any memory. Furthermore, his experimental study of the effects of cortical lesions indicates that a particular engram has multiple representation in the cortex. With such a huge number of neurons involved in the fixing of a single memory in the cortex, one might think that the capacity of even 10 billion neurons would be quickly exhausted. Lashley concludes, however, that a cortical neuron need not belong exclusively to one engram, but on the contrary each neuron and even each synaptic junction can be built into many engrams. The diagram on page 140 shows how two separate patterns of activation can spread through the same assemblage of neurons and emerge therefrom each with its own identity. Such economical employment of neurons gives the brain capacity to hold a lifetime of memories.

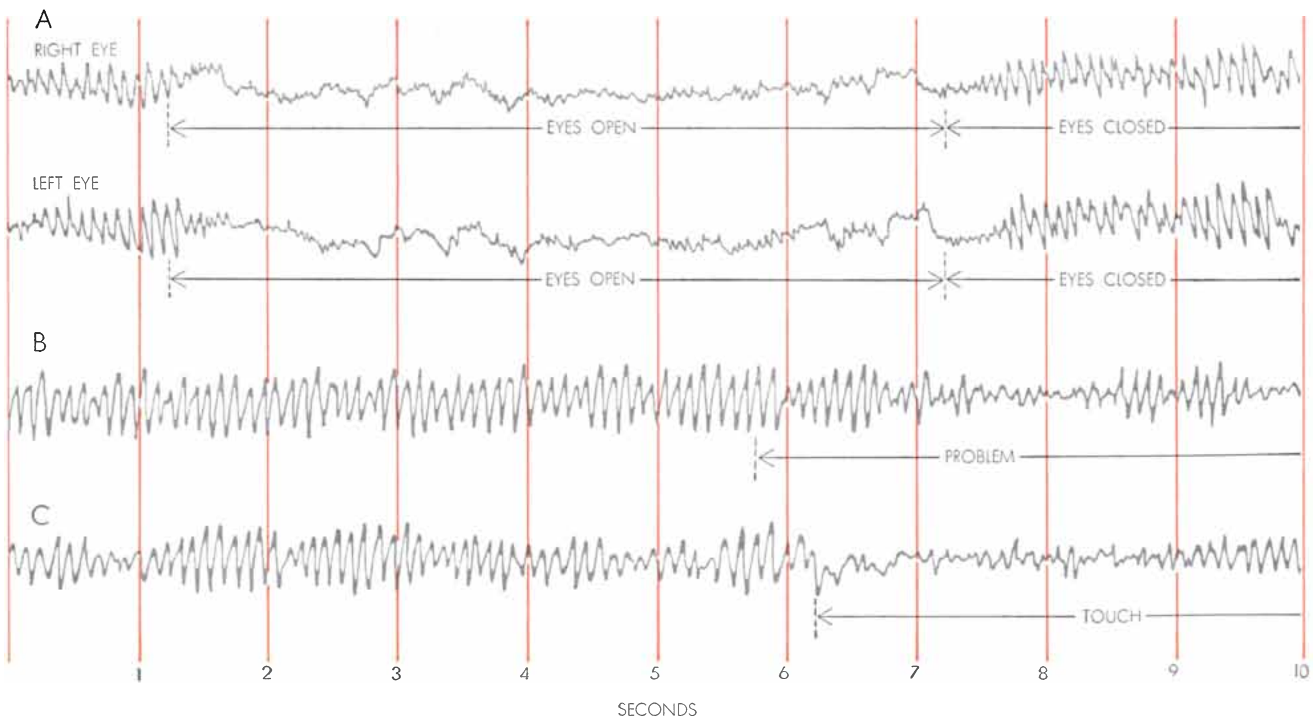
Here a caveat should be entered against any too-literal reading of the diagrams that have illustrated this discussion. They bear the same relationship to the presumed real three-dimensional patterns of the cortex as chemical formulas to their molecules. In particular it must be emphasized that, because of continued replaying and interaction with intersecting patterns, the "congealed" engrams will be continuously changing, growing into new branches and shedding others. Correspondingly, successive recollections of the same past experience tend to undergo a gradual change.

Thus we have envisaged the working of the brain as a patterned activity formed by the curving and looping of wavefronts through a multitude of neurons, now sprouting, now coalescing with other wavefronts, now reverberating through the same path—all with a speed deriving from the millisecond relay time of the individual neuron, the whole wavefront advancing through perhaps one million neurons in a second. In the words of Sir Charles Sherrington, the brain appears as an "enchanted loom where millions of flashing shuttles [the nerve impulses] weave a dissolving pattern, always a meaningful pattern, though never an abiding one; a shifting harmony of sub-patterns."

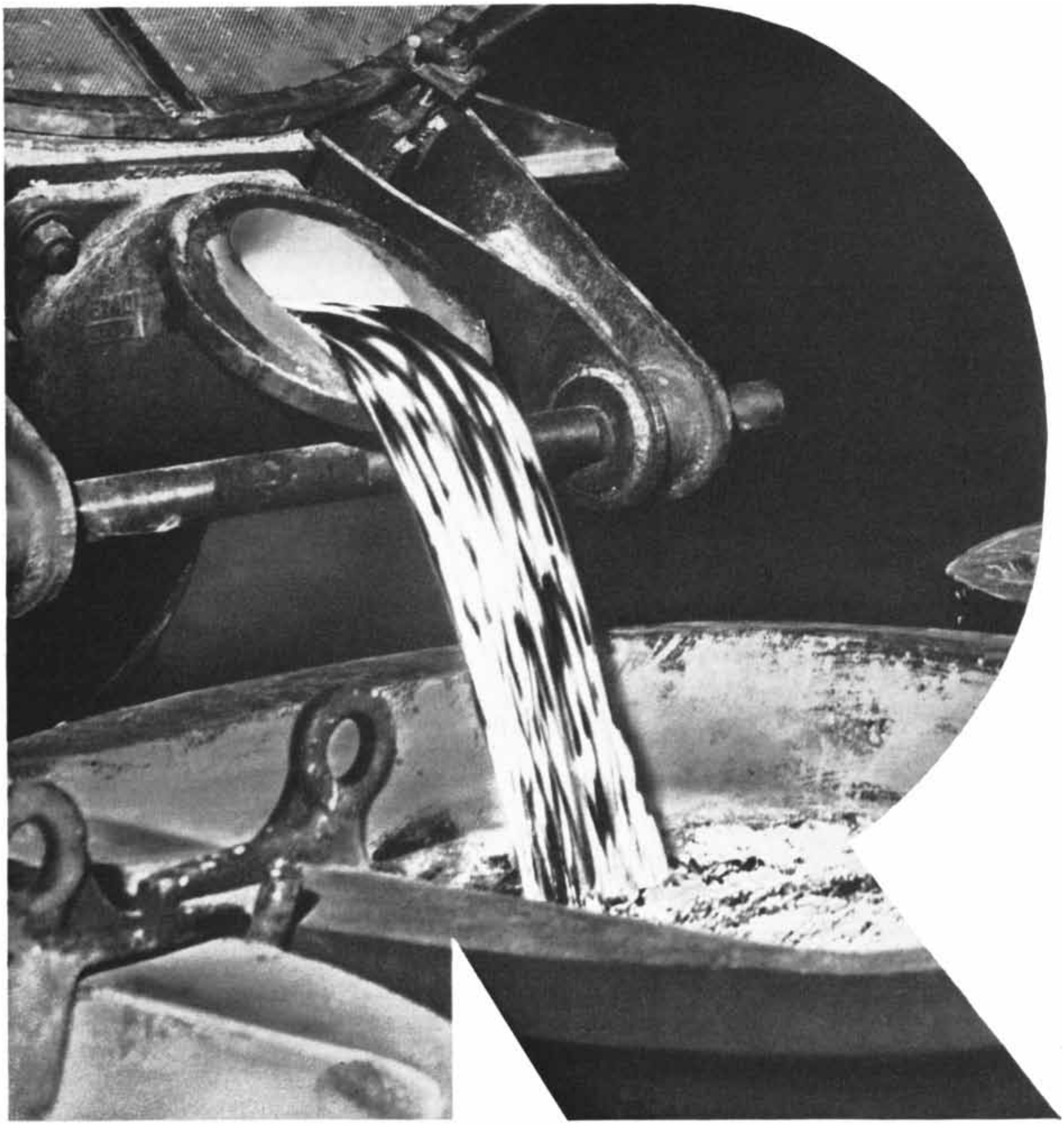
But how does the working of the brain give us valid experience of the external world? The communication from sense organ to cerebral cortex is by a signal quite unlike the original stimulus, and the spatio-temporal pattern evoked in the cerebral cortex must again be different. Yet as a consequence of this cerebral pattern of activity we experience an impression which we project to somewhere outside the cortex—to the surface of the body or even within it, or, as sight, hearing or smell, to the outside world. On the other hand, as René Descartes first clearly saw, the only condition necessary for us to see colors, hear sounds or experience the existence of our own body is that appropriate patterns of neuronal activity shall occur in appropriate regions of our brain. It is immaterial whether these events are caused by local stimulation of the cerebral cortex or some part of the afferent nervous pathway, or whether they are, as is usual, generated by impulses discharged by sense organs.

Actually a long period of education is required before the brain events produced by the sensory organs can be interpreted as belonging to an external world and so be useful in sensing this world. This is impressively illustrated by the behavior of adults who gain sight for the first time upon the removal of congenital cataracts, and by chimpanzees reared in darkness.

But so far the key problem in perception has remained beyond this discussion. We may ask: How can some specific spatio-temporal pattern of neuronal



BRAIN WAVES show contrasting patterns of the active and inactive brain. The dominant pattern of the resting brain is the large-amplitude wave of approximately 10 cycles per second. When the eyes are open or when the brain responds to other sensory input or when it is engaged by a mental problem, these "alpha" waves give way to irregular waves of higher frequency and smaller amplitude.



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activity in the cerebral cortex evoke a particular conscious experience? Furthermore, how does it happen that only when there is a moderate level of activity in the cerebral cortex does it come into liaison with mind to result in a conscious state? If our cortical activity is too low, we lapse into the unconsciousness of sleep or anesthesia or coma. If it becomes too intense, unconsciousness also supervenes, as during the convulsions of epilepsy or shock therapy.

Another problem relates to attention, for much organized cortical activity can be carried on at a subconscious level. How does it come about that our attention is diverted now to this patterned activity which then gives its unique conscious experience, now to that? Is the magnitude of the cortical activation significant in thus achieving conscious attention? These fundamental problems escape all but the vaguest formulation in fragmentary hypotheses.

Our speculation has covered only the simplest aspect of imagination: imagery or the re-experiencing of images. In passing beyond this stage let us first consider the peculiar tendency to association in imagery. The experience of one image is evocative of other images, and these of still more, and so on. When these images are of beauty and subtlety, blending in harmony, and are expressed in some language—verbal, musical or pictorial—to evoke transcendent experiences in others, we have artistic creation of a simple or lyrical kind. Alternatively, entrancing displays of imagery of great beauty and clarity can be experienced by ordinary people under the influence of hallucinogenic drugs such as mescaline. One may suspect that the cortex under these conditions tends to develop ever more complex and effectively interlocked patterns of neuronal activity involving large fractions of its neuron population. This would account for the withdrawal of the subject from ordinary activities during these experiences. Not unrelated to these states are the psychoses where the inner experiences of the patients also cause them to be withdrawn.

An entirely different order of image-forming is involved in creative imagination, the most profound of human activities. It provides the illumination that gives a new insight or understanding. In science that illumination takes the form of a new hypothesis which embraces and transcends the older hypotheses. Such a creation of the imagination has immediate esthetic appeal in its simplicity and scope; it must nevertheless be subjected to rigorous criticism and experimental testing. The illumination often has had the suddenness of a flash, as with Kekulé and the benzene ring, Darwin and the theory of evolution, Hamilton and his equations. But suddenness of illumination is no guarantee of the validity of a hypothesis. I have had only one such sudden illumination—the so-called Golgi-cell hypothesis of cerebral inhibition—and some years later it was proved false! Most of the great scientific hypotheses are the offspring of more labored births. They developed in stages, being perfected and shaped by critical reason, as with Planck and the quantum theory and with Einstein and the theory of relativity.

Before attempting to picture the brain activities that underlie innovation in science, let us recall that such illumination comes only to a mind that has been prepared by the assimilation and critical evaluation of the knowledge in its field. One can deliberately seek to experience some new imaginative insight by first pouring into one's mind hypotheses and the related experiments and then relaxing to give opportunity for the subconscious processes in the brain that may lead to the conscious illumination of a new insight. Such illuminations are often fragmentary and require conscious modification, or are so erroneous as to invite immediate rejection by critical reason. Nevertheless they all give evidence of the creativeness of the subconscious mind.

It may now be asked: What activity in the brain corresponds to this creative activity of the subconscious mind, and how eventually does it flash into consciousness? Let us consider first the prerequisites for such cerebral action. The wealth and subtlety of stored memories and critical evaluations imply that in the neuronal network there is an enormous development of highly complex engrams whose permanency derives from the postulated increase in synaptic efficacy. We may say that these congealed patterns supply the know-how of the brain; when there is a great wealth of expert knowledge, the engrams may occupy the greater part of the cortex. One can speculate further that some failure in the synthesis of the engrams or some conflict in their interrelationship is the neuronal counterpart of a problem that clamors for solution.

Such are the prerequisites leading to creative insight. We may surmise that the "subconscious operation of the mind" involves the intense and unimaginably complex interplay of the engrams. We have seen that on repeated activa-

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"This one tastes good — uh — like coffee should," replied the hornrimmed home economist, shyly.

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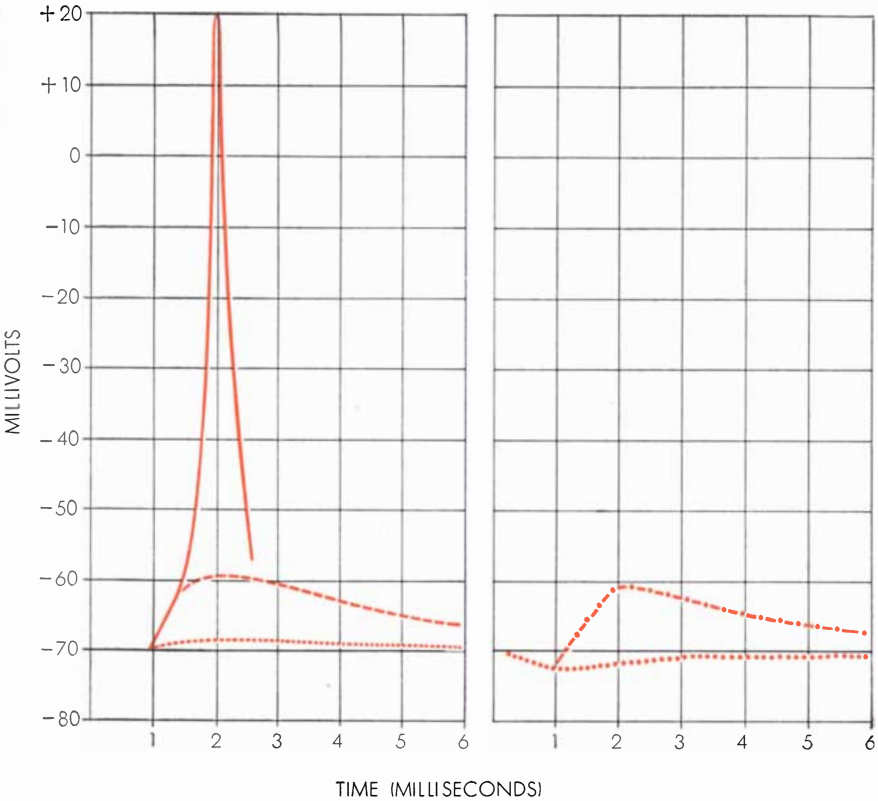

NEURONAL IMPULSE is triggered by an "all-or-nothing" excitation of the cell. In the diagram at left the lower broken line represents the change in potential induced by a single excitatory synaptic impulse; the upper broken line shows the summed action of a number of such impulses which triggers the spike potential, shown by the solid line. In the diagram at right the lower dotted line represents the change in potential induced by an inhibitory impulse, which depresses excitation of cell below the critical level for firing of impulse.

tion there tends to be a progressive change in their congealed patterns resulting particularly from interaction with other patterns. Thus we can expect that new patterns will arise during the subconscious phase of the effort. Should an emergent pattern combine and transcend the existent patterns, we may expect some resonant-like intensification of activity in the cortex, which will bring this pattern to conscious attention. There it comes to light as a new idea.

Then begins the process of conscious criticism and evaluation, the deliberate effort to discover flaws in the new idea. This done, there comes the crucial stage of the designing and carrying out of experiments that test predictions derived from the new idea. From the point of view of science, a creative imagination is fruitful if it develops new hypotheses that are powerful in their generality and stand up to experimental test.

Finally we may ask: What are the characteristics of a brain that exhibits creative imagination? In attempting an answer we must venture more deeply than ever into the realm of speculation. Certain general statements can be made, but their inadequacy will be apparent. The creative brain must first of all possess an adequate number of neurons, having a wealth of synaptic connection between them. It must have, as it were, the structural basis for an immense range of patterns of activity. But even this obvious generalization must be hedged. There is poor correlation between brain size and intelligence, even assuming proportionality of brain size and neuron population: a chimpanzee brain has a neuron population 80 per cent as large as a human brain and displays little or no creative imagination. The synapses of the brain should also have a sensitive tendency to increase their function with usage, so that they may readily form and maintain memory patterns.

Such a brain will accumulate an immense wealth of engrams of highly specific character. If in addition this brain possesses a peculiar potency for unresting activity, weaving the spatio-temporal patterns of its engrams in continually novel and interacting forms, the stage is set for the deliverance of a "brain child" that is sired, as we say, by creative imagination.

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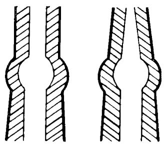

From all we've been able to discover, the men in the shop are quite enthusiastic about these rugged, heat-resistant glass tips that let them watch the welds go by. Likewise for the people who buy these tips from Corning and sell complete rigs to welders. They get what they need, when they need it, at a price that makes sense.

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Or put some data at your fingertips by sending for Bulletin B-91, "VYCOR brand industrial glassware by Corning." In it you'll find all facts about infrared and ultraviolet transmission, heat and chemical resistance, and forms in which you can get these glasses.

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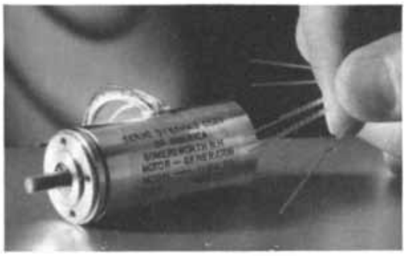

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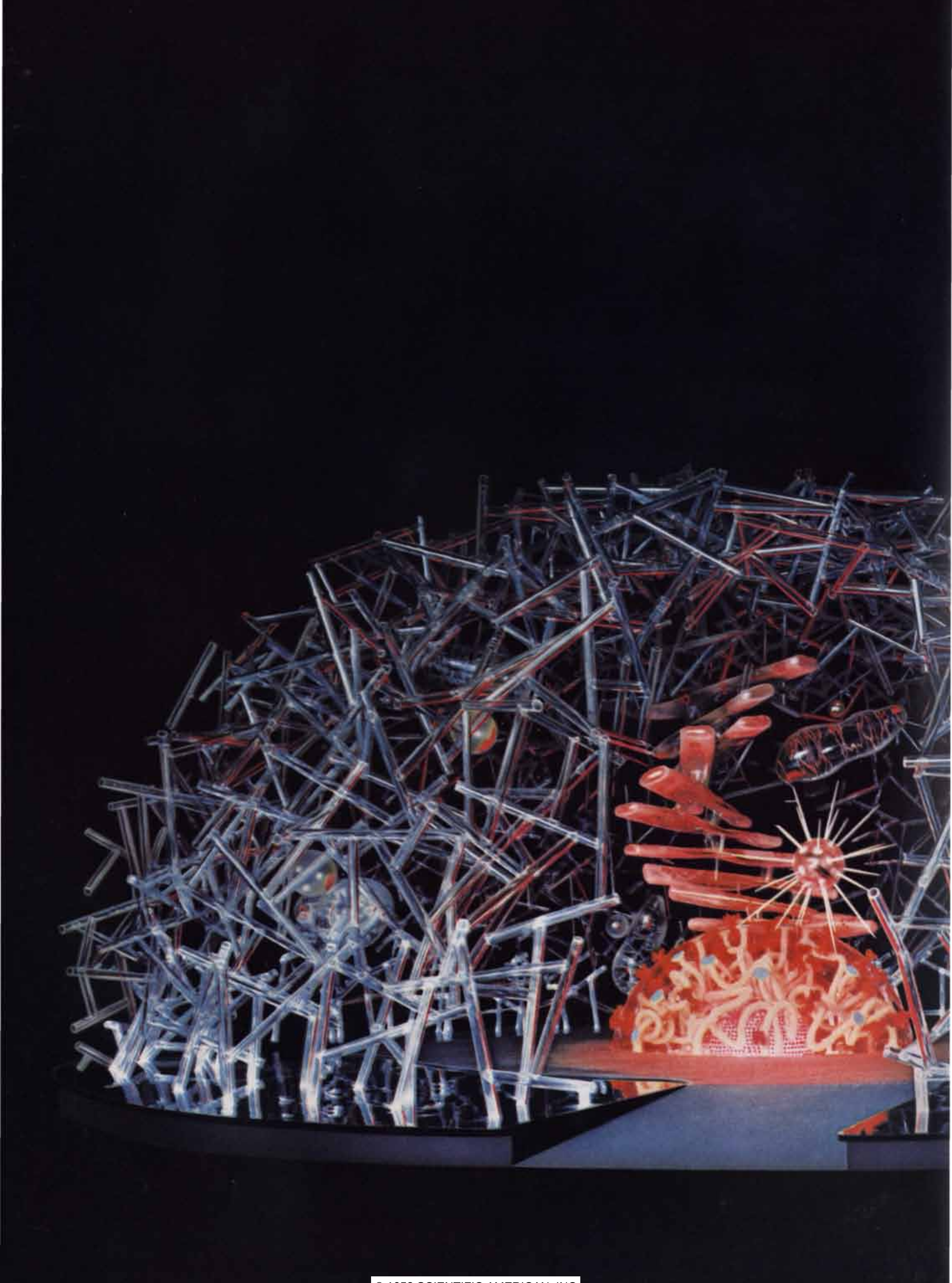

Upjohn

Model of a Basic Cell

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1,000,000 times enlarged, was first displayed at the June 1958 meeting of the American Medical Association, at San Francisco.

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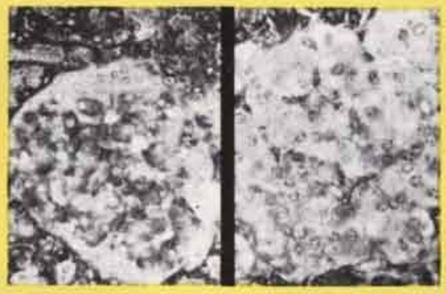
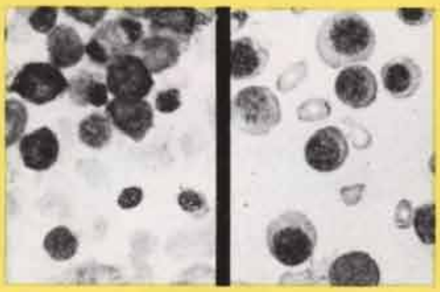


Left: Insulin (dark material) has accumulated in pancreatic islet cells. Right: Insulin has been released for use by Orinase* (tolbutamide), the new antidiabetic that is taken by mouth.



Left: Bone marrow of a patient with pernicious anemia. Large granular cells are abnormal. Right: Mature normoblasts (cells with sharply defined nuclei and clear cytoplasm) after injection of vitamin B-12.

The Cell—an illustrated 48-page monograph on cytology—is available to educational institutions, teachers and scientists. Please address requests to:

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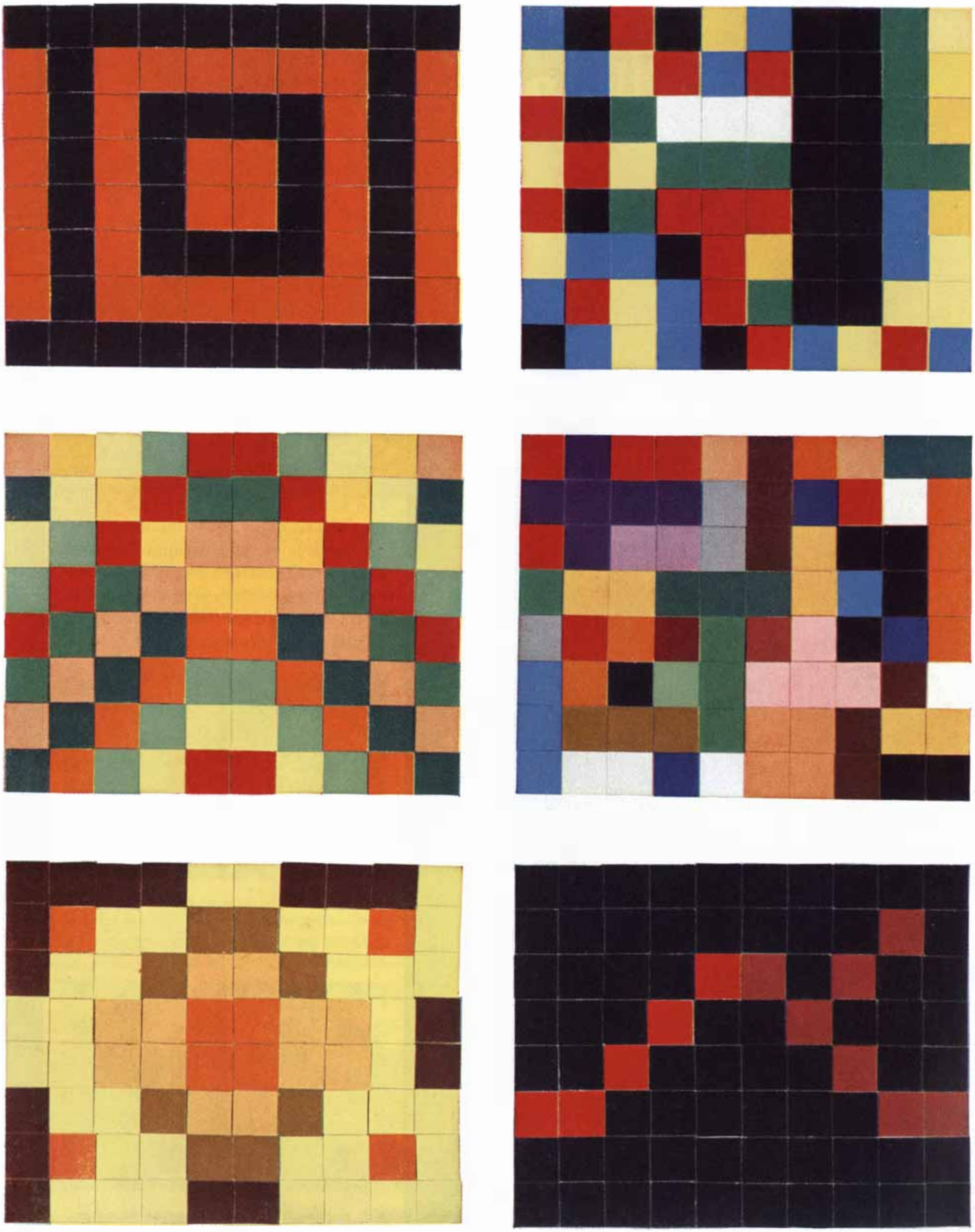


MOSAICS WERE CONSTRUCTED by subjects in a study of creative individuals undertaken by the Institute of Personality Assessment and Research of the University of California. Each of the relatively regular mosaics at left was made by a student who was chosen at random. Each of the more imaginative mosaics at right was made by an individual who was judged highly creative by his peers.

The Psychology of Imagination

Creativity has recently become the subject of formal study by psychologists. An account of one such study, which set out to ascertain the characteristics of creative individuals

by Frank Barron

By his imagination man makes new universes which are "nearer to the heart's desire." The sorcery and charm of imagination, and the power it gives to the individual to transform his world into a new world of order and delight, makes it one of the most treasured of all human capacities. Indeed, when we imagine divinity, we impute to it the power to have imagined *us,* and by an act of will to have created us. Ever since man became conscious of himself, imagination has had in it something of mystery and magic, and has seemed a process which cannot be completely understood.

Against this background of a somehow desirable and proper mystery which surrounds the creative act, it is perhaps a bit brash to undertake a scientific study of imagination and originality. The psychological research institute of which I am a member, however, has done just that, and for the past eight years we have been concerned to discover what kinds of individual possess in high degree the powers of constructive imagination and original thought.

If the undertaking seems brash, the techniques of study are modest enough, and in eight years of work we cannot claim to have greatly diminished the mystery. The best that can be said is that certain uniformities do seem to characterize highly original scientists and artists, and that these uniformities have suggested speculations which may provide the basis for further empirical investigations.

In this article I shall describe a study (for which I have been primarily responsible) of the characteristics of a large number of individuals in a group including painters, writers, physicians, physicists, biologists, economists and anthropologists. This is only one of several projects now under way at the Institute of Personality Assessment and Research of the University of California. The other projects are a study of distinguished American architects (carried on by Donald W. MacKinnon, director of the Institute), an investigation of conformity pressures and the response of creative individuals to demands for conformity (the work of Richard S. Crutchfield, associate director), a study of research scientists and engineers (headed by Harrison G. Gough) and a study of creative mathematicians, both men and women (under the direction of Ravenna Helson).

The way in which the common human need for order is related to the constructive possibilities and fruitful chal-

SUBJECT MAKES A MOSAIC at the Institute of Personality Research and Assessment. In the background another subject takes a different test. Between the two subjects is Barron.

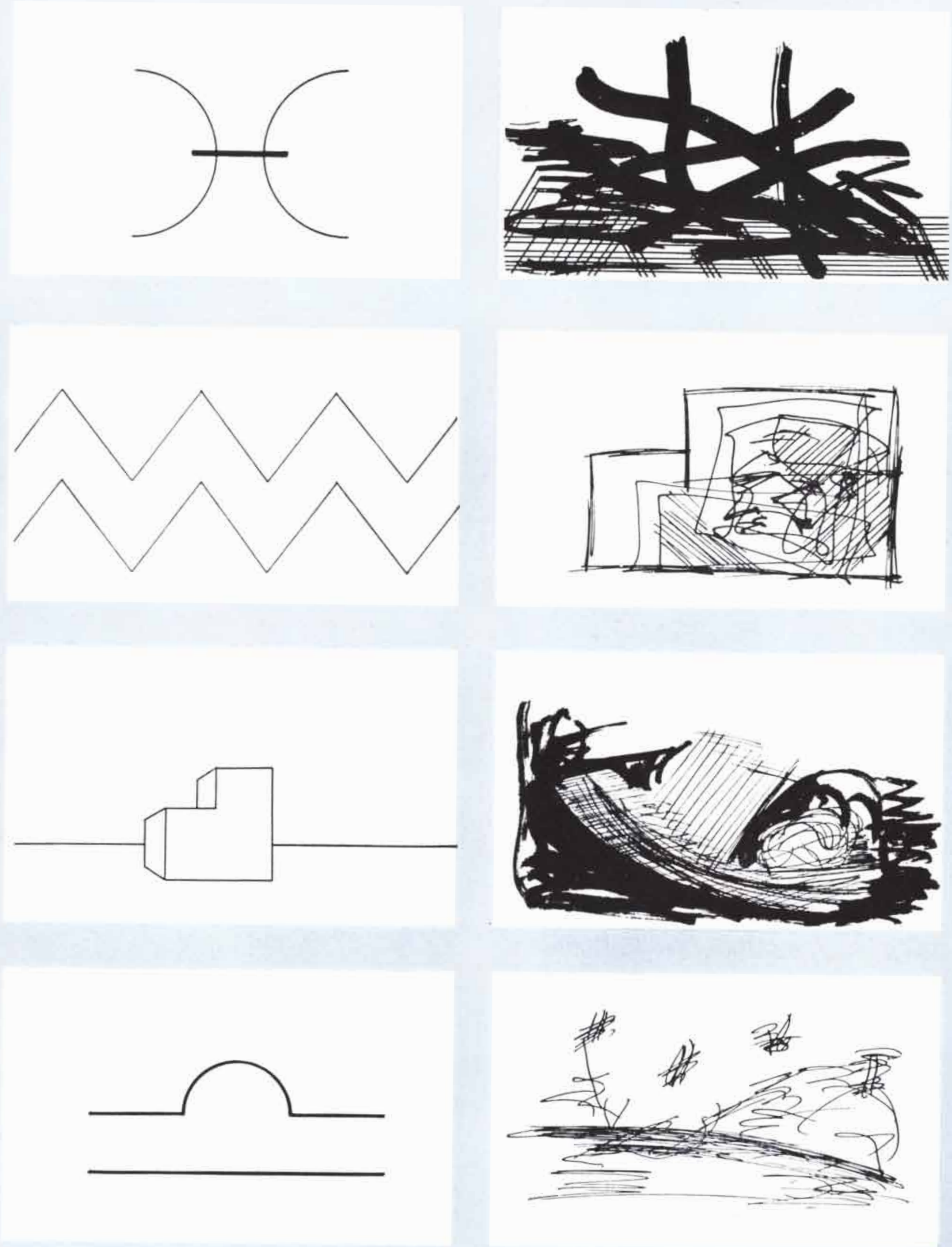


FIGURE PREFERENCE TEST required that subjects express a preference, or lack of preference, for abstract line drawings on cards. Subjects chosen at random tended to prefer drawings such as the four at left; creative subjects, drawings such as the four at right. The drawings are from the Welsh Figure Preference Test, published by the Consulting Psychologists Press of Palo Alto, Calif.

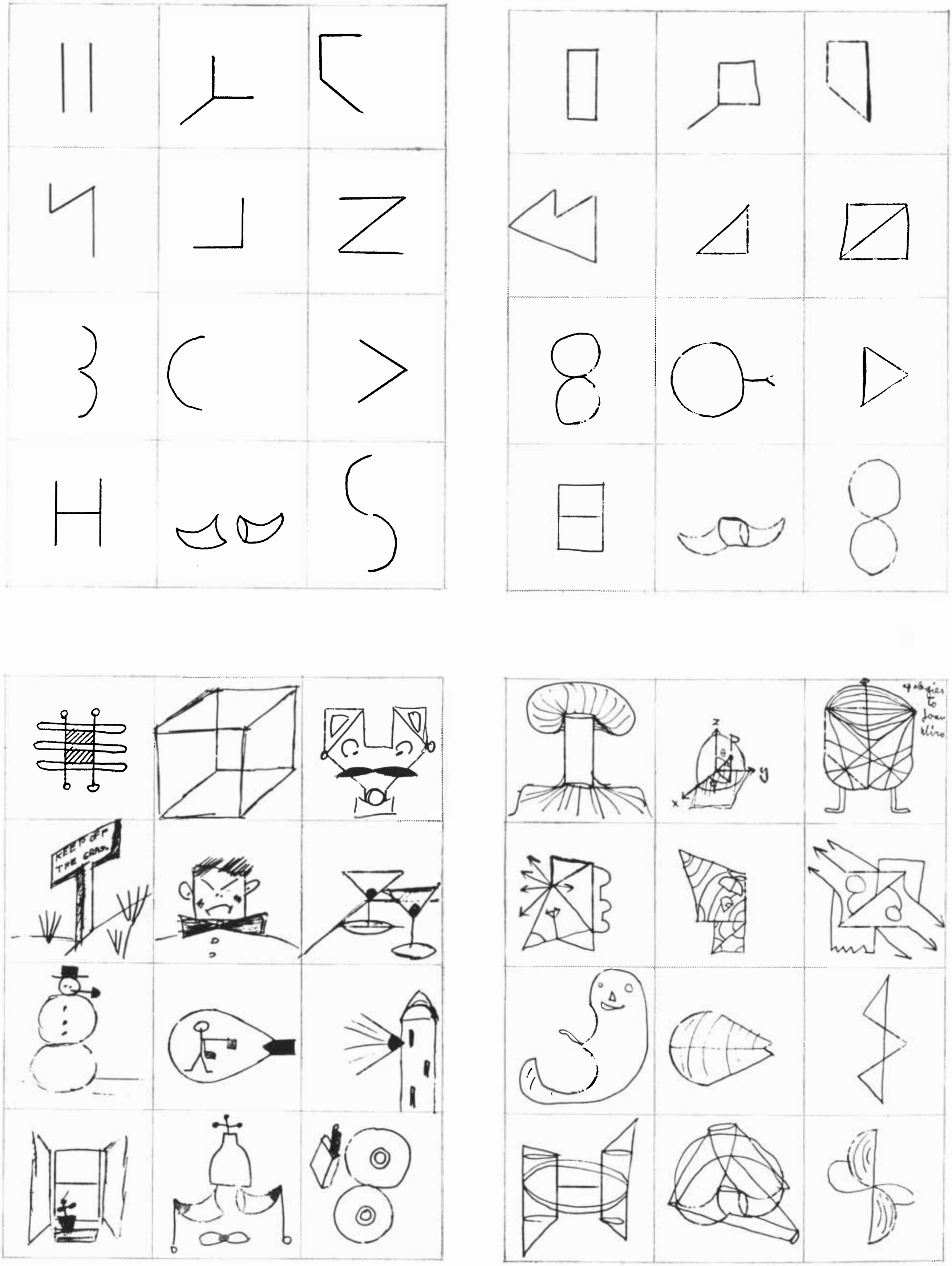
lenge which may be found in apparent disorder provided the focus for an early series of our experimental studies at the Institute. One dictionary definition of disorder links it to such terms as "confusion, neglect of rule, irregularity, disarrangement, tumult and disease." There is little doubt that most people dislike being confronted with disorder. In individuals who turn out original work in science or in art, however, a reversal of the usual attitude may be observed.

My own initial observation of this reversal occurred in a study of esthetic preferences and esthetic expression in individuals whose relative degree of originality could be estimated. The materials used in studying preferences included abstract line drawings, colored reproductions of several hundred famous paintings, architectural designs, and cartoons. In the study of expression we confronted the subject with incomplete drawings which he was to complete as he liked, written images from which he was to construct a poetic metaphor, inkblots of ambiguous form which he was to interpret, colored pasteboard squares from which he could assemble a mosaic of his own design, and stage properties from which he was to create a scene on a miniature stage.

The degree of creativeness of the individuals was estimated on the basis of opinions ventured by their colleagues or by experts in their medium of expression. These estimates we related to their preferences and performance as indicated by our tests. Our purpose was to determine how creative people respond to order and disorder, and whether their response differs from that of others.

To take one example, the abstract line drawings were made in black ink on three-by-five-inch white cards, and they were varied primarily in terms of the degree to which they were drawn according to a geometric principle visible at a glance. The simplest forms were the straight line, the circle, the square and the triangle. Complex polygons presented a somewhat less obvious principle of construction, and arrangements of curves a still less obvious principle. At the other pole from the simple geometrical figures were drawings which appeared to be childish scrawls or totally unarranged scribbles. When we asked the subjects to describe these figures, they applied such words as regular, neat, clean, orderly and static to the simple geometric figures, and such words as irregular, messy, whimsical, dynamic, disorderly and chaotic to figures at the other extreme.

The first group of subjects studied



DRAWING-COMPLETION TEST, devised by Kate Franck, required that subjects elaborate on the simple figures at top left. At top right is a typical response of a subject chosen at random. At bottom left and bottom right are the responses of creative individuals.

with these drawings, which are part of the Welsh Figure Preference Test, were some 80 painters from New York, San Francisco, New Orleans, Chicago and Minneapolis. The painters showed a marked preference for drawings which were complex, asymmetrical and, in their terms, vital or dynamic. They also displayed considerable tolerance for drawings which most people would consider chaotic. In general they expressed what can only be called aversion for the figures which were simple and obviously symmetrical.

We then presented the same drawings to doctoral candidates in some dozen teaching departments, primarily in the faculty of science, at the University of California. The candidates had been separated into two groups, the more original and the less original, on the basis of faculty ratings. We were somewhat surprised to discover that the more original scientists expressed preferences very similar to those of artists.

In preference for paintings, too, the more original subjects were inclined to like best the apparently unbalanced. Impressionism, cubism, abstract expressionism—these were the schools of painting whose products they preferred. What they seemed to like was the work of art which accented some usually unobserved aspect of nature, or which attempted a radical reconstruction of the common-sense world of reality.

The same tendencies were apparent in the tests which require active expression rather than mere preference—the completion of line drawings and the construction of mosaics. Original individuals were disposed to introduce asymmetry and complexity into their drawings and mosaics.

Behind this inclination to like and to construct what is not too simply ordered there appears to be a very strong need to achieve the most difficult and far-reaching ordering. When confronted, for instance, with the Rorschach inkblot test, original individuals insist to a most uncommon degree upon giving an interpretation of the blot which takes account of all details in one comprehensive, synthesizing image. Since some of these blots are quite messy, this disposition to synthesize points up the challenge of disorder. It also illustrates the creative response to disorder, which is to find an elegant new order more satisfying than any that could be evoked by a simpler configuration.

Another psychological trait which is commonly associated with originality of thought is independence of judgment. This trait has been studied experimentally by Solomon Asch at Swarthmore College [see "Opinions and Social Pressure," by Solomon Asch; SCIENTIFIC AMERICAN, November, 1955]. Both in Asch's subjects and in those who took part in a modified version of the Asch experiment in our own studies, a clear relationship has been established between independence of judgment and originality.

Asch's basic procedure has been to place an individual in radical conflict of judgment with other individuals who are understood by him to be possessed of no special information, but who are in fact confederates of the experimenter. The apparent experimental task is to match the length of a given line with one of three other lines which are not equal to one another. The confederates of the experimenter announce their judgments one at a time, and always in the same order. The individual who is not aware of the real nature of the experiment is placed so that he is one of the last to respond. On most of the trials the experimenter's confederates give answers which conform to the length of the lines, but on some trials they consistently give prearranged false answers. The uninformed subject then has a choice of giving the correct answer or contradicting the evidence of his senses and going along with the others.

Asch found a rather disconcerting readiness in his subjects to abandon the evidence of their senses and to bow to the prearranged group consensus. However, about 25 per cent of the subjects in the undergraduate groups he studied were not swayed by the false consensus, but persisted in giving the correct answer. Although Asch was not primarily interested in the personality characteristics of independent and yielding subjects, he made available to me for personality testing a group of 42 subjects who had remained independent and another 42 who had yielded consistently to the false group consensus. Among the opinions expressed significantly more often (in response to a true-false type of questionnaire) by the independent subjects were the following:

1. I like to fool around with new ideas, even if they turn out later to be a total waste of time. (True.)

2. The best theory is the one that has the best practical applications. (False.)

3. Some of my friends think that my ideas are impractical, if not a bit wild. (True.)

4. The unfinished and the imperfect often have greater appeal for me than

COMMON RESPONSES

1. SMUDGES
2. DARK CLOUDS

UNCOMMON RESPONSES

1. MAGNETIZED IRON FILINGS
2. A SMALL BOY AND HIS MOTHER HURRYING ALONG ON A DARK WINDY DAY, TRYING TO GET HOME BEFORE IT RAINS

COMMON RESPONSES

1. AN APE
2. MODERN PAINTING OF A GORILLA

UNCOMMON RESPONSES

1. A BABOON LOOKING AT ITSELF IN A HAND MIRROR
2. RODIN'S "THE THINKER" SHOUTING EUREKA

COMMON RESPONSES

1. AN AFRICAN VOODOO DANCER
2. A CACTUS PLANT

UNCOMMON RESPONSES

1. MEXICAN IN SOMBRERO RUNNING UP A LONG HILL TO ESCAPE FROM RAIN CLOUDS
2. A WORD WRITTEN IN CHINESE

INKBLOT TEST required that subjects describe what they could perceive in formless blots. Sample "common responses" were given by subjects chosen at random; "uncommon responses," by creative subjects. This version of the Rorschach test was devised by Barron.

the completed and the polished. (True.)

5. I must admit that I would find it hard to have for a close friend a person whose manners or appearance made him somewhat repulsive, no matter how brilliant or kind he might be. (False.)

6. A person should not probe too deeply into his own and other people's feelings, but take things as they are. (False.)

7. Young people sometimes get rebellious ideas, but as they grow up they ought to get over them and settle down. (False.)

8. Perfect balance is the essence of all good composition. (False.)

These results suggested that the subjects who remained independent were more open to innovation and to the challenge presented by apparent imbalance and imperfection on the surface of things. In addition, when using a self-rating scale which included among other traits that of "originality," the more independent subjects described themselves much more frequently as original than did the yielders. (While at first this might seem immodest, it must be remembered that in the presence of a psychological questionnaire one can feel quite alone.)

In any event, the results suggested the possibility of establishing by experiment that independence of judgment is associated with originality. The relationship has been shown directly by using in conjunction with a modified version of the Asch experiment a set of psychological tests which measure originality. These tests, a number of which have been developed by J. P. Guilford and his associates at the University of Southern California, are designed to elicit novel responses and unusual solutions to problems. While the actual test questions cannot be given here, some idea of their nature may be conveyed with substitute examples. In one such test the subject is given the names of common objects (such as wheelbarrow, light bulb, piano) and asked to suggest unusual uses to which these objects may be put. In another test he is asked to suggest consequences of highly improbable events (*e.g.*, all human beings have suddenly become deaf; an unexplained genetic alteration will result in an average decrease of two feet in stature in the next

STIMULUS IMAGE	COMMON RESPONSES	UNCOMMON RESPONSES
EMPTY BOOKCASES	1. AN EMPTY MIND	1. THE VACANT EYES OF AN IDIOT
	2. A DESERTED ROOM	2. AN ABANDONED BEEHIVE
SITTING ALONE IN A DARK ROOM	1. LYING AWAKE AT NIGHT	1. ONE LETTER IN A MAILBOX
	2. A BEAR IN A CAVE	2. A COFFIN IN AN OPEN GRAVE
SOUND OF A FOGHORN	1. A BELCH	1. THE CRY OF DESPAIR OF A GREAT UNSEEN ANIMAL
	2. A FROG'S CROAK	2. A PUBLIC ADDRESS SYSTEM ANNOUNCING DISASTER

SYMBOL-EQUIVALENCE TEST requires that subjects respond to a "stimulus image" presented by experimenter. Common and uncommon responses are listed at center and right.

generation; one nation in the world has found a way to raise its average I.Q. by 50 points). Other tests include anagrams (scored for rarity of proposed solutions), inkblots (scored for unusual interpretation), pictures of dramatic situations which serve as the starting point for storytelling (rated for originality), and plot situations for which titles are to be constructed (rated for cleverness). Judging by our results so far, individuals who regularly perform in an original manner on these tests are also independent in judgment when put under pressure to conform to a group opinion which is in conflict with their own.

Independence of judgment is linked not only to originality but also to the generalized preference for asymmetry, apparent imbalance and complexity described earlier. Subjects of the original Asch experiment were given the figure-preference test, and to a marked degree the independents preferred complex, asymmetrical figures. This makes sense, since in order to maintain his independence in the experiment the subject must come to terms with the troublesome fact that he is suddenly at odds with his fellows in a situation where, by ordinary standards of community of experience, he ought to be in agreement with them. Only a person who can live with complexity and contradiction, and who has some confidence that order lies behind what appears to be confusion, would be able to bear this kind of discord. There is a strong temptation to resolve the confusion and to end the pain of contradiction in a simple way, by denying the facts that conflict with the consensus. Order is thus achieved by a process of exclusion of evidence, and, in this instance, at the cost of correct judgment.

The relationship of creativity to psychological health and to peace of mind and body has long been argued. It was my pleasure recently to participate in a conference on the goals of psychotherapy, in which a number of extremely amiable psychoanalysts, psychiatrists and psychologists found themselves in considerable agreement about the goals of therapy, and, by implication, about the characteristics of a psychologically healthy human being. The traits most commonly mentioned as indicating a state of psychological health were: (1) accuracy of perception of reality, (2) stable body functioning and freedom from psychosomatic disorders, (3) absence of hostility and anxiety, (4) capacity for friendly and cooperative relations with other people, (5) spon-

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External leakage	*None*
Proof Pressure	*4500 psi*
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TEST WORD	GENERATION
COMMON SOLUTIONS	NATION RATE GENE
UNCOMMON SOLUTIONS	ONAGER ARGENTINE ERGOT

ANAGRAM TEST required that subjects find other words in a test word. They could rearrange the letters in the test word.

taneity and warmth, (6) social responsibility. An excellent combination, I said to myself. However, as I continued to listen in comfort and mild edification, I suddenly realized that my thoughts had drifted off to a description I had recently read of Robert Hooke, the brilliant 17th-century scientist whose achievements place him second only to Newton among his contemporaries, and whose prolific originality in experimentation has remained unsurpassed. Hooke suffered throughout his life from severe headaches, from indigestion so troublesome that he noted gratefully in his journals any meal that happened to agree with him, from giddiness and insomnia, and from fearful dreams during the few hours a day he was able to sleep.

Images of other figures drifted through my mind: of the apocalyptic rages of Beethoven, the savage indignation of Jonathan Swift, the terrible loneliness of van Gogh, the criminality of Rimbaud, the shameless preenings of Baudelaire, the stoical despair of Emily Brontë, the excruciating physical and spiritual pain endured by Heine. I felt distinctly uneasy; could it be that these creative people had been in need of psychotherapy?

Certainly one difference between them and the perfect product of psychotherapy and the happy life was that they did not *manage themselves* very well. I began to feel that some of the ideals we had been discussing were rather mechanical. The correct perception of reality, in the superficial sense of the term, began to lose its charm. The ideal of adaptation suggested a well-adjusted, frictionless machine, tended in genial fashion by a little mechanic known as the strong ego, or the self-esteemed self, or the voice of reason. I had heard warmth mentioned, but not heat; spontaneity, but not passion. No one had spoken of willfulness, fierce self-assertion, hatred of an established order. These are often the stamp of the creator, and, if adaptation and maturity in human relations are the essentials of psychological health, then the creative genius is frequently not healthy.

But one cannot readily abandon the idea that to create is in some sense—perhaps in the best sense—to be healthy in mind. Yet how can the maladjustment of many great creative minds be reconciled with the assertion that they are in some respects unusually healthy?

Perhaps some light is thrown on the matter by our finding that creative individuals are more at home with complexity and apparent disorder than other people are. In the evolutionary sense, the most advanced adaptation of the human organism is the faculty of conscious attention. This faculty subsumes discrimination, memory, reflection, judgment in the service of prediction—we have come to call it the ego. We associate the ego with order; the unconscious with disorder. Turbulence and instability characterize the organization of ideas and impulses which are outside conscious attention. The creative individual, in his generalized preference for apparent disorder, turns to the dimly realized life of the unconscious, and is likely to have more than the usual amount of respect for the forces of the irrational in himself and in others.

This respect consists in a faith that the irrational itself will generate some ordering principle if it is permitted expression and admitted to conscious scrutiny. To put the matter more strongly, I believe that the creative individual not only respects the irrational in himself, but courts it as the most promising source of novelty in his own thought. He rejects the demand of society that he should shun in himself the primitive, the uncultured, the naive, the magical, the nonsensical; that he must be a "civilized" member of the community. Creative individuals reject this demand because they want to own themselves totally, and because they perceive a shortsightedness in the claim of society that all its members should adapt themselves to a norm for a given time and place.

When an individual thinks in ways which are customarily tabooed, his fellows may regard him as mentally unbalanced. In my view this kind of imbalance is more likely to be healthy than unhealthy. The truly creative individual stands ready to abandon old classifications and to acknowledge that life, particularly his own unique life, is rich with new possibilities. To him, disorder offers the potentiality of order.

I would propose the following statements as descriptive of creative artists, and perhaps also of creative scientists:

Creative people are especially observant, and they value accurate observation (telling themselves the truth) more than other people do.

They often express part-truths, but this they do vividly; the part they express is the generally unrecognized; by displacement of accent and apparent disproportion in statement they seek to point to the usually unobserved.

They see things as others do, but also as others do not.

They are thus independent in their cognition, and they also value clearer cognition. They will suffer great personal pain to testify correctly.

They are motivated to this value and to the exercise of this talent (independent, sharp observation) both for reasons of self-preservation and in the interest of human culture and its future.

They are born with greater brain capacity; they have more ability to hold many ideas at once, and to compare more ideas with one another—hence to make a richer synthesis.

In addition to unusual endowment in terms of cognitive ability, they are by constitution more vigorous and have available to them an exceptional fund of psychic and physical energy.

Their universe is thus more complex, and in addition they usually lead more complex lives, seeking tension in the interest of the pleasure they obtain upon its discharge.

They have more contact than most people do with the life of the unconscious—with fantasy, reverie, the world of imagination.

They have exceptionally broad and flexible awareness of themselves. The self is strongest when it can regress (admit primitive fantasies, naive ideas, tabooed impulses into consciousness and behavior), and yet return to a high degree of rationality and self-criticism. The creative person is both more primitive and more cultured, more destructive and more constructive, crazier and saner, than the average person.

When the distinction between subject (self) and object is most secure, the distinction can with most security be allowed to disappear for a time (as in mysticism and in deep love). This is based on true sympathy with the not-

self, or with the opposite of those things which comprise defensive self-definition. The strong self realizes that it can afford to allow regression, because it is secure in the knowledge that it can correct itself.

The objective freedom of the individual is at a maximum when this capacity exists, and creative potential is directly a function of freedom.

Among the creative people my colleagues and I have studied during the past years has been a group of writers of considerable distinction. We were not surprised to encounter rather spirited objections from some of the writers whom we decided to ask to make a contribution to the study. In trenchant and not particularly orderly prose, about a fifth of those who responded to our initial letter pointed out the intrinsically evil character of psychological research. The objections to such research are mainly on these counts: it is vivisection; it is an expression of the effort of organized society to encroach upon the individual and rob him of his freedom; it is presumptuous because it seeks to describe and to understand what is intrinsically a mystery. Psychological diagnosis is, moreover, a form of name-calling; it is a way of having the last word; it does not respect the individual. Finally it is the present seeking to impose itself upon the future and to perpetuate the *status quo* through techniques which will identify the potentially constructive deviant and permit a stultifying society to control him.

Since psychological research at its worst may indeed be destructive in just such ways, socially responsible psychologists have reason to sleep almost as uneasily as socially responsible physicists. This particular study has proceeded in recognition of some of the dangers which may be inherent in it, and it has been able to proceed because most of the creative writers who have been asked to participate have been willing to trust the investigators and to accept the inevitable hazards of all efforts at increasing knowledge. Both scientists and artists have something to fear when they embark upon the unknown. In his *Life of William Blake* Alexander Gilchrist records three lines from Samuel Palmer's account of a conversation with Blake about the latter's designs for Dante's *Inferno:*

"He said he began them with fear and trembling.

"I said, 'Oh, *I* have enough of fear and trembling.'

" 'Then,' said he, 'you'll do.' "

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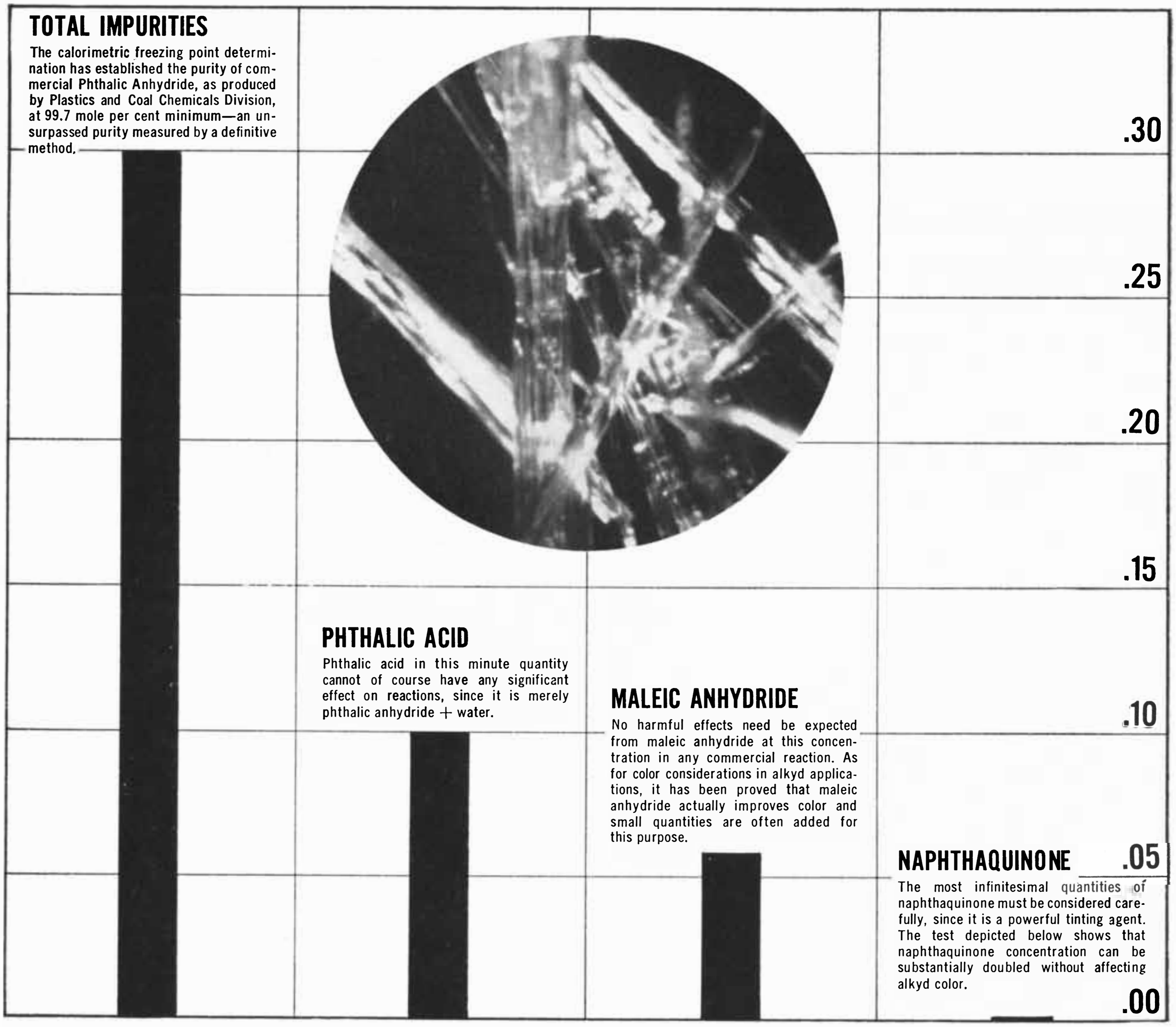
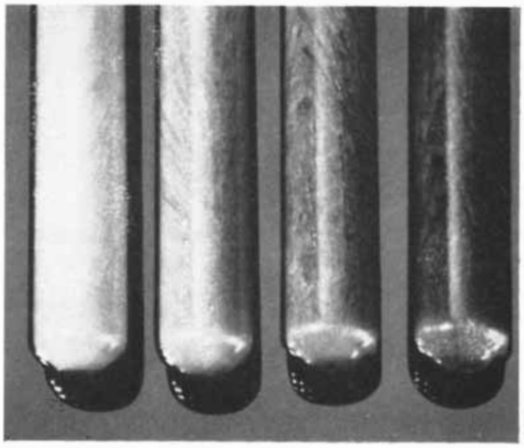
The Threshold of Purity



The vertical black bars indicate the mole percentages of certain impurities in Phthalic Anhydride of Plastics and Coal Chemicals Division. Notes above each bar describe the tolerance of alkyd resins with respect to that impurity. Thus the chart defines the threshold of purity and proves that this Phthalic Anhydride surpasses it.



The impurity naphthaquinone has been studied carefully because of its deleterious effect on phthalic color. In the table below and the corresponding molten color samples in photograph at left, you see the progressive deterioration of color as naphthaquinone concentrations are increased.

Naphthaquinone Wt. % based on Phthalic Anhydride	*Alkyd Resin Color* (Hellige)	*Molten Color* (Hazen)
0	6	10
0.001	6	25-50
0.01	10	100
0.1	12	300-350

When known concentration of naphthaquinone in our Phthalic Anhydride is substantially doubled (underlined figures), Alkyd Resin Color remains unchanged. Continuing tests of this kind have proved that our manufacturing controls keep naphthaquinone concentrations well below any harmful level.

in Phthalic Anhydride

One by one, the laboratories of the Plastics and Coal Chemicals Division have tracked down the impurities in commercial phthalic anhydride, seeking the limits at which these impurities have no effect on processes and end products. This set of limits may be called the threshold of purity, defined for phthalic anhydride in the chart at left. The fact that our Phthalic Anhydride is kept consistently above the threshold is one of vital significance to producers of alkyd resins, plasticizers and other phthalic derivatives.

The quest for chemical purity has been going on since the days of alchemy. Yet, the more we learn about purification, and the inevitable contamination that goes with it, the more we realize that absolute purity is attainable only in theory.

In the chemical industry, what we seek is effective purity. In some cases, impurities may assist rather than hinder. But in general, the aim of the chemical producer is to reduce impurities to the point of no effect. Attaining this for a particular chemical in a particular application, we may say we have passed the threshold of purity.

The problem comes into focus

The laboratories of the Plastics and Coal Chemicals Division have spent years divining the subtleties that make up the threshold of purity in phthalic anhydride. They have concentrated on phthalic anhydride in alkyd resins, an application where phthalic purity is thought to be related to color and other properties of the resin produced.

To begin with, the research group had to develop an effective method for measuring phthalic purity. The ideal method was found in the calorimetric freezing point determination. It involves the extrapolation of freezing points of an increasingly pure material to arrive at the freezing point of 100 per cent pure material. This becomes the standard of purity. Phthalic samples can be compared with it and their purity determined with new accuracy.

Using this method, the purity of our Phthalic Anhydride (commercial specification) has been established at 99.7 mole per cent minimum.

At last—a definition of purity

With the problem of measuring total impurities cleared up, the laboratories were ready to consider the color performance of phthalic anhydride in alkyd resins. Some of the questions they asked: What level of purity is needed to produce alkyd resins of good color? Are certain impurities more damaging than others? And most important, what are the precise requirements for maintaining commercial phthalic beyond the threshold of purity with respect to alkyd resin production?

They found the answers documented in the chart at left. Alkyd manufacturers may look there for the definition of the threshold of purity in phthalic anhydride—and for proof that our Phthalic fulfills every part of it.

A sharp eye on output

While our researchers have been busy defining the purity of phthalic anhydride, our manufacturing plants have been living up to the definition. Production samples from four different plants are closely checked for conformity in a central laboratory. Here our technical vigilantes pass judgment on the purity and uniformity of the collective phthalic output.

In developing this strict purity definition and abiding by it, Plastics and Coal Chemicals Division has taken the old-time menace out of trace contamination in phthalic anhydride. The *threshold of purity* concept opens a new age of confidence for the phthalic user, giving him every assurance of ideal kettle performance that our technology can muster.

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THE ENCOURAGEMENT OF SCIENCE

What can be done to promote innovation? Money is not enough. Science is most likely to flourish in a society which not only educates its members but also gives free rein to the curiosity of the individual

by Warren Weaver

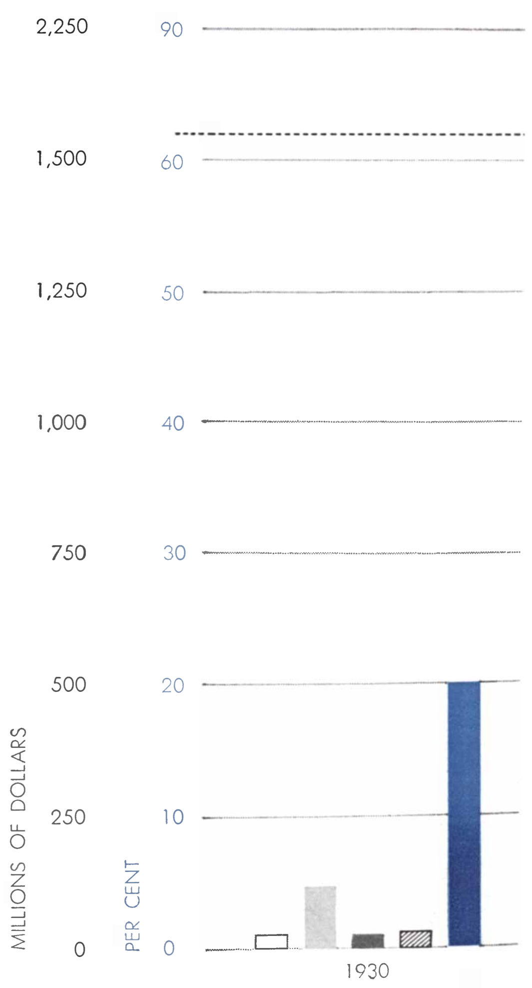
Mathematicians once needed only paper, pencil and a quiet corner; now they use electronic computers which cost almost as many dollars as the digits they can handle. Physicists recall nostalgically the day when they put together their experimental apparatus with "love and string and sealing wax"; to work on the present frontier of their science they need accelerators that cost a hundred million dollars to construct and several million a year to support. Biologists used to need a bottle, some alcohol and an optical microscope; today they must have electron microscopes, ultracentrifuges and other expensive precision devices, and must be furnished with rare chemicals, radioisotopes and thousands of experimental animals.

During the past 25 years science has become an immensely costly activity. In addition to the formidable instrumentation of conventional laboratories, science now needs specialized balloons, aircraft and rockets to explore the skies, research ships with elaborate mechanisms for sampling the deep waters and the solid floor of the sea, and whole scientific villages brought in by air to the remote places of the Arctic and Antarctic. And the cost goes on rising with the steady growth of demand for more supplies, more equipment, more auxiliary technical personnel, more publication, more travel. No branch of science can keep up with the pace unless money is made available in increasing sums.

On the whole, it seems, the U. S. has met the rising cost of science. Since 1930 this country has multiplied its annual expenditure on research and development some 25 to 30 times to the current rate of more than $5 billion [*see chart on these two pages*]. But money is not enough. We must not fall into the perilous error of supposing we have done all we need to do for the encouragement of science once we have made an appropriation. As the preceding articles in this issue of SCIENTIFIC AMERICAN effectively remind us, the work of science is not done by accelerators, telescopes, microscopes and the other things that money buys, but by men and women—highly trained individuals of high intelligence, integrity, imagination and dedication. These persons require something more than physical facilities. They cannot be truly effective unless they live and work in a climate which favors the creative process.

Our task here is to consider how we as a nation may provide the circumstances which encourage the sound and creative development of science. We shall see that this question involves a triangular relationship, with our government at one corner, our universities at the other and the public—meaning all of us—at the third.

A century and a half ago Thomas Jefferson had the floors of entire rooms in the White House strewn with the bones of prehistoric animals. It is a proud tradition of our government, from its earliest years, that holds the pursuit of science to be an essential activity of a free society. Within its own house the Federal Government has long supported research related to its established functions. The fruitful movement in agricultural research set in motion with



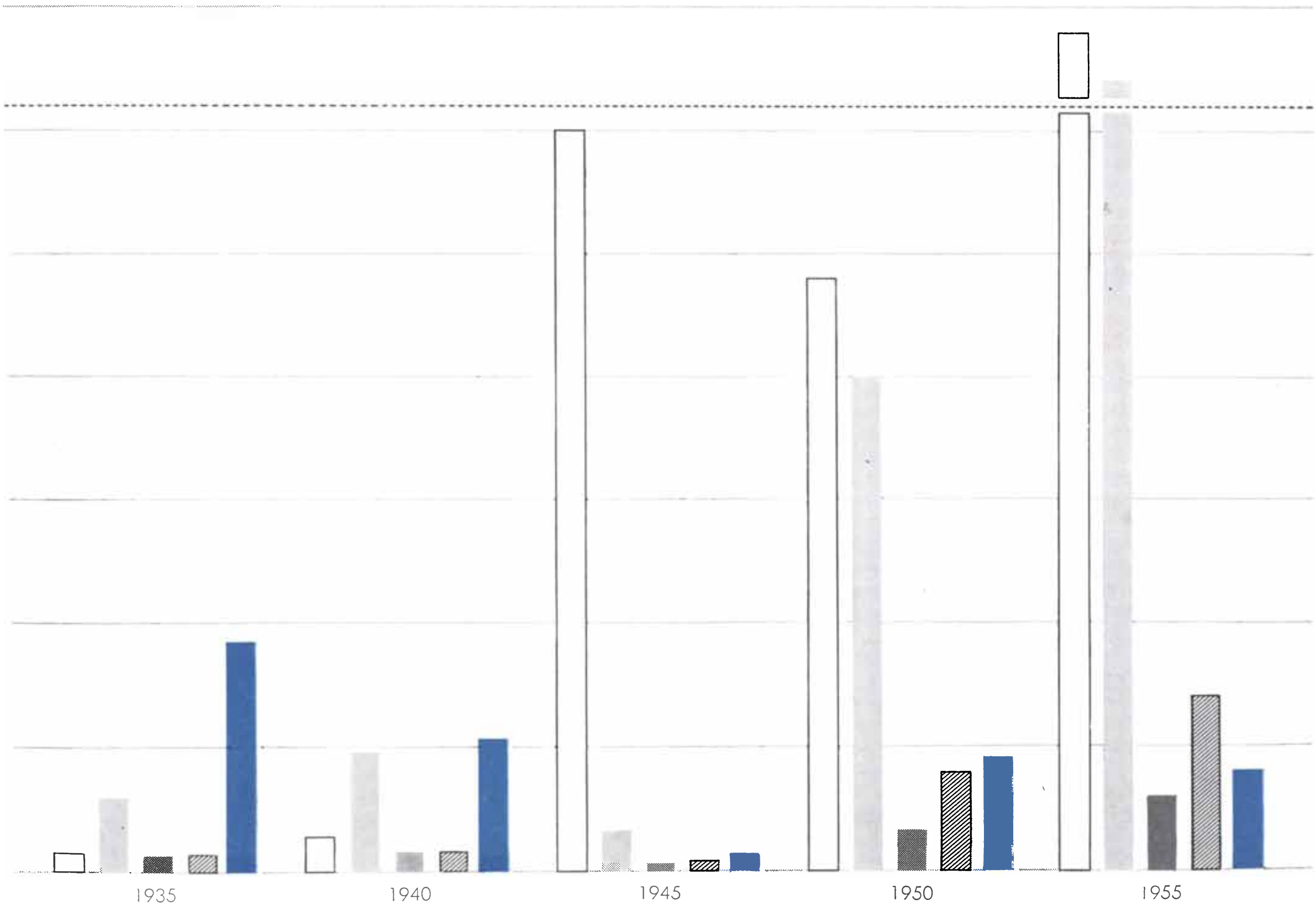
FINANCIAL SUPPORT of research and development in this country during the past 25 years is analyzed by principal sources of funds (*see key*). Total expenditure has multiplied the founding of the land-grant colleges provides today a model demonstration of the way federal aid can stimulate local enterprise under conditions that protect, in large measure, local enthusiasms and local freedoms. But it was not until World War II, and the revelation of the national necessity for a more vigorous development, that money really began to flow from Washington into the science laboratories of our universities.

There was never any choice in the matter: the Federal Government is the only institution in our society that commands funds equal to the needs of modern science. The income that used to support science in our universities—from endowment, grants, gifts and tuition—has multiplied several times over prewar levels. Yet today it contributes a junior 30 per cent to the university research budget; the Federal Government supplies virtually all the rest.

We need not here go into the arithmetic of the growth of the granting programs set up by such agencies as the Department of Defense, the Atomic Energy Commission, the National Institutes of Health and the National Science Foundation. It is important, however, to maintain the perspective of recent history as we examine the federal program for the support of science. From a modest but independent existence, supported by a plurality of patrons, science has moved into a state of dependence upon the single giant patron that is capable of financing its hugely expanding operations. If I now offer adverse criticism, it is only fair to recall that this transition has been sudden as well as profound. Without question, federal support has been decently and unselfishly administered; by and large, it has done a vast amount of good. But we must face nonetheless squarely the fact that we have yet to invent the institutions and procedures necessary to make governmental support fully compatible with the nature of science as a creative activity.

Of course no matter how inventive our legislation, the quality of the federal support of science will always be profoundly affected by the quality of the personnel who administer it. The intellectual leadership must, of course, be supplied by scientists. Yet it is difficult to persuade really first-rate persons to make careers out of this kind of government service. The administration of any one of the large federal programs, furthermore, involves problems of law, business, politics and public relations, hitherto foreign to the experience of scientists. Until we learn to accord this work appropriate pay and status, we cannot expect it to attract and hold persons of top ability. Scientists must share the blame for the low prestige of this sort of service to science. It is symbolic of their attitude that the National Academy of Sciences has no membership section which recognizes administrative statesmanship.

At present the lack of a sufficient number of really qualified individuals—together with lack of sufficient funds for travel—ties the administrators of govern-



25 to 30 times. Government and industry have supplied most of the increase, principally for military and hence applied research. The expenditure for basic research has multiplied only 10 times and has declined from 20 to less than 10 per cent of the national expenditure.

ment granting programs to their chairs in Washington, where they do their work looking at sheets of paper or listening to panel reports. They ought to be in the field, sitting down on stools in laboratories, talking directly with the scientists who are asking for funds. One who has spent many years in this kind of direct contact knows that paper evidence, even in multiple copies, is very difficult to judge.

Perhaps the primary difficulty for the administrators and recipients of governmental support is created by federal fiscal procedures. Presumably they are sound and important to the long-established activities of the Government, but they pose difficulties for the new agencies set up to stimulate and support science. Take the federal budgeting procedure: Some two or more years in advance, an agency must submit a statement of future requirements, solemnly and earnestly pretending that it knows what it is going to need; if two or more years later the agency actually gets what it has asked for, then obviously that agency must proceed to need what it has got, no matter how circumstances may have changed. This arrangement seriously hampers the programming of such major capital items as high-energy accelerators and astronomical observatories; physicists can tell what kind of accelerator they need now, but find it hard to predict the specifications for the ideal machine of three years hence. In the case of the National Science Foundation, the lag makes it difficult to respond to situations that call for a radical change in research appropriation.

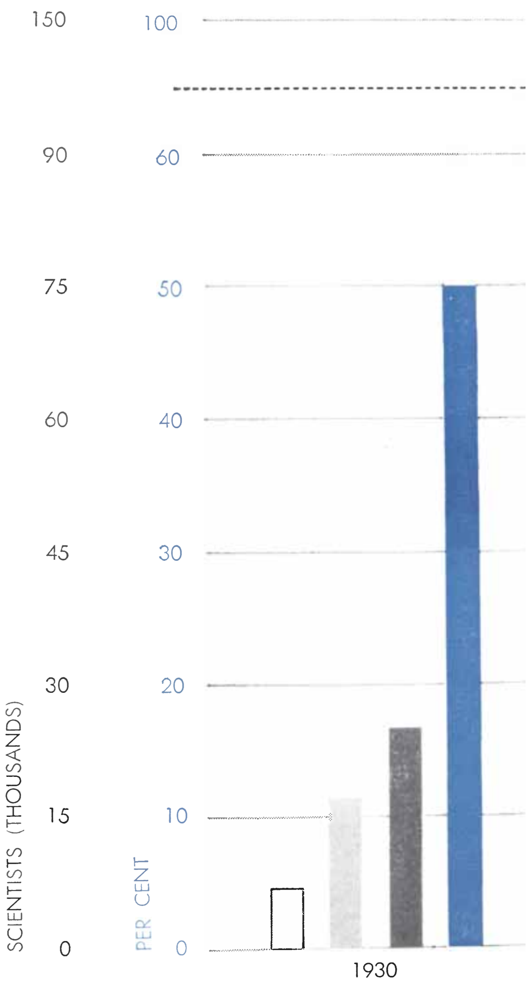
Such regulations work even greater hardship on the recipients of federal support. Worthwhile work in science is usually a scientist's lifework; ideally it should be assured something like lifetime support. It is difficult to reconcile this need for security with the uncertainty inherent in politically influenced annual appropriations. The British handle this far better than we do; every five years Parliament makes a no-questions-asked appropriation to the University Grants Committee, a body representing the country's universities which administers all governmental support for higher education and research. Some way must be found in our country to give similar stability to the funds which the Government devotes to science. It has been suggested that a small percentage of a five-year running average of the gross national product be fixed as the basis for the annual appropriation to science; such a sum would have the necessary stability and would still be responsive to major economic changes.

The Civil Service regulations, prescribing tables of organization and salary scales, constitute another handicap. Often these limitations are removed by setting up contract projects, which are then so free relative to salary ranges that the project organizations can proceed to raid university faculties. But the basic government operations are bound to stay within Civil Service. I know of one program, now on paper, which may be divided into two programs. The scientists involved view this bifurcation as unfortunate. Under Civil Service regulations, however, each of the two new programs would rate an officer of the top salary grade, each of them in charge of, say, two of the next to the highest grade, and so on down the line, upgrading the salary scale all the way, in accordance with the law of bureaucratic hierarchy propounded by C. Northcote Parkinson.

Problems of a different order have been created by the fact that more than half of the federal research and development funds expended via our universities has been supplied by the defense agencies. Naturally the overwhelming bulk of these defense funds has been used to seek immediate practical objectives, not the long-term ends of basic research. This has raised questions that deeply trouble the conscience of university administrators. As a result, some persons now deem it improper and undesirable for the Department of Defense to give any aid to basic research. I do not agree. A defense department surely ought to aid basic research in fields reasonably related to its mission (for example, the Navy can appropriately support theoretical hydrodynamics); since it is difficult to predict the relevance of a fundamental investigation, the military should also be allowed to foster some modest program in indirectly related fields. The national interest requires, furthermore, that a reasonable proportion of scientists, pure as well as applied, be acquainted with the personnel and the problems of national defense. Finally, support for pure science from the various defense agencies seems desirable to me if only to multiply and diversify the sources of support.

The crucial word diversify is at the heart of the dependence of science upon the Government. There are those who think that the National Science Foundation ought to sit, like an infinitely wise spider, at the center of a web which reaches into every governmental activity in science and presumably into every other scientific activity in our whole nation, planning just how science should advance, tightening up here, slackening off there. I do not think that many scientists hold this view. There is no person, and certainly no committee, which is wise enough to do this.

We should, I believe, be glad that this is so. For what keeps the total scientific effort from being chaotic and meaning-



EMPLOYMENT OF SCIENTISTS in this country during the past 25 years is here analyzed as among the three major employers (*see key*). The number employed has multiplied five

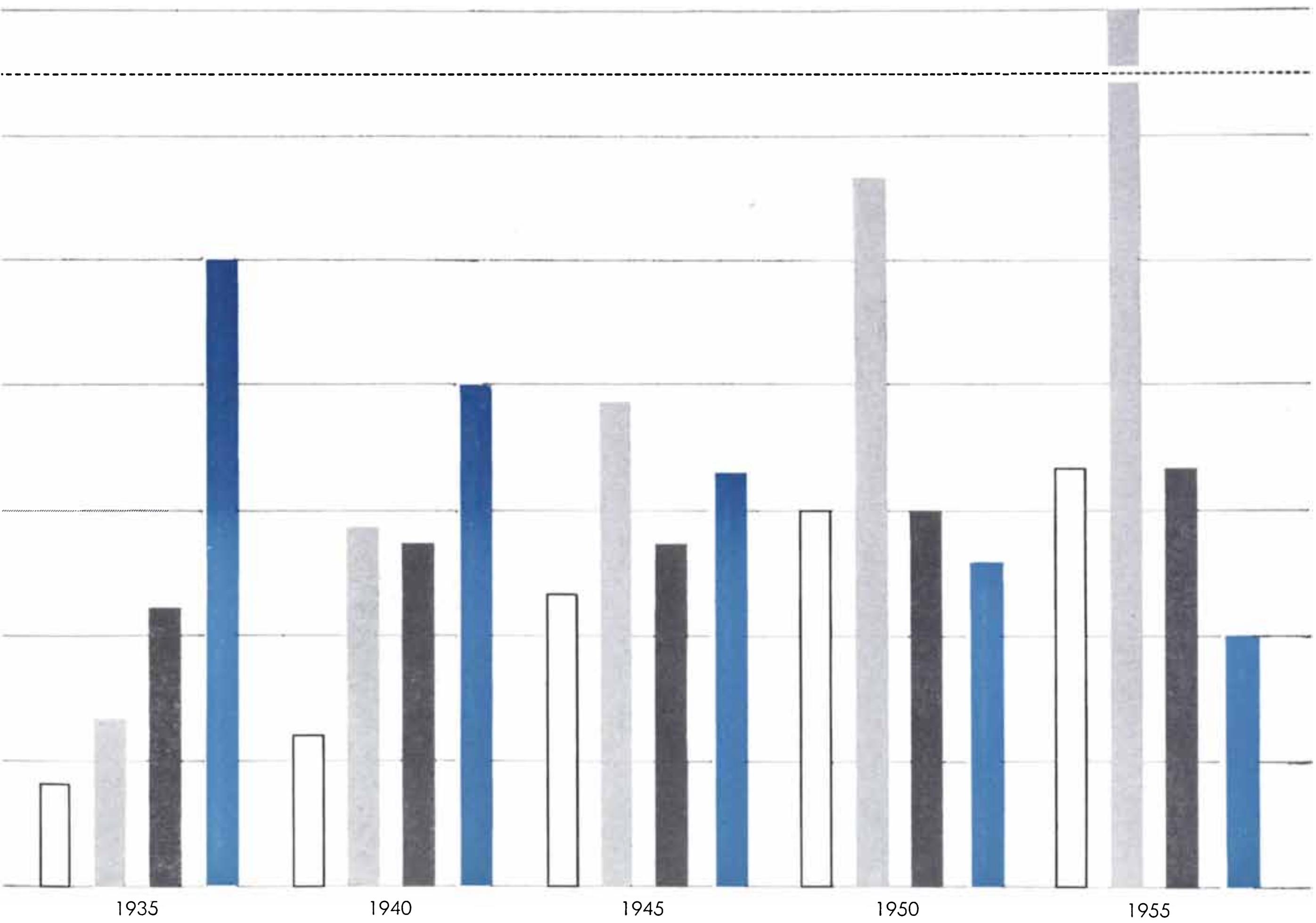
less is not central planning or any attempt to achieve it, but a kind of grand intellectual homeostasis, under which a multitude of influences interact in a natural way. What science needs is not a lot of planning, but a lot of convenient communication, so that controls may arise naturally from feedback.

Even in individual scientific efforts it is easy to overdo planning. One should of course plan to have space and supplies and equipment. But at the really significant levels, planning is not very effective. I was once present, many years ago, at a meeting of a board of trustees to which was proposed a rather flexible long-term grant in support of the general program of a first-rate scientist. After the necessarily broad presentation of the program, one of the trustees, an outstanding business leader, said: "I am afraid I don't know just exactly what this man proposes to do if he gets the grant." The question was answered by another trustee, a scientist: "Why, if he knew just what he was going to do, he wouldn't need to do it!"

It is my conviction that no one man, no one group, no one agency of government or of society, is wise enough, imaginative enough, or broad enough usefully to dominate national decision about the support of science. Hence it seems essential to preserve a diversity—a wide diversity—of agencies. As government outlays increase in magnitude, our society should make every countereffort to balance things up by retaining all the private sources, creating new and different foundations, stimulating such local agencies as state and municipal governments, developing aid from industry, and in every ingenious way preserving the local independence, the unregulated freedom and above all the flexible diversity which are such proud characteristics of our national life.

Whatever the volume and sources of support, we must in the end look to our universities for the imagination and wisdom that will secure the maximum benefit to science. It used to be considered obvious that basic research was the business of a university, in the noncommercial sense that professors received a modest but decent chance to live, and that they repaid society by the combined service of teaching and research. Back in my professorial days, 30 years ago, professors considered that society was giving them a marvelous privilege: the opportunity to earn a living by doing what they most wanted to do. It was, moreover, an essential and wonderful part of this arrangement that the decision as to what research they did was left to the free choice of the individual professors.

Nowadays research continues to be the business of universities, but there is a real danger that the word business has taken on connotations that are not appropriate to institutions of learning. The basic support of universities is so inadequate that there is an almost irresistible temptation in large-scale research contracts which pay substantial overhead



times. By far the largest increase is in industry, where scientists are employed by governmental as well as industrial funds; most of these scientists are engaged in applied research. The percentage of scientists employed by universities has declined steeply.

Peace and quiet and time to think: Albert Einstein at Schwielow See, Germany, in the summer of 1930 sums to the general coffers of the university. This source of revenue has become so important that certain universities have appointed special officials with titles like Coordinator of Research and Vice President in Charge of Research. They assist scholars to prepare applications for grants, negotiate with the granting agencies and, to put the matter bluntly, solicit business.

At some universities, when government-supported programs have become really large, the administration has had to decide that their size and often their involvement in military security would put the university out of balance. They have met this problem by setting up off-campus research institutes. But this stratagem raises even more sharply the question of what the basic purpose of a university really is.

Worst of all, in its ultimate effect on free scholarship, is the way individual scientists are forced to lose sight of their basic purpose. We have been permitting our universities to develop an atmosphere which encourages scientists to cook up projects which will fit into someone else's ideas of what is worthy of support. Bit by subtle bit and doubtless often unconsciously, scientists find themselves compelled to ask: "What sort of an application had I better make, to maximize my chances of a favorable reply?"

University salaries are so poor that it has become necessary—disgracefully necessary—for professors to supplement their incomes by summer earnings. To balance the family budget many a professor now works up a summertime research project. This provides economic relief; the project may even be good scientifically. But one is bound to think, rather wistfully, of the days when professors spent most of their summers reading and thinking.

Plainly our society has not yet evolved a satisfactory way of fostering creative scholarship. Our universities stand in desperate need of an ample expansion of financial support, buffered from political influence, protected against sudden and unpredictable variation in magnitude, and free from the restraints of detailed specification and accounting that would limit flexible and independent adjustment to changing circumstances. I do not think there is any single solution. In my judgment support should come from a wide variety of sources—individual friends, alumni, industrial corporations, foundations and so on, including, if you like, a cut on the total take from racetracks, sports attendance, cigarette and liquor consumption, or whatever. A very large number of relatively small gifts, coming from a wide variety of sources, would produce a total with the necessary degree of actuarial stability.

The Federal Government will almost certainly have to provide a substantial part of any expanded support for our universities. We may hope that our national leaders will be wise and ingenious enough to develop a scheme which will be better even than that used in Britain. Meanwhile the various government agencies should move still further (much progress has been made) in the direction of longer, broader and more flexible grants to scientists. Grants should be based more upon the general capacity and dedication of the applicant than upon project specifications, and influenced more heavily by evidence of imagination and curiosity than by conformity to standard procedures.

This brings us to the third corner of our triangle—to us. It is easy enough to spell out fiscal solutions. It is more difficult to realize them in actuality. What all of my recommendations imply is something more significant to the encouragement of science: a change in the climate that surrounds science in our country.

That climate is, at the moment, confused and disturbed. A fear-inspired willingness in some quarters would unbalance our culture by recruiting and training vast numbers of scientists and technological experts. With a disturbing overconfidence in our ability to assess the aptitudes and abilities of our children, some would reach into the early high-school years and attempt to purchase dedication to science through long-continued scholarships. As a nation we appear willing to wager millions in almost any sort of attempt to avoid being "beaten" in assumed scientific races with the Russians, to spend astronomical sums, for example, to put the first splash on the face of the moon. But we have not yet advanced to the point where an assistant professor of, let us say, dermatology, who really wishes to have a career of research in this vexatious and stubborn field, can get an academic salary large enough so that he can look forward to educating his children and leading a quiet, reasonably comfortable and thoughtful life.

Large numbers of the public, the polls tell us, regard a scientist as an unselfish saint if he wears a white coat and has a stethoscope, a magician if he is looking intently into a test tube which glows in the dark, and a potentially menacing

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creature if he is manipulating the controls of a nuclear reactor. As a nation we demand science, but we both overestimate and underestimate it. We continue wrongly to identify science and technology, and we largely fail to recognize that the most important aspect of science is that it gives to man a beautiful, rich and deep understanding of the world in which he lives.

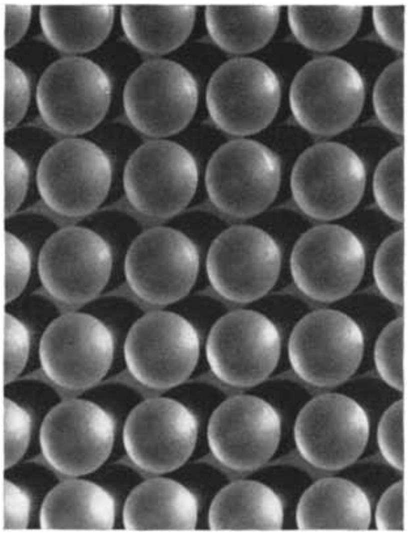
In reorganizing our approach to the support of science we need not set aside utilitarian objectives. Goal-oriented developmental research is exceedingly important; frequently it asks questions that inspire fruitful developments in basic research. But society must learn to recognize the importance of the able scientist who is motivated by pure curiosity, who wants to think about something solely because he likes to do so. The encouragement of science will be disastrously narrow in its view if it does not offer rewarding careers to these men, for they are almost always the greatest innovators.

The problem of encouraging creativity in science is an elusive one. In cases of outstanding genius—the Einsteins, the Ramanujans—there is really no evidence to indicate that society can either aid or hinder. These miracles just happen, and we can do little more than be thankful. At a slightly lower level, however, it does seem that we may stifle potentially creative scientists by standardized mechanisms of support and reward which are too little favorable to the unorthodox, to the modestly thoughtful, and to those who are uncontrollably curious in the passive as well as the active sense of this useful word. We can afford to support the competent and curious, and need not be so concerned about making correct judgments in specific cases. The borderline between the genius and the nut is sometimes rather fuzzy. In most instances (Einstein is an excellent example) one can confidently discriminate by asking: "Does this person have a thorough and scholarly knowledge of the general field in which he works?" But in other instances (Ramanujan!) even this reasonable criterion fails.

If our society is to encourage creativity in science, we must strive to learn more about science, to appreciate science in an intelligently discriminating way, and thus come to understand the essential role played by the apparently impractical drive of pure curiosity. Society must assure our universities of sufficient basic support so they can offer to competent and creative scholars a decent, stable and honored opportunity to think.

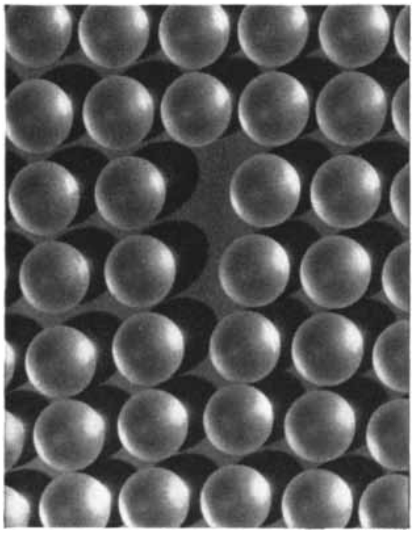
Atoms in a crystal once were thought to be arranged like this

A perfectly ordered arrangement of atoms. Uniform perfection like this was once thought to be characteristic of crystals.



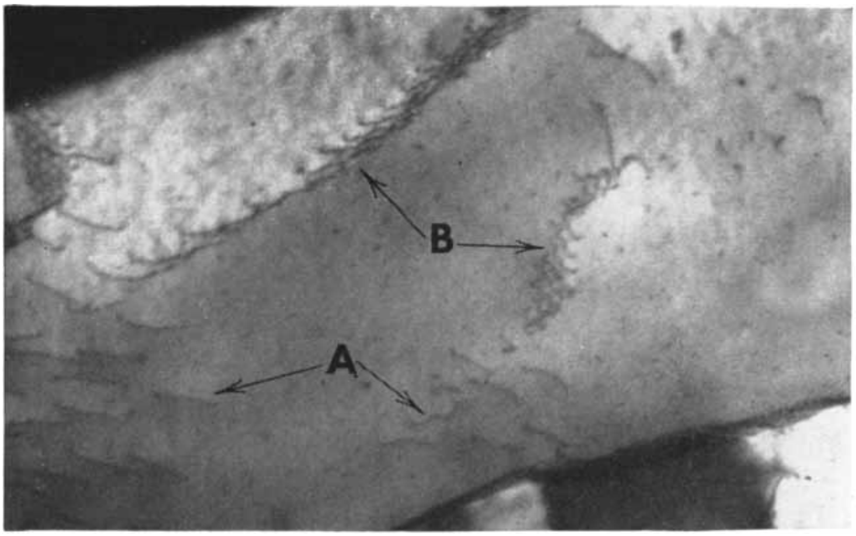
but indirect evidence more recently suggested this

Widespread occurrence of imperfections such as this was postulated to account for the behavior of metals. But for a long time the evidence remained only indirect for lack of effective experimental techniques.



... now confirmed by the electron eye

Electron micrographs, like this one of a single gold crystal magnified 120,000 times, reveal the existence not only of isolated imperfections (A) but also groupings (B) of these, which are key factors in determining the behavior of metals.



The Creative Process in any science usually proceeds about like this: Unanswered questions accumulate for a number of years; then, at least in cases we like to talk about, a new principle is enunciated, a new technique is developed; intensive study and thought follow and the questions yield to the onslaught. Answers are found, and we reach a sort of plateau in our understanding. During this period, there is a general feeling that the field is understood "in principle" but that mopping-up operations are in order. Gradually, though, unanswered questions again accumulate. The old answers no longer suffice, and the cycle repeats—over and over—without apparent end.

A good example of the process is our changing understanding of the grain structure of metals. The grain structure of some metals was recognized many centuries ago, because the grains could be seen with the naked eye. (The grains of a well-handled brass door knob may be seen easily.) With the advent of the high-power optical microscope and the development of improved metal-polishing techniques, men were better able to study the granular nature of all metals and formulate answers to many questions concerning the behavior of metals.

Additional understanding followed the discovery of X-rays in 1895 and their subsequent use in obtaining diffraction patterns of metals. Metallurgists then realized that the grains in metals are *individual crystals*—like diamonds or grains of salt. It was more or less taken for granted that the arrangement of atoms within each grain was perfect. This concept of crystal perfection was later to be modified, but it served us well. With the new knowledge X-rays gave us, we were able to improve the mechanical properties of metals and to control these properties more closely.

The decade of the thirties brought the first inklings that metallic grains usually are far from perfect . . . that *imperfections* are of vast importance in determining strength and other mechanical properties as well as chemical properties of a metal. Of the various imperfections, the *dislocations*, which are substantially linear or string-like in character, have received particular attention. The electron microscope has played a vital part in their study. It enables us to study dislocations by direct observation—*single* dislocations and dislocation "pile-ups," as well as arrays of dislocations that form subboundaries within a single grain of metal. The electron micrograph shown above, obtained at the United States Steel Research Center, shows these phenomena.

By studying crystals in this way we learn about imperfections in metal, the interactions between them, and their effect on metal behavior. Eventually these laboratory discoveries find their way into practice, to further improve the strength and performance of steels. But our basic research job is never done. There is always more to be learned. That's why fundamental study of the nature of metals is a continuing activity at the United States Steel Research Center. United States Steel, Pittsburgh 30, Pa.

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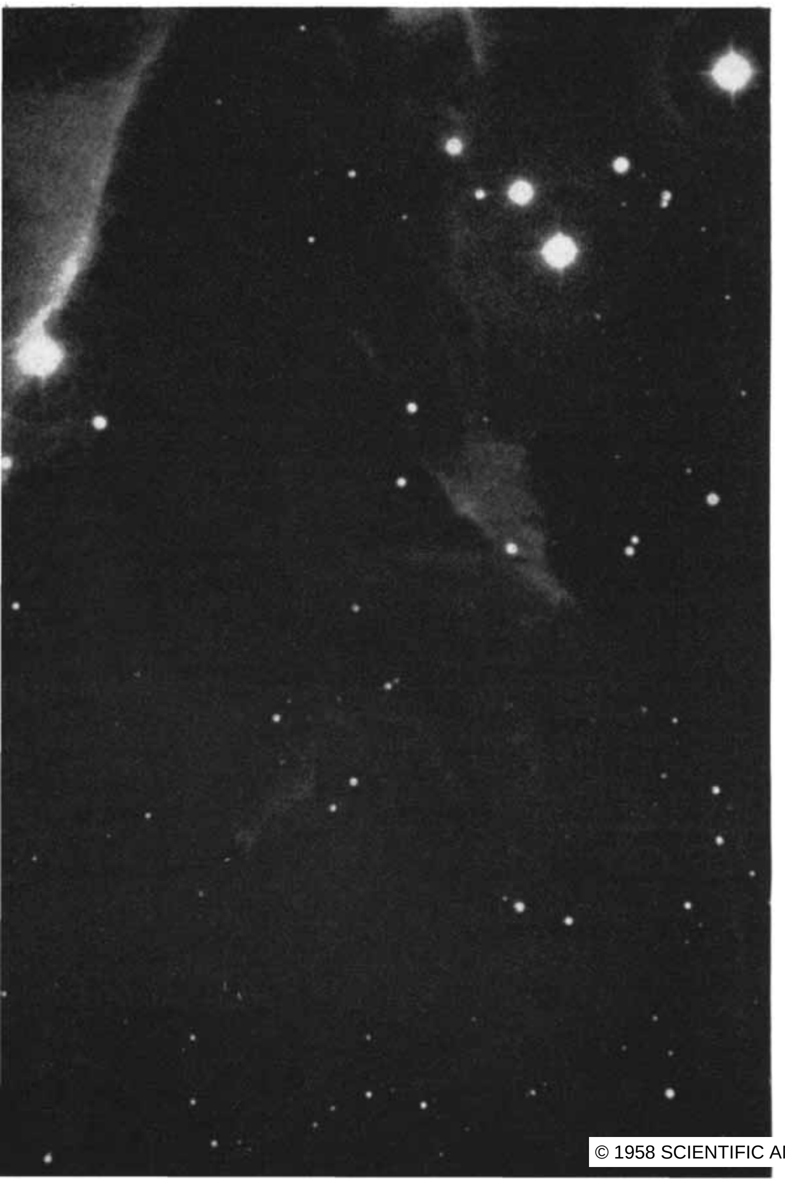

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MATHEMATICAL GAMES

A game in which standard pieces composed of cubes are assembled into larger forms

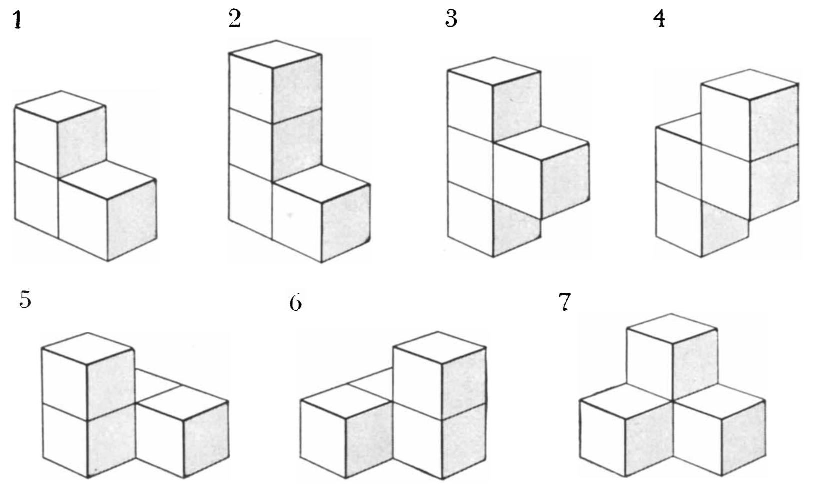
by Martin Gardner

The Chinese puzzle game called tangram, believed to be thousands of years old, employs a square of thin material that is dissected into seven pieces. The game is to rearrange those pieces to form other figures. From time to time efforts have been made to devise a suitable analogue in three dimensions. None, in my opinion, has been as successful as the Soma cube, invented by Piet Hein, the Danish writer whose mathematical creations have often been cited in this department.

Hein conceived of the Soma cube during a lecture on quantum physics by Werner Heisenberg. While the noted German physicist was speaking of a space sliced into cubes, Hein's supple imagination caught a fleeting glimpse of the following curious geometrical theorem. If you take all the irregular shapes that can be formed by combining no more than four cubes, all the same size and joined at their faces, these shapes can be put together to form a larger cube.

Let us make this clearer. The simplest irregular shape—"irregular" in the sense that it has a concavity or corner nook in it somewhere—is produced by joining three cubes as shown at 1 in the illustration below. It is the only such shape possible with three cubes. (Of course no irregular shape is possible with one or two cubes.) Turning to four cubes, we find that there are six different ways to form irregular shapes by joining the cubes face to face. These are pieces 2 to 7 in the illustration. To identify the seven pieces Hein labels them with numerals. No two shapes are alike, although 5 and 6 are mirror images of each other. Hein points out that two cubes can be joined only along a single coordinate, three cubes can add a second coordinate perpendicular to the first, and four cubes are necessary to supply the third coordinate perpendicular to the other two. Since we cannot enter the fourth dimension to join cubes along a fourth coordinate supplied by five-cube shapes, it is reasonable to limit our set of Soma pieces to seven. It is an unexpected fact that these elementary combinations of identical cubes can be joined to form a cube again.

As Heisenberg talked on, Hein swiftly convinced himself by doodling on a sheet of paper that the seven pieces, containing 27 small cubes, would form a $3 \times 3 \times 3$ cube. After the lecture he glued 27 cubes into the shapes of the seven components and quickly con-



The seven Soma pieces

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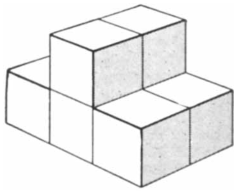


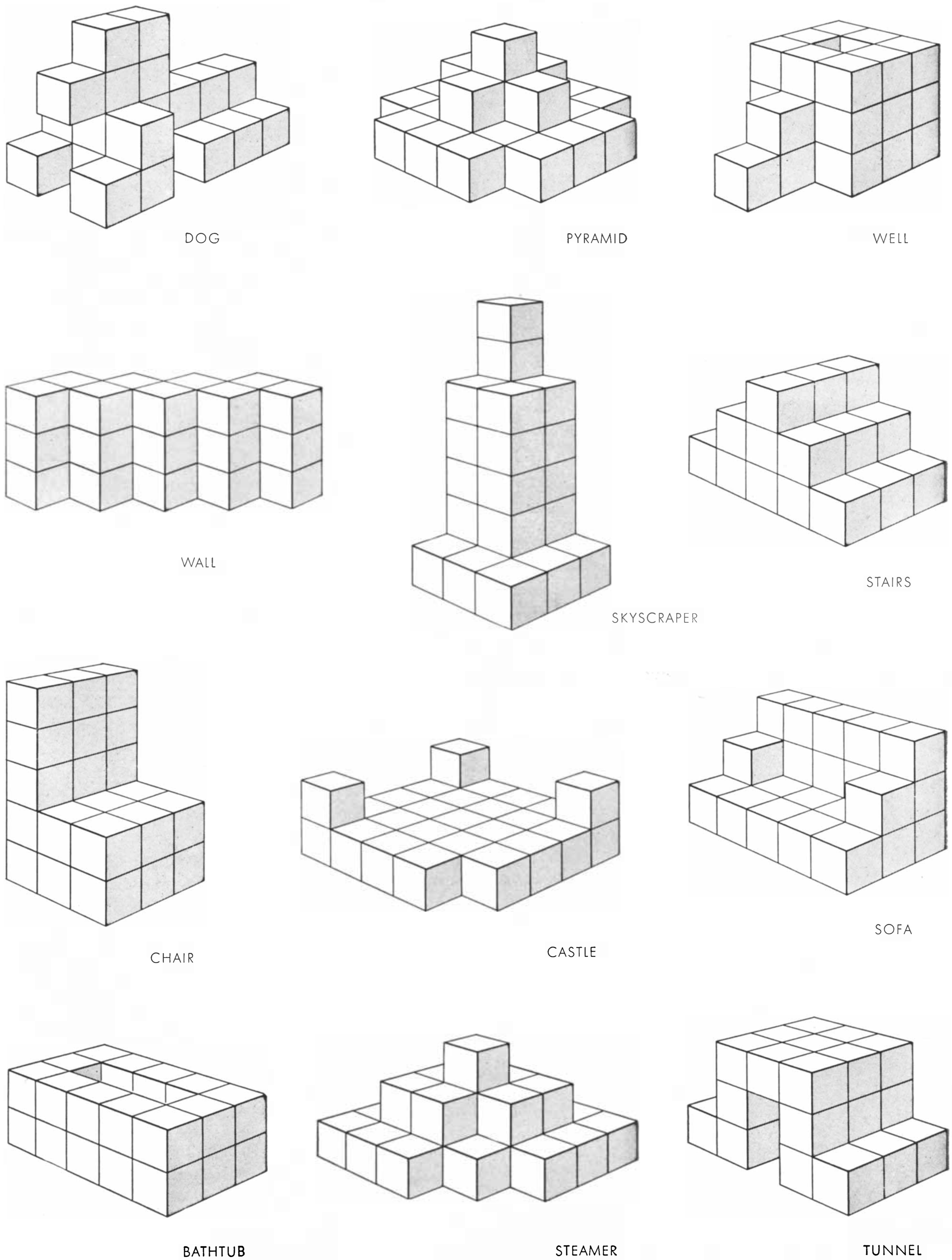
A form made up of two Soma pieces

firmed his insight. A few years ago a set of the pieces was marketed under the trade name Soma, and the puzzle has since become a popular one in the Scandinavian countries.

To make a Soma cube—and the reader is urged to do so, for it provides a game that will keep every member of the family entranced for hours—you have only to obtain a supply of children's blocks. The seven pieces are easily constructed by spreading rubber cement on the appropriate faces, letting them dry, then sticking them together. Actually the toy is a kind of three-dimensional version of polyominoes, discussed in this department last December.

As a first lesson in the art of Soma, see if you can combine any two pieces to form the stepped structure in the illustration above. Having mastered this trivial problem, try assembling all seven pieces into a cube. It is one of the easiest of all Soma constructions. In fact the well-known Swedish astrophysicist Hannes Alfvén made an analysis which disclosed more than a quarter of a million different ways of forming the cube! However, as you will soon discover when you try it, there are many more ways it cannot be done. A good strategy to adopt on this as well as other Soma figures is to set the more irregular shapes (Nos. 5, 6 and 7) in place first, because the other pieces adjust more readily to remaining gaps in a structure. Piece No. 1 in particular is best saved until last.

After solving the cube, try your hand at the more difficult seven-piece structures in the illustration on the next page. Instead of using a time-consuming trial and error technique, it is much more satisfying to analyze the constructions and cut down your building time by geometrical insights. For example, it is obvious that pieces 5, 6 and 7 cannot form the steps to the well. Group competition can be introduced by giving each player a Soma set and seeing who can build a given figure in the shortest length of time. To avoid misinterpretations of these structures it should be said that the far sides of the pyramid and steamer are exactly like the near sides; both the hole in the well and the in-



One of these 12 forms cannot be built up from Soma pieces terior of the bathtub have a volume of three cubes; there are no holes or projecting pieces on the hidden sides of the skyscraper; and the column that forms the back of the dog's head consists of four cubes, the bottom one of which is hidden from view.

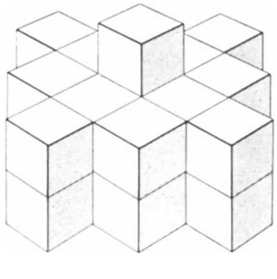
After working with the pieces for several days, many people find that the shapes become so familiar that they can solve Soma problems in their heads. Tests made by European psychologists have shown that ability to solve Soma problems is roughly correlated with general intelligence, but with peculiar discrepancies at both ends of the I.Q. curve. Some geniuses are very poor at Soma and some morons seem specially gifted with the kind of spatial imagination that Soma exercises. Everyone who takes such a test wants to keep playing with the pieces after the test is over.

Like the two-dimensional polyominoes, Soma constructions lend themselves to fascinating theorems and impossibility proofs of combinatorial geometry. Consider the structure in the top illustration on the next page. No one had succeeded in building it, but it was not until recently that a formal impossibility proof was devised. Here is the elegant proof, discovered by Solomon W. Golomb, mathematician at the Jet Propulsion Laboratory of the California Institute of Technology. (Readers may recall Golomb's similar work on polyomino impossibilities.)

We begin by looking down on the structure as shown in the bottom illustration on the next page and coloring the columns in checkerboard fashion. Each column is two cubes deep except for the center column, which consists of three cubes. This gives us a total of eight white cubes and 19 black, quite an astounding disparity.

The next step is to examine each of the seven components, testing it in all possible orientations to ascertain the maximum number of black cubes it can possess if placed within the checkerboard structure. The chart at the bottom of page 190 displays this maximum number for each piece. As you see, the total is 18 black to nine white, just one short of the 19-8 split demanded. If we shift the top black block to the top of one of the columns of white blocks, then the black-white ratio changes to the required 19-8, and the structure becomes possible to build.

I must confess that one of the structures in the illustration on the opposite page is impossible to make. It should take the average reader many days, however, to discover which one it is. Meth-



An impossible Soma form

A means of labeling the form

ods for building the other figures will not be given next month (it is only a matter of time until you succeed with any one of them), but I shall identify the figure which cannot be made.

The number of pleasing structures that can be built with the seven Soma pieces seems to be as unlimited as the number of plane figures that can be made with the seven tangram shapes. It is interesting to note that if piece No. 1 is put aside, the remaining six pieces will form a shape exactly like No. 1 but twice as high. If any reader hits upon a particularly unusual Soma figure not pictured here, I would be pleased to receive a sketch of its construction.

Here are the answers to the "brain-teasers" presented in this department last month:

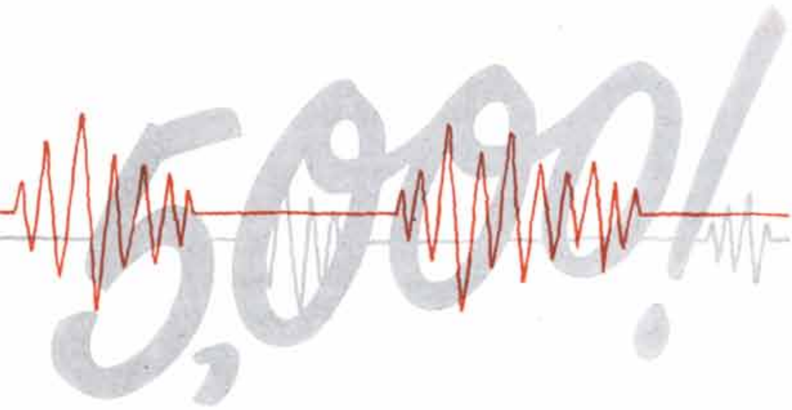
1.

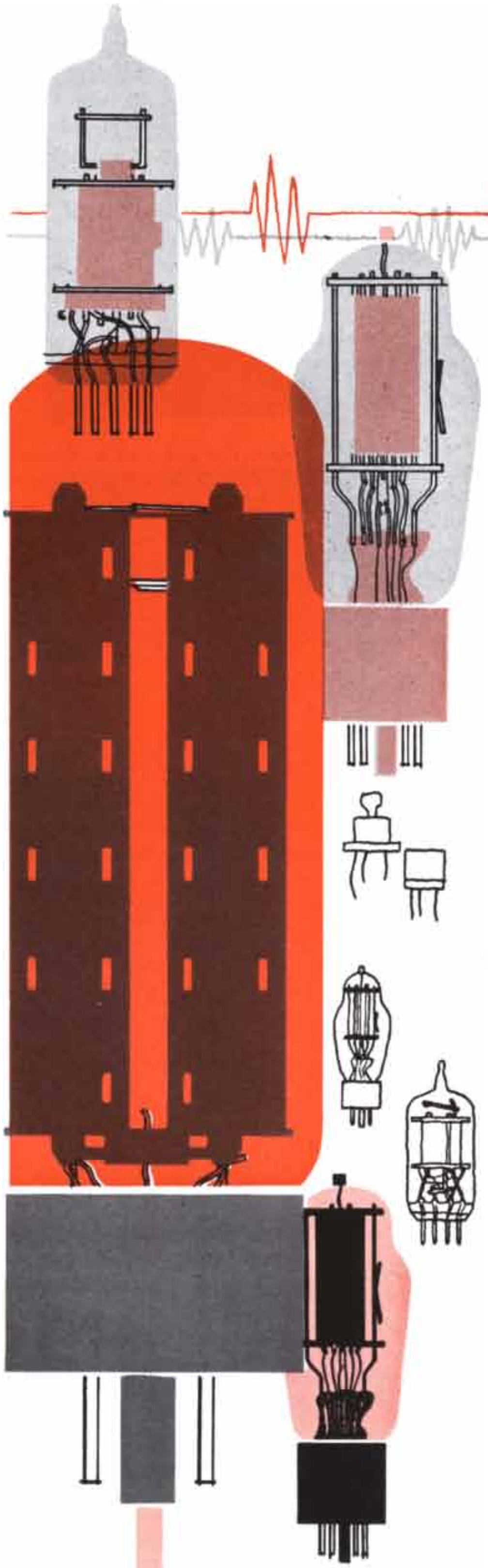
The heads of the twiddled bolts move neither inward nor outward. The situation is comparable to that of a person walking up an escalator at the same rate that it is moving down.

2.

Four airplanes will do the trick. One solution:

Planes 1, 2, 3 and 4 take off together. After going 1/6 of the distance around the earth, planes 1 and 4 transfer half their remaining fuel to planes 2 and 3. As 2 and 3 continue for another 1/6 of the way, planes 1 and 4 return to base. Plane 3 now transfers half its fuel to 2,





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CONVAIR IS A DIVISION OF GENERAL DYNAMICS CORPORATION while plane 4 refuels at the base. This permits 3 to cover half the distance back to the base, where it is met by 4. Plane 4 gives half its fuel to 3, and both planes return to base. Meanwhile plane 2, with a full tank, continues on its way until its fuel is gone. This occurs at a point 5/6 of the total distance. Either plane 1 or plane 4, flying of course in a direction opposite to that of previous take-off flights, can meet plane 2. Half of the fuel is transferred, and plane 2 continues to the base escorted by the plane that met it.

3.

If you place the point of a compass at the center of a black square on a chessboard with two-inch squares, and extend the arms of the compass a distance equal to the square root of 10 inches, the pencil will trace the largest possible circle that touches only black squares.

4.

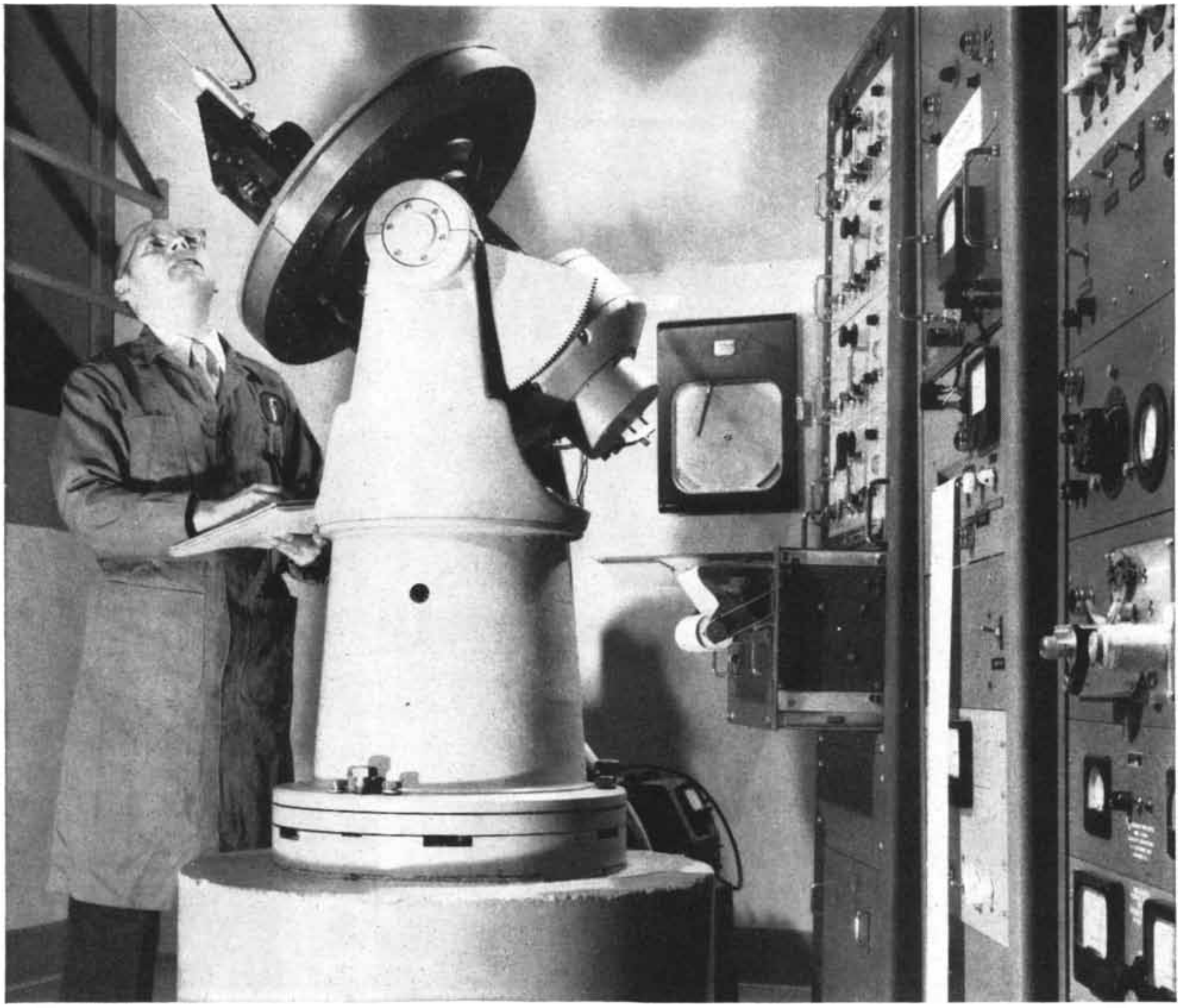
Any vertical cross section of the cork plug at right angles to the top edge and perpendicular to the base will be a triangle. If the cork were a cylinder of the same height, corresponding cross sections would be rectangles. Each triangular cross section is obviously 1/2 the area of the corresponding rectangular cross section. Since all the triangular sections combine to make up the cylinder, the plug must be 1/2 the volume of the cylinder. The cylinder's volume is 2π, so our answer is simply π.

5.

Writing a three-digit number twice is the same as multiplying it by 1,001. This number has the factors 7, 11 and 13, so writing the chosen number twice is equivalent to multiplying it by 7, 11 and

SOMA PIECE	MAXIMUM BLACK CUBES	MINIMUM WHITE CUBES
1.	2	1
2.	3	1
3.	3	1
4.	2	2
5.	3	1
6.	3	1
7.	2	2
	18	9

Table for the impossibility proof



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13. Naturally when the product is successively divided by these same three numbers, the final remainder will be the original number.

6.

The quickest way to solve this problem is to run the scene backward in time. A minute before the crash the 9,000 mile-per-hour missile is clearly 150 miles from the meeting point and the 21,000 mile-per-hour missile is 350 miles from the same point, making the distance between them 500 miles.

7.

Number the top coin in the pyramid 1, the coins in the next row 2 and 3, and those in the bottom row 4, 5 and 6. The following four moves are typical of many possible solutions: Move 1 to touch 2 and 4, move 4 to touch 5 and 6, move 5 to touch 1 and 2 below, move 1 to touch 4 and 5.

8.

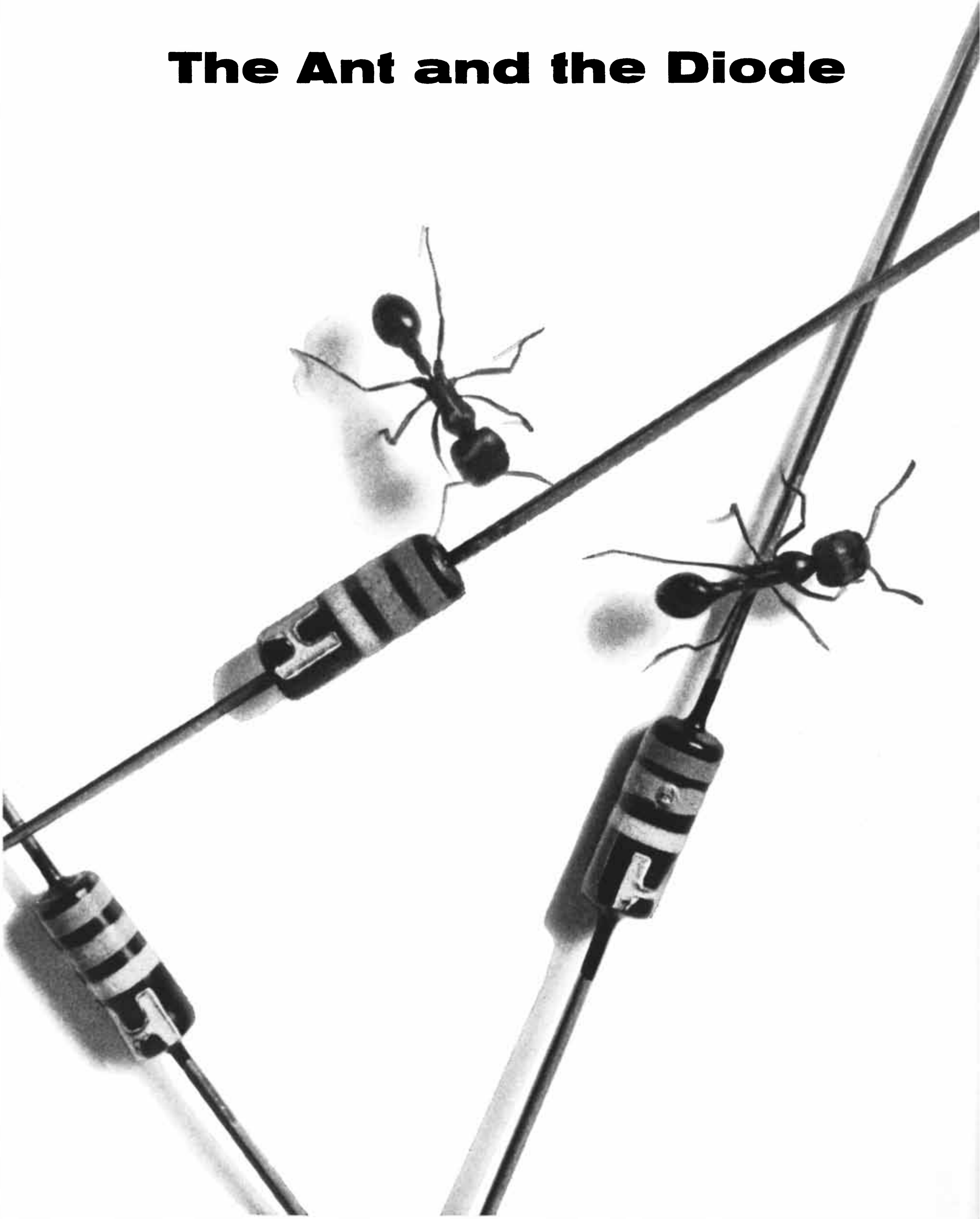
Because two people are involved in every handshake, the total score for everyone at the convention will be evenly divisible by two and therefore even. The total score for the men who shook hands an even number of times is, of course, also even. If we subtract this even score from the even total score of the convention, we get an even total score for those men who shook hands an odd number of times. Only an even number of odd numbers will total an even number, so we conclude that an even number of men shook hands an odd number of times.

9.

In the triangular pistol duel the poorest shot, Jones, has the best chance to survive. Since his two opponents will aim at each other when their turns come, Jones's best strategy is to fire into the air until one opponent is dead. He will then get the first shot at the survivor, which gives him a strong advantage. Computing the actual survival probabilities is somewhat tricky, but I have the assurance of several experts that Jones, who hits his target 50 per cent of the time, has a survival chance of 47/90; Smith, who is 100 per cent accurate, comes next with a chance of 27/90 or 3/10; and Brown, who is 80 per cent accurate, is last with a chance of 16/90. Perhaps there is a moral of international politics in this somewhere.

CREATING A NEW WORLD WITH ELECTRONICS...NO. 7

The Ant and the Diode



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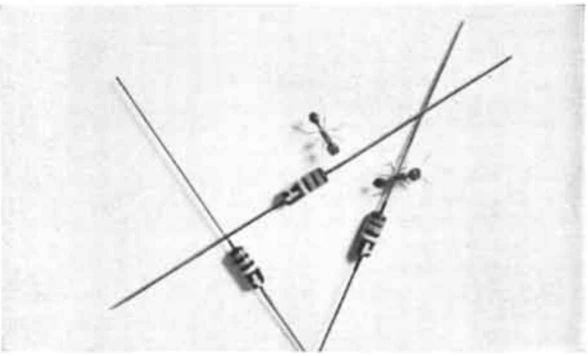

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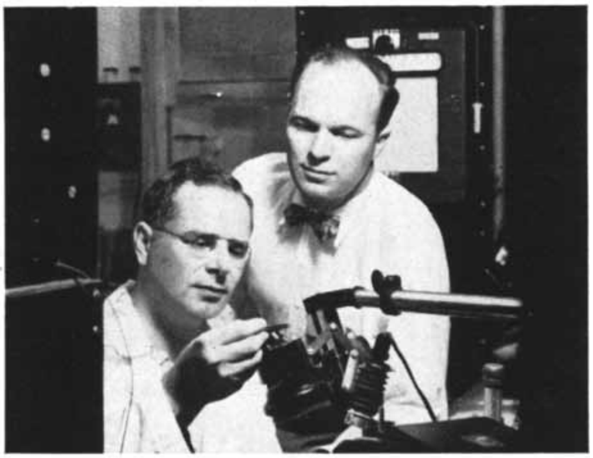

Research physicists, shown studying a silicon crystal with impurity atoms introduced, further HUGHES *advances in solid state physics.*

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THE AMATEUR SCIENTIST

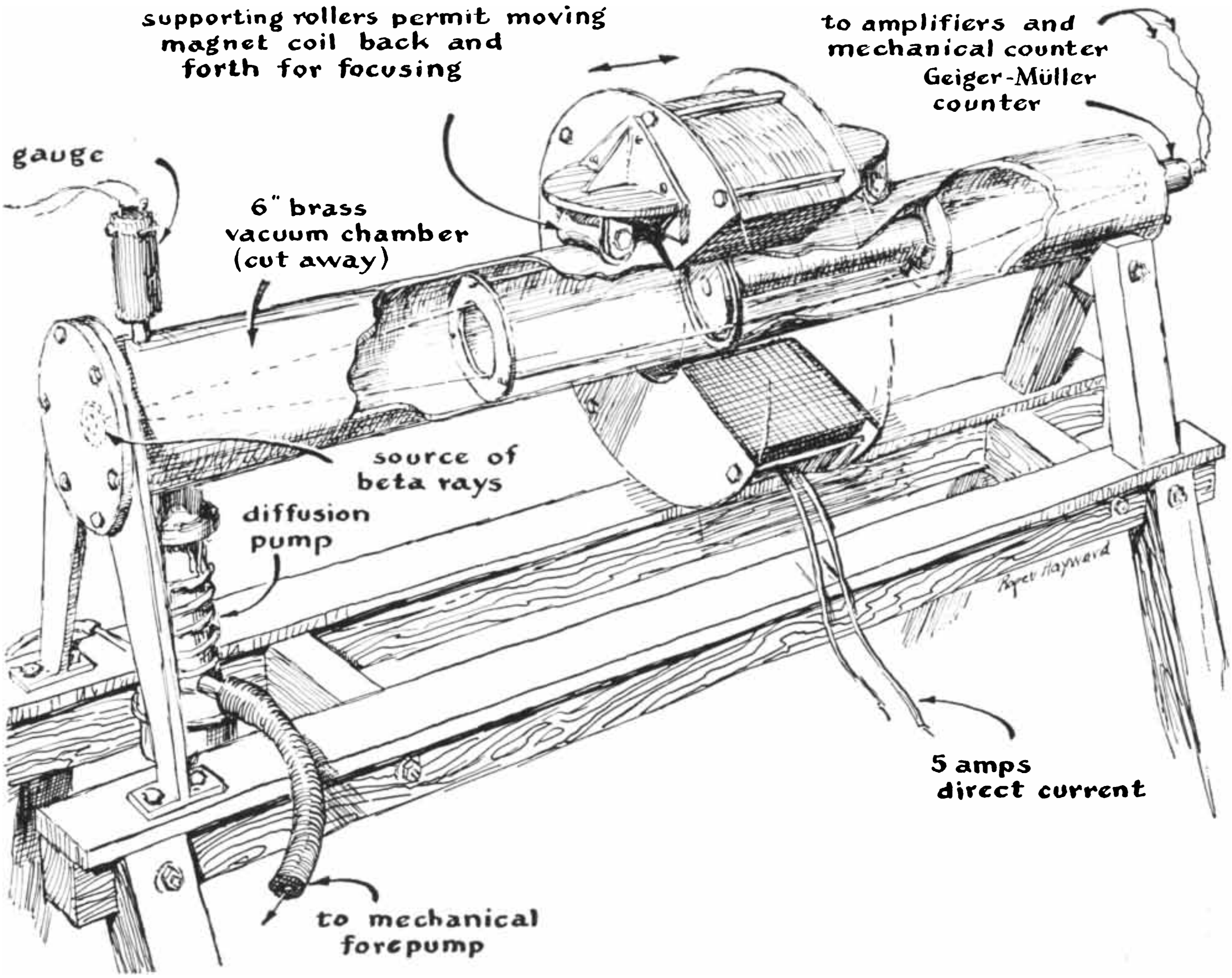
How a group of high-school students constructed a beta-ray spectrometer

Conducted by C. L. Stong

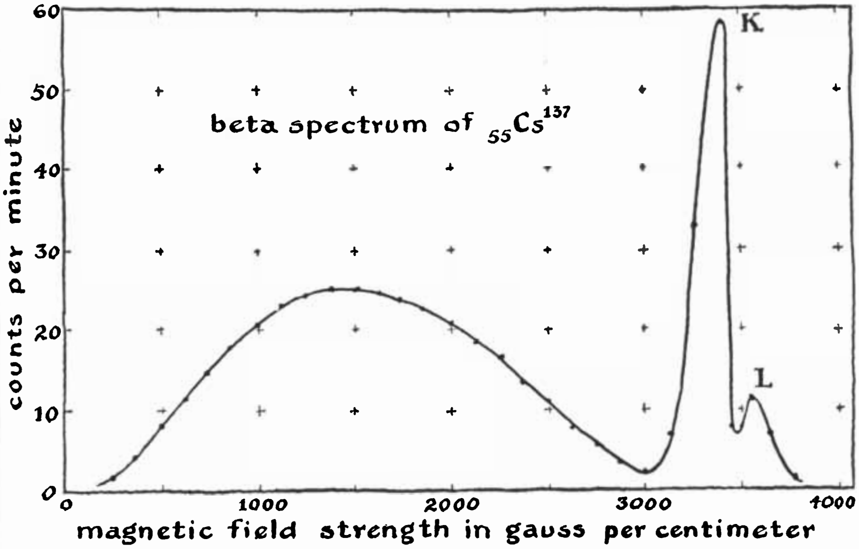
In 1899 a German physicist named Friedrich O. Giesel built an apparatus to investigate why a magnet alters the conductivity of air electrified by radium. He set up a glass tube so that rays emitted by radium at one end of the tube made a spot of light on a fluorescent screen at the other end. When Giesel put the tube between the poles of a magnet, the spot spread toward one side of the screen or the other, depending on the polarity of the magnet. He concluded that the screen must be excited by electrically charged particles from the radium, because such particles would be deflected by the magnetic field. But in answering this riddle the experiment posed others more difficult to solve. Why does radium emit charged particles in the first place—and does it do so?

These questions still challenge some of the best minds in physics. During the past half-century the particles detected by Giesel have been named beta rays and identified as electrons. Beta rays of opposite charge have been detected and identified as positrons. A sophisticated version of Giesel's tube, called the beta-ray spectrometer, has become one of the most important tools of modern physics. Nonetheless no completely satisfactory theory of the origin of beta rays has yet been proposed.

All this suggests that the serious study of beta rays lies beyond the reach of the amateur. But some amateurs, notably



This beta-ray spectrometer of the short-magnetic-lens type was built by students at Garfield High School in Seattle, Wash.



The beta-ray spectrum of cesium 137

those of high-school age, like to test their reach. A case in point is a group of boys in Seattle, Wash. They built a beta-ray spectrometer which, with its accessories, weighs more than half a ton. A measure of their success is the fact that the apparatus is now in use in the department of physics at the University of Washington.

The project, which spanned two years, is described by the boys responsible for its completion: John Kulander and Sydney Handlin, who are now students at the University. "As members of the newly organized Garfield High School Physical Science Club," they write, "we wanted to construct an instrument capable of serious research. A telephone call to Fred H. Schmidt of the University of Washington physics department resulted in an invitation to make a tour of the physics laboratories. We accepted in high excitement and examined many research instruments, including a 60-inch cyclotron, a cloud chamber and a beta-ray spectrometer.

"After much discussion, we finally decided to build a beta-ray spectrometer of the magnetic-lens type. Dr. Schmidt agreed to become our adviser. Many conferences were held with him as well as with graduate students at the University, including Richard Maltrud and John Penning.

"After completing the basic design and working drawings for the instrument, we tackled a practical side of scientific work which, as subsequent experience proved, had been dismissed too lightly: the promotion of funds. We needed pumps for the high-vacuum system, a motor-generator set with an output of a kilowatt, electronic components, a substantial quantity of magnet wire and other materials, to say nothing of tools and machine-shop facilities. We estimated that $1,000 would get us started, and decided to approach the *Seattle Post-Intelligencer* with the problem. The resulting story caught the eye of William Q. Hull, an editor of *Chemical and Engineering News*, and led to another article. We then solicited numerous business men and industrial organizations in the Seattle area. Help came from many. A local theater owner contributed the first $1,000. E. E. Hanselman, the principal of Garfield High School in 1954, gave us part of an old storeroom for a laboratory. During this phase of the project we learned that not only copper and steel but also a large quantity of shoe leather can go into the construction of laboratory apparatus.

"Instruments of the type we subsequently built measure the kinetic energy of beta particles emitted during the decay of radioactive isotopes. Much of what has been learned about the decay process has been inferred from such measurements. The instrument is also capable of measuring the energies of gamma rays. This is accomplished by covering the source of gamma radiation with a material from which the radiation dislodges electrons. The energies and intensities of the electrons are measured as though they were beta rays, and the properties of the gamma radiation are derived from this information.

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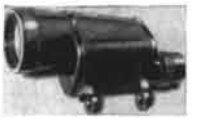

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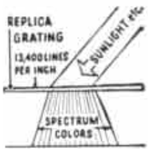

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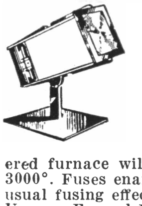

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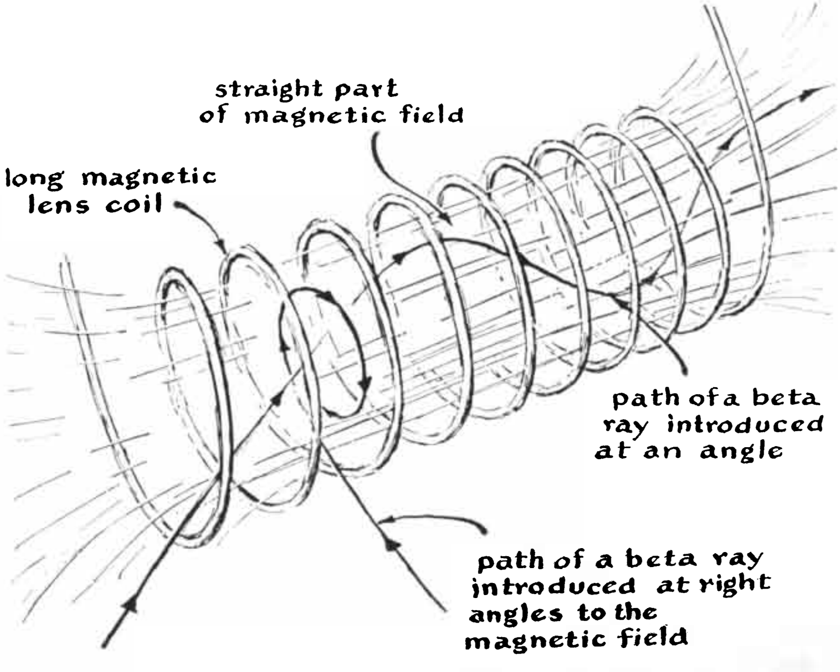
of particles are emitted with random energies: some low, some intermediate and some high. When plotted as a graph, the energy measurements make a broad, smooth curve which may have one or more sharp peaks. The peaks mark energy levels at which exceptionally large numbers of particles with the same energy are observed.

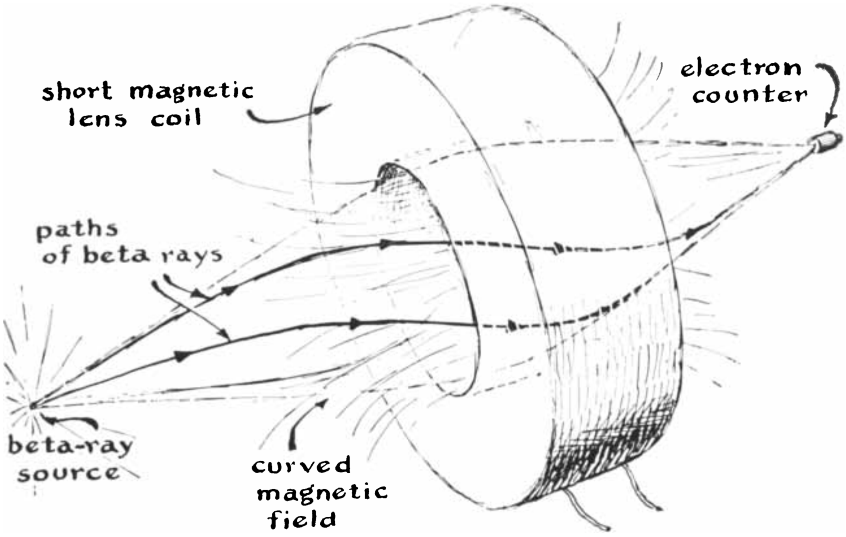
"The broad, smooth part of the curve is referred to as the continuous or primary energy-spectrum of the substance under measurement. The peaks are called line spectra. It has been found that the continuous spectrum is caused by particles ejected from nuclei, while the line spectra are due to the ejection of particles from one or more of the inner shells of the system of electrons which surround the nucleus. The curve of one radioisotope of cesium made by our instrument is shown in the accompanying illustration [*see page 198*]. The height of the curve is proportional to the number of electrons ejected at each level of energy. Energy increases are plotted from left to right. The peaks at K and L represent emission from the "K" and "L" shells of the cesium atom.

"Three types of beta decay are known. One involves the emission of high-energy electrons, observed by Giesel. In this form of decay a neutron emits an electron and is transformed into a proton. The atom has thereby gained a proton and is transformed into the element immediately above it in the periodic table. Cesium 137 undergoes such decay, and becomes barium 137. The barium is left in an excited state after the decay and returns to the "ground" state by emitting a gamma ray. Occasionally the gamma ray ejects an electron from the K or the L shell. In another kind of beta decay a proton emits a positron and becomes a neutron. Here the daughter element is one step down the periodic table. In the third type of beta decay a proton interacts with an electron in the innermost electron shell (the K shell) and also becomes a neutron. This transformation is called K-electron capture.

"How is it that the identical atoms of a beta-ray-emitting isotope can emit beta rays of various energies? What happens to the energy apparently left behind when a low-energy beta ray is ejected? This energy cannot simply vanish; that would violate the well-known law of nature which states that energy cannot be destroyed, but only transformed. A solution for this riddle was proposed in 1927 by the physicist Wolfgang Pauli. He invented a fictitious particle and assigned to it the responsibility of carrying precisely enough energy away from the decaying atom to balance the books. Called the neutrino, the particle had to be much lighter than the electron. It also had to carry no electric charge. A particle which met these specifications would be difficult to detect. The existence of the neutrino was demonstrated, however, in 1956 [see "The Neutrino," by Philip Morrison; SCIENTIFIC AMERICAN, January, 1956]. The beta-ray spectrometer cannot detect neutrinos direct-



Trajectory of a beta particle in a magnetic field



Refraction of beta particles by a short magnetic lens

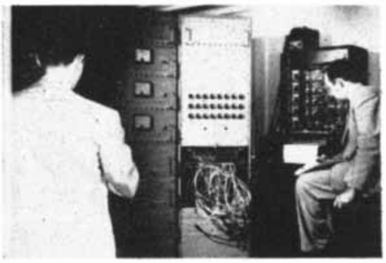
ly. But the amount of energy the neutrinos carry away from the decaying isotope can be established by measuring the energy of the beta particles.

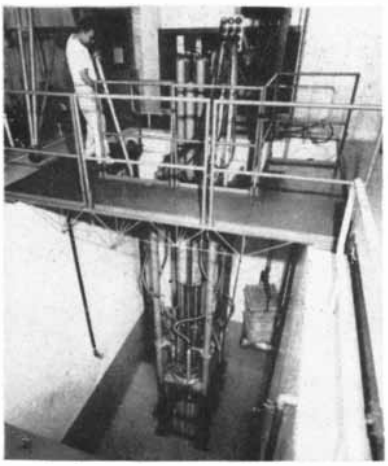
"In making such energy measurements the beta-ray spectrometer takes advantage of the fact that it is more difficult to change the course of fast-moving particles than that of slow ones. A charged particle is deflected by a magnetic field when its path makes an angle with the lines of force in the field. For a given angle and kinetic energy, particles of low energy are deflected more than those of high energy. Conversely, particles of any energy can be made to follow a prescribed trajectory by making appropriate adjustments in the strength of the magnetic field. The trajectory of a beta ray in a magnetic field is therefore determined by the speed and mass of the particle, the angle made by the heading of the particle with respect to the lines of magnetic force, and the strength of the field [*see illustration on page 200*]. Particles diverging from a source located on the axis of a short magnetic field follow a corkscrew trajectory; those of like heading and energy will come to focus on the axis at the opposite end of the field [*see illustration above*]. Particles of more or less energy can be brought to the same focus by adjusting the strength of the field. This assumes, of course, that no obstacles such as molecules of gas hamper the flight of the particles. The number of particles arriving at the focus can be detected by several methods, including Giesel's fluorescent screen. We used a Geiger-Müller counter to record the relative intensity of the particles.

"To provide a clear flight path for the beta particles, the radioactive substance under measurement is enclosed in an evacuated chamber. Some gas molecules remain to bounce around at random inside the chamber, however, because a perfect vacuum cannot be produced. These collide with and divert occasional particles. Some high-energy beta rays also dislodge electrons from molecules of gas, and even from the walls of the vacuum chamber. As a consequence some particles which should be counted do not reach the focus, and others which should not are deflected into the counter. The Geiger tube responds to gamma rays; these must also be excluded from the count. Error from these sources is reduced by equipping the chamber with a system of baffles [*see illustration on page 204*]. Depending upon the strength of the magnetic field, rays ejected from the source above a certain critical angle strike a ring baffle at the source end of the vacuum chamber. Those below this angle pass through the center opening and proceed to a baffle with a ring-shaped opening, located in the middle of the chamber. Here rays above a certain critical energy-level collide with the center stop. Those of lower energy pass through the ring-shaped opening. They proceed through a similar opening in another baffle and enter the counter. A cylinder of lead located on the axis between the latter two baffles shields the counter from gamma rays, which, because they are not deflected by a magnetic field, would travel in a straight line from the radioactive source.

"We began to build the instrument in the spring of 1955 by machining the vacuum chamber. This work was done





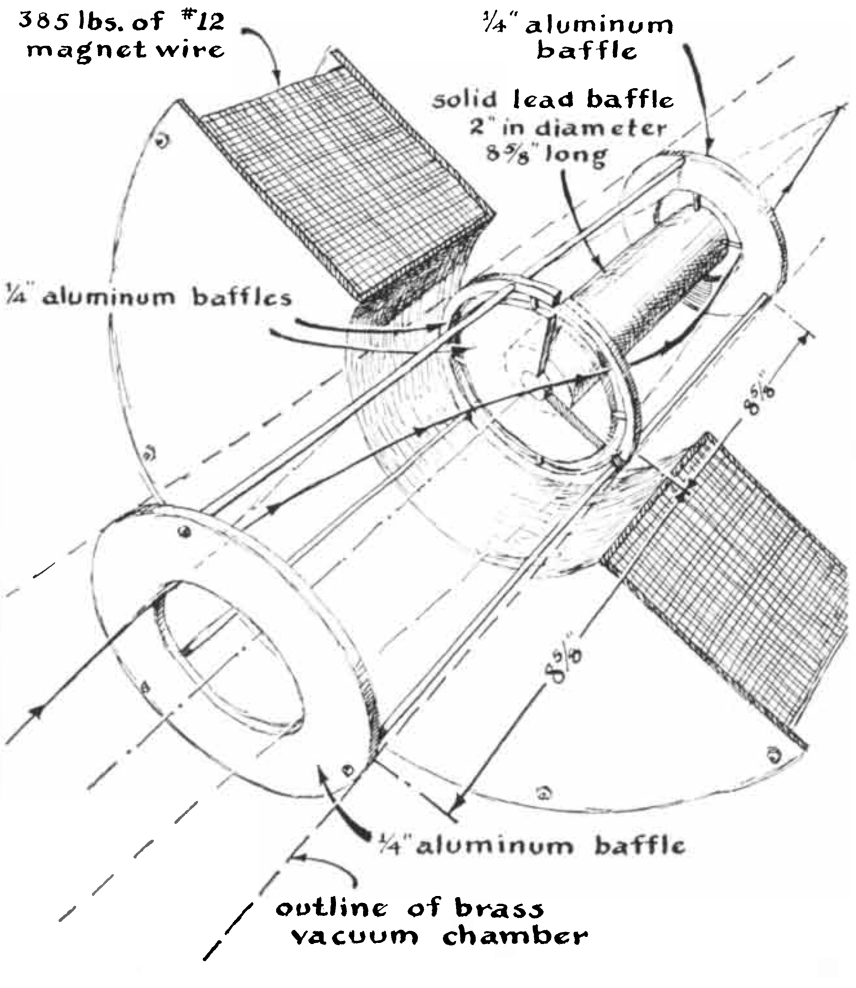



in the University of Washington physics shop. The chamber consisted of a heavy brass tube with an inner diameter of six inches. An outside flange was welded to the source end of the tube and an inside flange to the counter end. These were grooved to take rubber rings and provided with a set of end-plates. During final assembly the rubber rings were coated with silicone grease just before the end-plates were bolted in place. The center of the plate at the counter end was provided with a window of aluminum foil a thousandth of an inch thick. The foil was attached by a special vacuum-sealing compound. Work proceeded simultaneously on the electrical circuits, which included the counter and controls as well as a regulated power-supply for the magnet. Some of the electrical parts were gifts from local schools and industrial organizations, but most had to be purchased. By the summer of 1955 we had run out of money.

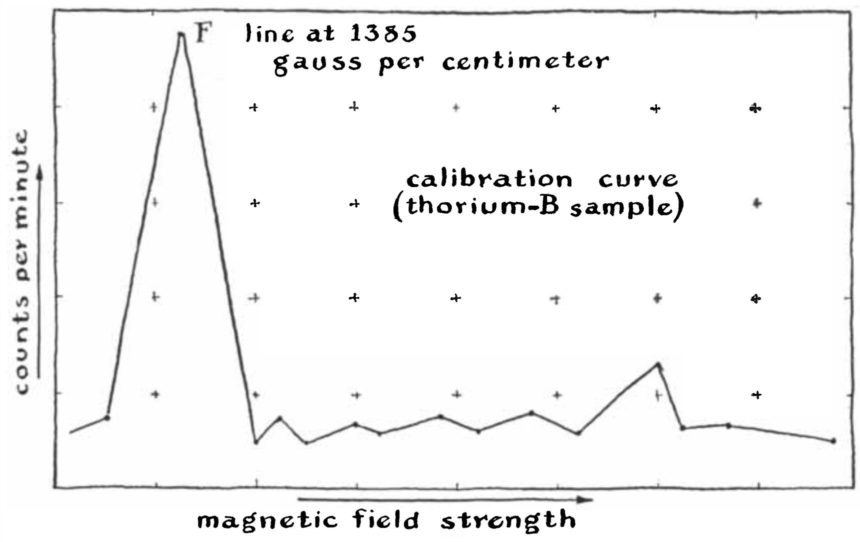
"This meant more fund-raising. Eventually we obtained oil-diffusion pumps from two large organizations. One pump was connected directly to the vacuum chamber at the source end [*see illustration on page 197*]. A Welch single-stage mechanical pump brought the vacuum down to five hundredths of a millimeter of mercury. The oil-diffusion equipment went into operation at this point, and reduced the pressure to about 10 microns of mercury.

"We employed three gauges for measuring air pressure in the system. A conventional high-pressure gauge calibrated from 0 to 760 millimeters of mercury was connected between the mechanical and diffusion pumps. Two low-pressure gauges were connected directly to the vacuum chamber. One, a National Research Corporation thermocouple gauge, could measure down to one micron. The other, a VG-1A ionization manometer made by the Consolidated Electrodynamics Corporation, extended the reading to a hundredth of a micron.

"The inner walls of the chamber were sanded and cleaned frequently with



The baffle system of the beta-ray spectrometer



The beta-ray spectrum of thorium B

acetone to remove substances which release gas after the pumps are started. Under ideal conditions we could reduce the pressure to about one micron.

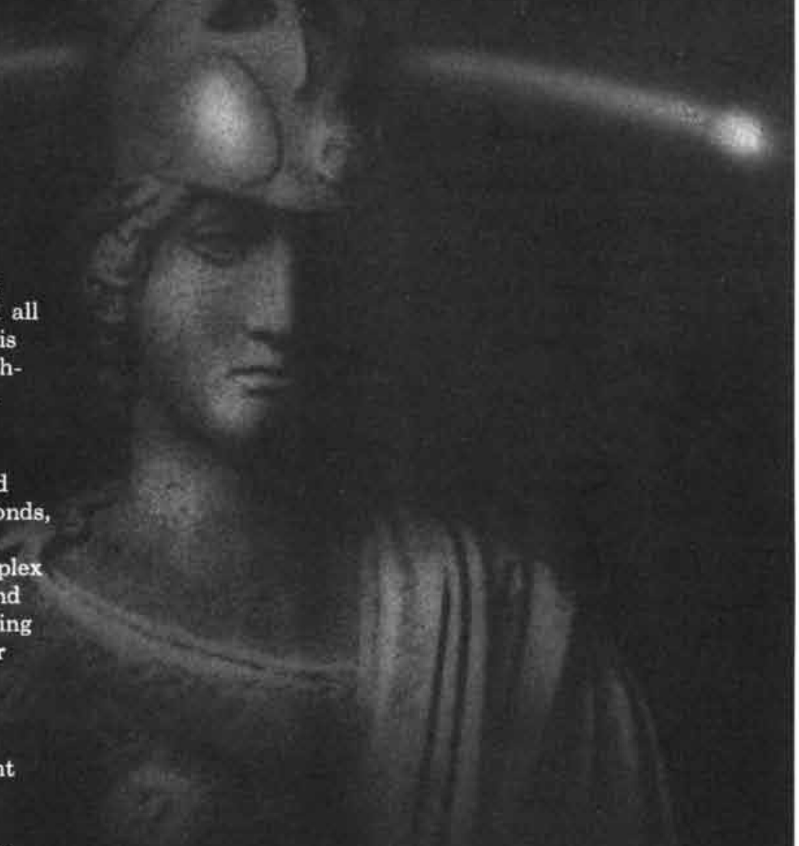
"The magnetic field was provided by a short coil placed symmetrically around the axis of the vacuum chamber. Wire for the magnet was contributed by A. S. Sheldon, president of the Kennecott Wire and Cable Company. Fortunately it arrived late in 1955, just as we had run out of money again. By this time the instrument was complete except for the magnet and the final assembly of the vacuum system, so we set to work on the coil immediately. It was a job we did not anticipate with relish, because the coil required some 380 pounds of wire. For a time we thought we would have to wind it by hand. Through the cooperation of our principal, however, we were given access to a lathe at a local trade school. Even so the job required 120 man-hours to complete. Each layer of wire had to be placed neatly atop the one beneath it so that the coil would not spread out at the top. Any spreading would distort the magnetic field and decrease the efficiency of the instrument. In all we wound some 18,500 feet of No. 12 magnet wire on a form which consisted of an aluminum tube six inches long and eight inches in diameter. The tube was made into a spool by welding circular plates to its ends. There were 70 layers, each of 78 turns—making a total of 5,460 turns. The coil could take a continuous current of about five amperes without overheating. It generated a field of more than 1,000 gauss at the center of the chamber. This enabled us to focus beta particles with energies of more than two million electron volts.

"The coil functions as a lens. Hence we took extreme care to make sure that it was centered accurately between the source and the focal point and that the axis of the magnetic field coincided precisely with that of the vacuum chamber. The mounting which determined the position of the coil consisted of two concave rollers which rode on the upper surface of the vacuum chamber. The rollers were supported by bearings held in position by a system of cams. The horizontal position of the coil with respect to the source and the focus could be altered merely by pushing the coil along the vacuum chamber. Vertical and lateral adjustments were easily made by changing the settings of the cams.

"The momentum of the focused particles varies in proportion to the current passing through the coil. Fluctuations in the current are therefore reflected in the performance of the lens. A major problem consisted in providing the coil with a source of ripple-free direct current. A motor-generator set was finally located, but we discovered that our power line was not large enough to carry the load. Our principal again came to the rescue and provided the necessary wiring at the expense of the school. Jack Orth of the cyclotron staff at the University helped us with the design of a voltage regulator. This unit maintained the output of the generator constant to one part in a thousand.

"The three baffles were made of aluminum plate 1/4 inch thick. The hole in the baffle nearest the source is four inches in diameter. The ring-shaped opening in the center baffle is 1/4 inch wide. The third baffle, like the first, is perforated with a four-inch hole. The

ATHENA



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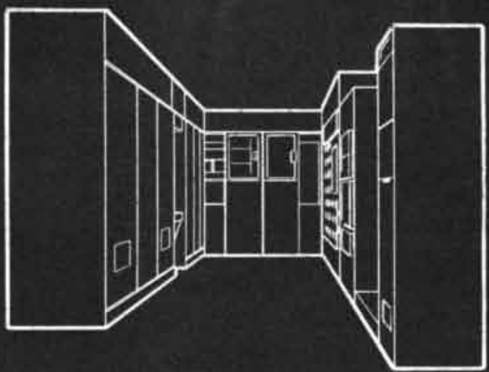

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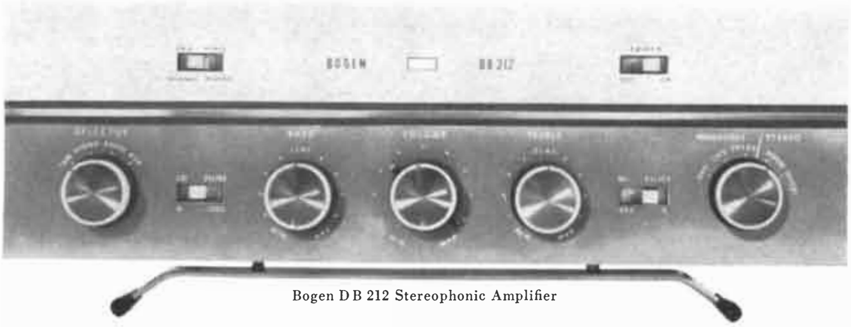

inner edge of the ring-shaped opening of the third baffle is formed by the lead cylinder of the gamma-ray shield [*see illustration on page 204*]. The components of the baffle system were mounted rigidly on three longitudinal rods of 3/16-inch aluminum.

"The instrument was completed and ready for calibration in January, 1956. For a calibration source we used thorium B, a naturally radioactive isotope. This material has a half-life of 10.6 hours and the F line has been established at 1,385 gauss-centimeters, the unit in which the momentum of beta particles is measured. The thorium sample, provided by the University, was applied to a disk of aluminum and anchored in place by a thin coating of Zapon lacquer. The disk was then inserted in the source holder and screwed into the source end-plate. After the vacuum chamber had been pumped down, current was applied to the coil and increased in equal amounts from zero to five amperes, as measured by a standard potentiometer circuit. Simultaneous readings of the beta-ray activity were taken and subsequently plotted as shown in the accompanying illustration [*see page 206*]. This same plot provided data for computing the resolution of the instrument: its capacity to bring beta rays of the same energy to the same focus, and to discriminate against those in other energy bands. The resolution was found to be 6 per cent—not quite as good as our design calculations had led us to expect but satisfactory for an instrument of this type and size.

"In the months remaining before graduation we made studies of various radioactive isotopes as a further check on the instrument's performance. The isotopes included cesium 137, cesium 134 and iodine 131. The specimens were mounted on disks of aluminum, nylon or rubber. When aluminum foil was used, as in most instances, the source was applied in liquid form and dried on the foil. The resulting crystals were then covered with Zapon to keep them from spilling.

"Our project brought us many unexpected and pleasant experiences. One day in the spring of 1956, for example, we received a call from the principal's office ordering us to report immediately. We could only wonder on the way down what we had done this time. The principal met us with a smile and explained that some engineering officials of the Boeing Airplane Company had invited us to lunch the following day. There we met Gil Hollingsworth, associate director of research, and a group of his fel-

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low-executives. One consequence of this visit was summer jobs with the physical research staff of Boeing's Seattle Division—not only that summer but every summer since.

"At the completion of our senior year we were faced with the final problem of disposing of the spectrometer. No one was left at the high school to carry on the project, so we gave the instrument to the University. There it is now in constant use.

"We feel that we learned a lot from the project, not only in learning how to solve technical problems but also in the art of working with other people. We hope this account of our experience will stimulate others to embark on a similar adventure."

Dexter H. Howard, assistant professor of infectious diseases at the University of California Medical School, feels that this department was too cautious in its March article about the cultivation of bacteria.

"May I take this opportunity," Howard writes, "to congratulate you on the article appearing in 'The Amateur Scientist' for March. This was certainly a much-needed introduction to an area of biology often overlooked by the amateur. When I had occasion a few years back to introduce a layman to the field of microbiology as a hobby, I chose a series of experiments much like those described in your article.

"There was one statement, however, which somewhat marred an otherwise very fine presentation. This statement, far from attracting interest, might easily serve to repel a person from undertaking bacteriology as a pastime. I am referring to the passage in which you warn the amateur not to expose a culture medium to airborne organisms and incubate the result. You state that this is dangerous because the amateur 'is likely to capture and cultivate deadly disease organisms.' This is in error, for it is almost impossible that 'deadly disease organisms' would be found in the immediate environment of an amateur experimenter. If he never intentionally introduces them into his laboratory, there is little likelihood of their ever getting there by chance to be cultured. Moreover, the medium recommended in the article probably would not support the growth of most highly pathogenic microbes. If there were any dangerous pathogens, then the experimenter would have just as much opportunity to breathe them in or swallow them as he would to culture them by mistake on his non-enriched nutrient agar."

WARHEAD

circa 400 A. D.

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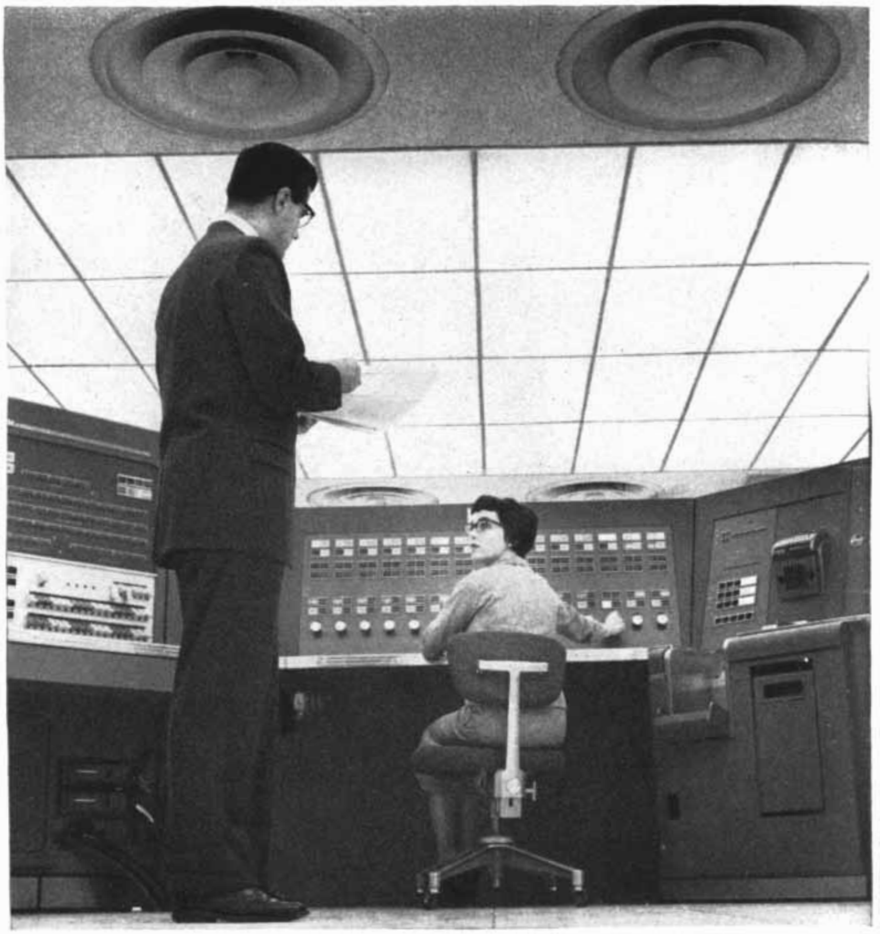
Should your child be a Mathematician?

by NORRIS E. SHEPPARD
Professor of Mathematics,
University of Toronto
(As told to DONALD ROBINSON)



Today, electronic "brains" such as the computer shown above can save months of human calculations in solving a problem. But the mathematician must first work out the complex details of the problem to be fed the computer, then put the answers to practical use.

THE BOY who chooses mathematics as a career will be joining illustrious company. He will become a colleague of Euclid, Descartes and Gauss. He will be walking with the great Johannes Kepler who figured out the three laws that govern the planets' movements around the sun; with Sir Isaac Newton who explained gravity in one mathematical formula; with Albert Einstein who postulated the magnificent theory of relativity that unlocked this atomic age.

Could one follow in more golden footsteps?

The actual associates whom the boy will have in his life as a mathematician will be distinguished, too. He may rub shoulders with the men who have helped to give the world radar, supersonic flight, and nuclear power for industrial use.

Could one want more exciting, stimulating partners?

Most important, the boy who makes mathematics his field has a chance to achieve greatness himself. Some people have a notion that mathematics is a dead science. They think that all its problems have been solved and tucked away in dry textbooks.

That isn't so.

There are vast, vital areas in mathematics awaiting exploration by deep mathematical thinkers. I feel certain, for example, that within our lifetime someone is going to make great forward strides toward understanding the behavior of the tiny particles of energy of which all matter is composed.

It could be your son or daughter.

Someone surely is going to work out the mathematical formulas that will enable mankind to travel safely to Mars and far beyond into distant space.

It could be your son or daughter.

Can you think of a more important, thrilling arena for a qualified individual to enter today? Recognition among science's immortals is within the realm of possibility for genuinely gifted boys and girls.

I can assure you of this as well. The young mathematician will receive the heartiest of welcomes in his profession. We have a crying need for new people. Excluding secondary school teachers, the total number of persons with college degrees or their equivalent who are earning a living as professional mathematicians in the United States and Canada is under 25,000. That is, fewer than one person in every 7,000.

The shortage of mathematicians is acute in every sphere. Universities, industrial companies, insurance firms, other businesses, and governmental agencies are all hungry for mathematically trained personnel. Job openings are plentiful both in Canada and the United States.

But this I warn you. To get ahead in mathematics, a youngster must be good.

A noted mathematician who holds a high-ranking position in industry remarked recently,

"No one wants the advice of mediocrity. Among mathematicians, there is no place for the so-called average man."

I fully agree with him.

The youngster who goes into mathematics will be taking up the oldest and one of the noblest of sciences. It is more than the science of numbers. It is even more than a science that allows us to grasp the real significance of time and space. It is the science which trains a man to cope with unknown quantities and to translate their relationships into logical, comprehensible patterns.

A wide variety of specialities is available to the new mathematician. Research in pure mathematics is one. Here a man seeks basic truths with no thought of any use to which they may be put. To the pure mathematician, truth is its own justification.

Such work may sound valueless to some people. They are wrong. Most of the practical mathematical tools now at our disposal came to us from these basic truths. As time went on, someone discovered an application for them.

It was that way with James Clerk Maxwell's theory of electro-magnetic waves. When Professor Maxwell first brought it forth in 1873, he wasn't thinking of TV broadcasts. But his theory made them possible. It explained the nature of radio waves.

As a rule, pure research of this sort is done at universities in conjunction with teaching. The young man interested in it usually starts as an instructor in the mathematics department.

A person who wants only to teach, and not to concern himself with research, can get a university post, too, of course. Or, should he prefer, he can obtain a place in secondary schools. The contribution he may make there cannot be overestimated.

For the man who likes immediate, practical results from his research, there is applied mathematics. In this he can employ established mathematical techniques to help resolve particular scientific and industrial problems.

More and more, Government and industrial organizations are turning to mathematicians for assistance along these lines. In the airplane field, for instance, mathematicians are working on turbulence, vibrations and stability, rocket propulsion. In oil, they are involved in reservoir studies, seismological investigations, questions of magnetics.

The fact is that a competent mathematician can be worth his weight in gold to an industrial concern. With his calculus and other techniques he can often predetermine the effects of various operations. This means that his company may not have to spend fortunes to run expensive experiments. The mathematician is often able to indicate the results in advance.

The mathematician is particularly useful during the very early stages of a project. He is the man with the coldly analytical viewpoint who sees where the major problems lie and is able to spell them out in terms that permit a solution.

When work commenced on Nike, the United States Army's crack anti-aircraft missile, a team of top experts was collected from the aerodynamic, radar, digital, circuitry and related fields. Plus the military. They were unable to move, however, until the mathematicians outlined the way.

Why?

It took mathematicians to spot the essential ideas that lay obscured among the many details and divergent languages of the other sciences.

"Frankly," a member of the Nike team has said, "if it hadn't been for the mathematicians, it would have taken us years more, perhaps decades, to perfect Nike."

Today the applied mathematician has a splendid ally in the electronic computer—the fabulous machine that can make 3,600,000 different computations in a single minute.

Don't be confused by these electronic "brains," though. They don't do the thinking. The mathematicians do. It is the mathematicians who define the problems, divide them into their component parts and prepare instructions for the computer so that it can solve them.

Another big field for mathematicians is statistics—the collection and interpretation of facts on a mathematical basis. It is also a highly challenging field.

Take government censuses. It is statisticians who design and direct them, and who interpret the findings.

Take government figures on foreign trade, business conditions, wage levels, cost-of-living, public health. It is statisticians who provide them.

Governments couldn't function without them.

Nor could industry. Statisticians keep management abreast of what's happening in a company. They develop statistical facts on production methods, distribution programs, sales trends and lots more. They are especially good at quality control. The systems they devise make it feasible for manufacturers to inspect just a few items going down the production line instead of every one.

Then there's polling. It's hard to believe, I suppose, that one can gauge the opinion of tens of millions of people by sampling merely 2,000 or 3,000. Thanks to the statisticians, it usually can be done with reasonable accuracy.

Is it any wonder that statistics is called "the arithmetic of human welfare"?

Finally, we reach my own specialty—that of the actuary. In the life insurance business the actuary is indispensable.

The actuary is the mathematical pilot of a life insurance company. He prepares the tables of death rates and calculates the premiums that must be charged. He determines the benefits that go into policies. He reckons the money that must be laid aside to provide for payment of these benefits in the years to come. He even determines the amount of dividends to be paid out.

His is a full desk.

Actuaries are important in government, too. The operation of our Canadian and American social security systems depends on them. And they can be found in private practice, where they act as consultants to various welfare and pension funds.

It is a very gratifying profession. You do so much good toward protecting people's futures.

I remember when I was called in as one of a three-man board to evolve a pension program for the employees of the United Nations—thousands of them. Our assignment was to develop a basis whereby these people, who'd come from the four corners of the globe to work for world peace, would be assured security in their old age.

It required weeks of hard labor, but eventually we arrived at a plan that did the job.

"The United Nations is deeply grateful," we were told.

Could one wish for higher recompense?

Naturally, you'd like to know the financial prospects for mathematicians. I would say that, in the main, they're excellent.

A college teacher of mathematics, with a Ph.D., generally begins at about $3,000 a year and may go up to $18,000. In addition, he is frequently requested to do consulting work during summer vacations. This can add thousands to his income. The earnings of a high school mathematics teacher are, unfortunately, lower. The ceiling is about $8,400. He may pass the $10,000 mark as a principal, however.

In industry, an applied mathematician, with a Ph.D., can start at $7,200 and soar to $30,000. Or more. In government service the wage scales are understandably less. They run between $3,100 and $14,000 in the United States, between $3,750 and $12,000 in Canada.

Actuarial salaries in life insurance companies can be especially good. The college graduate with a B.A. and the necessary qualifications can anticipate earning about $4,500 at the outset and worthwhile increases thereafter. Chief Actuaries may make as much as $35,000 a year. Some have gone even higher. They have risen to be presidents of life insurance companies with annual salaries of $75,000, $100,000 or even more.

No matter which field the mathematician enters, he can count on a high degree of security. Pension programs are widespread, and personnel turnover is small. The hours are not arduous, vacations are ample and the life is a pleasant one. Best of all, mathematicians enjoy the respect of their fellow-scientists and the public at large.

To be sure, there are drawbacks. If you do original research, you stand the chance of having your findings neglected. Big ideas can linger unrecognized for long periods. That can be a miserable experience.

Sometimes the problems you must tackle, in pure or applied research, are so mammoth in scope, so herculean, that they seem overwhelming. You become very discouraged.

"Oh, how I wish I'd never started on this!" I heard a researcher say the other day.

I understood just how he felt.

I said before that a person must be good to get ahead in mathematics. It is very true, and I would urge you to weigh carefully whether your child has the proper qualifications. Does he have a keen, logical mind and an insatiable curiosity? Is he imaginative? Does he relish mathematics courses and earn top grades in them? Is he quick at solving mathematical problems in his head?

The answers to all these questions should be a rousing "Yes!"

In addition, he should be the kind who won't accept any textbook answer as the final word on anything. He should know instinctively that there are no pat answers to most questions and should constantly seek different ways of doing things. Always your child should look on every new subject as a challenge.

What about girls?

Many women are in the field. There are good opportunities for them in statistical research positions with corporations. As a matter of fact, in the American Statistical Association, they make up ten per cent of the membership. There is a very urgent need for properly qualified teachers of mathematics, particularly in high schools. Women who have specialized in mathematics can be of real help in this area. It is, of course, a fact that while many women have the necessary talents to become successful mathematicians, few of them continue in this work long enough to reach the top in research or industry.

So far as education for a mathematical career is concerned, I would say the more of it the better. A Ph.D. is now almost imperative both in industry and the academic world. It helps in the actuarial profession, too, though it is not a prerequisite there. To achieve full professional status as an actuary, you have to pass a series of stringent examinations given by the Society of Actuaries or the Casualty Actuarial Society, in the United States and Canada. Graduate school training will help you through them.

Unquestionably, the six or seven years of schooling necessary for a Ph.D. can be expensive. When you include board and lodging as well as tuition, it can cost $15,000. However, large numbers of scholarships and fellowships are available. So many that there is no good financial reason why a talented student should have to go without the education he needs for success.

While we are on the subject of education, let me say this, too. Even if your child does not wish to become a mathematician, I would recommend that he take as much mathematics as he can, both in high school and in college. No matter what career your child embraces, the training in analysis and logical thinking which mathematics gives will prove invaluable to him in later life.

However, I hope that your child wants to be a mathematician. Mankind is now in the atomic age. We're on the verge of the space age. Mathematicians can guide our way. We need more of them—desperately—to broaden our horizons and to keep us free.

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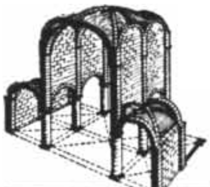

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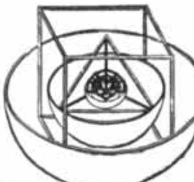

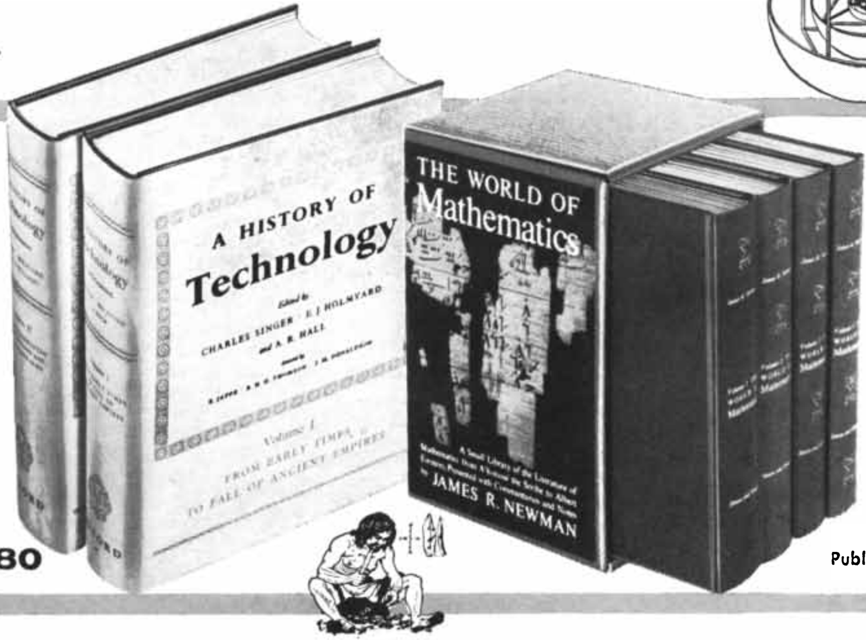

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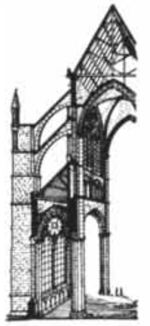

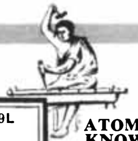

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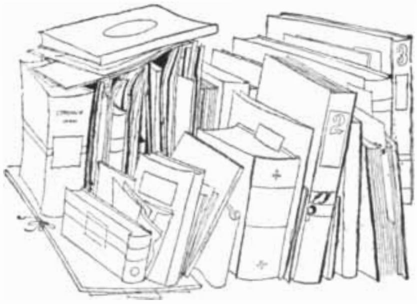

BOOKS

A book which discusses the philosophical impact of a profound innovation in physics

by Victor F. Weisskopf

Physics and Philosophy: The Revolution in Modern Science, by Werner Heisenberg. Harper & Brothers ($4).

The development of modern science during the past 300 years has worked revolutionary changes in every aspect of human life. The culmination of this development is modern physics. Thus any critical study of the significance of modern physical concepts automatically deals with the burning questions of our time. A book on physics and philosophy by one of the founders of the most important branch of modern physics—quantum mechanics—should engage the interest of anyone who wants to know what is going on in the heads of those two-legged animals which have so thoroughly changed the surface of the earth. Parts of the book are not easy to read. The chapter on quantum theory and the theory of relativity require a prior acquaintance with these problems. However, Heisenberg's clear and easy style, his untiring search for the right formulations, even his schoolmasterish repetitions, will be a great help to the general reader.

The book deals with two questions. The first has to do with the ways in which man has tried to explain the world around him. The other concerns the influence of man's ideas about the world upon his way of life. Heisenberg is much more effective in dealing with the first question. There are only a few chapters which come to grips with the second question, and they tend to fall a bit flat.

The book really begins with its second chapter: the history of quantum theory. (The first chapter is little more than an introduction.) Here we are immediately confronted with the central theme: What is the significance of the new phenomena discovered in quantum physics? What do they tell us about nature in general? Do these unexpected and strange phenomena correspond to "reality"? If so, in what sense? It is fascinating to read about the first impact these discoveries had upon physicists. Heisenberg has asked himself repeatedly: "Can nature possibly be as absurd as it seemed to us in these atomic experiments?"

The facts that seemed so absurd to him were the result of experiments which showed that particles behaved like waves, that light waves behaved like particles, and that the orbits of electrons, which according to pre-quantum mechanics should be deformed by any small perturbation, were actually remarkably stable. In spite of bewildering and seemingly contradictory findings of this kind, the physicists of that time were able to develop a mathematical formalism—quantum mechanics—which reproduced all the observed facts of atomic behavior with stunning accuracy. Furthermore, the same formalism opened up new avenues of understanding when it turned out that it contained the description of phenomena which had not been understood before. The nature of the chemical bond, the structure of crystals, the properties of metals and many other things could be explained by means of quantum mechanics. All these phenomena are revealed as the effects of simple electric attraction and repulsion between atomic nuclei and electrons. This great variety of phenomena could be reduced to simple electric forces because of the fact that quantum mechanics provided many more stable states of matter than classical mechanics could. The few years after 1926 were golden times for theoretical physicists; every Ph.D. thesis opened up a new field in which quantum mechanics could be applied.

Heisenberg is not so much concerned with the successes of quantum-mechanical formalism. He wants to discuss the problems of this formalism, and what it means and implies. Quantum mechanics contains the concept of probability at a very fundamental level. In quantum mechanics certain statements must in principle remain inexact. For example, one cannot predict the position of an electron in an atom, or the time at which a radioactive nucleus decays. Furthermore, the particle-wave duality prevents the use of mechanical atomic models, such as the model which represents the atom as a small solar system. Obviously we cannot picture an electron as a small particle circling around the nucleus if we are forced to ascribe certain wave properties to it. To use Heisenberg's words: "By playing with both pictures (particle and wave), by going from one picture to the other and back again, we finally get the right impression of the strange kind of reality behind our atomic experiments."

The nature of this new kind of reality is Heisenberg's central topic. The parts of the book devoted to it are probably the best available account of the current interpretation of quantum mechanics. Heisenberg presents two main ideas, the first of which follows:

We speak of physical observations only by using well-known concepts of classical physics, such as "particle," "position," "velocity," "energy," "wave" and so on. This is the language we use to describe the experimental setting and communicate the results of our experiments. Unfortunately the "atomic reality" within the small confines of atomic dimensions does not conform to this language; the classical concepts are not appropriate for its description. This lack of propriety manifests itself in the fact that from the classical standpoint the results of our experiments seem contradictory.

For example, when we experiment with an electron in one setting, it behaves like a wave, and when we experiment with it in another setting, it behaves like a particle. This is a contradiction as long as we admit only classical physics. Actually it is nothing but a description of the actual "atomic reality." For this situation Niels Bohr has coined the term complementarity.

The second of Heisenberg's main ideas is that atomic events have a certain individuality or "wholeness." They cannot be divided in time or in space into successive or parallel events. Hence some aspects of the interaction between the object and the apparatus remain uncontrolled. One example is the lowest energy state of an atom, in which the wholeness manifests itself by the impossibility of ascribing to the electron a definite position in its "orbit." In fact, every observation of that position would inevitably destroy the energy state and all its characteristic properties. Another example is the case of a quantum of light diffracted by a screen perforated with two slits. It makes no sense to ask which slit the quantum went through. One must consider the phenomenon as a whole. If one sets up an experiment to determine which slit the quantum went through, the character of the phenomenon is completely changed. One has destroyed its individuality. Obviously such conditions would give rise to situations in which the exact prediction of certain experimental results would be impossible. The complete determination, in the classical sense, of the state of an atom is impossible because the state would change its character; when examined, it would not remain the state which was to be examined. It should be noted that this state of affairs is by no means purely negative. It is true that we have lost the possibility of completely describing the phenomenon, but we have gained the possibility of including in our description wholly new features which would have been contradictory within a classical framework.

These intricate interrelations between observation and object form the basis of quantum-mechanical complementarity. Heisenberg says: "We have to remember that what we observe is not nature in itself, but nature exposed to our method of questioning." Since the questioning can only be done in the language of classical physics, and since this language is not appropriate to the object, the answers to our questioning are sometimes strange. If you ask inappropriate questions, you will get inappropriate answers!

The reviewer does not quite agree with Heisenberg's evaluation of "atomic reality." In the reviewer's mind this reality is as good as any other concept of reality. It obviously exists in nature, and we can be proud of having discovered it despite its elusive character. Heisenberg states: "But the atoms or the elementary particles themselves are not as real [as the phenomena of daily life]; they form a world of potentialities or possibilities rather than one of things or facts." Of course what we call "real" is always a matter of definition. Heisenberg wants to reserve that term for events that can be completely described by classical language. However, this restriction of reality may have the disadvantage that it sets atomic phenomena in a frame of unreality or subjectivity which they do not deserve. The fact that atomic phenomena are hard to catch and hard to describe does not make them less real.

A number of most interesting problems are raised in a chapter in which Heisenberg gives an account of the Greek philosophy of nature. How did various Greek philosophers view the question of what the world is made of? Heisenberg compares some of these ideas with our modern views on matter, and finds certain parallels. For example, Heraclitus maintained that the substance of everything is "fire," and all things we see are simply different forms of fire. This notion can be compared with the modern concept of "energy." Plato's idea was that the four fundamental elements—earth, air, fire and water—are made up of smallest parts which have simple regular shapes: cubes, octahedrons, tetrahedrons and dodecahedrons. Plato was struck by the fact that although there appear to be only four elements, there is a fifth simple regular solid—the icosahedron. He was led to the conclusion that "there was yet a fifth entity which God used in his design of the universe." This type of conclusion is strongly reminiscent of some modern theoretical methods, in which symmetries in the fundamental equations are related to new physical concepts. One might think of the way in which P. A. M. Dirac has recognized the spin of the electron as an expression of a special property of the electron wave-function.

Heisenberg adds a warning to this chapter. The comparison of Greek thought and modern physics should not imply that the Greek philosophers had a special intuition for finding scientific truths without the detailed experimentation of modern science. The Greek philosophical concepts cannot be compared with the concepts of modern science, which are tested by experience. Heisenberg might have given greater weight to a more fundamental difference between these philosophic ideas and the findings of modern science. In the minds of the Greek philosophers there was a final and definite answer to the question of the constitution of matter. They presupposed the existence of a definitive, all-embracing idea with which one could explain every phenomenon that would ever be observed. The results of modern science do not encourage us to believe

that such an idea exists, let alone that we ever will discover it. The deeper we look into nature, the more new phenomena we find. We must consider ourselves extremely lucky to have understood a good part of what we have perceived so far. There is not the slightest reason to believe that the laws which govern what we know today will also apply to what we may be fortunate enough to discover tomorrow.

In view of the fact that undiscovered phenomena must deeply influence what we presently observe, how do we make sense out of the physical world? The answer to this question is connected with an important fact of quantum theory: Most phenomena are apparent only at a certain threshold of energy. For example, atoms which encounter each other at low energy behave like billiard balls; their complicated interiors come into play only at higher energies. In the same way the nucleus of the atom acts like a billiard ball until it is involved in processes which require energy of more than 100,000 electron volts. And so it goes. The finer treats of nature are hidden behind higher energy-thresholds, and do not interfere with the run of events at lower energies. It is only because of this circumstance that we have been able to recognize what is going on in nature. We have had the luxury of being able to proceed step by step.

It is very unlikely that the evolution of our knowledge of the physical world will stop at a certain energy level, and that no new physical fact will turn up which we could not have predicted on the basis of what we know today. If this were so, we should have attained a final knowledge of matter, a fundamental key to the understanding of the universe. This is just what the Greeks dreamed of. Heisenberg seems to believe that the dream may someday be realized. He even tells us what kind of fundamental law of motion we might expect. This view would seem to contradict not only all previous experience, but also the widely held belief that nature is inexhaustible. Infinite possibilities of new and unexpected phenomena are probably hidden in the regions of still-unattained energies. How presumptuous of man to believe that he can fathom all possible phenomena within a construction of his mind!

Heisenberg's discussion of the development of scientific thought after the Renaissance centers around the ideas of Descartes. This philosopher is held responsible for the separation in natural philosophy of the subject and the object. He introduced a polarity between the *res cogitans* and the *res extensa*, the former being the mind and the latter the world of matter as an object of consideration by the mind. This polarity governed the development of science up to the advent of quantum mechanics: nature, the object of mind, was considered completely describable and understandable without any reference to the process of observation. This is the basic premise of the naive scientific attitude, and it is deeply anchored in the thinking of all scientifically minded people. It is only lately that quantum mechanics has undermined this point of view: "Natural science does not simply describe and explain nature; it is a part in the interplay between nature and ourselves; it describes nature as exposed to our method of questioning." Still, the Cartesian partition into subject and object has had an overriding influence upon the minds of all thinking people during the last three centuries. This is why we suffer such difficulties when we are confronted with the new "atomic reality."

As a revolution against the complete segregation of the observer and the real world, Locke, Berkeley and Hume introduced the empirical philosophy in which the external world is reduced to an aggregate of our perceptions and sensations. On this view the existence of a "real reality" behind our impressions is doubtful, since such a reality cannot accurately be defined. These skeptical trends of thought led to modern positivism, according to which one should thoroughly examine every simple concept by means of high-powered logical methods before making use of it. Heisenberg has little sympathy with the positivist point of view. He admits the usefulness of a critical attitude toward the naive use of concepts which do not have a well-defined meaning. But he opposes the trend toward discarding all concepts whose logical definition is not complete. At the frontiers of science new concepts must be tried out and old definitions must lose their validity. One never knows what limitations will be placed on the applicability of old concepts by the extension of our knowledge into new realms of nature. A question that is logically senseless in one frame of reference might become sensible in a new and unexpected context. Heisenberg says: "Insistence on the postulate of complete logical clarification would make [the progress of] science impossible. We are reminded here by modern physics of the old wisdom that the one who insists on

KAPL Metallurgist Richard L. Mehan taking a reading on a Zirconium alloy specimen being tested in a special strain-fatigue apparatus. Conceived, developed and built at KAPL, this new apparatus makes it possible to control and measure elastic and plastic strain developed in reactor materials under test. Conventional equipment controls only stress and strain within the elastic region.

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Richard L. Mehan is one of several metallurgists working on the development of new and more reliable reactor materials at KAPL. Dick Mehan joined General Electric after graduation from MIT in 1950 and came to KAPL in 1953, following two years of army service. He is also studying advanced metallurgy, evenings at Rensselaer Polytechnic Institute under G.E.'s advanced degree program.

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never uttering an error must remain silent."

Heisenberg also discusses the relationship of physics and the biological sciences. He restricts himself to a description of different views on the question of whether the phenomena of life require some fundamentally new concepts which are not describable in the language of modern physics. He does not take sides on this question, but he adds a timely warning: "One should perhaps not enter into speculations about the possible structure of sets of concepts that have not yet been formed."

A whole chapter of the book is devoted to the numerous attacks upon the current interpretation of quantum mechanics. As one might expect, Heisenberg disagrees sharply with the attackers and rejects every attempt to cast some doubt on the validity of the so-called Copenhagen interpretation. One of these attacks, by David Bohm, was recently published in the form of a book entitled *Causality and Chance in Modern Physics* and was reviewed by James R. Newman in the January issue of SCIENTIFIC AMERICAN. Heisenberg would certainly disagree with Newman's statement: "In this century the professional philosophers have let the physicists get away with murder. It is a safe bet that no other group of scientists could have passed off and gained acceptance for such an extraordinary principle as complementarity, nor succeeded in elevating indeterminacy to a universal law."

The famous principle of indeterminacy is not as negative as it appears. It limits the applicability of classical concepts to atomic events in order to make room for new phenomena such as the wave-particle duality. The uncertainty principle has made our understanding richer, not poorer; it permits us to include atomic reality in the framework of classical concepts. To quote from *Hamlet:* "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy."

Still, we who side with Heisenberg on this issue should not take lightly the arguments of so many learned people inside and outside the circle of physicists. We should worry about the fact that these people are deeply dissatisfied with the Copenhagen interpretation of quantum mechanics, and that they consider it to be, in Newman's words, "high-flown obscurantism." They suggest that "something is rotten in the state of Denmark." We certainly do not believe so. We are convinced that it is not the substance which should be blamed, but rather the form in which it has been presented. New attempts to interpret quantum mechanics should be tried more often. Heisenberg's book is a splendid example.

Short Reviews

MECHANICAL RESOLUTION OF LINGUISTIC PROBLEMS, by Andrew D. Booth, L. Brandwood and J. P. Cleve. Academic Press, Inc. ($9.80). The use of a machine to translate one language into another was, as stated in the introduction to this book, first suggested by one of the authors (Booth) in conversations with Warren Weaver in New York in 1946. At the time the problem "was simply an intellectual exercise directed at finding yet another use for the new high-speed digital calculators, which were just coming into existence." Soon afterwards a number of investigators devoted effort to the expansion of this work. At the Institute for Advanced Study, Booth and K. H. V. Britten produced a program enabling a calculator to make use of a dictionary stored in its "memory," so that words presented to the machine on a teletype input could be looked up. Later developments consisted of, among other things, improvements in the dictionary, which was to hold stems and endings rather than whole words; analyses of language syntax to facilitate the computer's capacity to digest a vocabulary; large-scale analyses of word frequency and word meanings in several languages; the construction of a logarithmic method for dictionary search, which makes it possible to define the position of any given word in a million-word dictionary in 20 "look-up operations," instead of the half million operations originally required. A good deal of work on machine translation, using the *Apex C* computer, was done at Birkbeck College, University of London, and the present book contains an account of some of the results which have been obtained. Apart from making translations, computers have been used to construct the frequency analyses required in mechanical translation; to assemble concordances for given texts (the International Business Machines Corporation is preparing a concordance for the works of Thomas Aquinas); to make stylistic analyses of literary works for the purpose of dating them or establishing authorship; to cross-reference libraries, index scientific and other information, and examine certain problems of mathematical logic. An interesting elementary application of a machine to linguistic analyses, in particular to the making of word counts, resulted in the vindication of the Estoup-Zipf law, first propounded in 1916 by J. B. Estoup. According to this law, if in a large segment of text the different words are numbered, and after each word the number of times it occurs is recorded; then if the words are arranged in order of frequency of occurrence (starting with the most frequent and proceeding to the least frequent), and the order of occurrence is called the rank, *R*, and the frequency, *F*, it has been discovered that the product $R \times F$ is very nearly constant. To illustrate, there are, as a machine count has shown, 260,430 words in James Joyce's *Ulysses;* this total contains 29,899 different words. The most frequent word appears about 26,000 times, and throughout the rank-frequency table $R \times F$ is approximately 26,000. Examination has demonstrated that this holds not only for *Ulysses*, but for such rather different works as U. S. newspapers and Homer's *Iliad*. The authors state that the British and the Russians have already devised valid methods of machine translation, but that the U. S. "has been particularly backward" in the testing of translation routines on any actual machine.

THE RELATIVISTIC GAS, by J. L. Synge. Interscience Publishers, Inc. ($4.50). The purpose of this book, a supplement to the author's admirable work on the special theory of relativity, is to develop some formulas for a relativistic gas, that is, "a system of material particles (and perhaps photons) which, by elastic collisions between them, take up certain equilibrium distributions." Synge points out the difficulties of passing from statistical mechanics based on Newtonian laws to mechanics based on relativistic laws. He has taken what is apparently the only possible course, namely "to treat molecules and photons as moving mathematical points of no size at all, interacting only by direct collision." How, one asks, can points collide? The author admits that this is a mystery which he cannot solve; instead, he cheerfully accepts it, reminding us that the theoretical physicist today does not expect his models to mirror nature, and is quite content if, despite their anomalies, the models help him occasionally to make accurate predictions. Moreover, if the ordinary principle of causality is laid aside in microphysics, it is possible to think of the gas particles "as in some way 'fated' to collide," especially if we regard the universe as "a statical thing in space-time, the histories of the particles appearing as a network of world lines, set timelessly before us." Synge admits using a paradox to circumvent a mystery—causality "keeps asserting itself"—but he offers his view tentatively until someone brings forward a simple, satisfactory relativistic treatment of interacting particles.

CULTURAL FOUNDATIONS OF INDUSTRIAL CIVILIZATION, by John U. Nef. Cambridge University Press ($4). A well-known economic historian devotes these lectures to showing that the origins of our industrial civilization cannot be solely explained in terms of economic growth and the advance of technology. This is an intriguing position, but the author never fully establishes it. He discusses the growing emphasis in the 16th and 17th centuries on quantitative thinking, measurement and statistical records; the advances in the use of mathematics as a scientific tool; the rise of empirical science. What he says about these matters is unobjectionable, but it has all been said before, and one's general impression is that in discussing the history of science the author is out of his depth. He is at home when he describes the exploitation of ores and minerals and the beginnings of mining, metallurgy and other industries—subjects to which he has given many years of study. The least satisfactory aspect of his book is the attempt to support the central argument: that changing attitudes toward art, religion, ethical and social values contributed as significantly to the making of industrial civilization as did technology and science. That the understanding of man as a whole is more important than the understanding of productivity statistics or steam engines or quantum theory requires no sermon. What one looks for in Nef's survey is some explanation of why broad changes in human values took place, and of the interrelation between these changes and the changes in economics, technology and science. This explanation is not forthcoming.

STUDIES IN ANCIENT TECHNOLOGY: VOL. V, by R. J. Forbes. W. S. Heinman ($6.50). This little volume, which continues the author's series of monographs on the history of ancient technology, describes the evolution of the manufacture of leather, honey and sugar, and glass. Forbes is careful and clear in his explanations of methods and processes; he is invariably interesting in his choice of material; he masters the literature. The illustrations are excellent. Criticism has been directed against details of his studies, but too often it is piddling criticism. These are valuable books, whatever their occasional shortcomings.

THE SOURCES OF INVENTION, by John Jewkes, David Sawers and Richard Stillerman. St. Martin's Press ($6.75). Another attempt, this time by a University of Chicago Law School group, to explain the career of invention. Has the lone inventor of the 18th and 19th century who gave so much to technology "all but disappeared," as James Bryant Conant has stated? Is it reasonable to suggest that the future flow of inventions will come mainly from large research institutions and from "teams"? Are corporate research laboratories a fruitful source of invention? What effect has business monopoly on technical innovation? These are some of the questions with which the authors deal. They also present many scraps of information about the habits of inventors, and a series of case histories of inventions from automatic transmissions to zippers. All this doesn't add up to much of a book. Some of the omissions are astonishing: the Wright brothers, for example, don't even merit a place in the index. And if the authors have come to any conclusion, other than that no one can come to any conclusions about the sources of invention, their study gives no sign of it.

AFRICAN DISCOVERY, edited by Margery Perham and J. Simmons. Faber and Faber (30 shillings). A reprint, with corrections of minor errors, of a fascinating anthology from the works of the British explorers of Africa, covering the period from 1769 to 1873. The editorial comment is exemplary, the illustrations are perfect, and the selections are superb. The book is much too short, but if it were three times as long one would feel the same way.

AUTOMOBILE YEAR 1957-1958. Hanover House ($9.95). The 1958 edition of this colorful international annual is as delectable as ever. It contains the usual wide assortment of information in text and pictures about the year's major auto races, mountain and touring championships, new and old cars. As always, there are a few stunning hand-wrought models which would tempt almost anyone who cannot afford one—and that means practically everyone—to a life of high crimes and misdemeanors.

RUSSIAN-ENGLISH GLOSSARY OF NUCLEAR PHYSICS AND ENGINEERING, edited by I. Emin ($10); RUSSIAN-ENGLISH GLOSSARY OF ELECTRONICS AND PHYSICS, edited by P. Robeson, Jr. ($10).

Consultants Bureau, Inc. These paperbound volumes are preliminaries to a permanent Russian-English physics dictionary scheduled for publication in 1959. The glossary of nuclear physics compiles Russian terms and expressions found in journals and proceedings. Similar sources underly the glossary of electronics and physics, which also contains an appendix giving U. S. equivalents for Soviet vacuum-tube notation, measuring units, names of components and abbreviations.

Automation and Management, by James R. Bright. Harvard University Press ($10). This volume, reporting on a research program conducted at the Harvard Graduate School of Business Administration, is worth reading for its description of the automation programs of 13 plants in different industries, and its analysis of the experience of these installations. In automation, one discovers, things are not always what they seem, and the expected benefits and liabilities often come out quite topsy-turvy.

Jane's All the World's Aircraft 1957-58, compiled and edited by Leonard Bridgman. McGraw-Hill Book Company, Inc. ($30). The latest Jane's, "corrected to September 30, 1957," has hundreds of new illustrations and a wide assortment of fresh information on a subject which is in such a constant ferment that anything earlier than tomorrow's aeronautical news seems stale. Even the word aircraft, whatever the design, sounds outmoded: one awaits *Jane's All the World's Spacecraft.*

The Growth of Logical Thinking from Childhood to Adolescence, by Bärbel Inhelder and Jean Piaget. Basic Books, Inc. ($6.75). This essay derives from studies at the University of Geneva with some 1,500 boys and girls to determine the development of their reasoning powers. The children were asked to interpret experiments involving the equality of angles of incidence and reflection, the law of floating bodies, the oscillation of a pendulum, the inclined plane, conservation of motion, equilibrium, centrifugal force and other physical principles. The authors graded, classified and analyzed the results. Whatever merit the book may have is almost entirely buried in the presentation, which is ponderous and turgid.

A History of Industrial Chemistry, by F. Sherwood Taylor. Abelard-Schuman Limited ($7.50). This comprehensive work by the late director of the Science Museum in London is more a history of chemistry than of the industry itself. Industrial chemistry is broadly defined as "all modifications of the composition of matter that have been undertaken for profit or use." Large portions of the text are devoted to the history of chemical theory, rather than to applied aspects of the subject; moreover, the emphasis is on ideas rather than on personalities.

A Hundred Years of Philosophy, by John Passmore. The Macmillan Company ($5.25). A history of philosophy from John Stuart Mill to Ludwig Wittgenstein and existentialism. The emphasis is on the British development, although U. S. and Continental philosophers holding related ideas receive attention; the subjects most fully treated are logic, metaphysics and the theory of knowledge. Lucid, fresh, attractively written, this survey gives a comprehensive and comprehensible picture of a difficult period in a difficult field.

Science for All. Cambridge University Press ($2). This annotated reading list for the nonspecialist contains nearly 700 titles of books on the physical and biological sciences. Included are reference and review books, histories and biographies, books on scientific method and communication, in-print classics, popularizations of mathematics, physics, chemistry, astronomy, astronautics, meteorology, geology, oceanography, biology, biochemistry, physiology, botany, zoology, technology. Prepared in consultation with the British Association for the Advancement of Science, the list is a little more convenient for British than U. S. readers (for example, only British publishers are given); nevertheless the selections are fully representative and well described, and the book is an invaluable reference tool and buying guide for students, librarians, teachers, parents and anyone else seeking information on the popular literature of science.

Probability, Statistics and Truth, by Richard von Mises. The Macmillan Company ($5). An English translation of the third German edition, revised by the author in 1951, of a leading book on the foundations of probability and statistics. The late Richard von Mises was a vigorous proponent of the relative-frequency interpretation of probability. He considered relative frequency a quantitative measure of probability in the same sense that the length

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of a column of mercury is the measure of temperature. Though it had been anticipated in the 19th century, this view, a sharp departure from the classical system of Pierre Simon de Laplace, first found expression in the second decade of the 20th century. Indeed, the first edition of this book played an important part in defining and spreading the relative-frequency theory. The revisions in the present edition incorporate a good deal of new material. Von Mises' uncommonly lucid style adds to the persuasiveness of his arguments.

An African Survey, by Lord Hailey. Oxford University Press ($16.80). This huge volume of 1,676 closely printed pages is a revised version of a noted comparative study of the different territories of Africa, originally published 19 years ago. It contains a mass of statistics and other data on the physical characteristics of Africa, the African peoples and their languages; analyses of political objectives, systems of government and methods of administration; chapters on agriculture and animal husbandry, forests, water supply and irrigation, soil conservation, health, education, economic development, labor problems, minerals and mines, transport and communication, organization of research. Lord Hailey is masterful in handling a vast, varied array of noncontroversial topics and in shaping facts into a handsome narrative; on political and social matters he is deft and apt to shy away from glowing coals. Even though the author does not always meet the issues, this remains by far the most enlightening survey of its kind.

Electromagnetism and Relativity, by E. G. Cullwick. Longmans, Green and Co., Inc. ($12.50). This book for advanced students and teachers is particularly concerned with moving bodies and electromagnetic induction, and includes a discussion of the special theory of relativity and its application to electromagnetism. Cullwick tackles the vexed clock-paradox and space-traveler problem and concludes, quite persuasively, that both the paradox and its alleged solution (that the stay-at-home twin ages faster than his go-away brother) are fallacious.

Theme for Reason, by James Ward Smith. Princeton University Press ($4). This philosophical essay is concerned with the question: Are deduction from postulates or probable inferences from evidence the only alternative procedures for determining rational behav-

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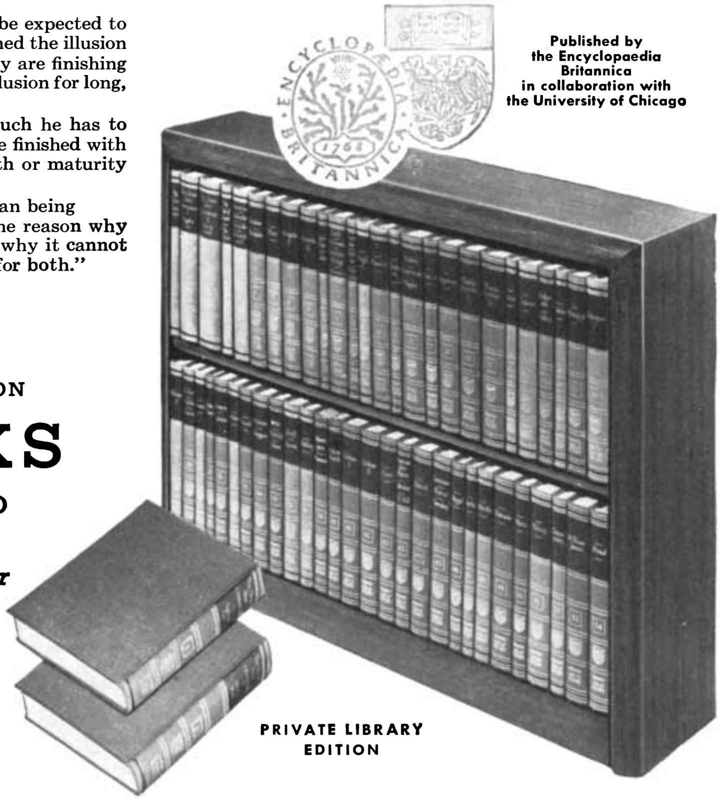

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FACTS AND THEORIES OF PSYCHOANALYSIS, by Ives Hendrick. Alfred A. Knopf ($6). Dr. Hendrick's primer of psychoanalysis, first published in 1934, has been long recognized for its uncommon clarity and freedom from jargon in a field whose literature is not noted for these qualities. In this third edition he has made many revisions. He has added material on the applications of psychoanalysis in the study of psychoses and in modern psychiatry, on child analysis and child psychiatry, on psychosomatic medicine, on the growth of psychoanalysis as a profession. As one can see from his treatment of the psychoanalytic schools and theories of the more recent period, and from his suggested reading list, Hendrick is not an admirer of those who in part or in whole have forsaken the Master's teachings. Regardless of how one values the "deviant" theories, one cannot be entirely satisfied with the author's sketchy appraisal of them.

A TREATISE ON LIMNOLOGY. VOL. I: GEOGRAPHY, PHYSICS AND CHEMISTRY, by G. Evelyn Hutchinson. John Wiley & Sons, Inc. ($19.50). Limnology is the study of bodies of fresh water, in this case lakes. The first volume of Professor Hutchinson's encyclopedic work covers their geographical, physical and chemical aspects. He treats the origin of lake basins, the morphology of lakes, the properties of water, the hydrological cycle and the water balance of lakes, their hydromechanics, their optical and thermal properties, oxygen in lake waters, the phosphorus, sulfur, silica and nitrogen cycles, and kindred topics. An extensive bibliography and abundant illustrative material are included. Hutchinson addresses his treatise to biologists (the second volume will cover biology, ecology, topology and stratigraphy of lakes), geologists and oceanographers, as well as those professionally concerned with limnology. He handles an enormous quantity of diversified material with commanding scientific skill and with literary grace. A small prefatory verse in German tells part of the story of lakes: the more the sun shines (says the poem), the more water evaporates, the more clouds form, and the less the

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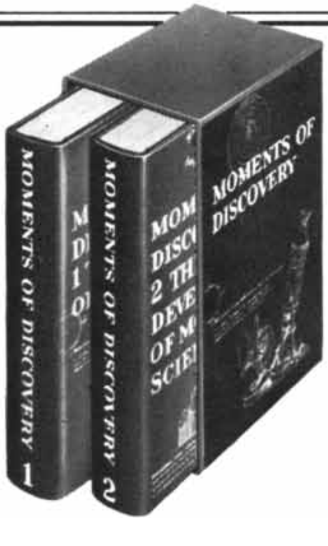

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GALEN ON ANATOMICAL PROCEDURES, translated by Charles Singer. Oxford University Press ($8.75). A translation, with introduction and notes, of Galen's lectures on anatomy and physiology delivered in the Greek language at Rome in A.D. 177. The text, taken down in shorthand, is a unique work in ancient literature, and the experiments it records "determined a physiological standpoint which was not improved upon for 1,450 years, that is, until Harvey published his results in 1628." The first Latin translation of Galen's book was made in 1531 and profoundly influenced Vesalius and other great Renaissance anatomists. Illustrations.

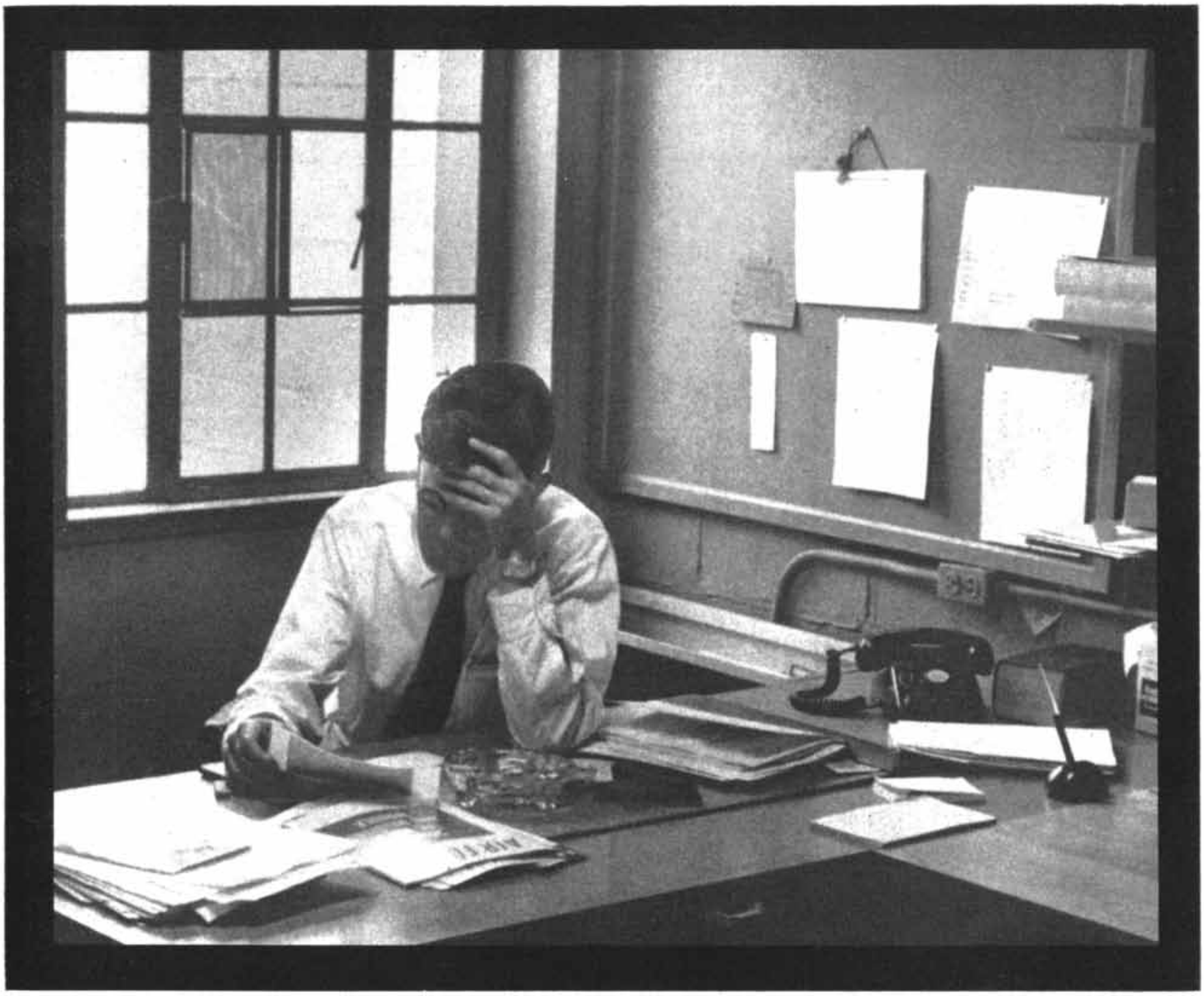
ADVANCES IN RADIOBIOLOGY, edited by George Carl de Hevesy, Arne Gunnar Forssberg and John D. Abbatt. Charles C. Thomas ($15.50). Proceedings of an international conference on radiobiology held in Stockholm in August, 1956. The rapid growth of this important field of inquiry is shown both by the number of papers presented and the wide range of topics. These include chemical and biochemical irradiation effects, physiological and morphological irradiation changes, the time factor in radiobiology, the distribution of isotopes in tissues, irradiation effects on the blood, radiation genetics. An impressive volume.

Notes

EGYPTIAN MAGIC, by Sir Wallis Budge. University Books ($5). A noted scholar's account, published in England in 1899 but now first issued in this country, of the magical side of the ancient Egyptian religion, as described in papyri and other native documents.

THE INSTITUTIONS OF ADVANCED SOCIETIES, edited by Arnold M. Rose. University of Minnesota Press ($10.50). A cooperative survey of the social institutions of 10 contemporary advanced societies: Britain, the U. S., Australia, Finland, Poland, Yugoslavia, Greece, Israel, France and Brazil.

THE FUNDAMENTAL CONSTANTS OF PHYSICS, by E. Richard Cohen, Kenneth M. Crowe, and Jesse W. M. Dumond. Interscience Publishers, Inc. ($7.50). A historical presentation of the derivation of fundamental constants and conversion factors of the physical sci-



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THE SAC AND FOX INDIANS, by William T. Hagan. University of Oklahoma Press ($5). A history of two once-prosperous and powerful tribes, now fallen so low that the warriors do their war dances under the auspices of the Chamber of Commerce. The 48th volume in the notable "The Civilization of the American Indian" series.

NORTHUMBERLAND, by Nikolaus Pevsner. Penguin Books Inc. ($1.95). A new paperback volume in Pevsner's invaluable survey of the buildings of England. Ian Richmond has added notes on the Roman antiquities.

THE BACTERIOLOGY OF TUBERCULOSIS, by Egon S. Darzins. University of Minnesota Press ($10). A survey of the literature from the late 19th century to the present, together with an account of unsolved problems and recently developed experimental methods for the study of the tubercle bacillus.

THE THEORY OF FUNCTIONS OF A REAL VARIABLE & THE THEORY OF FOURNIER'S SERIES, by E. W. Hobson. Dover Publications Inc. ($6). A two-volume paperback reprint of a noted mathematical reference work, long out of print.

THE PRINCIPLES OF QUANTUM MECHANICS, by P. A. M. Dirac. Oxford University Press ($5.60). The main change in this fourth edition of Dirac's classic of physical theory is that the chapter on quantum electrodynamics has been rewritten to express the theory in a form which includes the creation and annihilation of electron-positron pairs, and which abandons any close analogy with classical electron theory.

ORDINARY DIFFERENCE-DIFFERENTIAL EQUATIONS, by Edmund Pinney. University of California Press ($5). A monograph on the technique of applying difference-differential equations to practical problems which arise in physics, economics and other fields.

SCIENTIFIC SOCIETIES IN THE UNITED STATES, by Ralph S. Bates. Columbia University Press ($6.50). The second edition of this survey, which traces the history of the U. S. scientific societies beginning in the 18th century, has a new chapter to cover the period since the close of the last war.

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SEPTEMBER, 1958

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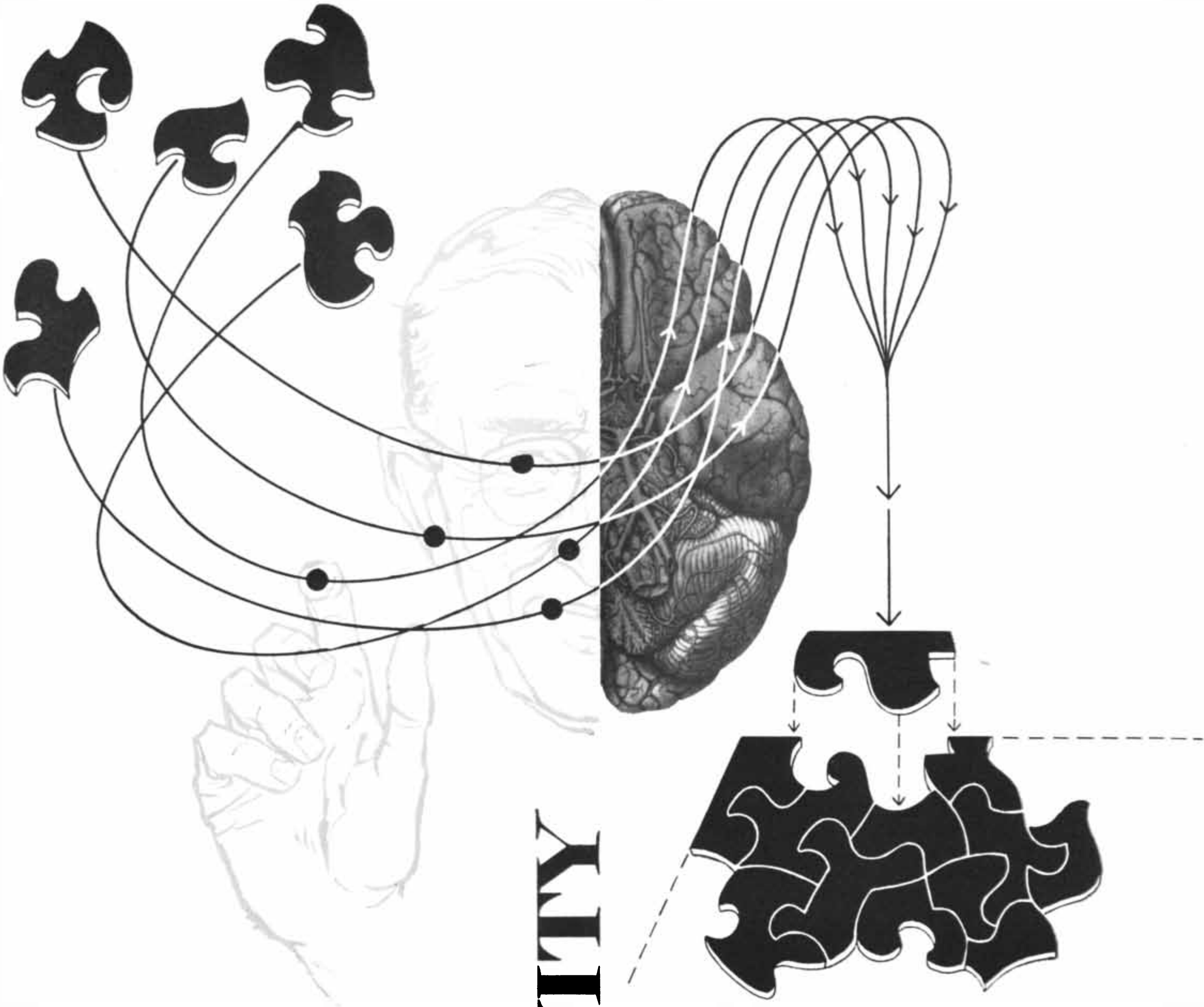

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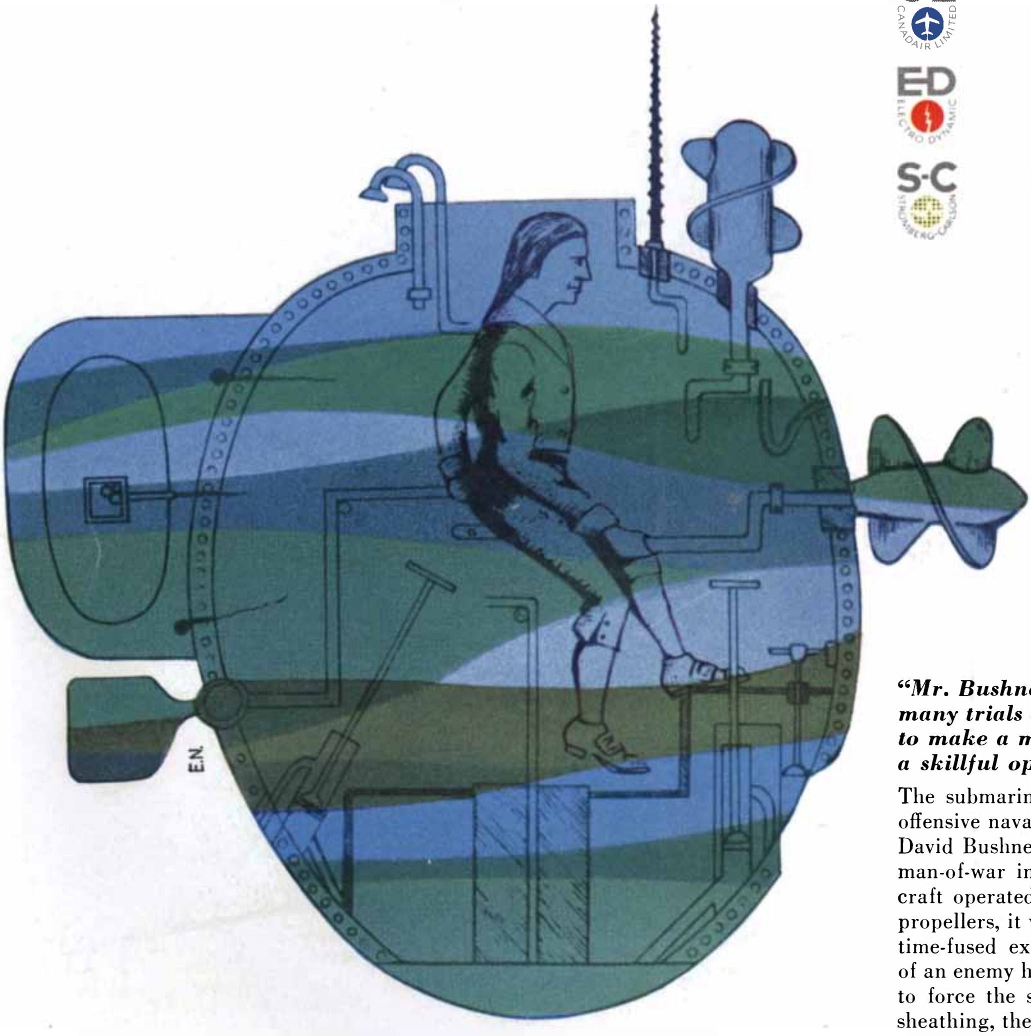

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