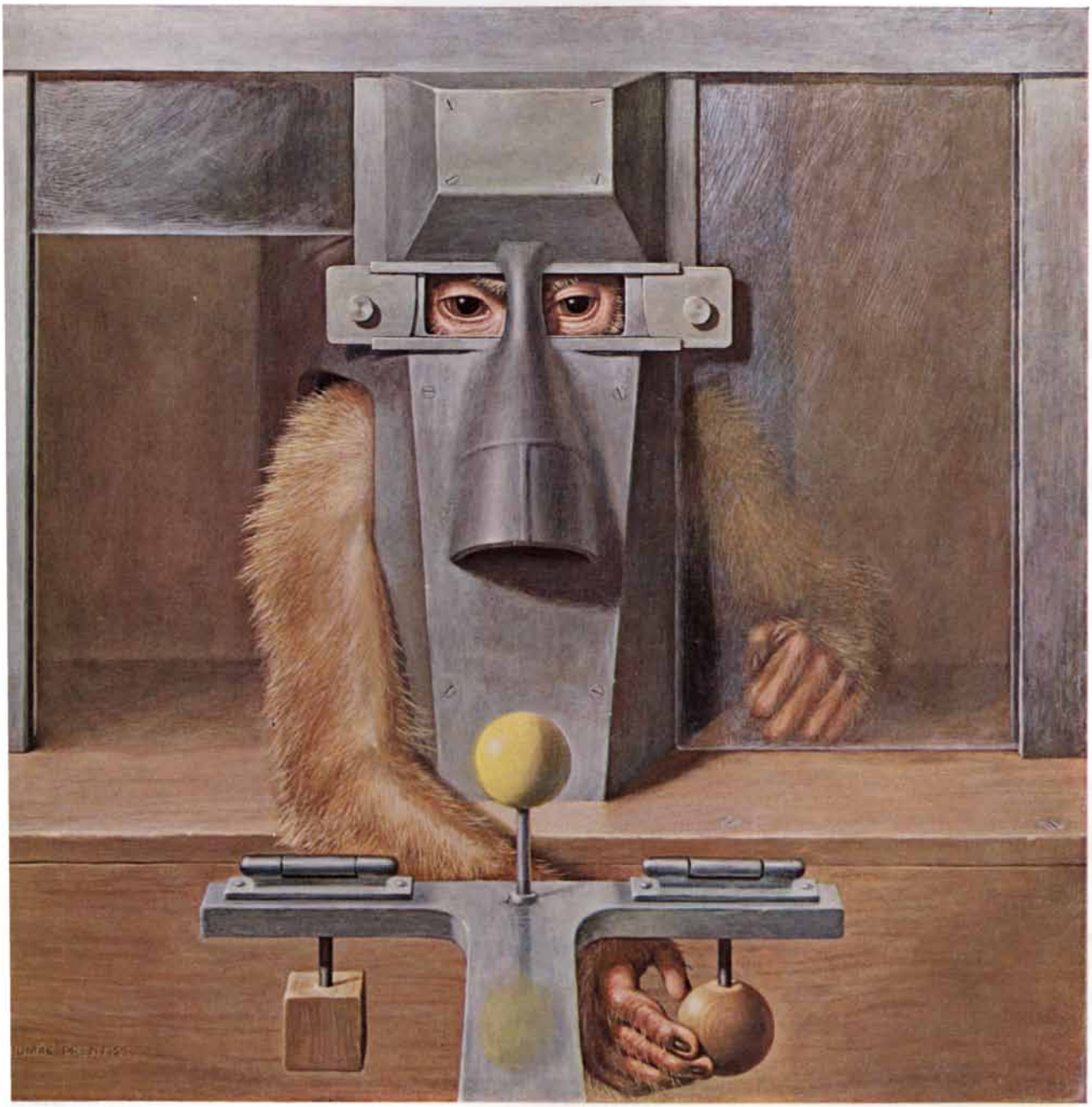
SCIENTIFIC AMERICAN



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FIFTY CENTS

January 1964

HOW RCA ELECTRON TUBES

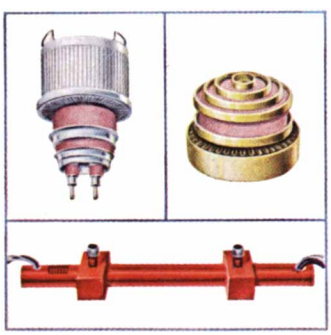
Link the Voices of the World

The radio "hot line" between Washington and the Kremlin stands sentinel against the risk of accidental war. High-speed radioteletype flashes market data to a dozen world trade centers. Through the magic of radio facsimile, photographs taken across the world appear in your newspaper the very same day.

Powerful RCA electron tubes make reliable world-wide communications like these possible and practicable. These tubes amplify electronic impulses at the radio transmitter . . . hundreds . . . thousands . . . even millions of times, to produce the high-frequency power it takes to bridge ocean and continent.

Via vast radiotelegraph, radiophone, facsimile, marine, and video networks, these electron tubes enable man to talk to man, business to communicate with business, government to keep in touch with government—from virtually any point on earth.

Linking the voices of man around the globe is another dramatic way in which RCA electronic components and devices play an indispensable role—in world commerce, in science and in international understanding.



RCA electron power tubes... heart of modern radio transmitters... make it possible to send messages round the world.

RCA ELECTRONIC COMPONENTS AND DEVICES

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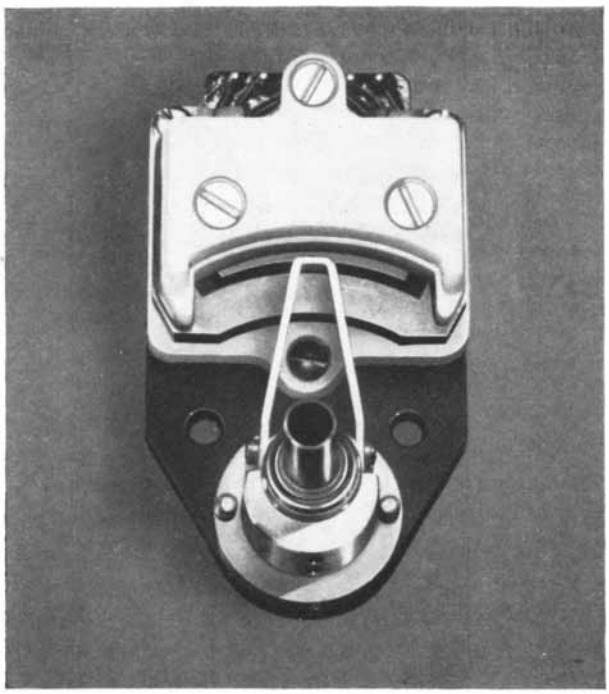

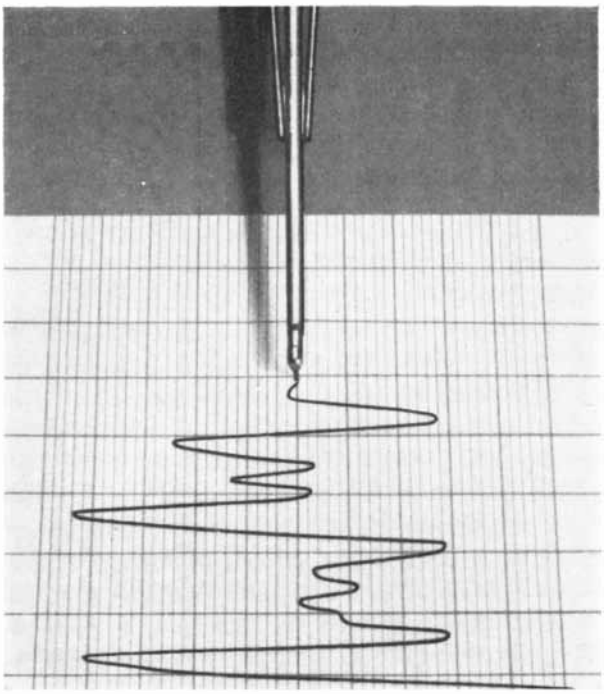

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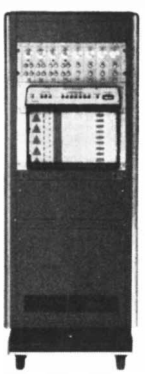

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Established 1845 **SCIENTIFIC AMERICAN** January 1964 Volume 210 Number 1

ARTICLES

DEPARTMENTS

PUBLISHED MONTHLY BY SCIENTIFIC AMERICAN, INC., 415 MADISON AVENUE, NEW YORK 17, N.Y. SECOND-CLASS POSTAGE PAID AT NEW YORK, N.Y., AND AT ADDITIONAL MAILING OFFICES. SUBSCRIPTION RATE: $6 PER YEAR.

THE COVER

The painting on the cover shows a monkey being tested in a laboratory at the California Institute of Technology for sensory and motor abilities and eye-hand co-ordination. The monkey has a "split brain": its corpus callosum, a cable connecting the two cerebral hemispheres, has been severed (see "The Great Cerebral Commissure," page 42). Such animals function well in general but behave as if they had two separate brains; what is learned by one side of the brain is not learned by the other. The test enclosure has windows with which the monkey's vision and its arms can be restricted. In the situation depicted in the painting the monkey is able to see with both eyes but it can only manipulate the levers with one hand.

THE ILLUSTRATIONS

Cover painting by Thomas Prentiss

Page	Source
24	Max Tatch, Shostal
26	James McClanahan
27	Joan Starwood
28	Joan Starwood (*top*), Dan Todd (*bottom*)
29	Dan Todd
30	Joan Starwood
31	Joan Starwood (*top*), Dan Todd (*bottom*)
32–33	B. E. Westerlund
34	James Egleson
35	A. R. Hogg (*top*), B. E. Westerlund (*bottom*)
36–39	James Egleson
40	S. C. B. Gascoigne
41	Bart J. Bok
43	Todd Walker
46	Eric Mose
47	Todd Walker (*top*), Eric Mose (*bottom*)
48–49	Eric Mose
50–52	Todd Walker
63	David S. Smith
64	John Langley Howard
65	Humberto Fernandez-Moran
66	Joan Starwood (*top*), John Langley Howard (*bottom*)
68	Humberto Fernandez-Moran
70	Joan Starwood (*top*), John Langley Howard (*bottom*)
72–74	John Langley Howard
80–81	Bunji Tagawa
82–83	Bunji Tagawa (*top*), Georges H. Werner (*bottom*)
84	Bunji Tagawa (*top*), Georges H. Werner (*middle and bottom*)
86	Bunji Tagawa
88–89	Allen Beechel
90–91	Joan Starwood (*top*), Allen Beechel (*bottom*)
92–97	Allen Beechel
99	The Newcomen Society, London
100	New York Public Library
101	Burndy Library
102	New York Public Library (*top*), Eugene S. Ferguson (*bottom*)
103–104	James Egleson
105	Eugene S. Ferguson
106	British Crown Copyright; Science Museum, London
109	James Egleson
110	James Egleson (*left*), Field Emission Corporation (*right*)
111–112	James Egleson
114	James Egleson (*top*), Joan Starwood (*bottom left*), United States Army Ballistic Research Laboratory (*bottom middle and bottom right*)
116	Field Emission Corporation
122–128	Joan Starwood
131	Roger Hayward
132	Louis A. Graham
133–138	Roger Hayward

It's a SAAB. And this one belongs to ski champions Egon and Penny Pitou Zimmermann.

White sidewalls optional at extra cost.

If there's such a thing as a winter car, you're looking at it.

Egon and Penny Pitou Zimmermann need a good winter car. They live in the heart of New Hampshire ski country. Actually, their SAAB is designed to bite through the unbelievably tough winters of Sweden. Over there, deep drifts pile up on rutted, unpaved roads; every curve or corner is icy and dangerous; at night, it dips down towards 40° below. Imagine how a car like this takes an American winter in stride.

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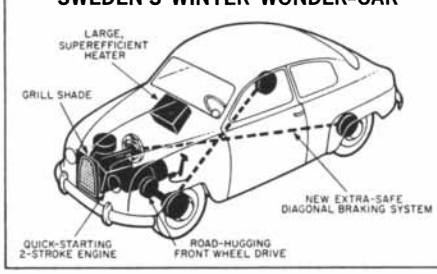

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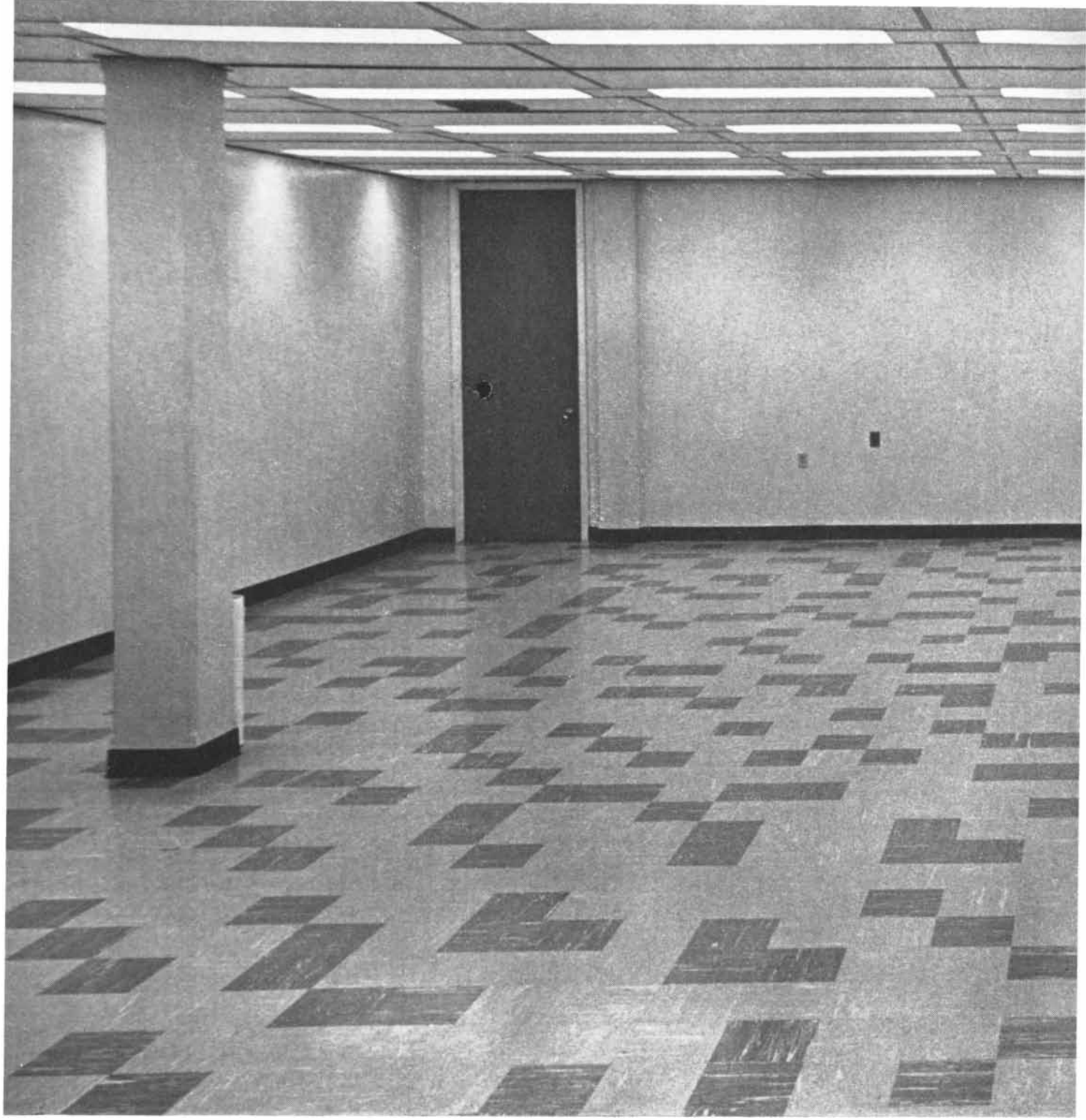

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It's a versatile little box. It is designed as an off-shelf item which can be integrated into almost any aerospace system. Feed it information (linear and non-linear) from any number of subsystems. The NDC-1000 will digest it, then transmit orders to activate and direct other subsystems.

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Systems are our business. And computers are the brains of systems. We design and produce computers to meet specific problems of system integration.

This aerospace computer measures 10.18x10.5x13.8 inches. A general purpose computer with the same capabilities would fill this entire room.

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To integrate still another system, GAM-87, we came up with a solid-state unit, 2 cubic feet in size, which was 5 computers in one: two general purpose computers, two digital differential analyzers, and a star tracker computer. It interfaced, reliably, with 11 other subsystems.

This is the kind of imaginative thinking and inventiveness you can call on when you put a systems integration problem up to Northrop Nortronics.

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LETTERS

Sirs:

I found Edward J. Sachar's article "Behavioral Science and Criminal Law" [SCIENTIFIC AMERICAN, November, 1963] most intriguing. Surely Sachar has put the differences between the lawyers and the behaviorists most clearly and succinctly—the former have traditionally been interested in upholding morality chiefly through the use of punishment as a "deterrent"; the latter have argued that *any* technique that induces a felon to change his behavior is to be preferred to punishment (which chiefly makes the moralists feel revenged but doesn't alter the felon's way of life very much). . . .

It is odd, however, that Sachar fails to present what are surely the most encouraging types of technique for the control of human behavior, leaning instead far too heavily on the chiefly untested and rather pedestrian psychiatric techniques. Surely there is precious little experimental evidence (of the sort to pleasure hardheaded scientists) that "talkative" psychotherapy, be it group or individual in nature, is a very effective way of changing human behavior. . . . The behavioral scientist has in his repertory many much more efficacious methods of shaping behavior than psychotherapy—why should we not be honest and say so? Perhaps the lawyer, stanch

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defender of the traditional that he is, is wise in not shedding punishment as his chief weapon when he's offered only conventional psychotherapy as a substitute. Perhaps when scientists of a nonpsychiatric bent, such as D. O. Hebb and B. F. Skinner, are encouraged to bring their critical intelligence to this problem, a more suitable and powerful arsenal of techniques for changing felons can be given to the lawyer.

JAMES V. MCCONNELL

University of Michigan
Ann Arbor, Mich.

Sirs:

I appreciate Dr. McConnell's interest in my article, but his comments suggest that I should clarify some points that perhaps were not sufficiently stressed.

I made a distinction between punishment as an expression of moral wrath and punishments (or penalties) meted out for the practical purpose of shaping behavior. Contrary to Dr. McConnell's implication, in regard to this latter aim the psychiatrist has no objection to a penalty system, although the psychiatrist believes that such a system *alone* is inadequate to purposes of effective behavior change. As I stated in my article, a firm disciplinary system is considered essential for any "therapeutic" prison. Only when antisocial behavior is firmly controlled can the emotional tensions that prompt such behavior become accessible to psychotherapy.

Dr. McConnell doubts the effectiveness of psychotherapy in general and, in particular, its usefulness for the relatively nonverbal prison population. Certainly a major goal of psychotherapy with such prisoners would be to teach them to put feelings into words rather than actions. Furthermore, as is the accepted practice with sicker patients, psychotherapy would focus more on developing a trusting doctor-patient relation than on achieving insight in the classical sense.

Although he does not specify them, Dr. McConnell believes that there are other techniques of behavioral science that might be more usefully adapted for treating prisoners. If the methods he has in mind are compatible with the rights and integrity of the individual, I hope Dr. McConnell will join me in encouraging comparative research in this area.

EDWARD J. SACHAR, M.D.

Massachusetts Mental Health Center
Boston, Mass.

CAN YOU PASS THIS AIR TRAVEL QUIZ?

(ANSWERS AT LOWER RIGHT)

1. Which airline has the world's largest jet fleet?
UNITED ☐ TWA ☐ AMERICAN ☐

2. Which airline serves the most U.S. cities by jet?
UNITED ☐ TWA ☐ AMERICAN ☐

3. Which airline operates the only commercial jet ever to fly faster than the speed of sound . . . the DC-8?
UNITED ☐ TWA ☐ AMERICAN ☐

4. Which airline offers flights with a single class of service that combines a first class feeling with a close-to-coach price?
UNITED ☐ TWA ☐ AMERICAN ☐

5. Which airline flies the quietest jet in the world, the Caravelle?
UNITED ☐ TWA ☐ AMERICAN ☐

6. Which airline was the first to take delivery of the tri-jet Boeing 727, the newest airliner in the world?
UNITED ☐ TWA ☐ AMERICAN ☐

7. Which airline operates the most complete variety of jets?
UNITED ☐ TWA ☐ AMERICAN ☐

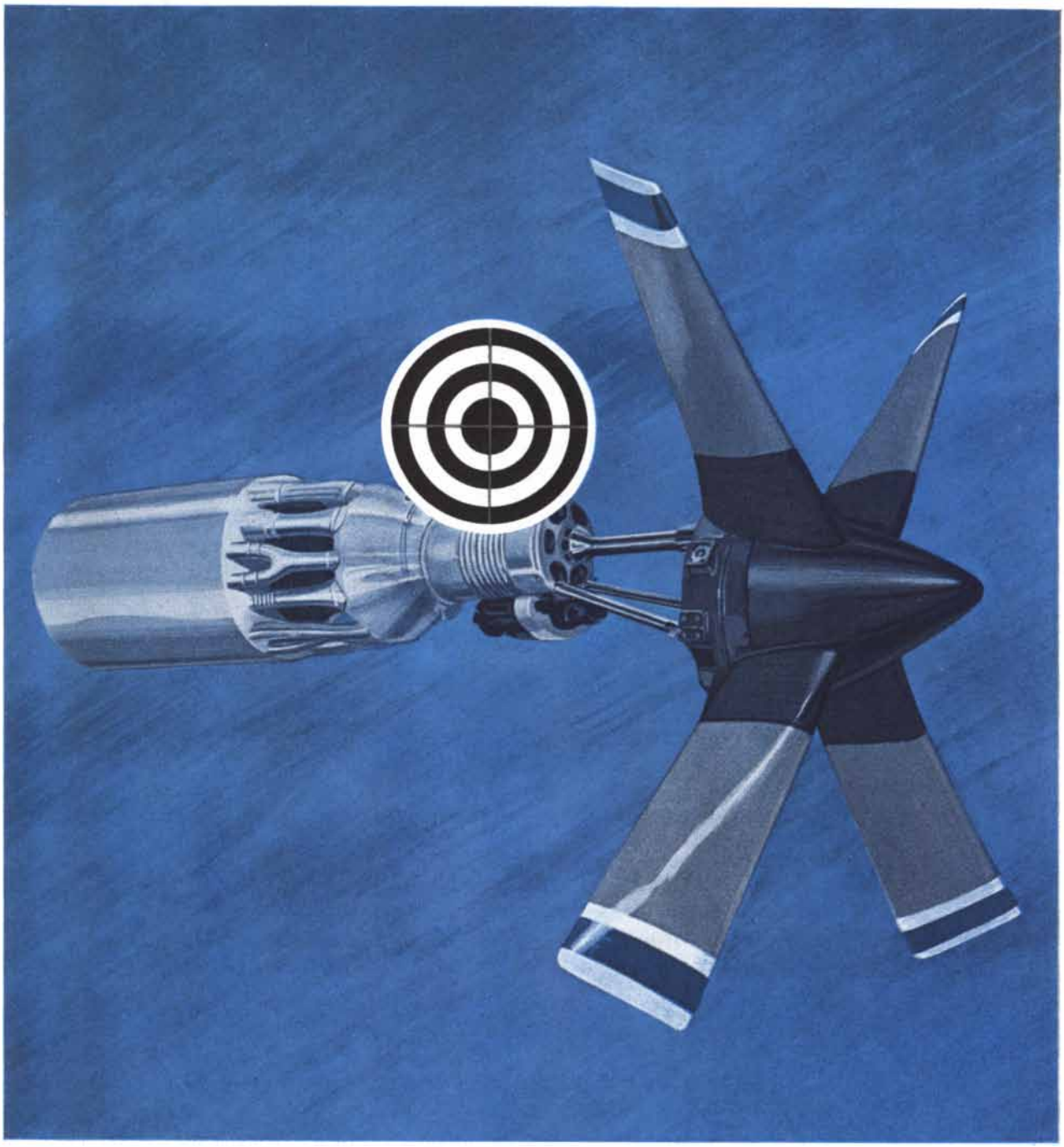
8. Which airline flies the jet that holds the long-distance record for nonstop flight, the DC-8?
UNITED ☐ TWA ☐ AMERICAN ☐

9. Which airline offers the most jet service throughout the nation?
UNITED ☐ TWA ☐ AMERICAN ☐

10. Which airline serves the most U.S. vacation areas, including Hawaii?
UNITED ☐ TWA ☐ AMERICAN ☐

11. Which airline is chosen by more people than any other airline in the world?
UNITED ☐ TWA ☐ AMERICAN ☐

{Answer to questions 1 through 11: United Air Lines.}



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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

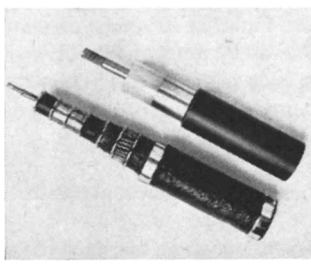
JANUARY, 1914: "The opening of the year 1914 finds the United States in the humiliating position of a third-rate naval power—third-rate in so far as the strength of its first fighting line is concerned. This is because of two things. First, the revolution in naval rating which has been brought about by the advent of the 'dreadnought,' and second, the disposition of congressmen to play politics with naval policies and cut down national in favor of local appropriations. There is one first-rate power—Great Britain, with 42 dreadnoughts built and building; there is one second-rate power—Germany, with 26 such ships built and building; there are three third-rate powers—the United States, France and Japan, respectively with 12, 11 and 10 dreadnoughts built and building. Altogether, the year 1913 must be considered as finding the naval-diplomatic situation as regards this country in a critical condition, with its navy sunk to the third-rate rank at a time when the Administration is adopting a policy with regard to neighboring states which for audacity and grave portent has never been equaled in the history of the country."

"By far the most important astronomical announcement of the year came from Prof. George E. Hale, director of the Mount Wilson Solar Observatory. It will be remembered that some years ago Prof. Hale discovered the Zeeman effect in sunspots, thereby conclusively proving that sunspots must rotate and establishing a field of magnetic influence on the sun. Even more important was the later discovery to which we refer, which is nothing more or less than the fact that the entire sun may be regarded as a rapidly rotating magnet."

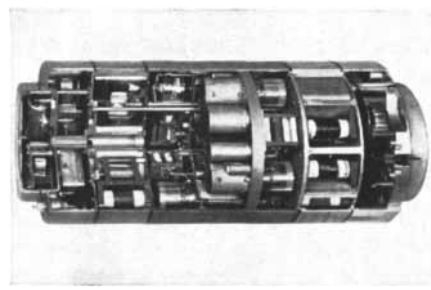
"The most powerful electromagnet in the world was recently installed in the laboratory of Prof. Jean Becquerel, in the Paris Museum of Natural History. This electromagnet, which was constructed by Prof. Pierre Weiss of the Zurich Polytechnicum, is capable of producing a magnetic field of 50,000 gauss at least.

Report from

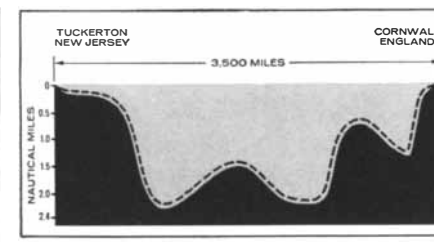
BELL LABORATORIES



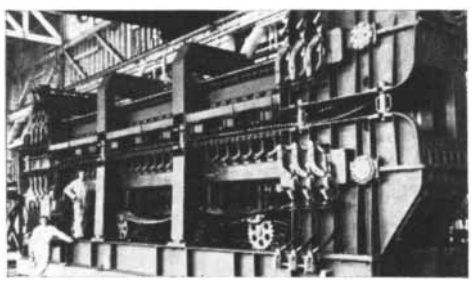
New armorless deep-sea cable (upper right) is of simpler construction, and has lower transmission losses than previous cables of the same overall diameter (lower left). Unlike armored cable, it twists very little during laying.



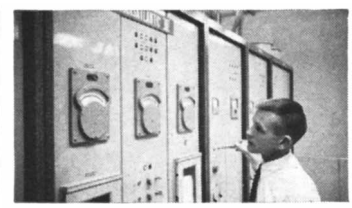
New type of deep-sea amplifier amplifies signals 100,000 times. A 3500-mile route requires 180 such amplifiers, including more than 36,000 electronic components. Each component is designed for stability and reliability far in excess of the requirements for land systems.



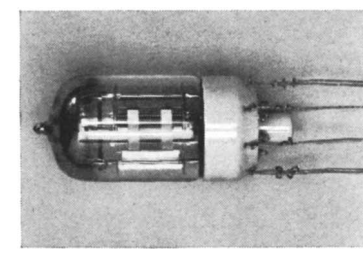
New approaches to cable laying—taking into account the dynamic characteristics of the cable, the motion of the ship, and the contours of the ocean bottom—make it possible to use a minimum length of cable to follow the mountains and valleys of the ocean floor. Care is taken to avoid mechanical strains and deformations that might cause changes in transmission performance.



New type of shipboard cable engine holds both small-diameter cable and large-diameter amplifiers between flexible tracks. The engine pays out cable and amplifiers smoothly at a constant rate, permitting close implementation of the engineering approaches discussed above.



To energize the amplifiers, a new highly reliable 6000-volt d.c. shore-based power supply was developed. It sends precisely regulated current along the same coaxial conductors that carry the communication channels, despite varying earth potentials between the continents or islands on which the terminals are located.



New high-vacuum tube so designed that its characteristics will not change significantly over a twenty-year life-span. Essential to this long-life performance is a new cathode material consisting of nickel with two percent tungsten and two hundredths of one percent magnesium.

Latest ocean cable system made possible by new developments

These new developments, along with others, and the scientific advances behind them, made possible our most recent telephone cable system across the Atlantic Ocean. In service beginning October 14, 1963, it transmits 128 simultaneous two-way telephone conversations. In 1964, a cable of this kind will be laid between Hawaii and Japan, providing an extension across the Pacific Ocean of the telephone cable system now in service to Hawaii.

BELL TELEPHONE LABORATORIES

World center of communications research and development

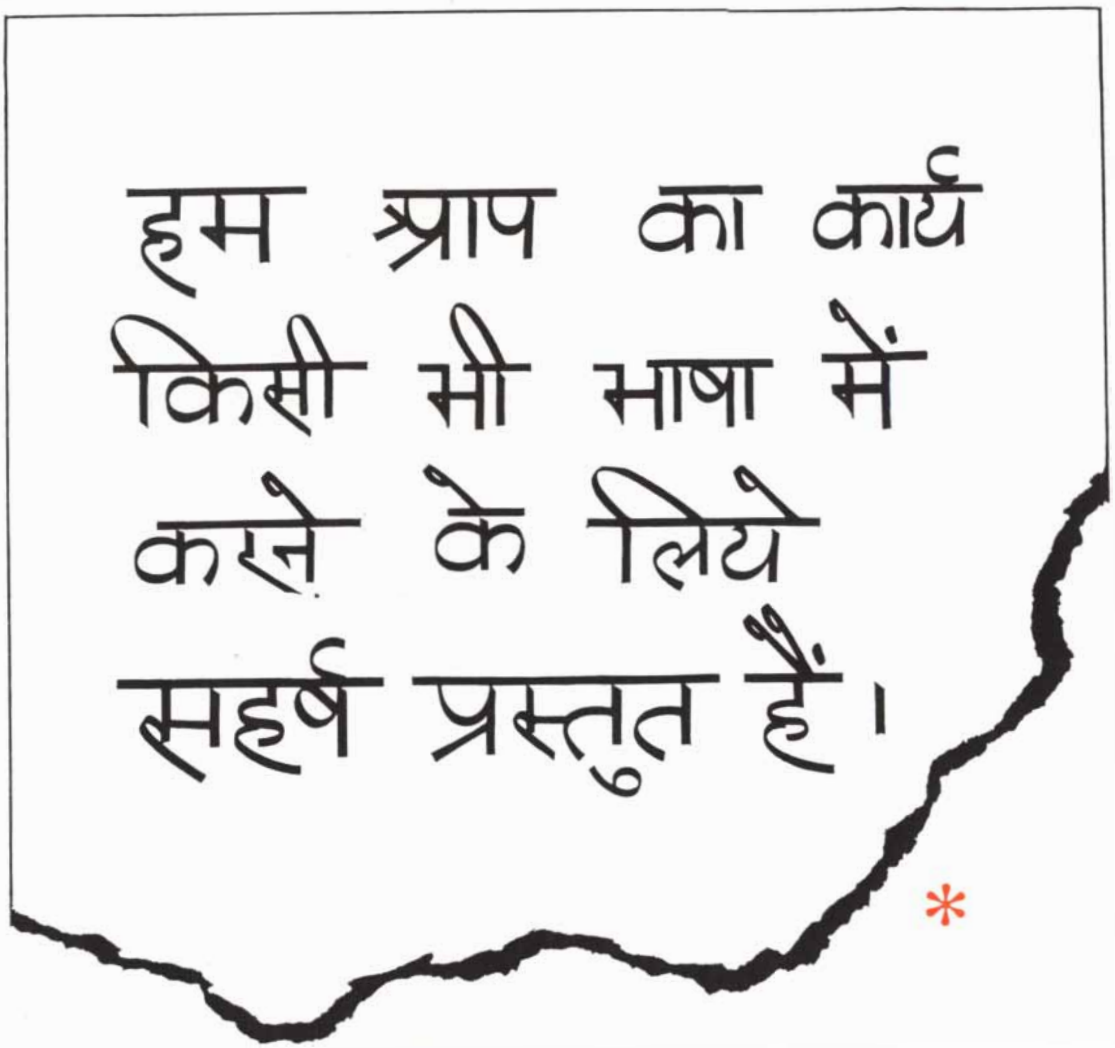
The first experiments that Prof. Becquerel purposes making with this powerful apparatus will have for their object the elucidation of some obscure points in the theory of the Zeeman effect. 'It is well known,' Prof. Becquerel said, 'that there is something yet unknown in this phenomenon, something that is at the limit of visibility with our present instruments. With the aid of my new electromagnet and its few thousand additional gauss, I hope that I shall be able to make visible this phenomenon, which explains the intimate structure of matter. Molecular and atomic life will reveal, perhaps, part of its secret. When these experiments have been completed, I shall continue the study of the effects of magnetic force on matter in rapid conditions of temperature and pressure.' "

"The decision which has been handed down by the Circuit Court of Appeals in the infringement suit brought by the Wright Company settles once and for all, in this country at least, the question: Who invented the flying machine? To be sure, there was never any doubt in the popular mind. Practical achievement counts for so much and paper discussion for so little that the inventor who rises above the mere theoretical presentation of his ideas is inevitably glorified. The decision of the Circuit Court of Appeals stamps the popular verdict with approval and recognizes Orville and Wilbur Wright as the inventors of the man-carrying, motor-driven aeroplane."

"The present transatlantic record is four days 10 hours from the coast of Ireland to the entrance to Ambrose Channel, New York. It was made by the *Mauretania*. The *Lusitania* on her last westward passage, in spite of strong winds and head seas for the whole voyage, crossed in four days 18 hours five minutes. This performance gives promise of the *Lusitania*'s surpassing the record of her sister ship under favorable weather conditions, for during the above-mentioned trip, for a period of eight hours, she made 197 revolutions and averaged 27 knots. It is likely that during the present year the record average speed across the Atlantic of 26.01 knots will be considerably exceeded."

Scientific American.

JANUARY, 1864: "The production of steel from pig iron by what is called the 'Bessemer process' is rapidly extending



THERE ARE FEW LANGUAGES in which Allis-Chalmers products are not known today. By helping nations of the free world to achieve better standards of living through increased productivity ***ALLIS-CHALMERS*** does its share to help you share in a better future.

* As they say in Hindi "We will be happy to work with you in any language"

in Europe. This metal is employed for making tires for locomotive wheels and is coming into general use for rails. After careful experiments with iron and steel rails, it has been found that the latter are about five times more durable than the former, and several great railway companies in England have adopted them exclusively. Such rails will effect a great saving in the cost of maintaining railways, and we can expect to see them come into extensive use in America. One establishment in Troy, N.Y., is engaged in the manufacture of this metal for such purposes."

"The following extracts are from the *Lancet* (London) and the *British and Foreign Medical and Chirurgical Review:* 'Dr. Mackenzie, in his great work on ophthalmology, expresses his belief that tobacco is a *frequent* cause of amaurosis and adds that "one of the best proofs of tobacco being the cause of amaurosis is in the great improvement in vision—sometimes complete restoration—which ensues on giving up the use of this poison." M. Sichel observes that among cerebral amaurosis there are two forms but little known. One of these, observed in drinkers, he himself described as symptomatic of delirium tremens several years ago. The other, due to the use of tobacco and first indicated by Mackenzie, he once doubted the existence of. Subsequent experience has, however, convinced him of its reality; so much so that he is now of opinion that there are few persons who have smoked during a long period more than five drachms of tobacco per diem without having their vision and frequently their memory enfeebled. M. Mercier, in corroboration of the unsuspected effects of tobacco in generating disease, related a case in which a cough, which had persisted for a year, and purpura, which had lasted for seven months, soon yielded after the cessation of smoking, which had been excessive.' "

"The steamship *Great Eastern* has changed owners and is advertised to sail from Liverpool on January 14, 1864. The career of this vessel heretofore has been one of financial misfortune. Perhaps a change of owners may lead to superior management and success. As a work of engineering skill the *Great Eastern* has been a success. She was buffeted by a terrific tempest for a long time, without a rudder; she struck upon a sunken rock at Montauk Point and had 36 feet of her plates ripped off, and yet no symptoms of weakness were exhibited in any part of her hull."

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THE AUTHORS

A. J. HAAGEN-SMIT ("The Control of Air Pollution") is professor of bio-organic chemistry at the California Institute of Technology. He was born in the Netherlands in 1900 and obtained an A.B. and a Ph.D. from the University of Utrecht in 1922 and 1929 respectively. After seven years of teaching organic chemistry at Utrecht he joined the faculty of Harvard University in 1936; the following year he went to Cal Tech. In 1950 he received the Fritzsche Award of the American Chemical Society for his work on essential oils and in 1958 he won the Chambers Award of the Air Pollution Control Association. He is a consultant to the Los Angeles Air Pollution District, California's State Motor Vehicle Pollution Control Board and various other state and county agencies dealing with atmospheric sanitation.

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R. W. SPERRY ("The Great Cerebral Commissure") is Hixon Professor of Psychobiology at the California Institute of Technology. Sperry received an A.B. and an M.A. in psychology from Oberlin College in 1935 and 1937 respectively and a Ph.D. in zoology from the University of Chicago in 1941. He did research at Harvard University and at the Yerkes Laboratories of Primate Biology before joining the Chicago faculty in 1946. From 1952 to 1954 he was chief of developmental neurology for the National Institutes of Health. He has been at Cal Tech since 1954. Sperry's

work has covered various aspects of the central nervous system, including the mechanisms involved in perception, learning and memory.

DAVID E. GREEN ("The Mitochondrion") is professor of enzyme chemistry and codirector of the Institute for Enzyme Research at the University of Wisconsin. A graduate of New York University, Green acquired a Ph.D. in biochemistry from the University of Cambridge in 1934. He did research at Cambridge from 1934 until 1940, when he returned to this country to continue his work at the Harvard Medical School. In 1941 he joined the staff of the College of Physicians and Surgeons of Columbia University, where he later became head of the enzyme laboratory. He joined the Wisconsin faculty in 1948.

GEORGES H. WERNER, BACHISIO LATTE and ANDREA CONTINI ("Trachoma") work in France and Italy on different aspects of the blinding eye disease. They met during the summer of 1962 in Sardinia, one of the last areas of western Europe where trachoma is still prevalent, and decided to combine their knowledge to write the present article. Werner is head of the Virus Research Division of the Rhône-Poulenc Chemical Company near Paris. A native of France, he received a Ph.D. in biology from the University of Geneva and a diploma in bacteriology from the Pasteur Institute in 1949. He did research for a year at the Public Health Research Institute in New York before joining the faculty of the New York Downstate Medical Center in 1951. He taught microbiology at the University of Pennsylvania School of Medicine and did research at the Wistar Institute of Anatomy and Biology in Philadelphia from 1954 until 1958, when he took up his present post. His work on chemotherapeutic agents for the mass treatment of trachoma and on the pathogenic and immunizing properties of the trachoma virus brought him to the island of Sardinia, where Latte and Contini do their work. Latte is an expert on the clinical and epidemiological aspects of trachoma and has done much research on these problems. Contini, who succeeded in isolating the trachoma virus from Sardinian patients a short time after Chinese and British investigators announced their success in this effort, is continuing his work on the virus.

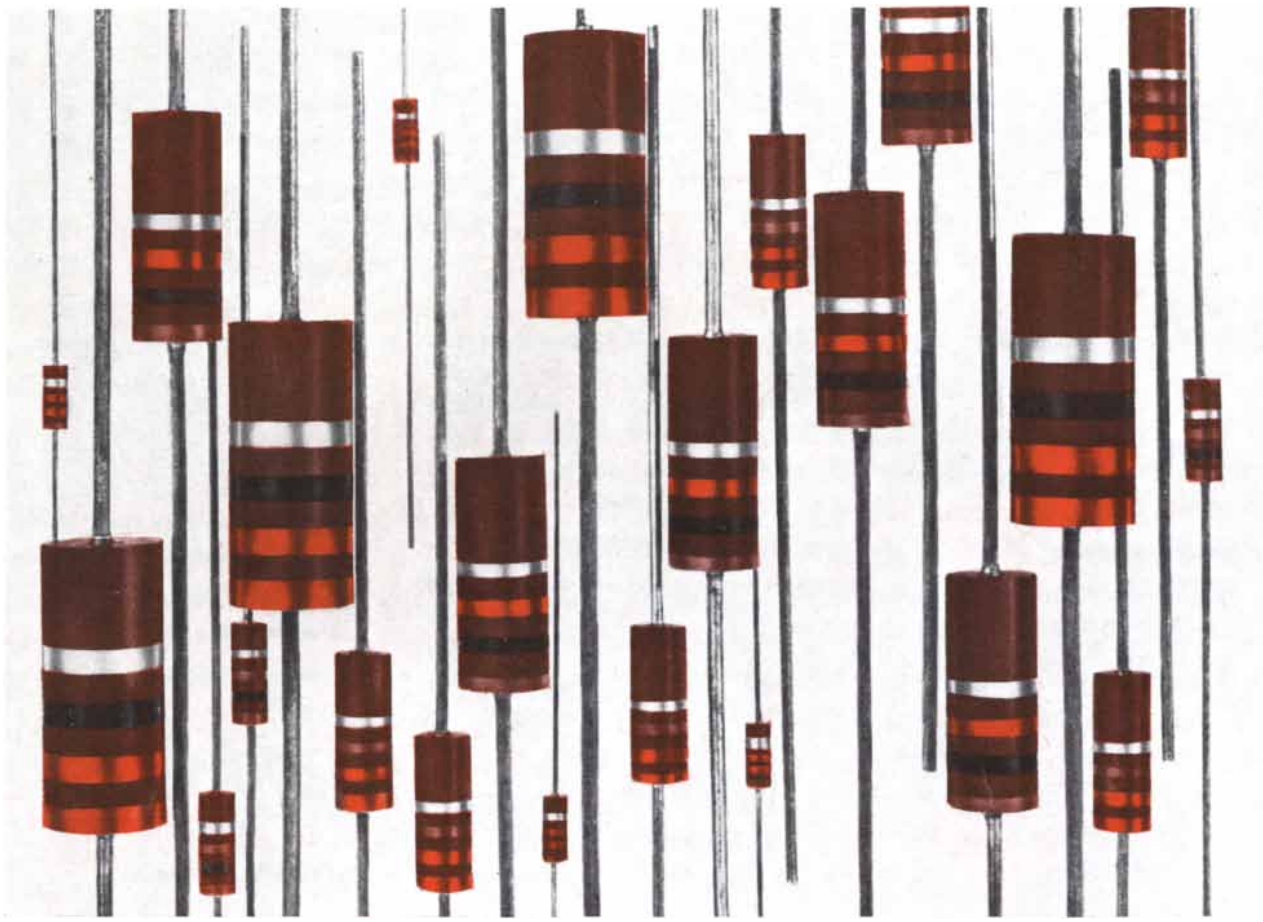
A. G. MASSEY ("Boron") is lecturer in inorganic chemistry at Queen Mary College of the University of London. Massey was born in Wigan, Lancashire,

in 1935 and was graduated with honors in chemistry from the University of Liverpool in 1957. He obtained a Ph.D. from Liverpool in 1959 for his work on the boron subchlorides. He taught for the next three years at Liverpool and at the University of Cambridge before taking up his present post in 1962.

EUGENE S. FERGUSON ("The Origins of the Steam Engine") is professor of mechanical engineering at the Iowa State University of Science and Technology, where he also teaches courses in the history of technology. Ferguson received a B.S. in mechanical engineering from the Carnegie Institute of Technology in 1937 and an M.S. from Iowa State in 1955. He joined the Iowa State faculty in 1946. In 1958 he became curator of the Division of Mechanical and Civil Engineering in the Smithsonian Institution's new Museum of History and Technology. He returned to Iowa State in 1961 to introduce undergraduate courses in the history of technology. About this subject he writes: "Believing with Eric Ashby that 'the path to culture should be through a man's specialism, not by bypassing it,' I have assumed the challenge of showing students the relevance of their engineering heritage and of the interactions of technology and the culture in which it develops."

W. P. DYKE ("Advances in Field Emission") is president of the Field Emission Corporation in McMinnville, Ore. A graduate of Linfield College in McMinnville, Dyke acquired a Ph.D. in physics from the University of Washington in 1946. During World War II he did research on air-borne radar at the Radiation Laboratory of the Massachusetts Institute of Technology; following the war he was awarded the Presidential Certificate of Merit for this work. He returned to Linfield College in 1946 as professor of physics and director of research. In 1955 he founded and became director of the Linfield Research Corporation Institute, a nonprofit, corporate subsidiary of Linfield College engaged mostly in research on field emission devices. He founded the Field Emission Corporation in 1958.

LEON H. KEYSERLING, who in this issue reviews Gunnar Myrdal's *Challenge to Affluence*, is a consulting economist and lawyer who has written extensively on employment, taxation and economic growth. From 1950 to 1953 he was chairman of the President's Council of Economic Advisers.



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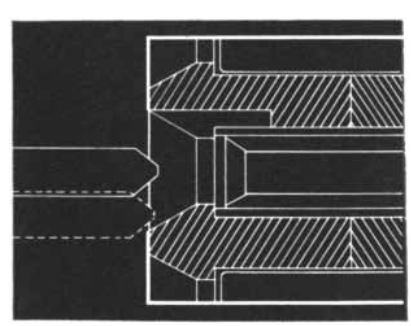

Figure 1. Slight misalignment is self-corrected by the beveled entry of the Ultra-Mate connector. Badly bent pins will prevent mating until they are replaced.

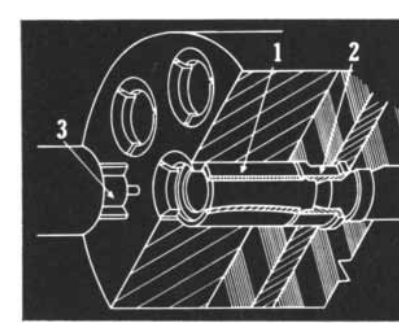

Figure 2. Standard removal tool depresses activation sleeve (1) which spreads tangs of retention clip (2) apart. Tool (3) never directly touches clip.

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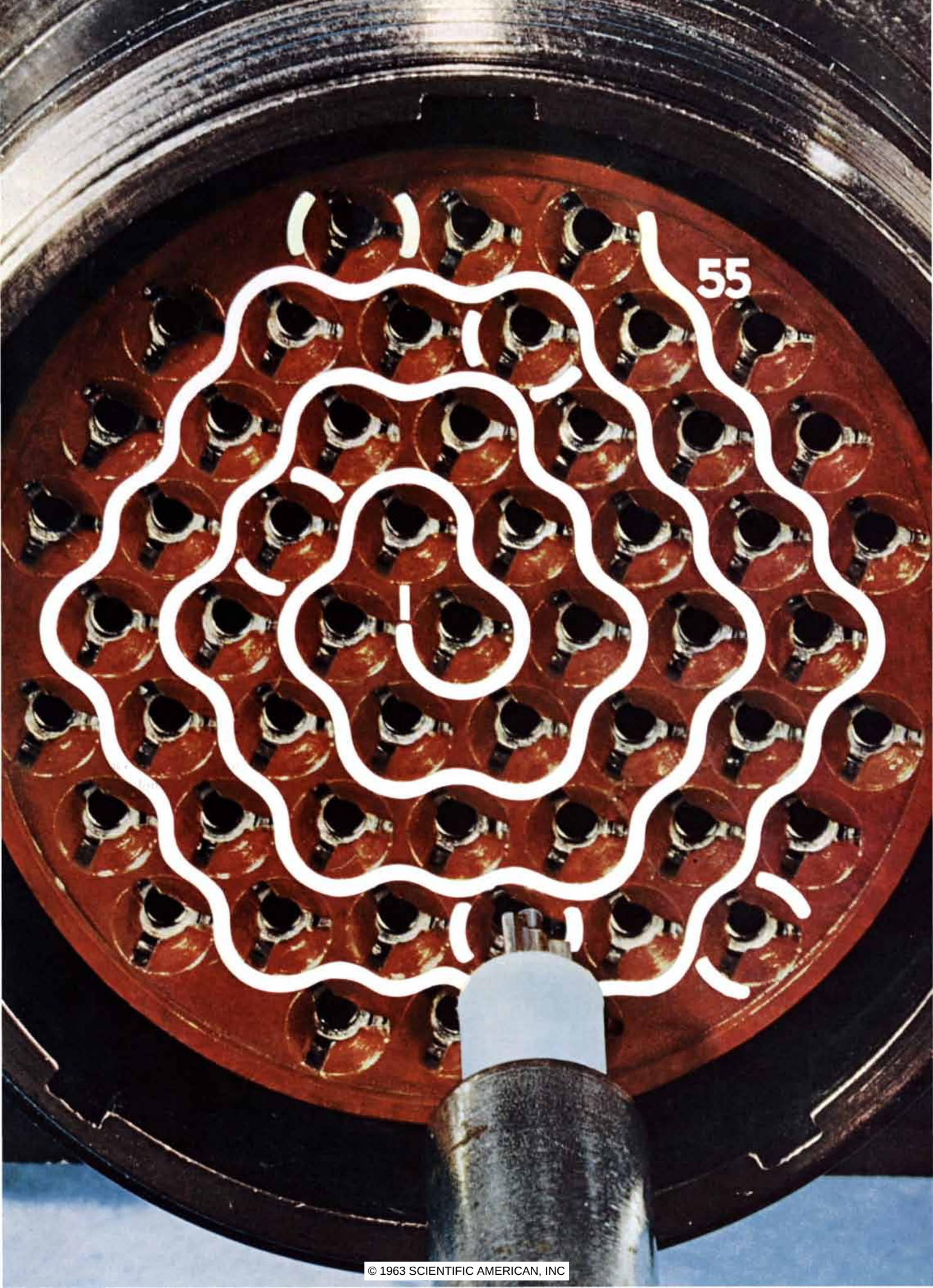

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The Control of Air Pollution

It is now clear that smog is not only annoying but also injurious to health. Los Angeles is a leading example of a city that has analyzed the sources of its smog and taken steps to bring them under control

by A. J. Haagen-Smit

The past decade has seen a change in the public's attitude toward air pollution. Formerly the tendency was to deplore smog but to regard it as one of the inescapable adjuncts of urban life. Now there is a growing realization that smog, beyond being a vexatious nuisance, may indeed present hazards to health, and that in any case the pollution of the air will inevitably grow worse unless something is done about it. As a result many communities have created agencies to deal with air pollution and have, with varying degrees of effectiveness, backed the agencies with laws.

Going considerably beyond these efforts is the program in Los Angeles, a city rather widely regarded as the smog capital of the U.S. There the authorities have adopted the attitude that it is not enough to know smog exists; they have undertaken extensive studies to ascertain its components and to understand something of the complex processes by which it is created. Moreover, with help from the state they have taken pioneering steps toward curbing the emissions of the automobile, which is both a major cause of air pollution and a far more difficult source to control than such stationary installations as petroleum refineries and electric power plants. As a result of California's activities a device to control the emissions from the crankcases of automobiles is now standard equipment on all new cars in the U.S. The state is also working toward a program that will result in a measure of control over emissions from the automobile exhaust.

LOS ANGELES SMOG, shown in photograph on opposite page, casts thick pall over city. Persistence and severity of smogs led the city to undertake pioneering and extensive programs to curb air pollution.

Complaints about polluted air go far back in time. As long ago as 1661 the English diarist John Evelyn declared in a tract entitled *Fumifugium, or the inconvenience of the Aer and Smoak of London* that the city "resembles the face Rather of Mount Aetna, the Court of Vulcan, Stromboli, or the Suburbs of Hell than an Assembly of Rational Creatures and the Imperial seat of our Incomparable Monarch." Air pollution has drawn similar complaints in many cities over the centuries.

For a long time, however, these complaints were like voices in the wilderness. Among the few exceptions in the U.S. were St. Louis and Pittsburgh, where the residents decided at last that they had inhaled enough soot and chemicals and took steps several years ago to reduce air pollution, primarily by regulating the use of coal. These, however, were isolated cases that did not deeply penetrate the consciousness of people in other parts of the country.

It was probably the recurrence of crises over smog in Los Angeles that awakened more of the nation to the possibility that the same thing could happen elsewhere and to the realization that air, like water, should be considered a precious resource that cannot be used indiscriminately as a dump for waste materials. By the time residents of Washington, D.C., complained of eye irritation and neighboring tobacco growers suffered extensive crop damage, it was clear that Los Angeles smog was not just a subject for jokes but a serious problem requiring diligent efforts at control. As a result the pace of antipollution activity has quickened at all levels of government. In addition to the community efforts already mentioned, a national air-sampling network now exists to assemble data on the extent of air pollution, and extensive studies of the effects of smog on health and the economy are under way.

Still, these efforts seem modest when viewed against the size of the problem. Surgeon General Luther L. Terry spoke at the second National Conference on Air Pollution late in 1962 of "how far we have to go." He said: "Approximately 90 per cent of the urban population live in localities with air-pollution problems—a total of about 6,000 communities. But only half of this population is served by local control programs with full-time staffs. There are now about 100 such programs, serving 342 local political jurisdictions. The median annual expenditure is about 10 cents per capita, an amount clearly inadequate to do the job that is necessary."

Enough has been done, however, to demonstrate that a concerted attack on

the smog problem can produce a clearing of the air. Los Angeles, which Terry has called "the area in the United States that's devoting more money and more effort toward combating the problem than any other city," provides an example of the possibilities, the difficulties and the potential of such an attack.

Los Angeles certainly qualifies as a community where air pollution has created an annoying and at times dangerous situation. Two-thirds of the year smog is evident through eye irritation, peculiar bleachlike odors and a decrease in visibility that coincides with the appearance of a brownish haze. According to the California Department of Public Health, 80 per cent of the population in Los Angeles County is affected to some extent.

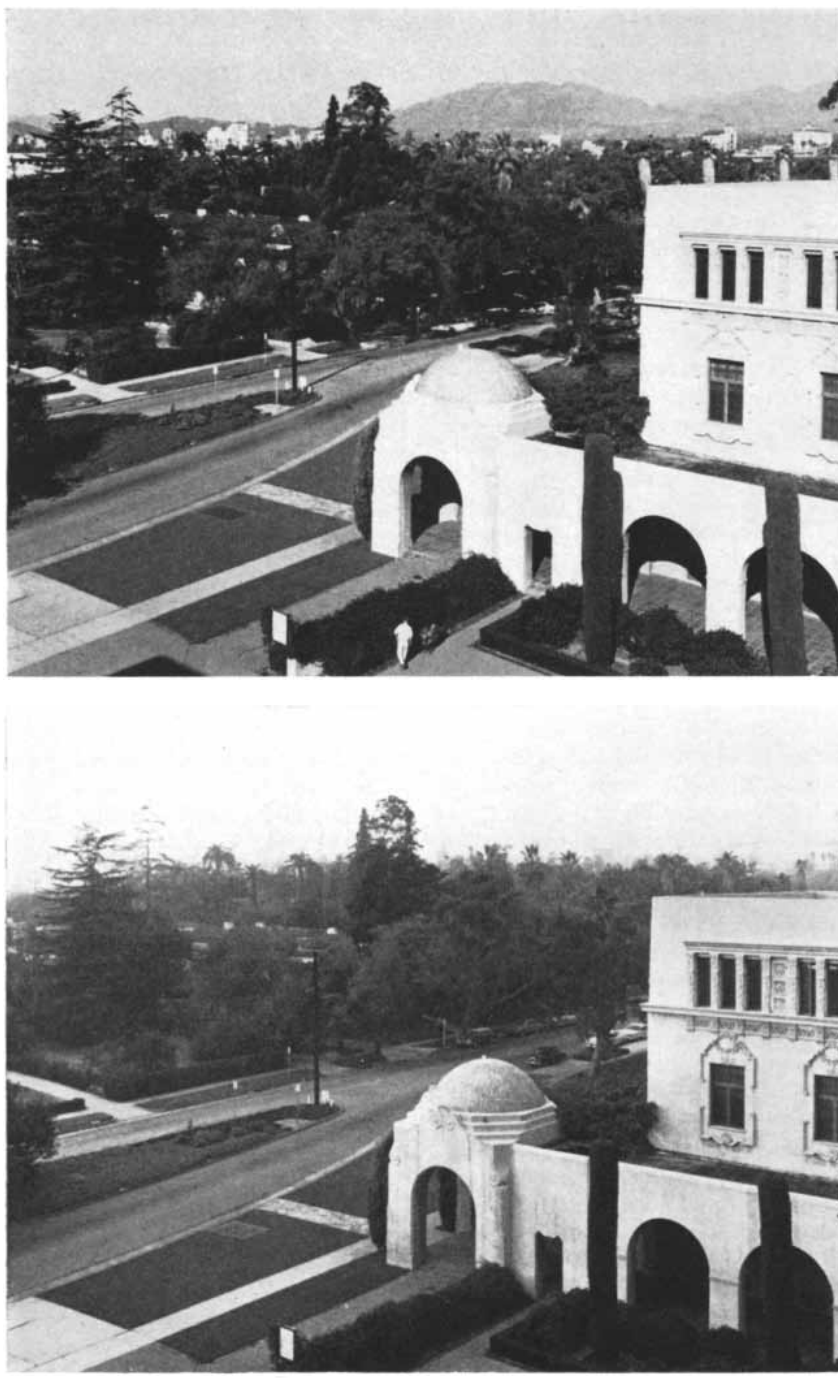
The city's decision to attack the smog problem dates from a report made in 1947 by Raymond R. Tucker, who as an investigator of air-pollution problems played a major role in the St. Louis smog battle and is now the mayor of that city. His report on Los Angeles enumerated the sources of pollution attributable to industry and to individuals through the use of automobiles and the burning of trash. The report recommended immediate control of known sources of pollution and a research program to determine if there were any other things in the air that should be controlled.

Largely on the basis of the Tucker report, *The Los Angeles Times* started with the aid of civic groups a campaign to inform and arouse the public about smog. As a result the state legislature in 1948 passed a law permitting the formation of air-pollution control districts empowered to formulate rules for curbing smog and endowed with the necessary police power for enforcement of the rules. Los Angeles County created such a district the same year.

The district began by limiting the dust and fumes emitted by steel factories, refineries and hundreds of smaller industries. It terminated the use of a million home incinerators and forbade the widespread practice of burning in public dumps. These moves reduced dustfall, which in some areas had been as much as 100 tons per square mile per month, by two-thirds, bringing it back to about the level that existed in 1940 before smog became a serious problem in the community. That achievement should be measured against the fact that since 1940 the population of Los Angeles and the number of industries in the city have doubled.

Although the attack on dustfall produced a considerable improvement in visibility, the typical smog symptoms of eye irritation and plant damage remained. The district therefore undertook a research program to ascertain the origin and nature of the substances that caused the symptoms. One significant finding was that the Los Angeles atmosphere differs radically from that of most other heavily polluted communities. Ordinarily polluted air is made strongly reducing by sulfur dioxide, a product of the combustion of coal and heavy oil. Los Angeles air, on the other hand, is often strongly oxidizing. The oxidant is mostly ozone, with smaller contributions from oxides of nitrogen and organic peroxides.

During smog attacks the ozone content of the Los Angeles air reaches a level 10 to 20 times higher than that elsewhere. Concentrations of half a part of ozone per million of air have repeatedly been measured during heavy smogs. To establish such a concentration directly would require the dispersal of about



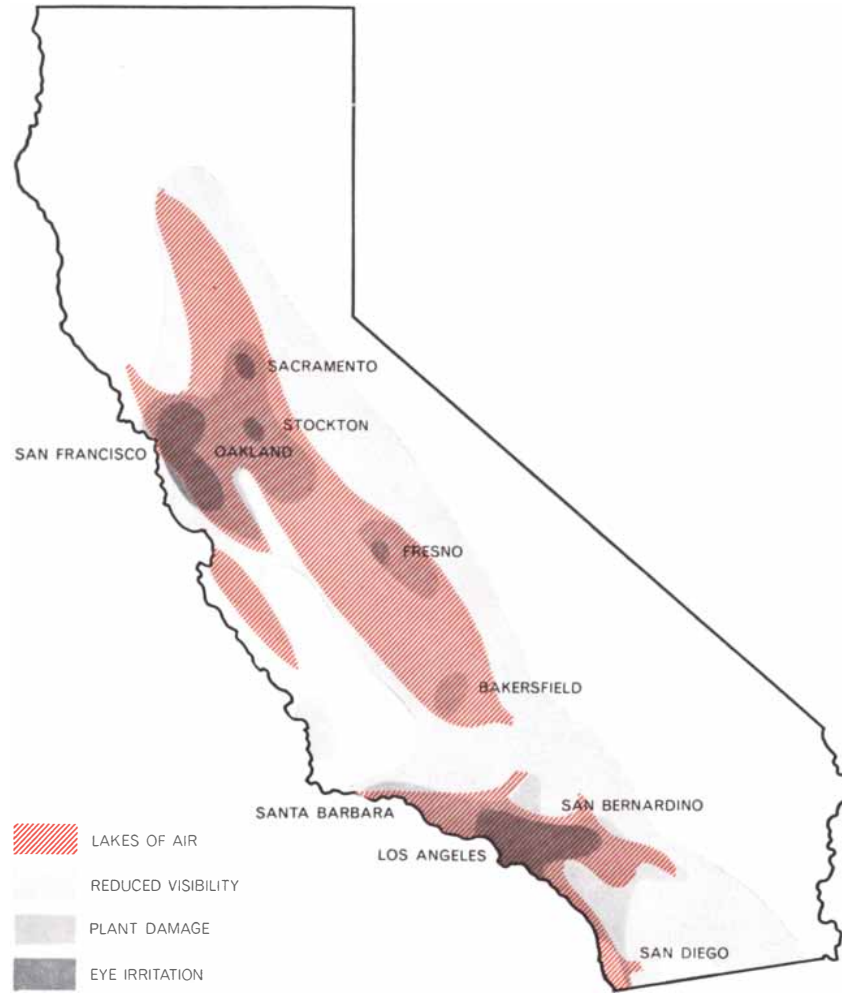
SMOG CURTAIN falls over the view from the campus of the California Institute of Technology. At top is the scene on a weekday morning; at bottom, the same scene that afternoon.

1,000 tons of ozone in the Los Angeles basin. No industry releases significant amounts of ozone; discharges from electric power lines are also negligible, amounting to less than a ton a day. A considerable amount of ozone is formed in the upper atmosphere by the action of short ultraviolet rays, but that ozone does not descend to earth during smog conditions because of the very temperature inversion that intensifies smog. In such an inversion warm air lies atop the cold air near the ground; this stable system forms a barrier not only to the rise of pollutants but also to the descent of ozone.

Exclusion of these possibilities leaves sunlight as the only suspect in the creation of the Los Angeles ozone. The cause cannot be direct formation of ozone by sunlight at the earth's surface because that requires radiation of wavelengths shorter than 2,000 angstrom units, which does not penetrate the atmosphere to ground level. There was a compelling reason, however, to look for an indirect connection between smog and the action of sunlight: high oxidant or ozone values are found only during daylight hours. Apparently a photochemical reaction was taking place when one or more ingredients of smog were exposed to sunlight—which is of course abundant in the Los Angeles area.

In order for a substance to be affected by light it has to absorb the light, and the energy of the light quanta has to be sufficiently high to rupture the chemical bonds of the substance. A likely candidate for such a photochemical reaction in smog is nitrogen dioxide. This dioxide is formed from nitrogen oxide, which originates in all high-temperature combustion through a combining of the nitrogen and oxygen of the air. Nitrogen dioxide has a brownish color and absorbs light in the region of the spectrum from the blue to the near ultraviolet. Radiation from the sun can readily dissociate nitrogen dioxide into nitric oxide and atomic oxygen. This reactive oxygen attacks organic material, of which there is much in the unburned hydrocarbons remaining in automobile exhaust. The result is the formation of ozone and various other oxidation products. Some of these products, notably peracylnitrates and formaldehyde, are eye irritants. Peracylnitrates and ozone also cause plant damage. Moreover, the oxidation reactions are usually accompanied by the formation of aerosols, or hazes, and this combination aggravates the effects of the individual components in the smog complex.

The answer to the puzzle of the oxidizing smog of the Los Angeles area thus lay in the combination of heavy automobile traffic and copious sunlight. Similar photochemical reactions can of course occur in other cities, and the large-scale phenomenon appears to be spreading.

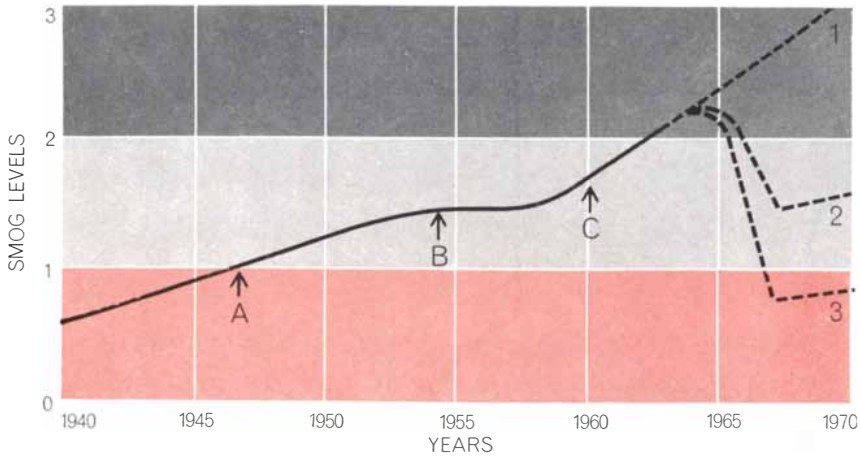


EXTENT OF AIR POLLUTION in California is indicated by gray areas on this map. Colored areas show the main natural airsheds, or lakes of air, into which pollutants flow. Sunlight acting on pollutants produces substances that irritate eyes and damage plants.

The more or less temporary effects of smog alone would make a good case for air-pollution control; there is in addition the strong likelihood that smog has adverse long-range effects on human health [see "Air Pollution and Public Health," by Walsh McDermott; Scientific American, October, 1961]. Workers of the U.S. Public Health Service and Vanderbilt University reported to the American Public Health Association in November that a study they have been conducting in Nashville, Tenn., has established clear evidence that deaths from respiratory diseases rise in proportion to the degree of air pollution.

For the control of air pollution it is of central importance to know that organic substances—olefins, unsaturated hydrocarbons, aromatic hydrocarbons and the derivatives of these various kinds of molecules—can give rise to ozone and one or more of the other typical manifestations of smog. Control measures must be directed against the release of these volatile substances and of the other component of the smog reaction: the oxides of nitrogen. The organic substances originate with the evaporation or incomplete combustion of gasoline in motor vehicles, with the evaporative losses of the petroleum industry and with the use of solvents. A survey by the Los Angeles Air Pollution Control District in 1951 showed that losses at the refineries were more than 400 tons a day; these have since been reduced to an estimated 85 tons.

This reduction of one source was offset, however, by an increase in the emissions from motor vehicles. In 1940 there were about 1.2 million vehicles in the Los Angeles area; in 1950 there were



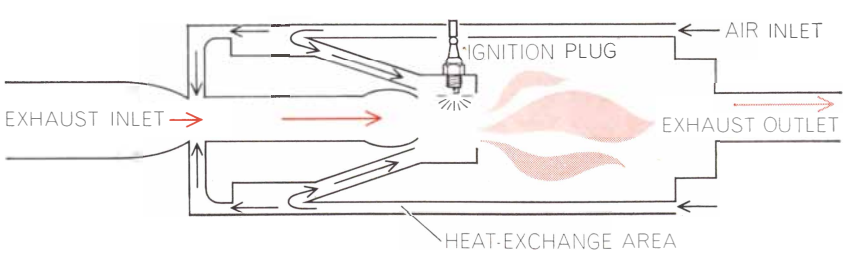
POLLUTION LEVELS in Los Angeles are plotted on scale (*left*) where *1* is 1947 level, *2* double and *3* triple that. *A* represents state pollution control law; *B*, control over refineries; *C*, motor vehicle controls. Broken lines indicate smog potential without new controls (*1*), with hydrocarbon controls (*2*) and with both hydrocarbon and nitrogen oxide controls (*3*).

two million; today there are 3.5 million. These vehicles burn about seven million gallons, or 21,500 tons, of gasoline a day. They emit 1,800 tons of unburned hydrocarbons, 500 tons of oxides of nitrogen and 9,000 tons of carbon monoxide daily. These emissions outweigh those from all other sources.

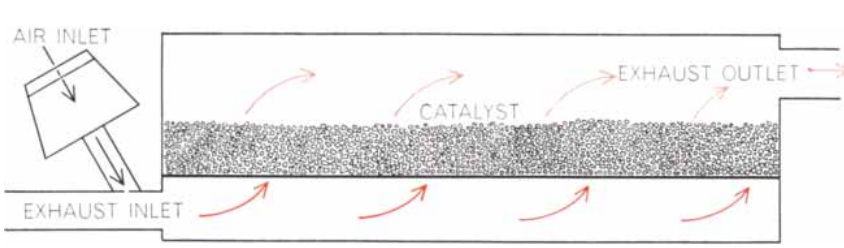
When motor vehicles emerged as a major source of air pollution, it was evident that state rather than local government could best cope with these moving sources. As a first step, and a pioneering one for the U.S., the California Department of Public Health adopted community standards for the quality of the air [*see top illustration on page 31*].

The adoption of these standards provided a sound basis for a program of controlling automobile emissions. Of special importance for that program was the establishment of the figure of .15 part per million by volume as the harmful level of oxidant. Years of observation have demonstrated that when the oxidant goes above .15 part per million, a significant segment of the population complains of eye irritation, and plant damage is readily noticeable. The standards also set the harmful level for carbon monoxide at 30 parts per million by volume for eight hours, on the basis of observations that under those conditions 5 per cent of the human body's hemoglobin is inactivated. A further stipulation of the standards was that these oxidant and carbon monoxide levels should not be reached on more than four days a year. To attain such a goal in Los Angeles by 1970 would require the reduction of hydrocarbons and carbon monoxide by 80 and 60 per cent.

On the basis of these standards the California legislature in 1960 adopted the nation's first law designed to require control devices on motor vehicles. The law created a Motor Vehicle Pollution Control Board to set specifications and test the resulting devices. In its work the board has been concerned with two kinds of vehicular emission: that from the engine and that from the exhaust.



EXHAUST CONTROL, directed at hydrocarbon emissions of automobile, involves reburning in an afterburner. Shown here is a type of direct-flame afterburner now being tested.



SECOND TYPE of afterburner involves leading exhaust gases through a catalyst bed; they can then be burned at lower temperatures than are possible in a direct-flame afterburner.

About 30 per cent of the total emission of the car, or 2 per cent of the supplied fuel, escapes from the engine. This "blowby" loss results from seepage of gasoline past piston rings into the crankcase; it occurs even in new cars. Evaporation from the carburetor and even from the fuel tank is substantial, particularly on hot days. Until recently crankcase emissions were vented to the outside through a tube. California's Motor Vehicle Polution Control Board began in 1960 a process leading to a requirement that all new cars sold in the state have by 1963 a device that carries the emissions back into the engine for recombustion. The automobile industry thereupon installed the blowby devices in all 1963 models, so that gradually crankcase emissions will come under control throughout the U.S. California is going a step further: blowby devices will have to be installed soon on certain used cars and commercial vehicles.

Two-thirds of the total automobile emission, or 5.4 per cent of the supplied fuel, leaves through the tail pipe as a result of incomplete combustion. For complete combustion, which would produce harmless gases, the air-fuel ratio should be about 15 to 1. Most cars are built to operate on a richer mixture, containing more gasoline, for smoother operation and maximum power; consequently not all the gasoline can be burned in the various driving cycles.

The exhaust gases consist mainly of nitrogen, oxygen, carbon dioxide and water vapor. In addition there are lesser quantities of carbon monoxide, partially oxidized hydrocarbons and their oxidation products, and oxides of nitrogen and sulfur. Most proposals for control of these gases rely on the addition of an afterburner to the muffler. Two approaches appear most promising. The direct-flame approach uses a spark plug or pilot light to ignite the unburned gases. The catalytic type passes them through a catalyst bed that burns them at lower temperatures than are possible

with direct-flame burners [*see bottom illustrations on opposite page*].

Building a successful afterburner presents several problems. The high temperatures require more costly materials, thereby increasing initial and replacement costs. Complications in operation arise from the burning of a mixture of gases and air of highly variable concentration. During deceleration the mixture may be so rich that without a bypass ceramics and catalysts will melt. In other cycles of operation there may not be enough fuel to keep the flame going. Moreover, the California law on exhaust-control devices stipulates that they must not be a fire hazard, make excessive noise or adversely affect the operation of the engine by back pressure.

Nine makes of afterburner—six catalytic and three direct-flame—are now under test by the California Motor Vehicle Pollution Control Board. Much testing and modification will be necessary before they are ready for the rough treatment to which they will be subjected when they are attached to all cars. Even after they have been installed a rigorous inspection program will be necessary to make certain that they are properly maintained and periodically replaced.

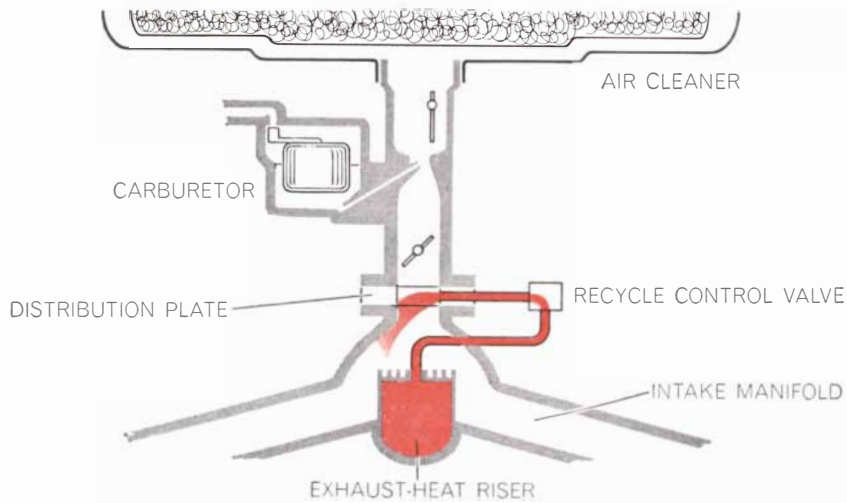
A preferable method of controlling hydrocarbon emissions from automobile tail pipes would be better combustion in the engine. Automobile engineers have indicated that engines of greater combustion efficiency will appear in the next few years. How efficient these engines will be remains to be seen; so does the effect of the prospective changes on emissions of oxides of nitrogen.

From all the emissions of an automobile the total loss in fuel energy is about 15 per cent; in the U.S. that represents a loss of about $3 billion annually. It is remarkable that the automobile industry, which has a reputation for efficiency, allows such fuel waste. Perhaps pressure for greater efficiency and for control of air pollution will eventually produce a relatively smogless car.

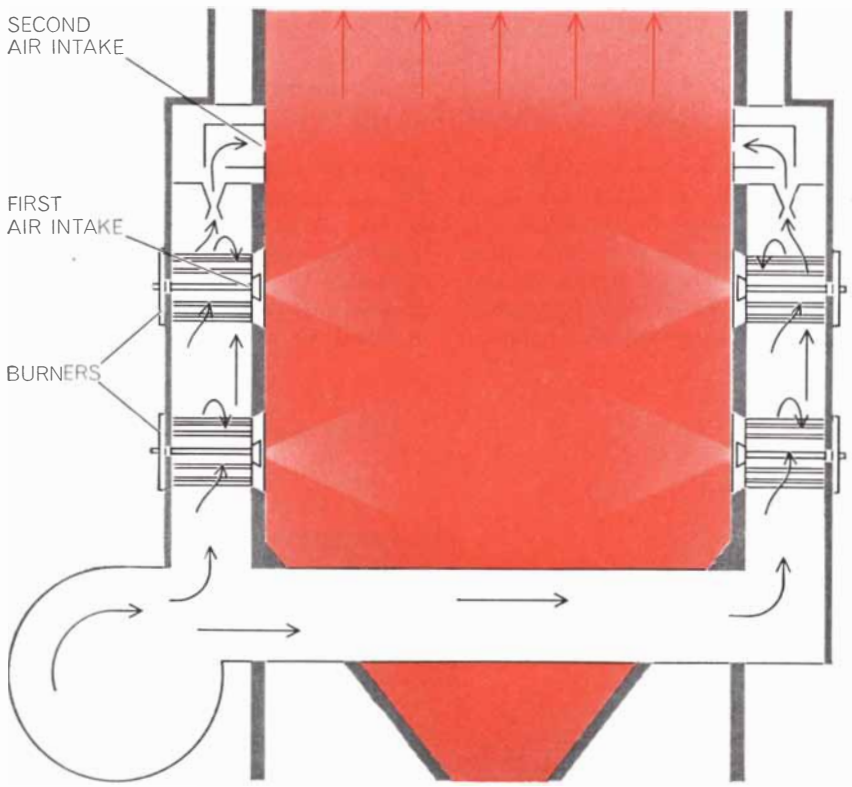
In any case it appears that the proposed 80 per cent control over motor vehicle emissions is a long way off. An alternative is to accept temporary controls at lower levels of effectiveness. It is possible to reduce unburned hydrocarbons and carbon monoxide by modification of the carburetor in order to limit the flow of fuel during deceleration, and by changing the timing of the ignition spark. Proper maintenance can reduce emissions by 25 to 50 per cent, depending on the condition of the car.

Accepting more practical but less efficient means of curbing vehicular emissions requires making up the deficiency in the smog control program some other way. This can be done by control of the other smog ingredient: oxides of nitrogen. At one time it was thought that control of these oxides would be very difficult, and that was why the California law concentrated on curbing emissions of hydrocarbons. It has now been shown, however, that control of oxides of nitrogen, from stationary sources as well as from motor vehicles, is feasible. Oil-burning electric power plants have reduced their contribution by about 50 per cent through the use of a special two-phase combustion system. Research on automobiles has shown that a substantial reduction of oxides of nitrogen is feasible with a relatively simple method of recirculating some of the exhaust gases through the engine.

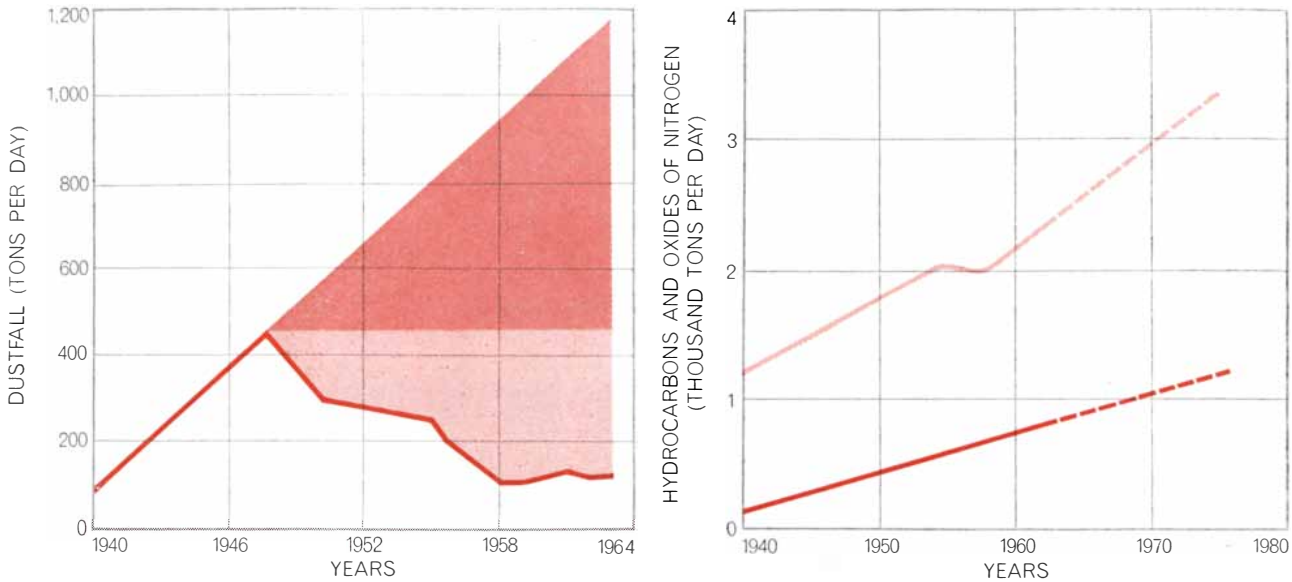
To arrive at an acceptable quality of air through the limitation of hydrocar-



OXIDES OF NITROGEN emitted by automobiles may be curbed by this system, which takes exhaust gases before they leave the engine and recycles them through the combustion process.



INDUSTRIAL FURNACES have curbed emissions of oxides of nitrogen by two-phase combustion. It lowers temperatures by introducing air at two stages of the burning process.



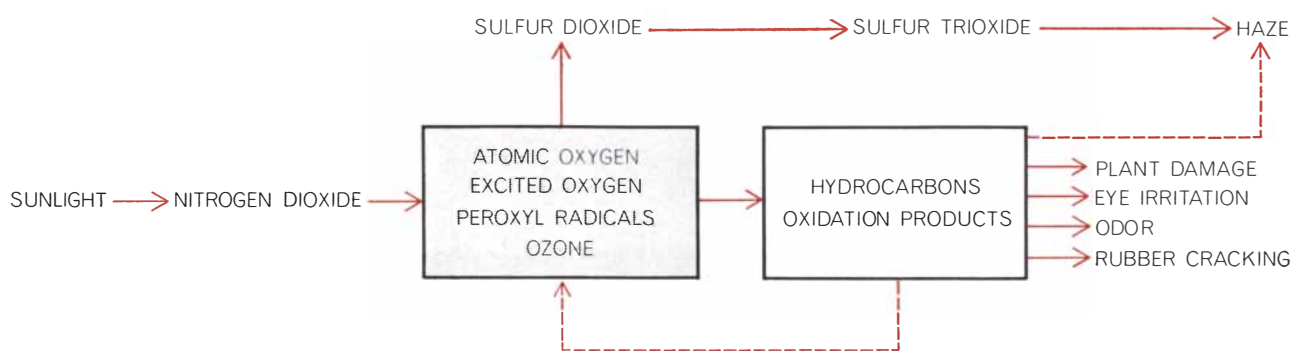
MAJOR POLLUTANTS in Los Angeles County are charted. Dustfall (*left*) has been visibly reduced (*light color*) by control measures; potential without controls is indicated by darker color. At right, light line shows actual and potential levels of hydrocarbons; dark line similarly represents oxides of nitrogen. Rises in spite of controls reflect growth of population and number of vehicles.

bons alone would require a reduction in the hydrocarbons of about 80 per cent, which could be achieved only with rigorous and efficient controls. The plateau of clean air can also be reached, however, by dealing with both hydrocarbons and oxides of nitrogen. The advantage of such an approach is that each one of the reductions would have to be less complete. An over-all reduction of the two major smog components by half would achieve the desired air quality [*see bottom illustration on opposite page*].

This combined approach offers the only practically feasible way to return to a reasonably smog-free atmosphere in Los Angeles as well as in other metropolitan areas plagued by photochemical smog. The California Department of Public Health is now considering the expansion of the smog control program to include curbs on emission of oxides of nitrogen. For such a program to succeed, however, there would have to be regular inspection of motor vehicles, control of carburetor and fuel tank losses, stringent additional controls over industry and the co-operation of citizens. Moreover, these efforts must be organized in such a way that they take into account the area's rapid population growth, which will mean proportionate rises in motor vehicle and industrial emissions.

Beyond the efforts to control industries and vehicles lie some other possibilities, all of which would have the broad objective of reducing the amount of gasoline burned in the area. They include electric propulsion, economy cars, increased use of public transportation and improvement of traffic flow. A strong argument for resorting to some of or all these possibilities can be found in an examination of the carbon monoxide readings at a monitoring station in downtown Los Angeles. The readings show clear peaks resulting from commuter traffic. The carbon monoxide increase during a rush period is about 200 tons, representing the emission of about 100,000 cars. That figure agrees well with vehicular counts made during the hours of heavy commuting.

Greater use of public transportation would produce a considerable reduction of peak pollution levels. So would improved traffic flow, both on the main commuter arteries and on the roads that connect with them. Reduction of the frequent idling, acceleration and deceleration characteristic of stop-and-go driving



PHOTOCHEMICAL REACTION playing a major role in smog formation begins with sunlight acting on nitrogen dioxide, a product of combustion, to yield oxidants (*gray box*). They attack hydrocarbons, which come mainly from automobile exhausts, to produce irritating materials. Oxidants also attack sulfur dioxide, a product of coal and oil burning. Broken lines indicate interactions.

—the very cycles that produce the most hydrocarbons and oxides of nitrogen—could curb vehicular emissions by 50 per cent or more over a given distance. Detroit has a system of computing the optimum speed on certain freeways according to the density and flow of traffic; the speed is then indicated on large lighted signs. The result is a smoother flow. More techniques of this kind, more imaginative thinking about transportation in general, are necessary for a successful attack on smog.

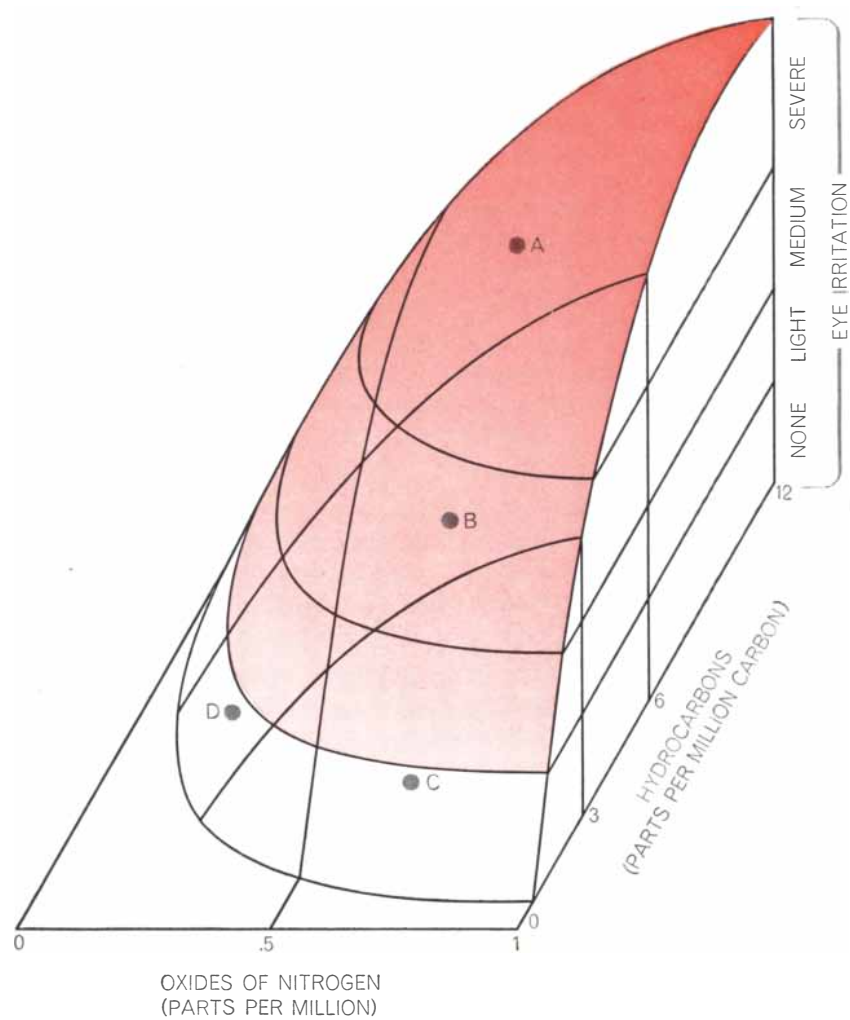
There can be no doubt that the smogs of Los Angeles represent an extreme manifestation of a problem that is growing in every heavily populated area. Similarly, the control steps taken by Los Angeles will have to be duplicated to some degree in other cities. In those cities, as in Los Angeles, there will be difficulties. One is the cost of air-pollution control for communities that already find their budgets stretched; the Detroit City Council annually votes down an ordinance to ban the burning of leaves because it believes the city cannot afford the estimated cost of $500,000 for carting the leaves off to dumps. Industry also may balk at smog controls out of concern for maintaining a competitive position. There is a related problem of co-ordination: industries are reluctant to install devices for curbing smoke while the city burns trash in open dumps.

Another problem involves mobilizing the public behind air-pollution control programs. Even though smog looks unpleasant, is occasionally offensive to the smell and irritating to the eye, and sometimes precipitates a public health disaster (as in Donora, Pa., in 1948 and in London in 1952), it nonetheless tends to be regarded as a fact of urban life and something that communities can live with if they must. Moreover, so many political jurisdictions must be involved in an effective attack on air pollution that any one community attempting a clean-up may find its efforts vitiated by another community's smog.

Nevertheless, a growing segment of the public is alert to the dangers of air pollution and determined to do something about it. If anything effective is to be done, however, it will require intelligent planning, aggressive public-education programs and resoluteness on the part of public officials. Then leadership by government and civic groups at all levels, united behind well-designed plans, could generate progress toward the goal of cleaner air.

POLLUTANT	PARTS PER MILLION FOR ONE HOUR		
	"ADVERSE" LEVEL	"SERIOUS" LEVEL	"EMERGENCY" LEVEL
CARBON MONOXIDE		120	240
ETHYLENE	.5		
HYDROGEN SULFIDE	.1	5	
SULFUR DIOXIDE	1	5	10
HYDROCARBONS	.15 ON "OXIDANT INDEX"	NOT ESTABLISHED	NOT ESTABLISHED
NITROGEN DIOXIDE			
OXIDANT			
OZONE			
AEROSOLS			

AIR-QUALITY STANDARDS adopted by California set three levels of pollution: "adverse," at which sensory irritation and damage to vegetation occur; "serious," where there is danger of altered bodily function or chronic disease; "emergency," where acute sickness or death may occur in groups of sensitive persons. Blanks mean "not applicable." Pollutants listed in colored type are involved in or are the products of photochemical reaction. These standards, the first adopted by any state, provided a basis for pollution control measures.



CONTROL POTENTIALS are depicted. Los Angeles is at *A* in degree of eye irritation on a day of heavy smog. Controls reducing hydrocarbons by 50 per cent would bring city down the slope to *B*, still not in clear zone shown in white. Hydrocarbon controls to *C* are impractical; control of both hydrocarbons and oxides of nitrogen would attain clear zone at *D*.

The Large Cloud of Magellan

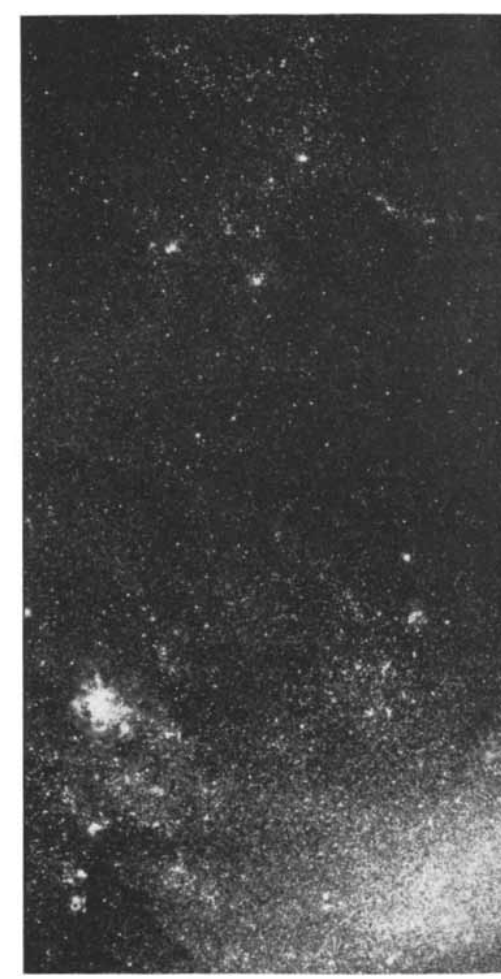
One of a pair of small galaxies visible only in the Southern Hemisphere, it is so near our own galaxy that it is a unique laboratory for the study of the birth and evolution of stars

by Bart J. Bok

Far to the south of the celestial equator, out of the reach of all the world's largest telescopes, lie two great treasures of astronomy: the twin assemblages of stars known as the Clouds of Magellan. These satellite systems of our galaxy are unique laboratories for the study of the birth and evolution of stars and therefore for increasing our understanding of the structure and dynamics of galaxies in general. The most luminous supergiant stars—young and rapidly evolving types that are hard to identify in our galaxy—are spread out in rich array in the Clouds of Magellan, often surrounded by glowing masses of hydrogen in which new stars are in process of formation. The Clouds are only about 180,000 light-years away, a tenth of the distance of the Great Nebula in Andromeda, the spiral galaxy so intensively examined with the 200-inch reflector on Palomar Mountain and the other large telescopes of the Northern Hemisphere. In investigating the Clouds a telescope with a mirror 20 inches in diameter equals the performance of the 200-inch reflector at the distance of the Andromeda galaxy. One can thus see why an astronomer's eyes glisten when he considers what a 150-inch reflector in the Southern Hemisphere might do for astronomical research. The Clouds of Magellan have still another major attraction: they are not obscured by the cosmic dust that blocks our view of much of the Milky Way, the star-rich central plane of our galaxy.

The Clouds bear the name of the explorer Ferdinand Magellan, whose chronicler mentioned them in his log of 1521 during the first circumnavigation of the globe. Although they have been known for more than four centuries, it is only during the past 60 years that they have come to be recognized as prime astronomical resources. Until a decade ago the Harvard College Observatory and its Boyden Station in South Africa had a virtual monopoly in research on the Clouds. Early in the century Henrietta S. Leavitt of the Harvard Observatory discovered in the Clouds hundreds of the pulsating stars known as cepheid variables. It was found that the period of pulsation of each cepheid is directly related to its luminosity; in general, the longer the period, the brighter the star. The relation could not have been demonstrated with cepheid variables in our galaxy because one could not tell their absolute magnitude, or luminosity corrected for distance; a star of a given brightness in the sky can be either a faint star that is relatively close or a bright star that is farther away. This problem does not arise with respect to the Clouds of Magellan because their stars are all at roughly the same distance from us. Once the period-luminosity relation was established, it could be used to determine the absolute magnitude of cepheid variables in our galaxy and others. By comparing the absolute magnitude of a variable with its apparent magnitude, the distance of the star could be calculated, and the cepheid variables became valuable milestones for measuring the universe. Although complications such as the discovery of different types of cepheids have called the period-luminosity relation into question, new techniques of light measurement are reinstating it. Under the leadership of Harlow Shapley, numerous Harvard investigators, notably Jenka Mohr and Virginia McKibben Nail, did much useful spadework on the variables and other aspects of the Clouds.

Since the early 1950's several other observatories have entered the field. Between 1951 and 1958 A. D. Thackeray and A. J. Wesselink of the Radcliffe Observatory in South Africa discovered in the clouds a number of RR Lyrae variables: pulsating stars with periods of less than a day. The apparent magnitude of these stars is so faint that they are just within the reach of the best telescopes in the Southern Hemisphere, but they are



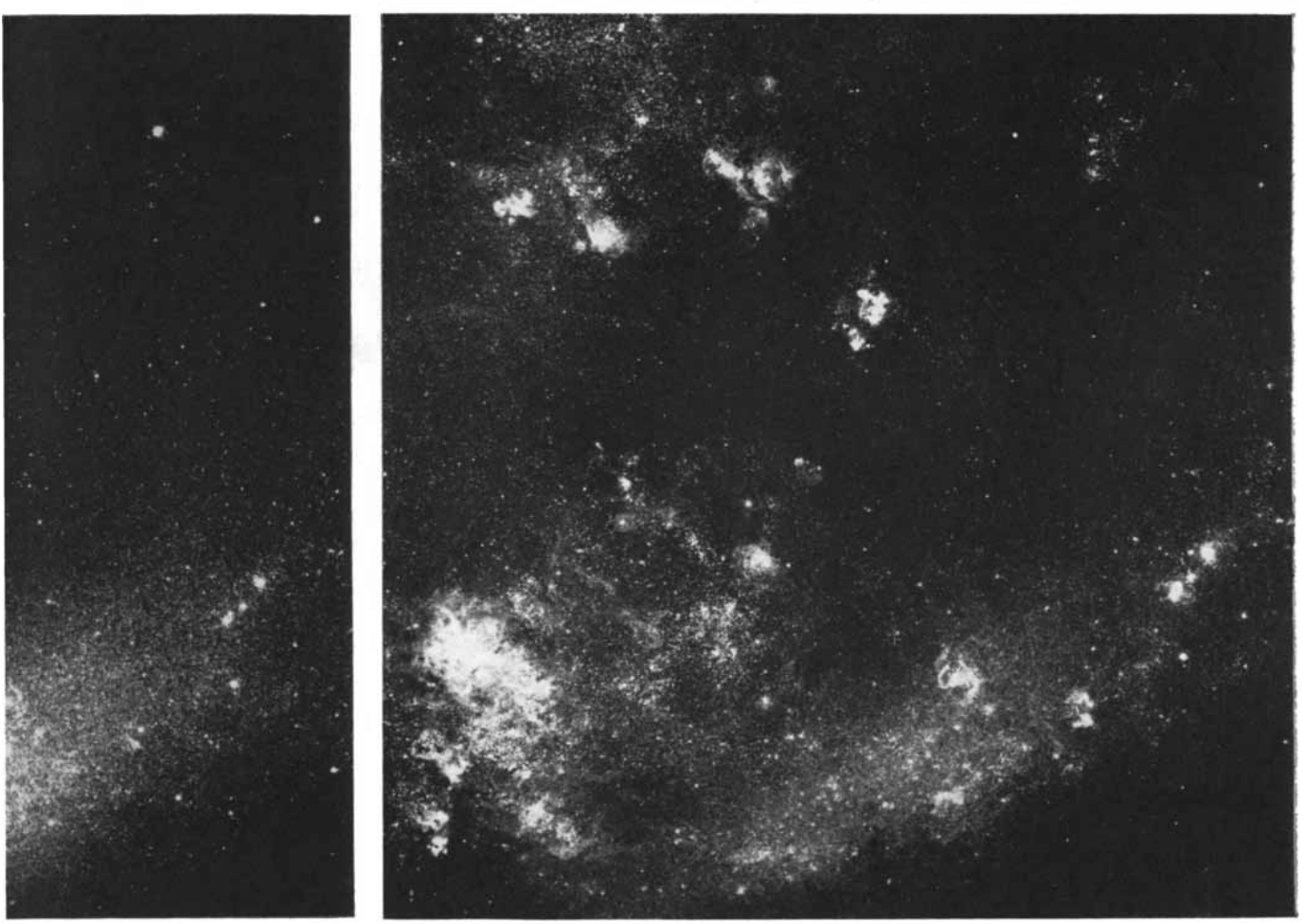
LARGE CLOUD OF MAGELLAN, photographed with an emulsion sensitive to infrared radiation (*left*), displays "broad bar" and

receiving much attention. They provide the best distance scale to the clouds; indeed, it is from observations of a few of them that we have concluded that the clouds are 180,000 light-years away. The period-luminosity relation of RR Lyrae variables in our galaxy has been clearly established, and if it can be proved that the variables in the Clouds are of the same type as those in our galaxy, we can be quite certain of our figure for the distance to the Clouds.

Today all aspects of the study of the Clouds of Magellan have become so important that astronomers operating the two largest telescopes in the Southern Hemisphere, the 74-inch reflectors at the Radcliffe Observatory and at our observatory on Mount Stromlo in Australia, concentrate largely on the Clouds from August to March, the most favorable months for observation. The 210-foot radio telescope at Parkes in Australia, the largest fully steerable antenna in the hemisphere and one of the world's finest, also scans the Clouds frequently.

In this article I shall be concerned for the most part with the Large Cloud of Magellan. It lies some 68 degrees south of the celestial equator; on moonless nights both the Large Cloud and the Small Cloud are clearly visible to the unaided eye, resembling little misplaced patches of the Milky Way. They appear to have an angular diameter of six and three degrees respectively, but photographs show that the Large Cloud, including its outlying clusters of stars, has a diameter of about 12 degrees, or 40,000 light-years. The main body, however, is no more than 20,000 light-years across. (Our galaxy is about 100,000 light-years in diameter.) Although the eye sees the two Clouds separated by a generous 25 degrees, they probably constitute one system; in photographs a faint bridge of star clusters, blue-white supergiant stars and gas seems to connect them. Radio observations by the Radiophysics Laboratory of the Commonwealth Scientific and Industrial Research Organisation in Australia indicate that both clouds are embedded in a common envelope of neutral (un-ionized) atomic hydrogen and are apparently connected by a tenuous bridge of gas [*see illustration on page 36*]. Even more striking, the contour-like lines of equal radiation intensity at a radio wavelength of 21 centimeters are crowded together on the edge of each Cloud that faces away from the other Cloud. F. J. Kerr of the Radiophysics Laboratory has suggested that it looks as though the two Clouds are rushing away from each other.

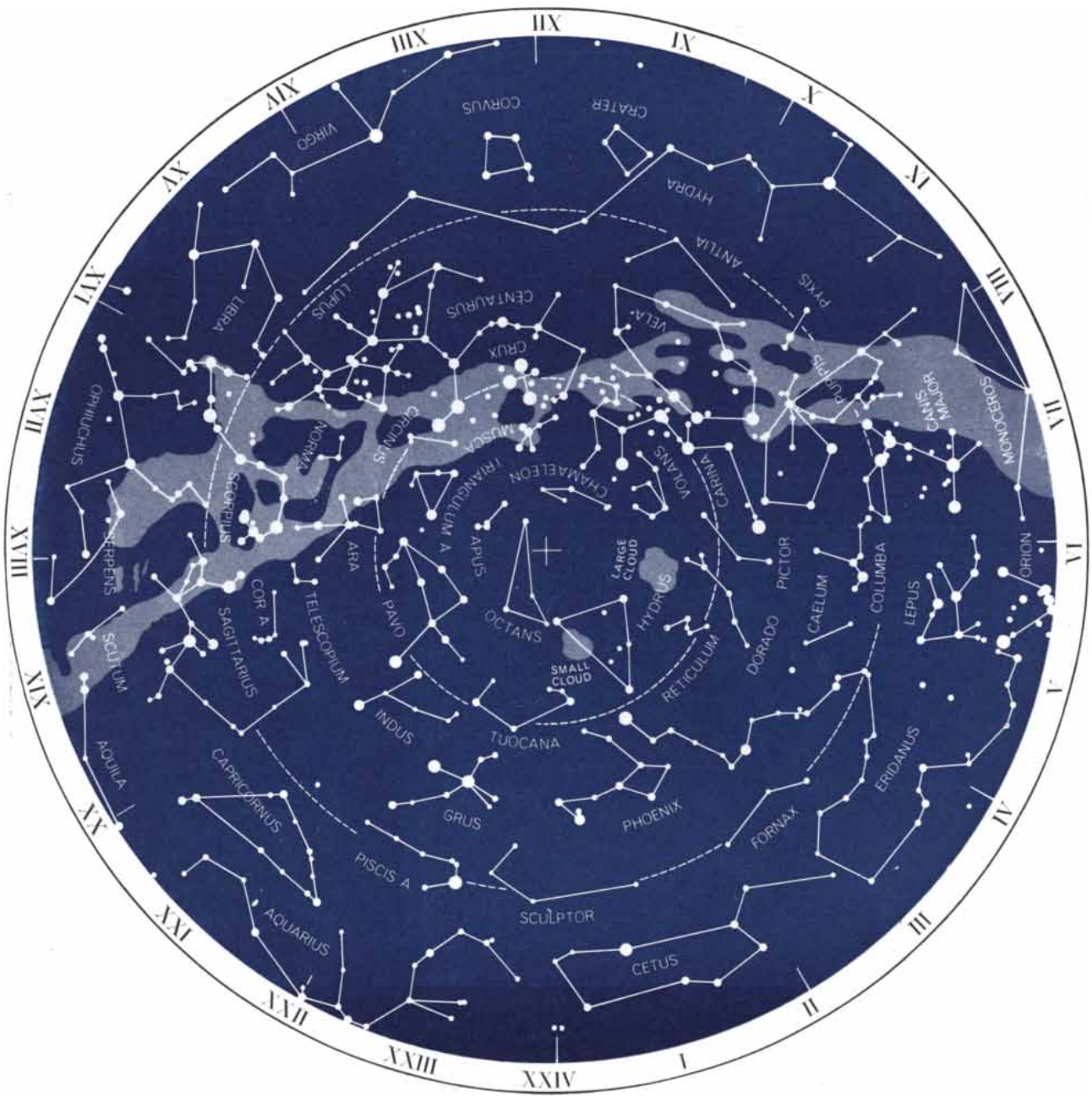
At first glance the Clouds appear to be irregular, or structureless, galaxies, but a growing body of evidence favors the hypothesis that they are really thin, rotating disks like our galaxy. Gérard de Vaucouleurs of the University of Texas has provided increasingly convincing evidence that the Large Cloud in particular is a barred spiral galaxy with a single well-developed spiral arm [see "The Clouds of Magellan," by Gérard



other regions of older stars. When a filter is used to pass only ultraviolet radiation, the young and evolving blue-white stars and glowing gas clouds stand out (*right*). The Tarantula Nebula is at lower left in each photograph. Constellation I, shown also on page 41, is above center. These photographs were made by B. E. Westerlund with the Schmidt telescope at Mount Stromlo Observatory in Australia.

de Vaucouleurs; SCIENTIFIC AMERICAN, April, 1956]. In photographs separate features stand out nicely from their surroundings; I know of no instance in which two distinct features overlap, as they would in an irregular galaxy or a spheroidal one. Measurements of the radial velocity of recession, or movement along the line of sight, of objects in the Large Cloud supply convincing dynamical evidence that it is thin. When the position of various objects across the face of the galaxy is plotted on a graph against the velocity of each object, a smooth curve connects the points; there is little evidence of major differences in average velocity for neighboring features. An irregular or spheroidal galaxy would have a far more random distribution of radial velocities. The plane of the disk of the Large Cloud is tilted to our line of sight at an angle of about 30 degrees (according to De Vaucouleurs) or as much as 45 degrees (according to B. E. Westerlund of the Mount Stromlo Observatory).

The uncertainty in the angle makes it impossible to arrive at an exact figure for the total mass of the Large Cloud. The mass of a galaxy is derived from measurements of the velocity of its rotation, which reflects the amount of force necessary to keep the galaxy from collapsing from the mutual gravitational attraction of its constituents and is therefore directly related to its mass. The best estimates place the mass of the Large Cloud at about a tenth that of our galaxy. Radio observations indicate that gas alone, mostly neutral atomic hydrogen, makes up about 7 per cent of the entire mass. This gives the galaxy a far greater potential for the formation of new stars than is possessed by our galaxy, in which the gas represents more nearly 2 per



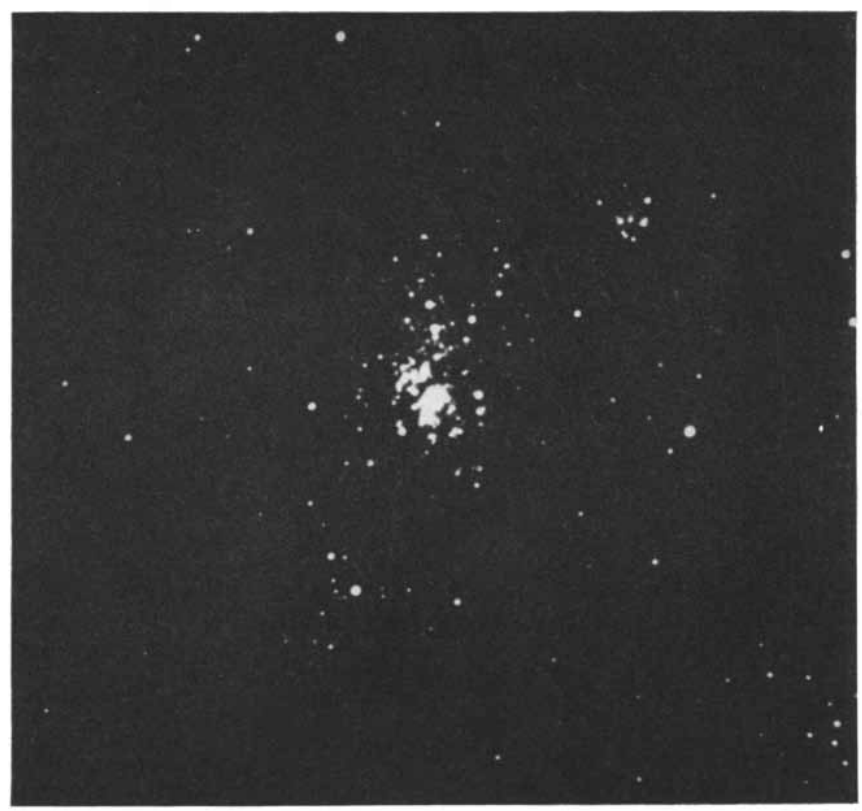
SOUTHERN HEMISPHERE STAR CHART displays constellations, Milky Way (*light colored band*) and Clouds of Magellan (*light patches*). The two concentric circles between center and edge of chart mark declinations 30 degrees and 60 degrees south on the celestial sphere. Roman numerals indicate right ascension. The South Celestial Pole, in the center of the chart, is marked by a cross.

cent of the mass. A small fraction of the gas in the Large Cloud is ionized hydrogen; an even smaller fraction, helium and heavier elements. A putative constituent of the gas, molecular hydrogen (H_2), cannot be measured in any galaxy because it radiates mostly in parts of the electromagnetic spectrum that do not penetrate the earth's atmosphere. There may be a great deal in the Large Cloud or very little.

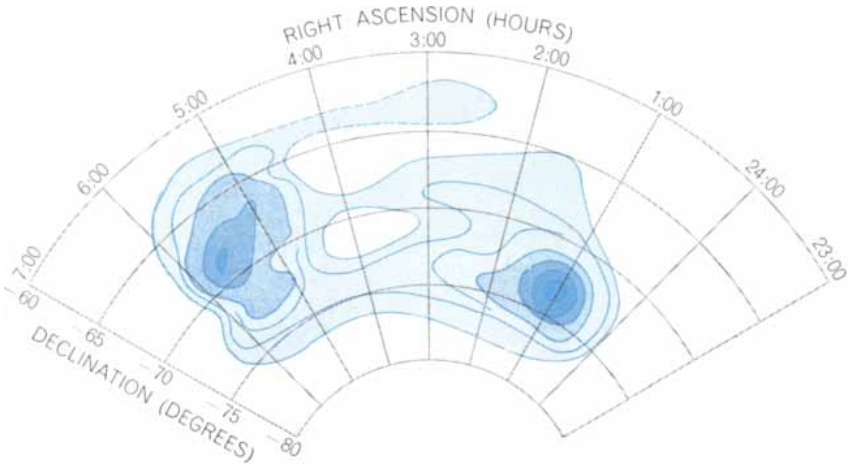
Although the astronomer has a clear view of the Large Cloud, he repeatedly encounters the problem of sorting the foreground of stars in our galaxy from those of the Cloud, particularly in the more open regions of the Cloud. If radial velocity can be measured, that settles the problem; the motion of the sun and earth around the center of our galaxy makes most stars in the Large Cloud appear to recede at 250 to 300 kilometers per second, whereas stars in our galaxy rarely exceed 50 kilometers per second. Obtaining stellar spectra for measurements of radial velocity is difficult in some parts of the Cloud, but recently Charles Fehrenbach, Marcelle Duflot and their associates at the Marseilles Observatory have made the task easier by employing the technique of mass measurement, in which the spectra of a large number of stars are recorded on a single plate. Where stars are crowded, however, the spectra overlap. In another promising approach Sir Richard Woolley, the British Astronomer Royal, superimposes photographs of certain regions made in South Africa early in the century with photographs of the same regions made recently. He then measures the proper, or crosswise, motion of the stars in seconds of arc per year. The foreground stars show perceptible motion but stars in the Cloud show none; they are so far away that a proper motion of 50 kilometers per second gives rise to a shift of only one second of arc in 6,000 years. A third technique of sorting the Cloud stars from the foreground stars involves the determination of color at several wavelengths. After such determinations have been made, a star that was assumed to be in our galaxy but is actually in the Cloud, or vice versa, will often appear to have some quite odd characteristics because of the great difference in its assumed and actual distance. Th. and J. Walraven applied this technique successfully when they were at the Leiden Observatory's Southern Station in South Africa.

The illustrations on pages 32 and 33 provide a good over-all view of the structure of the Large Cloud. The photograph

TARANTULA NEBULA, the most massive gas cloud known, is shown in photograph made by A. R. Hogg with the 74-inch reflector at Mount Stromlo Observatory. The plate recorded primarily the red light of the "alpha" line in the spectrum of hydrogen.



HEART OF TARANTULA NEBULA holds the giant blue-white stars shown here in photograph made by Westerlund with the same telescope. He used a filter that eliminated virtually all light emitted by the gas. The field is smaller than in the top photograph.



COMMON HYDROGEN ENVELOPE of Large Cloud (*left*) and Small Cloud (*right*) is apparent on radio map. Contours represent equal brightness for radiation at the wavelength of 21 centimeters, emitted by neutral atomic hydrogen. Observations were made by J. V. Hindman, F. J. Kerr and R. X. McGee with 210-foot radio telescope at Parkes in Australia.

at left was made with an emulsion sensitive to infrared radiation; the photograph at right, which covers exactly the same central portion of the Cloud, was made with a special filter that passes only ultraviolet radiation. The infrared photograph shows primarily the distribution of older stars, particularly the red giants that appear in such fantastic concentration in the "broad bar" of the Cloud. The ultraviolet photograph brings out the large numbers of young and rapidly evolving blue-white stars that populate regions outside the bar, as well as the magnificent emission nebulae, or glowing clouds of gas, that surround many of these stars. The nebulae emit light because the gas has been excited by ultraviolet radiation from the stars. By far the most remarkable of these gas clouds is the bright region at the lower left in the ultraviolet photograph: the Tarantula Nebula, also known as the Loop Nebula and the 30 Doradus Nebula. It is practically the only nebula strong enough to come through at all on the infrared photograph.

A plate sensitive primarily to the red light of the "alpha" line in the spectrum of hydrogen [*see top illustration on preceding page*] brings out the fine detail of this nebula. The diameter of the nebula is some 15 minutes of arc, or 800 light-years! Our galaxy possesses no object like it. The familiar Great Nebula in Orion, which is only 25 light-years across, is a mere pygmy in comparison. The total mass of the Tarantula Nebula is 500,000 times greater than that of our sun, whereas the Orion nebula has a mass of only 100 suns. If the Tarantula Nebula were at the distance of the Orion nebula (1,600 light-years), we would see it as a permanent luminous cloud covering 25 to 30 degrees of the sky and having a total brightness two or three times greater than that of Venus at its brightest. It unquestionably ranks as the largest and most massive gas complex within reach of the astronomer.

A filter that suppresses all the radiation from the gas reveals the remarkably beautiful cluster of stars at the center of the nebula [*see bottom illustration on preceding page*]. The cluster was first photographed at the Boyden Station in 1937 by Shapley and J. S. Paraskevopoulos, who pointed out that the majority of the stars are blue-white supergiants. These young stars and their rich environment of interstellar gas indicate that the Tarantula Nebula is a major site of stellar birth and evolution.

On the radio map of the Large Cloud [*see illustration on opposite page*] the Tarantula Nebula is by all odds the most prominent object. Many of the other outstanding features of the ultraviolet photograph are also emphasized. The broad bar, however, hardly appears, because it consists mostly of stars and contains little gas. Surprisingly, radio studies show that the center of rotation of the Cloud is not in the bar, as is the case in other galaxies classified as barred spirals. Instead the center of rotation is well north of the bar in a relatively empty region. It is even farther from the Tarantula Nebula, which has some of the characteristics often associated with the central regions of a galaxy.

Recently B. Y. Mills and C. A. Shain of the Radiophysics Laboratory of the Commonwealth Scientific and Industrial Research Organisation have detected celestial radio waves at wavelengths of about a meter. The origin of this radiation is uncertain, but it may well come from electrons spiraling around lines of magnetic force in space. The magnetic fields involved should measurably polarize light, and the search for such polarization is a primary current assignment for the optical astronomer. Preliminary observations by N. Visvanathan at Mount Stromlo has already demonstrated polarization of from 2 to 5 per cent in the light of some stars of the Large Cloud, but the work is only beginning. It is important to seek and study galactic magnetic fields; along with gravity they may act strongly on gas clouds and exert a pronounced influence on the structure and development of a galaxy.

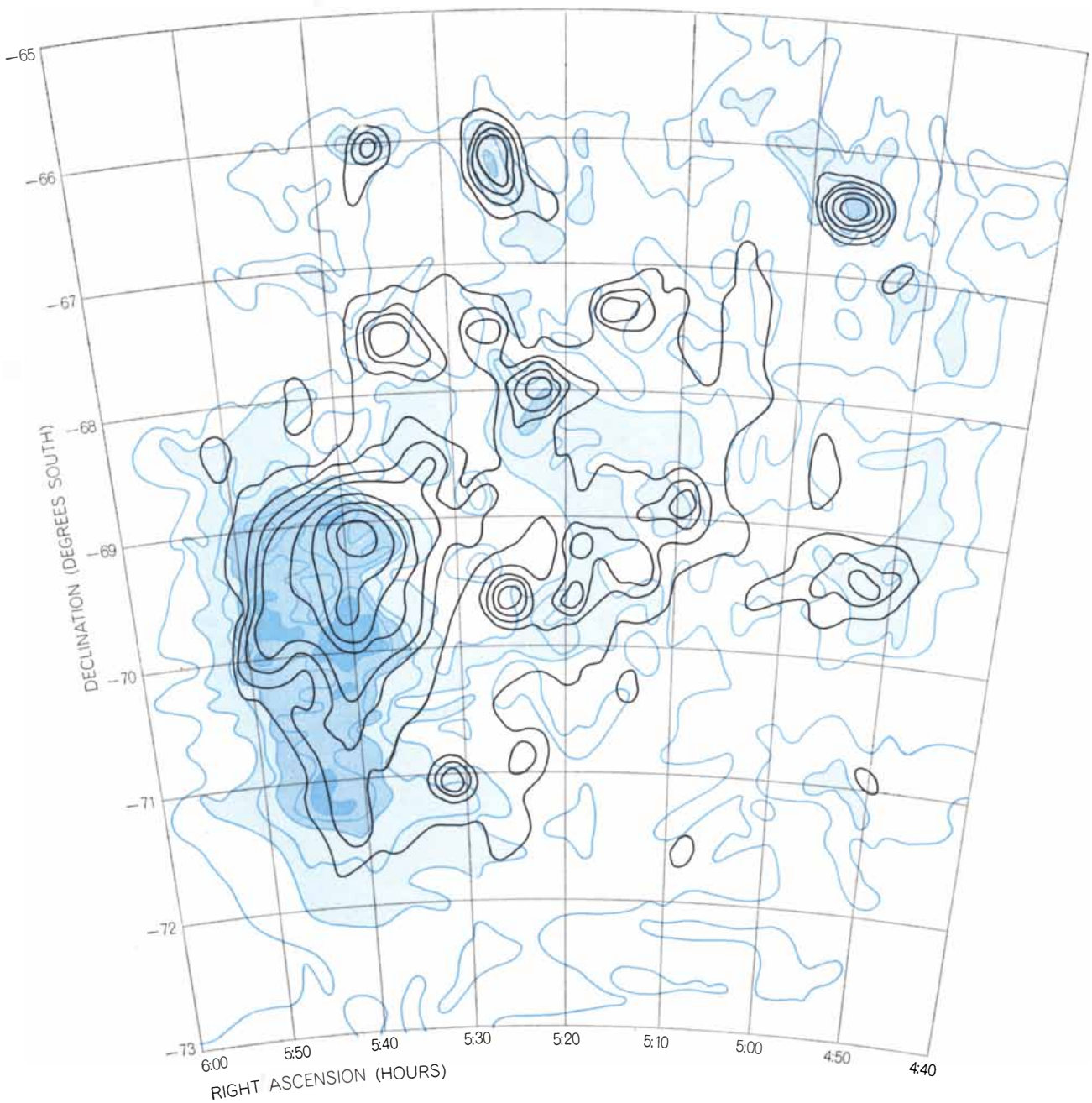
Quite conspicuous in the Large Cloud and distributed in a highly irregular manner across it is radiation at the radio wavelengths near 20 centimeters. Most of it is thermal radiation, which originates when free electrons pass near the bare nuclei of ionized hydrogen atoms. Since the radiation comes from ionized hydrogen, it is not surprising, although it is extremely satisfying, to find that many points of strongest emission at 20 centimeters can be identified with known regions of ionized hydrogen, which appear as emission nebulae on ultraviolet photographs. D. S. Mathewson and J. R. Healey of the Radiophysics Laboratory have identified 43 of 145 observed 20-centimeter radio sources with optically visible regions of ionized hydrogen.

Further proof of the irregular distribution of the interstellar gas in the Cloud comes from studies by R. X. McGee of the Radiophysics Laboratory, who analyzed 21-centimeter observations of neutral atomic hydrogen. The data were obtained with the 210-foot radio telescope at Parkes and a 48-channel receiver. It turns out that most of the regions of ionized hydrogen are embedded in larger and presumably more massive regions of neutral atomic hydrogen, which suggests that the beautiful nebulae are only the kernels of far more extended hydrogen complexes. Altogether most of the optical and radio observations lead to the idea that, although the Large Cloud contains objects of all ages, young stars and young groups of stars associated with gas are preponderant. Offhand it would appear that the Cloud is a galaxy suffering from retarded star birth and evolution.

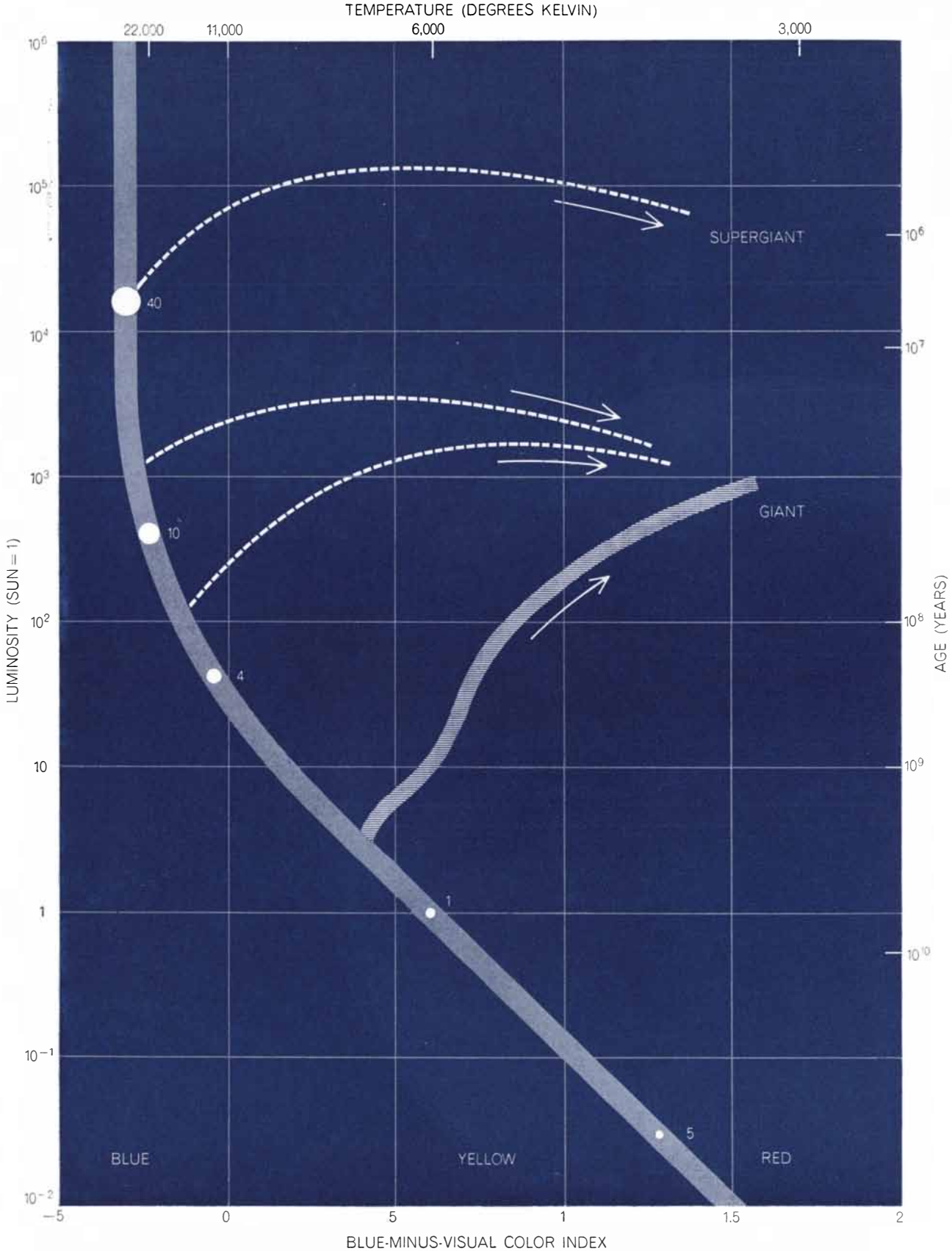
In the remainder of this article I shall discuss some of these young stellar groups as they compare with other groups, young and old, in the Large

Cloud and in our galaxy. From studies of the comparatively few young blue-giant stars visible to us in our galaxy, we know that although they may be only 100 or 1,000 times more massive than the sun, their intrinsic brightness is 100,000 or even a million times greater. Since all stars generate energy by building heavier elements out of lighter ones and can use less than 1 per cent of their mass in the process, these massive stars are eating up their fuel at a prodigious rate. Our sun has existed in its present form for five billion years and will last for another five billion, but some blue giants can have a lifetime of only a million years, and the largest can endure for perhaps a mere 100,000 years.

M. W. Feast, Thackeray and Wesselink have made a special study of the brightest stars in the Large Cloud. These are four blue-white supergiants and four red supergiants, with apparent magnitudes between nine and 10 (extremely bright at the distance of the Large Cloud). The intrinsic brightness of the dimmest of these stars is 100,000 times greater than that of the sun; the brightest approaches the million mark. Astrophysicists believe these stars are between 60 and 100 times more massive than the sun, which means that they are consuming their substance 1,000 to 10,000 times faster than the sun is. Since they could not last even a million years —some probably only a tenth of that



RADIO MAP OF LARGE CLOUD consists of contours of equal intensity at 20 centimeters (*black*) and at 21 centimeters (*color*). The former is the "thermal" radiation that comes from ionized hydrogen excited to emit radiation by ultraviolet radiation from stars embedded in gas clouds. Increasing intensity of 21-centimeter radiation is shown by deeper colored shading. It is apparent that the ionized hydrogen is surrounded by far larger clouds of neutral atomic hydrogen, which emits at 21 centimeters. Tarantula Nebula (*left, below center*) dominates picture. Data were obtained by McGee, D. S. Mathewson and J. R. Healey with Parkes antenna.



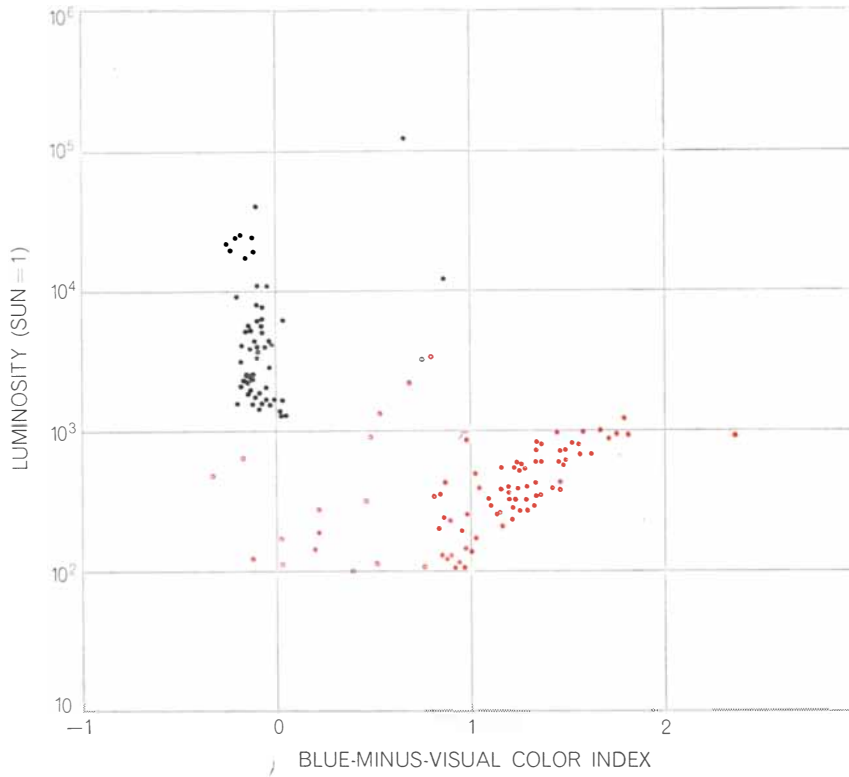
COLOR-MAGNITUDE ARRAY provides basic information on evolution of stars. Intrinsic brightness is given on vertical scale at left in terms of sun's luminosity. Vertical scale at right is total lifetime of stars. Horizontal scale at bottom is color index (*explained in text*). It can be correlated with temperature at surface of stars (*scale at top*) and with their color. Stars spend most of their existence on the main sequence (*long shaded curve*). Five stars (*white dots*) and their masses in terms of sun's mass (which is 1) are shown. The giant branch (*hatched*) represents path of evolution away from main sequence for stars in a typical globular cluster of our galaxy. The broken arrows are similar paths taken by larger stars. The diagram above is based on one by Westerlund.

time—it again becomes clear that in the Large Cloud stellar birth and evolution go on continuously before our eyes.

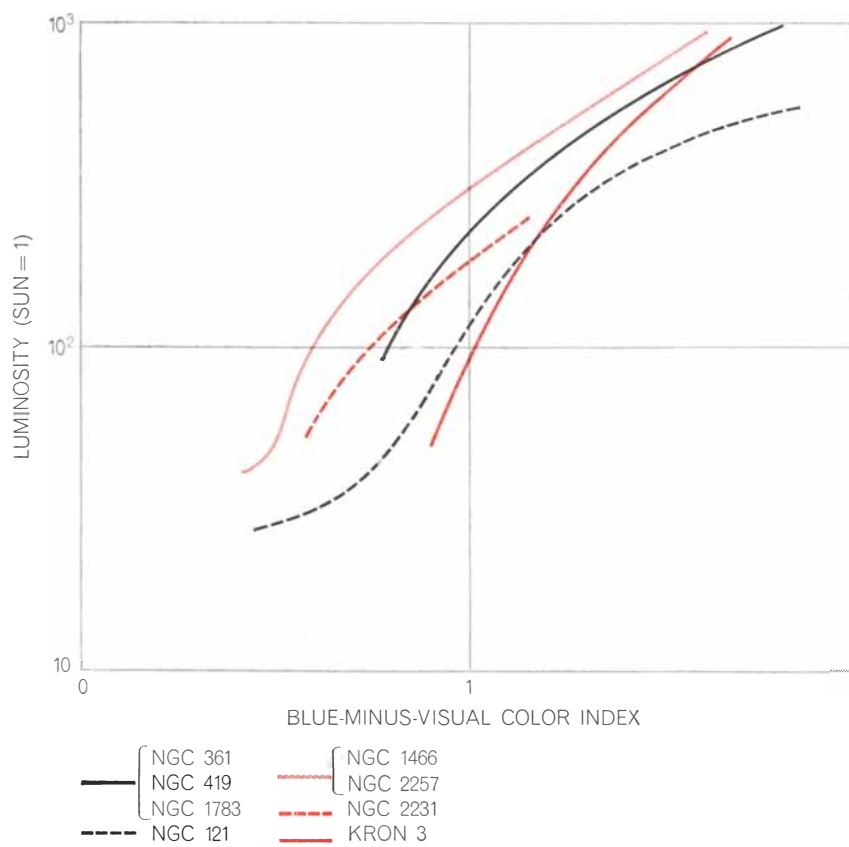
For his basic information on stellar evolution the modern astronomer employs color-magnitude arrays, which are variations of the celebrated Hertzsprung-Russell diagram. In one type of array the absolute visual magnitude of a star is plotted vertically and the star's color index horizontally [*see illustration on opposite page*]. The latter is defined as the logarithmic difference between the brightness of the star as measured in blue ("photographic") light and in yellow ("visual") light. As a star evolves it moves across the array, and it spends most of its lifetime on the curve called the main sequence. The most massive stars pass the largest part of their brief lives near the top of the curve; the less massive, less bright and longer lasting stars are farther down the curve. It is probable that stars with an absolute magnitude of minus five (extremely bright) are on the main sequence for less than 10 million years and those rare stars that are even brighter, with absolute magnitude of minus seven or eight, for less than a million years. The various types of stars also move along different paths and at different speeds in entering and leaving the main sequence. From the characteristics of a star and its position on the color-magnitude array one can estimate its age.

In our galaxy there are two types of star clusters: "globular" and "galactic." The 100 or so known globular clusters, each a compact spheroidal assemblage of 10,000 to a million stars and each about 10 billion years old according to color-magnitude arrays, form a "halo" above and below the plane of the galactic disk. Their stars are rich in hydrogen and poor in heavier elements, which suggests that they formed when the galaxy was young; stars that contain heavier elements are believed to belong to second or later generations of stars made out of the debris of earlier generations. The galactic clusters are more numerous assemblages of 20 to perhaps 2,000 stars; they are either loose or compact and have various ages. The Large Cloud of Magellan contains both types of cluster (although its globular clusters do not form a halo, a further indication of youth) and in addition a type unknown in our galaxy: globular clusters of blue-giant stars. These clusters were first studied 10 years ago by S. C. B. Gascoigne of the Mount Stromlo Observatory and G. E. Kron of the Lick Observatory of the University of California.

About 35 of the globular clusters in



TWO CLUSTERS in Large Cloud have different color-magnitude arrays. NGC 1983 (*stars in black*) is a young cluster with mostly blue-white stars. NGC 1783 (*stars in color*) is older and the stars fall along the same giant branch as those in globular clusters in our galaxy. The array in black was plotted by Westerlund, the other was plotted by S. C. B. Gascoigne.



GIANT BRANCHES of seven globular clusters in the Clouds of Magellan are shown by these curves. NGC 1466 and 2257 are most like globular clusters in our galaxy but still have slightly bluer (younger) giant branches. NGC 2231 is quite unlike our globular clusters.

FIELD OF STAR CLUSTERS south of the Tarantula Nebula in the Large Cloud also contains dust. Gascoigne made the photograph with the 74-inch reflector on Mount Stromlo.

the Large Cloud closely resemble those in our galaxy. A color-magnitude array for one of them plotted by Gascoigne [*see top illustration on preceding page*] has a nicely delineated branch of giant stars evolving away from the main sequence on the same path taken by stars in globular clusters in our galaxy. It is, however, only about a billion years old. Curiously, the stars in this cluster are rich in hydrogen and poor in metallic elements, whereas metal-poor clusters in our galaxy are 10 billion years old. Metallic elements are synthesized in the successive birth, explosion and rebirth of stars, and, as one might expect, the million-year-old stars in the Large Cloud have a full complement of these elements. Why, then, are they absent from the billion-year-old stars? It has been thought that a billion years is too short a time for the synthesis of metals, yet in the Large Cloud either they have appeared in that time or the gas in the cloud is not well mixed—some regions contain metals and others do not. Only further study will solve this puzzle.

A comparison of the giant-star branch in the color-magnitude diagrams of several globular clusters in the Clouds of Magellan [*see bottom illustration on preceding page*] shows that for the most part they are evolving like stars in the clusters of our galaxy. Even the oldest of these clusters, however, contain giant stars that are slightly bluer—and hence younger—than their counterparts in our galaxy. Gascoigne has concluded that the Large Cloud of Magellan contains no globular clusters as old as 10 billion years and that in the Large Cloud globular clusters are still being formed. It will be of great interest to find out why the Cloud differs so markedly in this respect from our galaxy.

The Large Cloud is rich in young clusters; the color-magnitude array for the cluster NGC 1983 by Westerlund [*see top illustration on preceding page*] is characteristic of them. The principal features of the array are the vertical main sequence of white stars running to very great intrinsic brightness, a lack of stars with color indexes between 0 and .7 and a few red stars with color indexes in excess of .7. If one may assume that the stars in the last group are true members of the cluster, they are probably giants and supergiants that have evolved away from the main sequence. Westerlund, Priscilla F. Bok, Jane M. Basinski and I have studied at least 20 of these young clusters in the Large Cloud and find that most of them are irregularly shaped and are embedded in emission nebulosity. There are also some that are highly regular in appearance, almost globular; they have no associated nebulosity but still have the characteristic vertical main sequence indicating comparative youth. Three of these unusual clusters have the same color-magnitude array as the irregular young clusters, according to studies by Woolley, Olin J. Eggen of the California Institute of Technology and Allan R. Sandage of the Mount Wilson and Palomar Observatories.

I should point out that we have not investigated a fair sample of the star clusters in the Large Cloud. Clusters to be studied are selected from photographs such as those on pages 32 and 33; as a result the astronomer favors the extended clusters containing bright stars and the dense globular clusters of fairly large dimensions. A star cluster in our galaxy such as the Pleiades, with a total absolute magnitude close to minus 4 and a diameter of less than 15 light-years, would, at the distance of the Large Cloud of Magellan, be an object of the 15th magnitude with a diameter of less than 20 seconds of arc. It would even be difficult to detect as a cluster and would not readily be selected for study. A cluster such as the Hyades would fare worse, because its total brightness is almost two magnitudes fainter than that of the Pleiades. Kappa Crucis, the "Jewel Box" in the constellation the Southern Cross, might make the grade; at the distance of the Large Cloud it would be an object close to the 12th magnitude with a diameter of 30 seconds of arc. Undoubtedly there are hordes of inconspicuous star clusters in the Large Cloud, but most of them must await investigation until we have in the Southern Hemisphere a 150-inch reflector.

Paul W. Hodge of the Harvard Observatory has nevertheless made a start by studying some of the smaller and less conspicuous open clusters. He finds that they are basically much like the more heavily populated young blue globular clusters. Woolley and Elizabeth Epps of the Royal Greenwich Observatory have recently investigated one star-poor and fairly open galactic cluster in the Large Cloud that appears to be of intermediate age. Its color-magnitude array resembles the arrays of clusters in our own galaxy that are thought to be about 100 million years old.

Since the assortment of objects in the Large Cloud is much like that in our galaxy, we have wondered if the relative abundances of the chemical elements in

the two galaxies are the same. The spectra of stars in the Large Cloud show the same abundances of elements as the spectra of stars in our galaxy, and the abundances of elements in the Tarantula Nebula are similar to those in the Orion nebula. Detailed investigations of 50 nebulae by Helene R. Dickel, L. H. Aller and D. J. Faulkner at the Mount Stromlo Observatory and the Mount Bingar Field Station in Australia, and work on the Tarantula Nebula by Faulkner, indicate that these nebulae contain at most 30 per cent less helium and oxygen with respect to hydrogen than emission nebulae in our galaxy. On the whole the Large Cloud and our galaxy seem to be made of the same basic stuff.

When Shapley and his co-workers made a survey of the Large Cloud in 1953, they recorded for special further study a number of conspicuous assemblages of stars associated with nebulosity; to these assemblages Shapley applied the label "constellations." He had already noted that most of the brighter stars in the constellations were exceedingly blue and had vouchsafed the opinion that these were the places where stars are now being born and where the evolutionary pots are boiling fiercely. His assertions have all proved to be true, and I should like to conclude with a description of Shapley's fascinating Constellation I [*see illustration at right*].

Practically all the stars measured so far in this assemblage are exceedingly blue. The constellation is even bluer than it seems to be; it is embedded in dust that tends to redden it slightly. It probably contains no red supergiants at all. It is located near right ascension five hours 22 minutes and declination minus 68 degrees, and it can be seen quite plainly on the radio map of the Large Cloud in both 20- and 21-centimeter contours.

Constellation I appears to have a diameter of 500 light-years. Mrs. Basinski and I have estimated the total mass of its stars at about 24,000 solar masses, with an uncertainty of no more than 20 per cent. Faulkner has estimated the total mass of ionized hydrogen in it from spectra obtained at the Mount Stromlo Observatory and Mathewson has estimated this mass from radio data. With remarkable agreement, they find that the mass of ionized hydrogen is equivalent to between 50,000 and 60,000 solar masses. This is a large mass, but the mass of neutral hydrogen in the constellation is extraordinary. McGee has estimated it at five million solar masses, mostly contained within a diameter of 1,100 light-years. We thus find a few hundred stars, all formed less than 10 million years ago, located in the midst of a huge hydrogen cloud 200 times more massive than all the stars combined.

If one may ignore the unlikely hypothesis that the association of stars and gas is a chance one, the conclusion that Constellation I is expanding seems almost inescapable. On photographic plates we can see few, if any, faint or red—that is, older—stars within the confines of the grouping. If the birth of stars in the constellation is a continuing process, and if the older stars were retained by the constellation, then a minimum of 6,000 older stars should accumulate in a billion years. Obviously no such numbers are observed. The gas in the constellation can supply building material for an additional 200 generations of stars similar to the ones we see. Hence we have concluded that stars are continually being formed from the gas, presumably at a fairly steady rate, and that these stars at the time of their formation are already moving fast enough to enable them to escape from the parent cluster. A little more than five kilometers per second—nothing extravagant—would suffice. At this speed it will take a star only something of the order of 25 million years to get well beyond the limits of the constellation. The escaped stars gradually evolve to become red giants and supergiants, then intrinsically faint stars. Therefore assemblages such as Constellation I may well be the steady suppliers of ordinary stars older than 25 million years in the Large Cloud. Nowhere in our galaxy do we find the processes of star birth and evolution so neatly portrayed as they are in the Large Cloud of Magellan.

CONSTELLATION I in the Large Cloud was photographed by the author with the 74-inch reflector. These very young, extremely massive stars are embedded in a huge cloud of gas.

THE GREAT CEREBRAL COMMISSURE

This broad nerve cable and lesser bridges connect the two halves of the mammalian brain. If the connections are cut, the organism functions quite well but behaves much as though it had two brains

by R. W. Sperry

The body plan of a mammal provides for two lungs, two kidneys and paired organs such as eyes, ears and limbs. In a sense it also provides for a paired brain. In structural detail and functional capacity the two halves of the mammalian brain are mirror twins, each with a full set of centers for the sensory and motor activities of the body: vision, hearing, muscular movement and so on. Each hemisphere of the brain is mainly associated with one side of the body, the right brain presiding over the left side and the left brain over the right side. Each hemisphere's influence is not, however, always restricted in this way: when an area in one hemisphere is damaged, the corresponding area in the other often can take over its work and so control the functions involved for both sides of the body. In short, either half of the brain can to a large extent serve as a whole brain.

Anatomically, of course, the two halves of the brain are linked together and normally function as one organ. They are united not only by the common stem that descends from the brain into the spinal cord but also by a number of cross bridges between the hemispheres. Especially striking is the system of connections between the two halves of the cerebrum: the upper part of the brain. The cerebral hemispheres are linked by discrete bundles of nerve fibers, called commissures, that form reciprocal connections between parallel centers in the two hemispheres. By far the most prominent of these bridges is a broad cable known as the great cerebral commissure or, more technically, as the corpus callosum [*see illustration on pages 44 and 45*]. This massive structure, which is particularly large in primates and largest in man, contains most of the millions of nerve fibers that connect the two halves of the cerebral cortex, which is the highest integrating organ of the brain.

The size and obviously important position of the corpus callosum suggest that it must be crucial for the proper performance of the brain's functions. Many years ago, however, brain surgeons discovered to their surprise that when the corpus callosum was cut into (as it sometimes had to be for medical reasons), this severing of fiber connections between the cerebral cortices produced little or no noticeable change in the patients' capacities. The same was true in the rare cases of individuals who lacked the corpus callosum because of a congenital failure in development. Experiments in severing the corpus callosum in monkeys tended to confirm the apparent harmlessness of the operation. Accordingly in the late 1930's surgeons tried cutting the entire corpus callosum in some cases of severe epilepsy as a measure to prevent the spread of epileptic seizures from one brain hemisphere to the other. Efforts to pinpoint losses of function in this series of cases were again unsuccessful.

Exactly what purpose the corpus callosum served became more and more a mystery. In 1940 the nerve physiologist Warren S. McCulloch, then working at the Yale University School of Medicine, summarized the situation with the remark that its only proved role seemed to be "to aid in the transmission of epileptic seizures from one to the other side of the body." As recently as 1951 the psychologist Karl S. Lashley, director of the Yerkes Laboratories of Primate Biology, was still offering his own jocular surmise that the corpus callosum's purpose "must be mainly mechanical . . . i.e., to keep the hemispheres from sagging." The curious capacity of the brain to carry on undisturbed after the destruction of what is by far its largest central fiber system came to be cited rather widely in support of some of the more mystical views in brain theory.

Intrigued by the problem of the great cerebral commissure and the theoretical implications of this problem, my colleagues and I began an intensive investigation of the matter, starting in the early 1950's at the University of Chicago and continuing after 1954 at the California Institute of Technology. This research, carried on by many workers at Cal Tech and elsewhere, has now largely resolved the mystery of the corpus callosum; today this bundle of fibers is probably the best understood of any of the large central association systems of the brain. The investigation has gone considerably beyond the question of the corpus callosum's functions. From it has emerged a new technique for analyzing the organization and operation of the brain; this approach has already yielded much interesting information and promises to open up for detailed study many heretofore inaccessible features of brain activity.

The technique essentially consists in the study or application, in various ways, of the split brain: a brain divided surgically so that the performance of each half can be tested separately. It has entailed a series of experiments with animals, starting with cats and continuing with monkeys and chimpanzees. The findings are not confined to animals; there has also been opportunity to study human patients who had been operated on for severe epilepsy and emerged from the operation with a split brain but freed of convulsive attacks and still in possession of most of their faculties.

The split-brain studies have borne out the earlier observation that the cutting of the entire corpus callosum causes little disturbance of ordinary behavior. This is generally true even when the

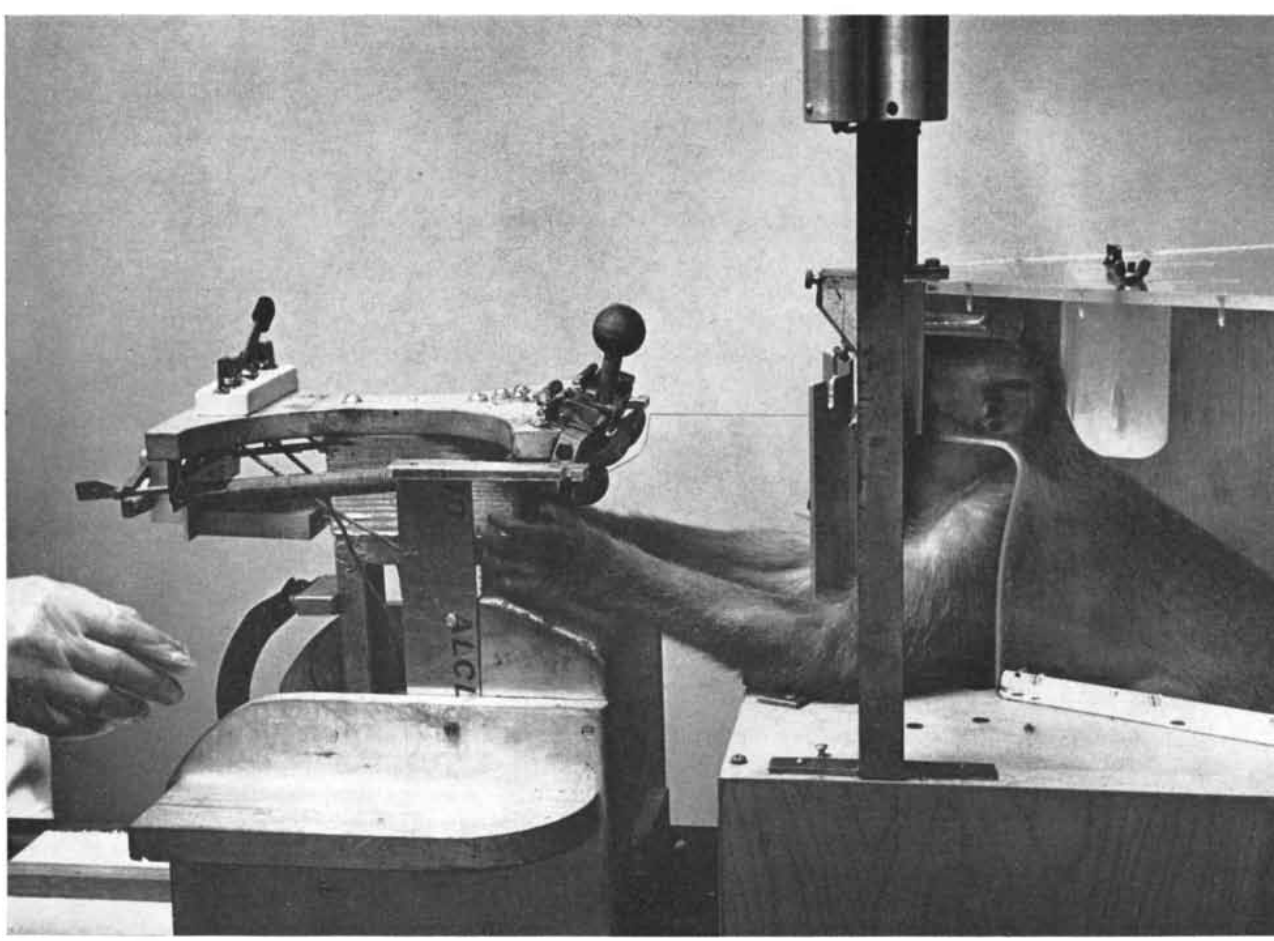
operation severs not only the corpus callosum but also all the other connections between the right and left sides of the brain down through the upper part of the brain stem. Cats and monkeys with split brains can hardly be distinguished from normal animals in most of their activities. They show no noticeable disturbance of co-ordination, maintain their internal functions, are alert and active, respond to situations in the usual manner and perform just about as well as normal animals in standard tests of learning ability. Their individual traits of personality and temperament remain the same.

It required specially designed tests to show that the split brain is not, after all, entirely normal in its function. The first convincing demonstration was provided by Ronald E. Myers, in his doctoral research started in 1951 in our laboratory at the University of Chicago and continued at Cal Tech. Testing the performance of the two brain halves separately, he found that when the corpus callosum was cut, what was learned by one side of the brain was not transferred to the other side. In fact, the two sides could learn diametrically opposed solutions to the same experimental problem, so that the animal's response in a given situation depended on which side of the brain was receiving the triggering stimulus. It was as though each hemisphere were a separate mental domain operating with complete disregard—indeed, with a complete lack of awareness—of what went on in the other. The split-brain animal behaved in the test situation as if it had two entirely separate brains.

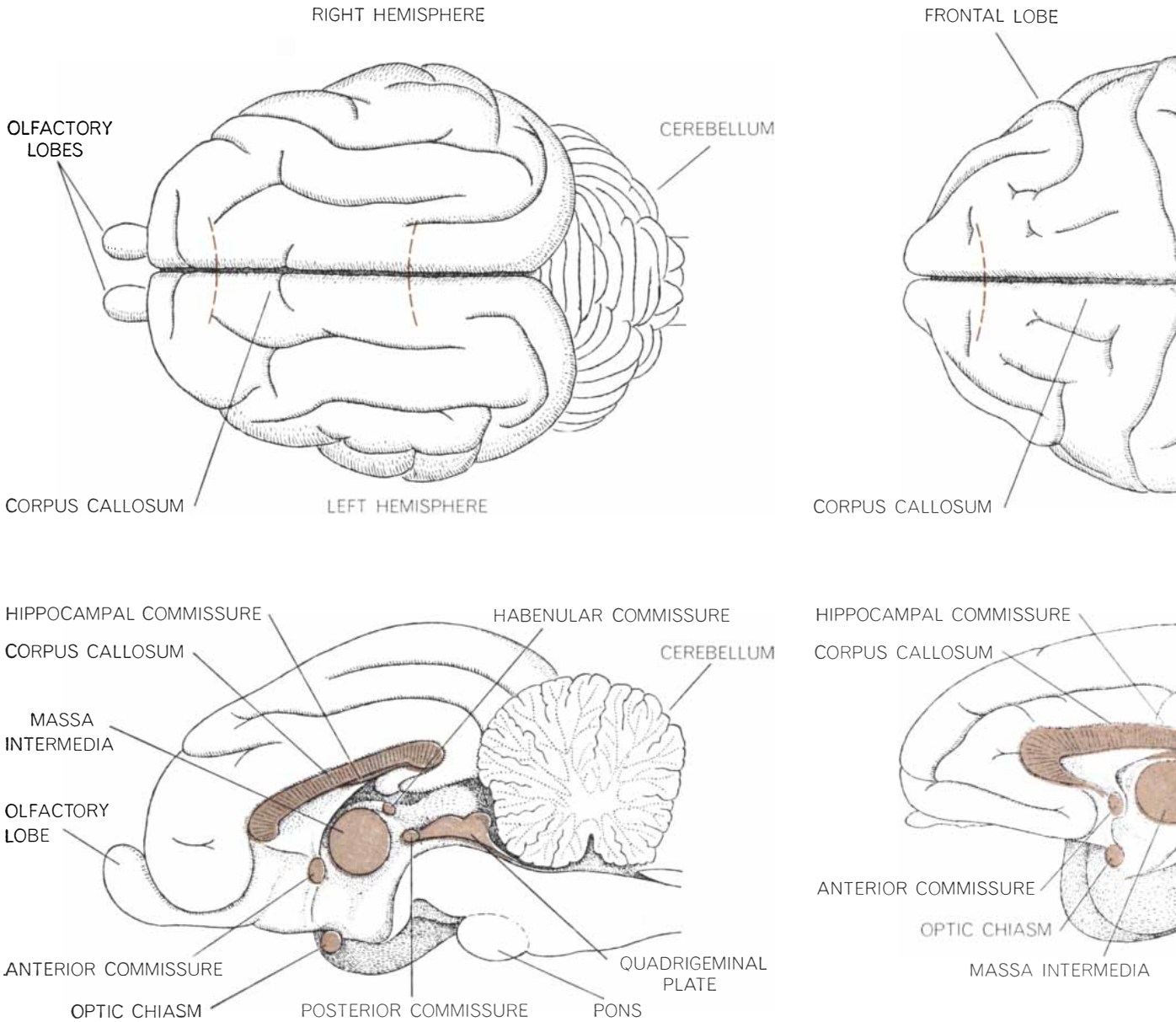
The initial experiment involved segregating each eye with half of the brain as a separate system. This was accomplishing by cutting both the corpus callosum and the structure called the optic chiasm, in which half the nerve fibers from each eye cross over to the brain hemisphere on the opposite side of the head [*see illustration on page 46*]. The effect of this combined operation is to leave each eye feeding its messages solely to the hemisphere on the same side of the head.

The animal was then trained to solve a problem presented only to one eye, the other eye being covered with a patch. The problem might be, for example, to discriminate between a square and a circle; if the animal pushed a panel bearing the correct symbol, say the square, it got a reward of food. After it had learned to make the correct choice with one hemisphere, the problem was then presented to the other eye and hemisphere, the first eye now being blindfolded. When the subject used the second eye, it reacted as if it had never been faced with the problem before. The number of trials required to relearn the problem with the second eye showed that no benefit carried over from the earlier learning with the first eye. The transfer of learning and memory from one hemisphere to the other occurred readily in animals with the corpus callosum intact but failed completely in those with the corpus callosum cut. Each hemisphere, and its associated eye, was independent of the other.

This was again demonstrated when the two hemispheres were trained to make opposite choices. The animal was



EFFECT OF BRAIN DIVISION is tested on animals trained to perform a variety of tasks in response to visual or tactile cues. In this test designed by the author the monkey must pull one or the other of two levers with differently shaped handles.

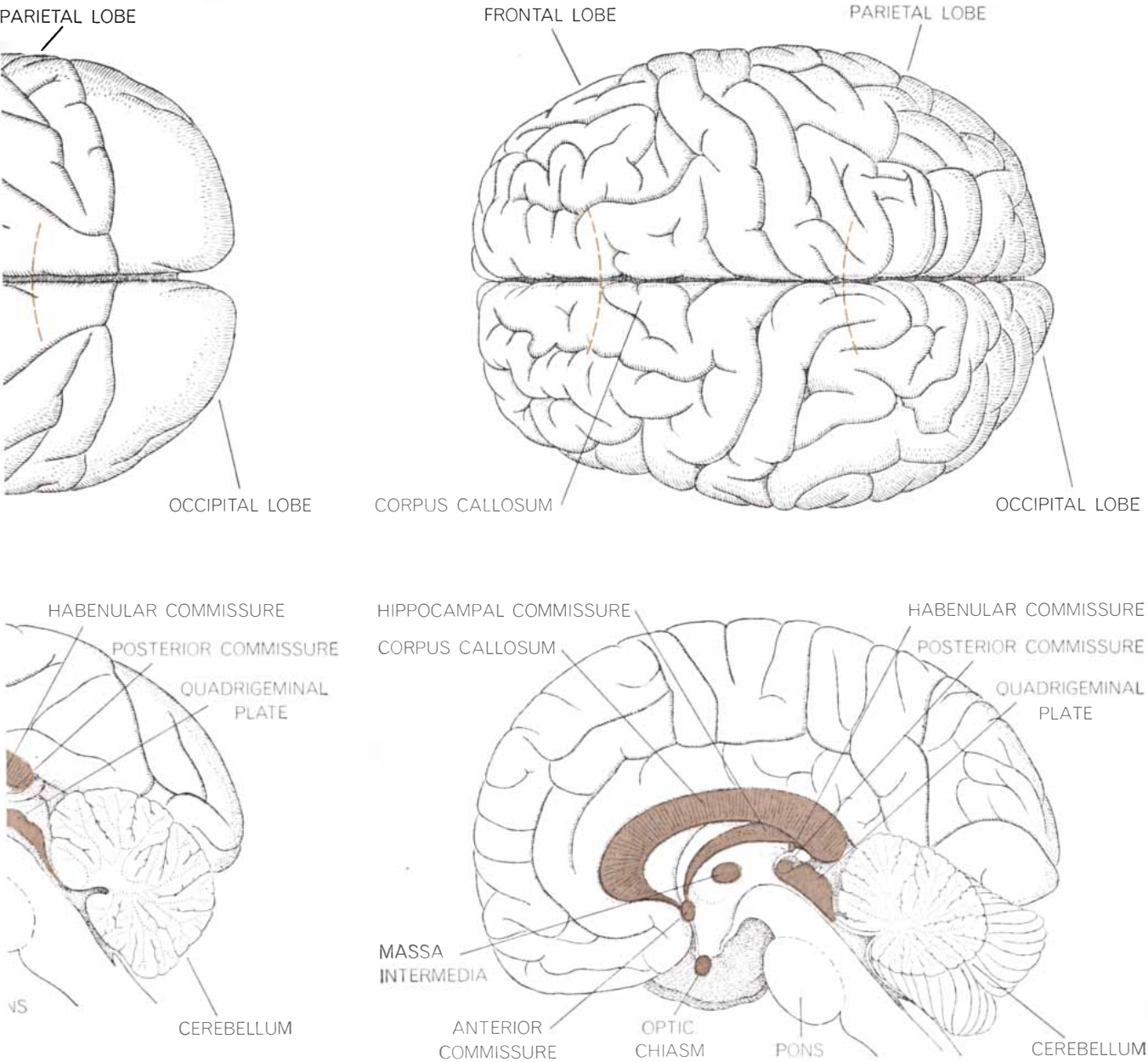


CORPUS CALLOSUM and the other commissures connect the two halves of the mammalian brain. The drawings on these two pages show the brains of a cat (*left*), a monkey (*center*) and a human being (*right*). In each case the top drawing shows the top of the

first trained to choose the square when the pair of symbols was seen through one eye. After learning was complete the eye patch was shifted and the animal was taught with the other eye to reject the square and pick the circle. This reversed training through the separate eyes gave rise to no sign of interference or conflict, as it does in an animal with an intact corpus callosum.

Subsequent studies, many dealing with forms of learning other than the visual—discrimination by touch, motor learning and so on—support the same conclusion. For example, in a special training box in which the animals could not see what their forepaws were doing, John S. Stamm and I trained cats to get food by using a paw to choose correctly between a hard pedal and a soft one, or a rough pedal and a smooth one, or two pedals of different shapes [*see illustration on page 47*]. With the corpus callosum intact, an animal trained to use one paw is generally able to carry out the learned performance when it is made to use the untrained paw; normally the training transfers from one side to the other. But when the corpus callosum has been cut beforehand, the training of one paw does not help the other; on shifting from the first paw to the second the cat has to learn discrimination by touch all over again. The same applies to the learning of a motor task, such as the pattern of finger or paw movements necessary to push a lever or open the hasp and cover of a food well. What is learned with one hand or paw fails, as a rule, to carry over to the other when the corpus callosum has been severed, be it in a cat, a monkey, a chimpanzee or a man.

In short, it appears from the accumulated evidence that learning in one hemisphere is usually inaccessible to the other hemisphere if the commissures between the hemispheres are missing. This means that the corpus callosum has the important function of allowing the two hemispheres to share learning and

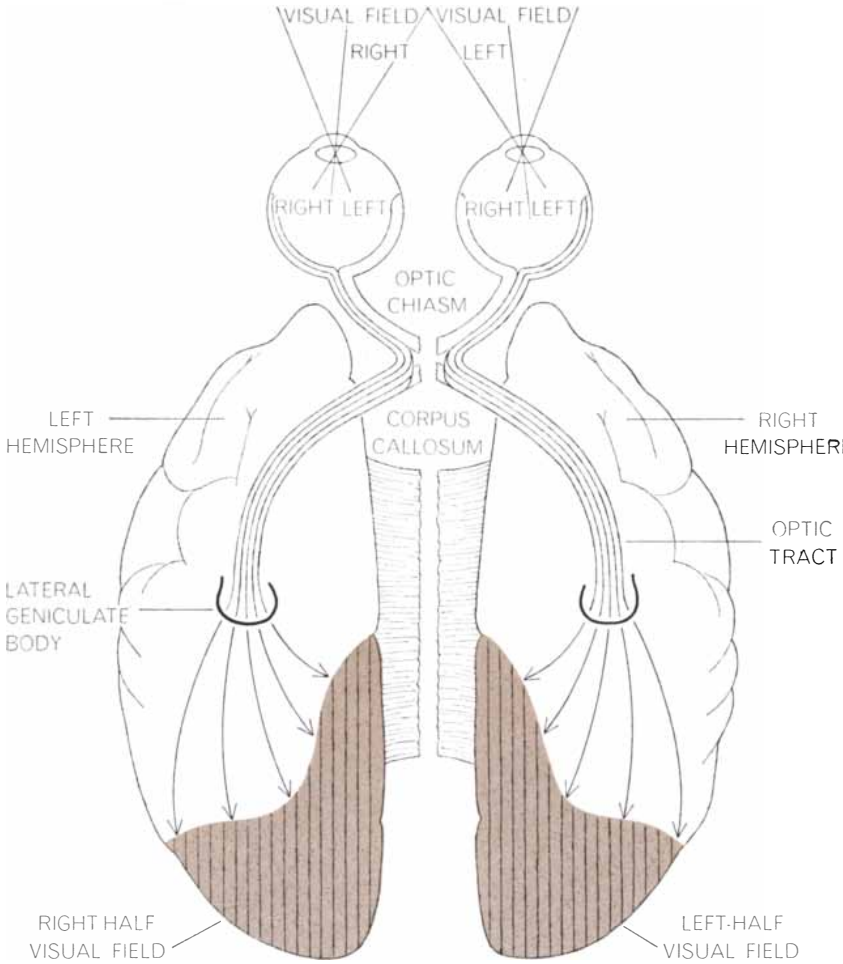


cerebral hemispheres, with the position of the corpus callosum indicated in color. The bottom drawings are sectional views of the right half of the brain as seen from the mid-line; the connecting structures cut in split-brain investigations are designated in color.

memory. It can do this in either of two ways: by transmitting the information at the time the learning takes place, or by supplying it on demand later. In the first case the engrams, or memory traces, of what is learned are laid down both in the directly trained hemisphere and, by way of the corpus callosum, in the other hemisphere as well. In other words, intercommunication via the corpus callosum at the time of learning results in the formation of a double set of memory traces, one in each half of the brain. In the second case a set of engrams is established only in the directly trained half, but this information is available to the other hemisphere, when it is required, by way of the corpus callosum.

By cutting the corpus callosum after learning, and by other methods of investigation, it is possible to determine which of these two memory systems is used in different learning situations and in different species. It appears from present evidence that the cat tends to form engrams in both hemispheres when it is learning something. In man, where one hemisphere is nearly always dominant, the single-engram system tends to prevail, particularly in all memory relating to language. The monkey seems to fall somewhere in between. It sometimes uses the double-engram system, but under other conditions it may lay down engrams in only one of its hemispheres.

Thanks to a wide variety of experiments with cats and monkeys, involving one-side training and testing of various eye-limb and other combinations, we are now beginning to get a fairly detailed picture of the functions of the corpus callosum. It is needed for correlating images in the left and right halves of the visual field; for integrating sensations from paired limbs, or for learning that requires motor co-ordination of the limbs; for unifying the cerebral processes of attention and awareness, and for a number of other specific activities that involve direct interaction of the hemispheres. Furthermore, the corpus callosum seems



VISUAL FIELDS and the visual centers of the brain are related as shown in this diagram of the monkey brain. Cutting optic chiasm and corpus callosum leaves each eye feeding information to one side of the brain only and eliminates the normal overlap of visual fields.

to play important roles of a more general nature. Its absence slows down the rate of learning, at least in some situations. And, like other large nerve-fiber tracts, it has a general tonic effect on the brain cells to which it feeds impulses.

Many of these findings in animals have been checked and confirmed recently in studies conducted on a human patient in whom the hemispheres were surgically separated in an effort to control intractable epileptic convulsions. The seizures had been building up for 10 years in this man after a brain injury sustained in World War II. Philip J Vogel and Joseph E. Bogen, surgeons at the Institute of Nervous Diseases of Loma Linda University in Los Angeles, cut through the corpus callosum and other commissures. The operation was remarkably successful in ending the attacks. Moreover, the patient, a 49-year-old man above average in intelligence, was left without any gross changes in his personality or level of intellect. In the months after the operation he commented repeatedly that he felt much better than he had in many years. In casual conversation over a cup of coffee and a cigarette one would hardly suspect that there was anything at all unusual about him.

With the collaboration of the patient and his physician, Michael S. Gazzaniga of our laboratory has carried out a series of careful tests probing the man's performances with one or both sides of the brain and body. Like most people, the patient is right-handed, and his dominant cerebral hemisphere is the left one. He is able to perform quite normally most activities involving only the left brain and right side of the body. For example, he can easily read material in the right half of his visual field, name and locate objects in that half, execute commands with his right hand or foot and so on. He does, however, have certain difficulties with activities on his left side.

Up to a point the left side of his body can function normally: he appears to see clearly in the left half of his visual field and has good sensitivity to touch and good motor function on his left side. But in any task that requires judgment or interpretation based on language, which is stored only in his left cerebral hemisphere, he clearly shows the effects of the cerebral disconnection. He cannot read any material that falls in the left half of his visual field, so that when he reads with full vision he has difficulty and tires easily. Nor can he write anything at all meaningful with his left hand. As a rule he cannot carry out verbal commands with his left hand or left leg. When an object is presented solely in the left half of his visual field, he may react to it appropriately but he cannot name or describe it. The same is true of an object placed in his left hand when he is blindfolded. While blindfolded he is unable to say where he has been touched on the left side of the body or to describe the position or movements of his own left hand. In fact, if the dominant hemisphere of his brain is occupied with a task, anything happening to the left side of his body may go completely unnoticed. When his dominant left hemisphere is questioned about nonverbal activities that have just been carried out successfully by the left hand via the right hemisphere, it cannot recall them; this is often the case even when both of his eyes have been open and their visual fields unrestricted. Evidently the dominant hemisphere of the brain neither knows nor remembers anything about the experiences and activities of the other hemisphere.

The separation of the two hemispheres is further indicated by certain specific tests. For instance, when the skin on one side of the subject's body is lightly tapped with the point of a pencil, he can locate the point touched with the hand on that side but not with the other hand. When a spot of light is flashed on a screen in one half of the patient's visual field, he can point to it only with the hand on the same side. In generalized motor activities his left hand usually co-operates with the right, but not always. At times the left hand may go off in a distracted way on independent and even antagonistic activities of its own, which can be troublesome.

These findings are generally confirmed in work begun with a second patient who has more recently recovered from the same kind of brain operation. The results in this individual are not complicated by an earlier brain injury, and two months after the operation the overall recovery picture is even better than it was for the first patient. In particular,

motor control of the left hand is not so markedly impaired.

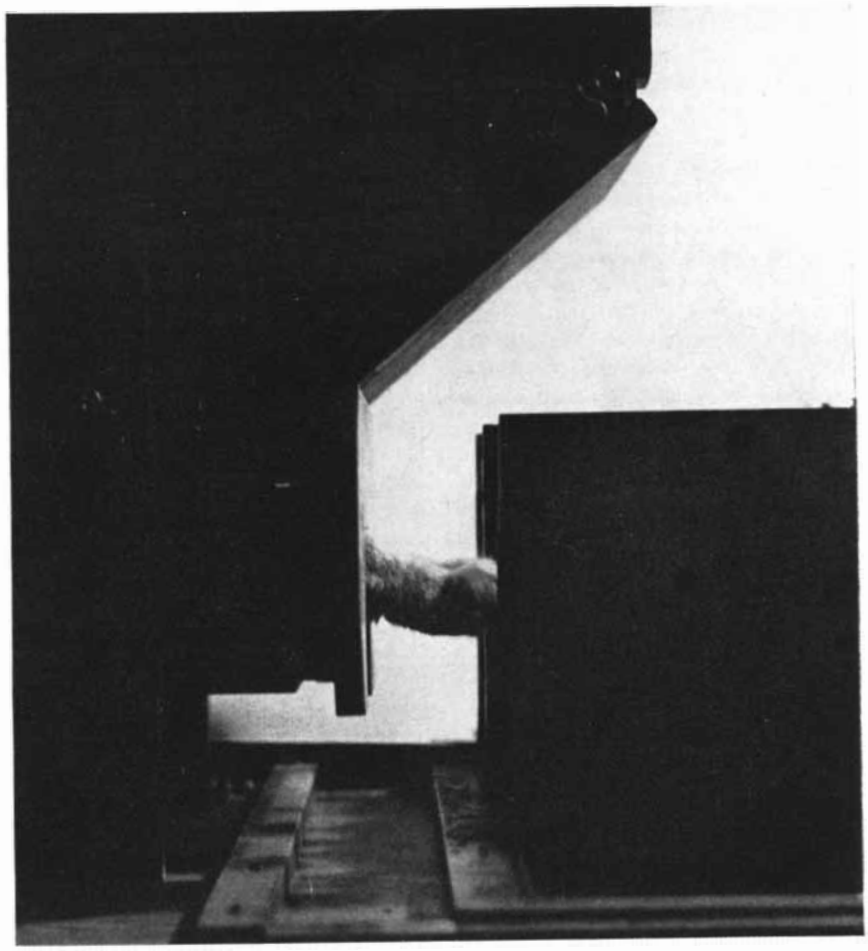
It should be noted again that most of the impairments of brain function from such surgery do not show up in the common activities of daily life. They are detected only under special testing conditions, such as blindfolding the subject, restricting his movements to one or the other hand, using quick-flash projection to confine vision to half of the visual field and so on. One can hope that where the impairments do cause difficulty in ordinary activities, they will be correctible by re-education and other measures as further investigation adds to our understanding of the properties and capacities of the bisected brain.

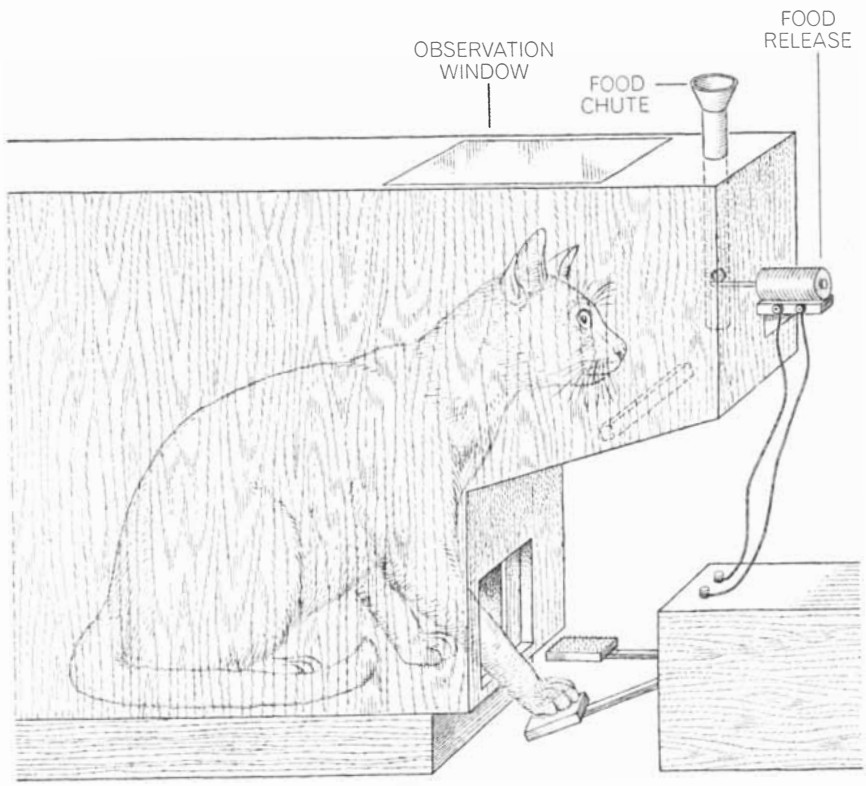
In any case, it is now clear that the loss of the commissural connections between the two halves of the cerebrum does have important and well-marked effects on the functioning of the brain. If the corpus callosum fails to develop at all because of some congenital accident, centers for language and other functions may develop in compensation on both sides of the brain. This seems to have occurred in a nine-year-old boy lacking a corpus callosum, whom we recently tested. As in some earlier cases in the medical literature, he shows almost none of the impairments we observe in the two adult patients.

In other older cases distinct impairments were observed, but they were ascribed to damage in brain areas near the corpus callosum. In the light of present knowledge these cases reinforce the view that damage to the corpus callosum interferes with normal functioning in a number of clearly defined ways. For example, Norman Geschwind of the Veterans Administration Hospital in Boston has recently noted that a patient with a damaged corpus callosum, and similar individuals in the medical literature, have shown effects such as word-blindness, word-deafness and faulty communication between the right and left hands.

Once the enigma of the great cerebral commissure was cleared up and it was firmly established that the commissure really does serve important communication purposes, our interest shifted to more general questions that might be explored by investigation of the bisected brain. Such a brain offered an extraordinary opportunity to examine the many functions and interrelations of parts of the brain, structure by structure and control center by control center.

Bisection of the brain leaves each hemisphere virtually undisturbed. Each





TACTILE DISCRIMINATION is tested with the apparatus shown in the photograph (*top*) and in the diagram (*bottom*). The animal is trained to distinguish between two pedals with different shapes or surface textures. In a normal cat, whatever is learned with one paw is transferred to the other one. But in a split-brain animal each side must learn a task anew.

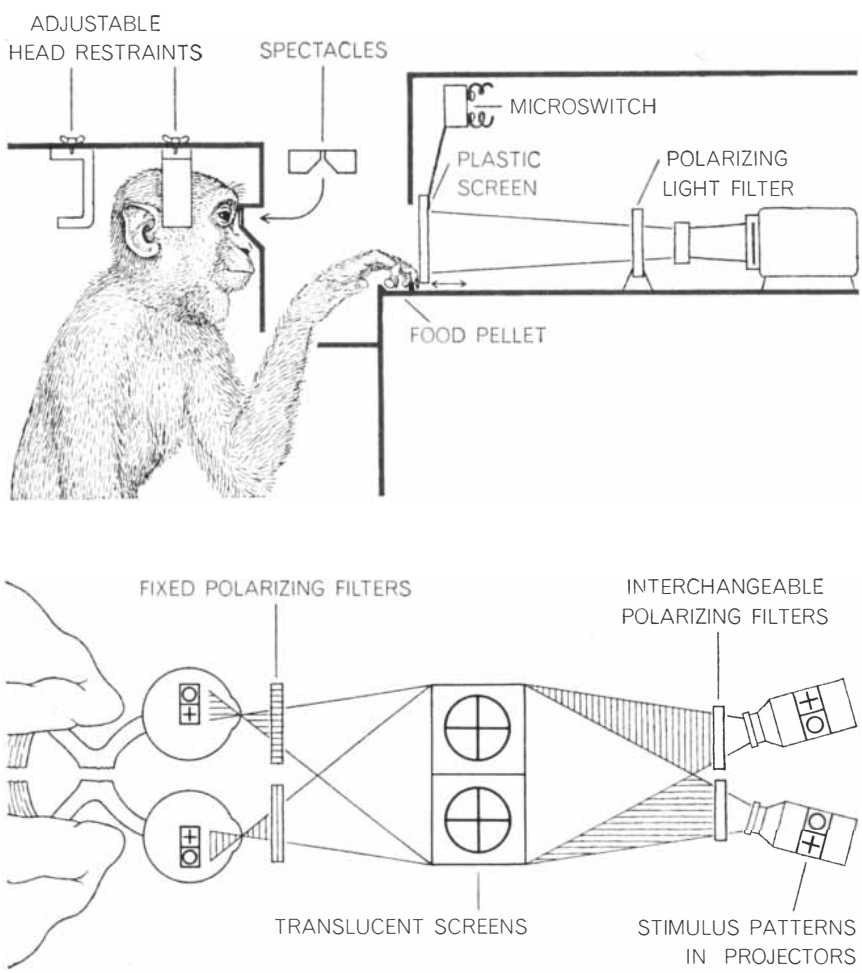
half preserves intact its internal organization, the inflow of sensory messages and the outflow of motor commands. Each retains its full set of cerebral control centers and the potentiality for performing nearly all the functions of a whole brain. Even the human brain, in spite of the normal dominance of one side, can adapt itself to carry on fairly well when one hemisphere is eliminated early in life because of a tumor or an injury. A monkey with one cerebral hemisphere removed gets along better than a man in a comparable condition, and a cat does much better than a monkey.

Because of the independence of the two halves of the bisected brain, it is possible to study nearly all brain functions by concentrating on one half while the animal carries on normally with the other half. The situation affords certain uniquely helpful experimental conditions. Since the experiments are performed with one hemisphere, the identical opposite hemisphere can serve as a built-in control for comparison. Moreover, the fact that one half of the brain suffices to deal with the animal's needs makes it possible to remove or isolate parts of the experimental half, without disabling aftereffects to the animal, in order to identify the functions of each part.

A first question to arise in this connection is: How far can the brain be divided without grossly disrupting brain-mediated processes? We have already noted that cutting the cerebral commissures does not seriously interfere with the functioning of the two hemispheres. In monkeys the bisection has been carried down through the roof of the brain stem and completely through the cerebellum, leaving intact for cross communication only the tegmentum, or floor of the brain stem [*see illustration on opposite page*]. Such monkeys show some motor unsteadiness, weakness and uncertainty, but they eventually recover their strength and stability. Deeper splits through the tegmentum into the upper part of the pons have been made in the cat by Theodore Voneida of our laboratory. A curious blindness ensued, but it cleared up after several weeks and the animals made a good recovery. The effects on learning and perception of these deepest bisections have not yet been studied in detail. In general, however, it can be said that the two halves of the brain function well even when they are divided down into the upper regions of the brain stem, provided that only cross connections are cut.

The effect on behavior of severing the cross connections between the two halves of the brain is not always simple and unambiguous. An animal with a split brain sometimes behaves as if the two hemispheres were still in direct communication in one way or another. Some of these cases can be explained without difficulty; others are puzzling and call for further investigation.

One case involved the ability to respond to differences in the brightness of light. Thomas H. Meikle and Jeri A. Sechzer of the University of Pennsylvania School of Medicine trained cats to discriminate between brightness differences seen with one eye and then tested them with the other eye. With the corpus callosum severed the cats were able to transfer this learning from one hemisphere to the other when the brightness distinctions were easy to make, but not when they were fairly difficult. The transfer disappeared, however, when cross connections in the midbrain, as well as the corpus callosum, were cut. This case therefore appears to be explainable on the basis that in the cat the process involved is simple enough to occur at a level lower than the corpus callosum. In the monkey and in man, however, the corpus callosum seems to be required for the transfer of even the simplest brightness or color discrimination.



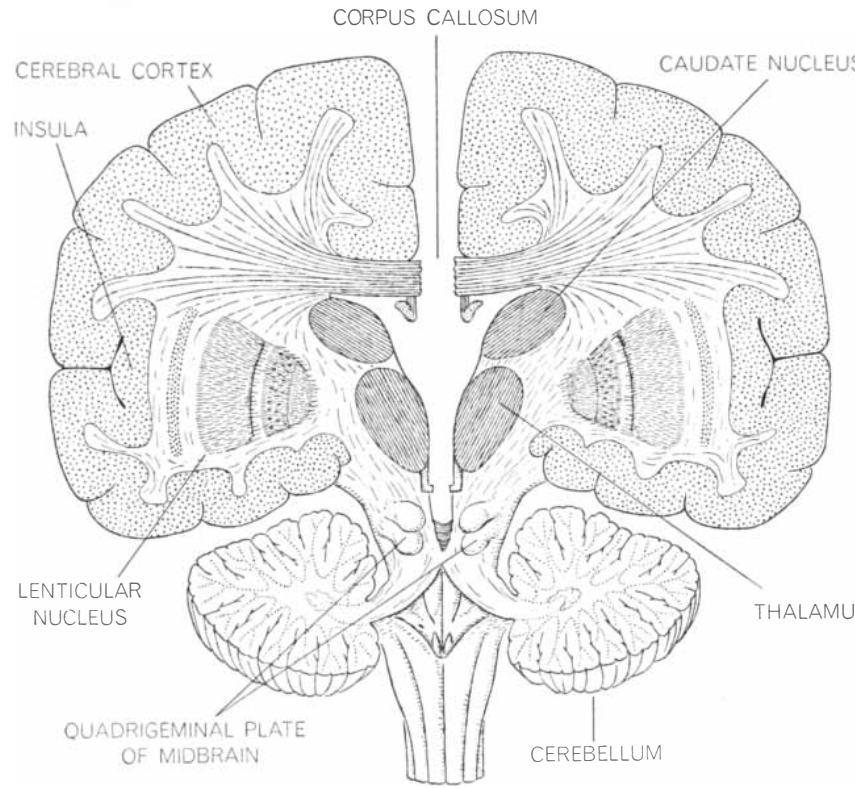
PERCEPTUAL CONFLICT in split-brain monkeys is tested with the apparatus shown in the top drawing. It presents a different image to each eye, as seen in the bottom diagram. While one of the animal's isolated eye-brain systems learns that pushing the panel with the cross is rewarded by food, the other eye-brain system learns to push the circle instead.

There are types of cross communication that can take place in a split brain because both sides of the brain are directly connected to the motor system or sensory organ involved. For example, each brain hemisphere receives sensory messages from both the right and the left sides of the face and other parts of the head; consequently the separation of the hemispheres does not interrupt the communication of sensations between the two sides of the head. Hearing in each ear is likewise extensively represented in both cerebral hemispheres. The same may apply in lesser degree to certain sensations in the limbs and the rest of the body; this may explain why learning involving hand and arm movements in monkeys

with split brains may on occasion transfer from one side to the other.

There is also the possibility of indirect communication between the split halves of the brain through feedback from activity in the body. A motor activity directed from one hemisphere may involve widespread bodily movements that will feed back messages to the opposite hemisphere as well as the active one. For instance, an action performed by one hand is likely to involve adjustments in posture and muscular activity that spread to the other side of the body and thus make themselves known to the other hemisphere. Unifying factors of this sort help to account for the fact that the two sides of the body do not act more independently in a split-brain situation. They do not, however, change the general inference that the two brain hemispheres are for the most part separate realms of knowledge and awareness.

A special case of cross transfer that was at first quite surprising was discovered recently in our laboratory by Joseph Bossom and Charles R. Hamilton. Their experiments dealt with the way in which the brain adjusts itself to overcome the distortions produced by looking through a wedge prism. Such a prism so displaces the visual scene that in reaching for an object the hand misses its mark. With a little practice, however, the eye-brain system soon achieves the necessary corrections to hit the target every time. Bossom and Hamilton trained split-brain monkeys to adapt themselves to the problem using one eye. After the monkeys had learned to correct for the displacement of the prism, they were switched to using the other eye. The learning was fully and immediately transferred—even in monkeys with a deep bisection through the brain-stem roof and cerebellum. This seemed to contradict the earlier experiments showing a lack of transfer of learning from one eye to the other. But when Hamilton followed up with repetitions of the experiments in which the monkey was made to practice the prism adaptation using only one hand, he found that corrective adjustments achieved through the one hand, in combination with either eye, do not transfer to the other hand. This suggested that the central adjustment to deflections of a target by a prism depends primarily on the brain centers concerned with motor activity and bodily sensations rather than on those involved in vision. This interpretation has now been supported in an extension of the study to human subjects. It is still not clear, however, how split-brain monkeys achieve this adjustment so easily when the visual inflow is confined to one hemisphere and the only hand in use is the one governed primarily from the other hemisphere.

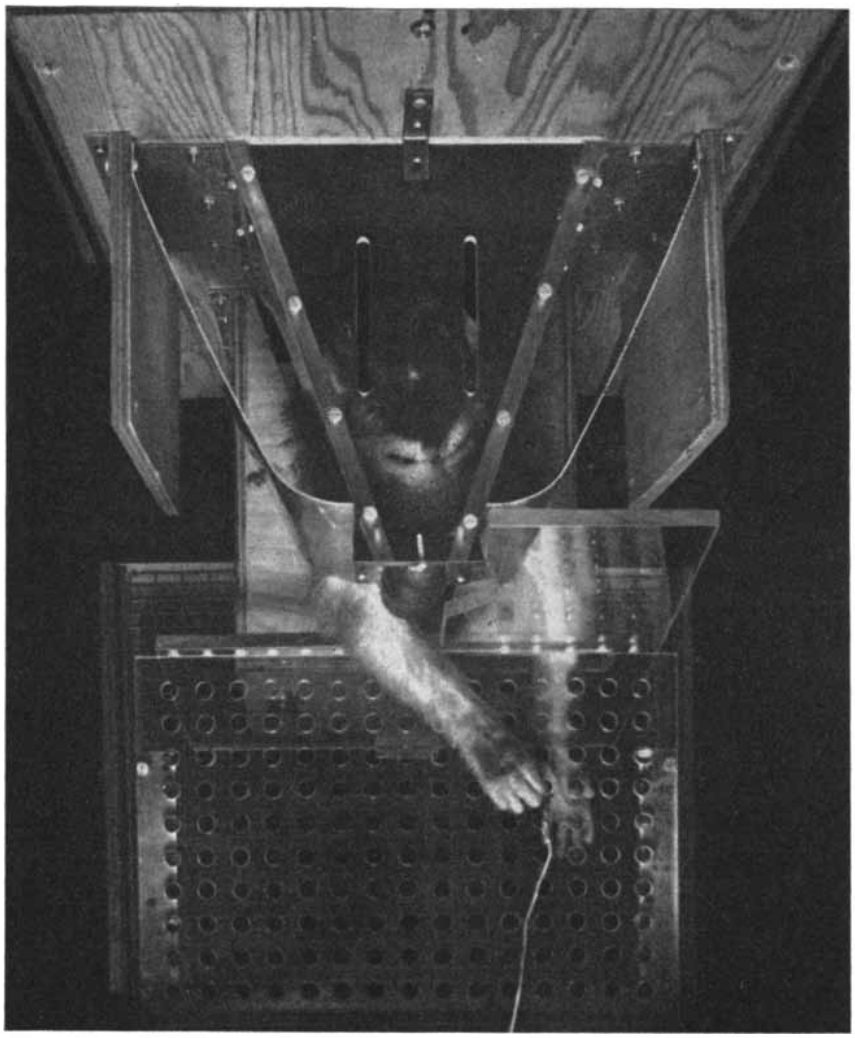


DEGREE OF SEPARATION among the higher brain centers that is produced by the surgical procedures discussed by the author is shown in this semisectional diagram of the brain.

Certain other performances under study in our laboratory that appear to involve cross integration in the divided brain are even harder to explain. For example, Colwyn B. Trevarthen and I have found that a split-brain monkey can learn to select the larger (or smaller, as the case may be) of two circles of different sizes presented separately to the two brain hemispheres, the larger to one and the smaller to the other. To make the *relative* size count, the circles are selected from a series of five graded sizes. It would seem that to make the comparison successfully the two hemispheres, although cut apart, must collaborate in some way. Similarly, I have found that split-brain monkeys grasping two handles separately, one in each hand, can pick the larger or the rougher of the pair. Here again five different sizes and five degrees of roughness are paired in random right-left position.

Difficult as it is to avoid the conclusion that the two brain hemispheres are working together in these cases, the strong evidence of many experiments on the independence of the divided hemispheres suggests that one should seek other explanations. It is conceivable, for example, that a combination of independent strategies used by the two hemispheres might have produced a high score without any real exchange of information. The discrimination of handles by touch might have been aided by cross communication through related sensations of movement or from motor feedback. It is also possible that the apparent communication between the hemispheres may have been achieved by way of interactions taking place in the lower brain stem or even in the spinal cord. These and other possibilities are being investigated.

Another group of observations revealed an interesting and significant difference between animal and human brains. The tests had to do with the ability of one side of the body to respond to visual cues received only by the cerebral hemisphere that directs the opposite side of the body. For example, with the corpus callosum divided and with vision restricted to one hemisphere, the animal is trained to reach out and pick by vision the correct one of two objects; can the subject do this when allowed to use only the hand or paw that normally is associated with the unseeing hemisphere? The cat proved to be able to use either forepaw under these conditions with about equal ease. The monkey does not



HAND-TO-HAND CO-ORDINATION is tested in this experiment. The split-brain monkey cannot see the plastic divider that prevents contact between its hands. By groping, it finds a peanut with its upper hand. It can retrieve the peanut only by poking it down through a hole and catching it with its lower hand. The only cues it has for placing the lower hand are based on a joint-and-muscle sense of the position and movement of the upper hand.

do so well; sometimes it can co-ordinate its motor response with the visual message and sometimes not. In human patients, on the other hand, this ability is severely disrupted by the severing of the corpus callosum. As we have already noted, in the split-brain patient who was extensively tested the left hand generally is unable to respond correctly to commands or visual stimuli presented only to the left cerebral hemisphere. The patient without prior brain injury does somewhat better, but even so the performance is markedly poorer than that of the monkey.

The same applies to stimuli of other kinds. For instance, when the human patients are blindfolded and hold a pencil in one hand, the other hand is unable to find the end of the pencil if the hand holding the pencil shifts its angle or changes its position in some other way. When monkeys whose corpus callosum had been cut were put to similar tests by Richard F. Mark and me, however, they performed almost normally [*see illustration above*]. And when all the cross connections down through the roof plate of the midbrain, with the exception of the corpus callosum, were cut, the performance also went well. Subsequent cutting of the corpus callosum in this last situation finally abolishes the performance, showing the participation of the corpus callosum. Even so, the difference between man and monkey in the expendability of the corpus callosum for such hand-to-hand activities remains striking.

Here we are probably seeing a reflection of the evolution of the brain. The appearance and development of the corpus callosum in evolution parallels the appearance and development of the cerebral cortex. As in the course of evolution central controls are shifted from more primitive brain-stem areas to higher stations in the ballooning cerebral cortex, the role of the corpus callosum becomes more and more critical. So also do the phenomena of dominance and specialization in the hemispheres of the cerebrum. In cats and lower animals the two hemispheres seem to be essentially symmetrical, each learning equally and each capable of serving by itself almost as a whole brain. In the monkey the two hemispheres are apparently somewhat more specialized. As the accumulation of memories, or the storage of information, becomes more important in the higher animals, the duplication of memory files in the two brain hemispheres is given up for a more efficient system: the division of labor by the assignment of specialized files and functions to each hemisphere. This evolution has culminated in the human brain. Here a distinct separation of functions prevails: language is the task of the dominant hemisphere and lesser tasks are largely taken over by the other hemisphere.

The question of dominance is crucial for the effective functioning of the brain as the master control system. Bear in mind that the brain is composed of twin hemispheres, with a full set of control centers in each hemisphere that enables it to take command and govern the general behavior of the animal. What happens, then, if the two halves of an animal's split brain are taught to give completely conflicting responses to a given situation?

The devices developed in our laboratory allow a great variety of experiments, using all sorts of combinations of brain control centers with the sensory and motor organs of the body. They can restrict the animal to the use of one eye or the other with one hand or the other, to the tactile sense without vision, to vision in one brain hemisphere and the tactile sense in the other, and so on. A representative apparatus for the monkey, designed for experiments involving visual stimuli and responses with the hand, is shown in the illustration on page 43. The monkey stations itself behind a barrier that can be adjusted to let it see with both eyes or the right eye or the left eye or neither, and to let it use both hands or only the right or the left. By the use of light-polarizing filters, the visual stimulus (for example a circle) can be split and the two images projected separately to the two halves of its visual field in order to determine if the subject can integrate them. The monkey's responses consist in pressing buttons, pulling levers

and so forth; these responses are rewarded when they are correct. We can hook up to this apparatus automatic equipment that is programed to present any of a number of different problems to the animal. In that case the apparatus is attached to its home cage as a kind of porch where the monkey can station itself as the spirit moves it and work at its leisure.

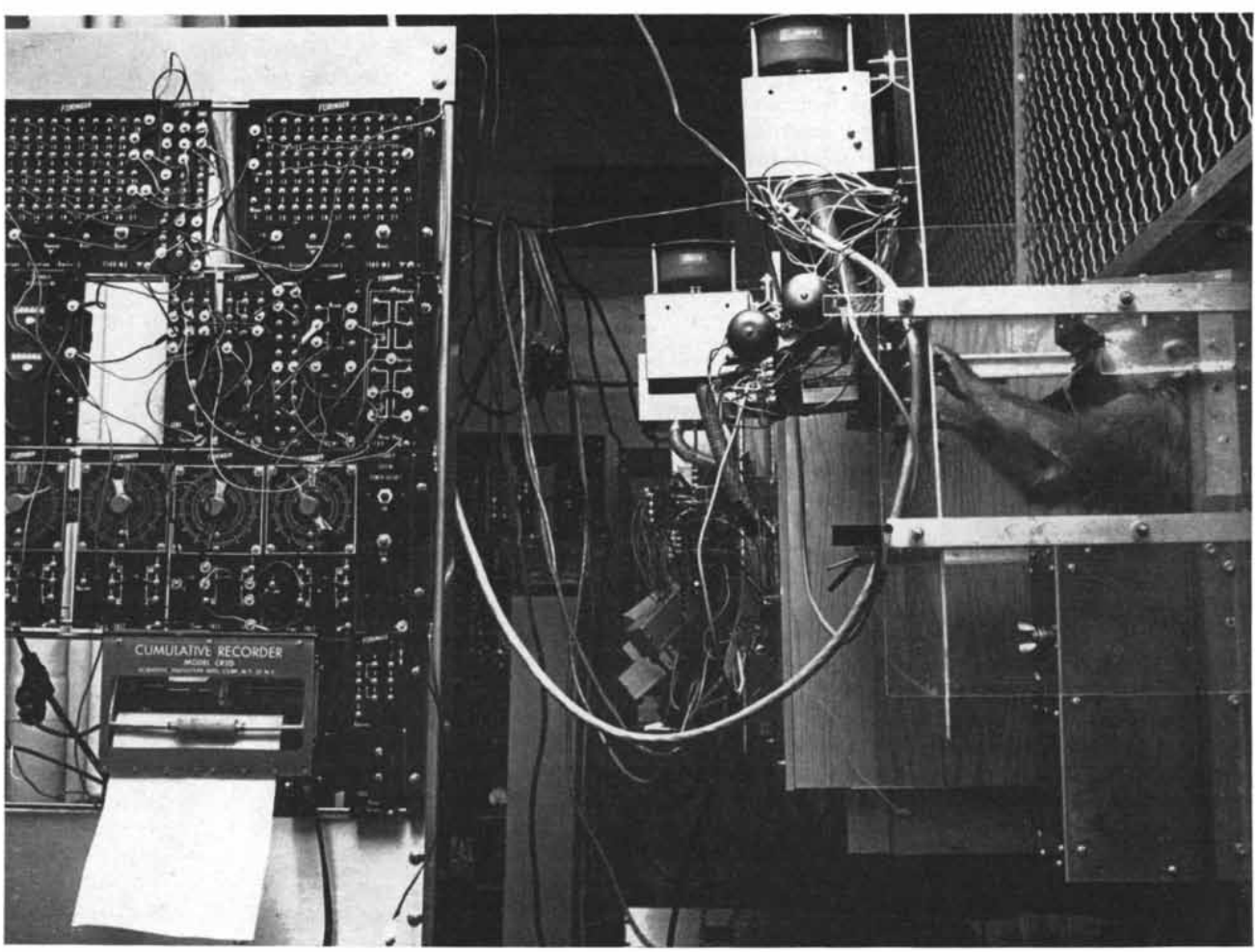
With this apparatus a split-brain monkey can be trained, let us say, to choose between a triangle and a square as the rewarding stimulus. Looking through its left eye, it learns to select the triangle as the reward; through the right eye, the square. It is trained for a few trials with the left eye, then for a few trials with the right, and this alternation is continued until each eye comes to give a nearly perfect performance, even though the responses with the separate eyes are contradicting each other. As we have already noted, the animal usually evinces no conflict in this paradoxical situation: the left eye unhesitatingly chooses the triangle and the right eye the square. Here the split-brain monkey learns, remembers and performs as if it were two different individuals, its identity depending on which hemisphere it happens to be using at the moment.

What if the two hemispheres are asked to learn these mutually contradictory answers simultaneously instead of one at a time alternately? Can each hemisphere attend to its own lesson and file one answer in its memory while the other is filing a conflicting answer in *its* memory?

Trevarthen found a way to investigate this question by introducing polarizing filters to present reversed pictures simultaneously to a monkey with both eyes open [*see illustration on page 48*]. A pair of patterns (say a cross and a circle, but any pair of patterns or colors will do) is projected separately to the two eyes. To one eye it appears that the food reward is won by pushing the cross; to the other eye it seems that the circle is being pushed. In other words, for one hemisphere the correct answer is "cross" and for the other it is "circle," but the panel that is pushed is the same in both cases. After the monkey, using both eyes, has learned to push the correct panel 90 per cent of the time, it is tested with each eye separately.

It turns out that there is a strong tendency for one hemisphere (usually the one governing the arm that is first used to push the panels) to learn the answer sooner and more fully than the other. This suggests that active attention by one hemisphere tends to weaken the attention of the second, although the activities of the two have no direct connection. Trevarthen has found, however, that sometimes both hemispheres learn their respective answers fully and simultaneously. That is, the split-brain monkey in these cases divides its attention between the two hemispheres, so that it masters the two contradictory problems in about the same time that a normal, single-minded monkey would be learning one problem.

This doubling of attention is also manifest in Gazzaniga's tests on the split-



AUTOMATED EQUIPMENT is adapted to tabulating and recording the data from a number of trials conducted with several monkeys over a period of time. The animals work at their tasks at their leisure, moving to apparatus affixed to the rear of their cages.

brain human patient discussed earlier. The test consisted in asking the man to pick a certain figure out of a pair of figures flashed very briefly (for less than a tenth of a second) and simultaneously in each of his visual fields—one pair in the left field and one pair in the right. The subject abruptly points to the correct figure in the left field with his left hand (governed by the nondominant hemisphere) and at the same time indicates the correct figure in the right field verbally or by pointing (this act being governed by the dominant hemisphere, which controls language and speech). Discussing such responses afterward, the patient typically has no recollection of having pointed with his left hand; the dominant hemisphere seems completely ignorant of what went on in the other one.

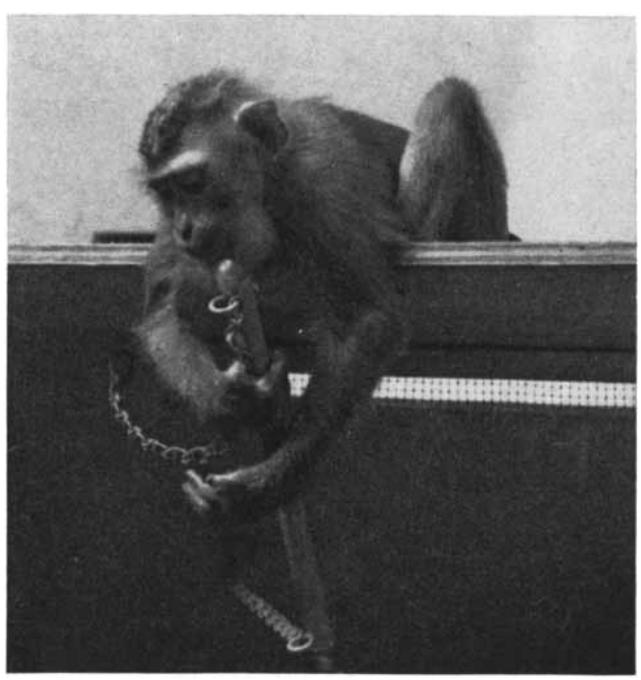
These remarkable indications of a doubling of the psychic machinery in the brain raise a number of new questions about the roles played in the learning process by attention, perception and motivation. There are also many intriguing philosophical implications. When the brain is bisected, we see two separate "selves"—essentially a divided organism with two mental units, each with its own memories and its own will—competing for control over the organism. One is tempted to speculate on whether or not the normally intact brain is sometimes subject to conflicts that are attributable to the brain's double structure.

How does an animal with a split brain resolve the dilemma of being conditioned to two directly opposite answers to a given problem? Suppose it is confronted with a situation in which it must make a choice between two "correct" answers? Can it master the conflict or is it paralyzed like the proverbial donkey between a bag of oats and a bale of hay?

The kind of answer that is usually obtained is illustrated in an extension of the experiment with polarizing filters. After the split-brain monkey has been trained so that one hemisphere considers as correct the panel marked by a cross and the other hemisphere considers as correct the panel marked by a circle, one of the eye filters is turned 90 degrees. Now instead of the images being reversed in the two eyes, both eyes see the pair of symbols in the same way—say the cross on the left and the circle on the right. Will the animal, with both eyes open, choose the cross or the circle or waver in confusion between the two? In such tests the monkeys, after only a little indecision and hesitation, make a choice and adhere to it: they consistently select the cross or the circle for a series of trials. That is, one hemisphere or the other takes command and governs the monkey's behavior. This dominance may shift from time to time, each hemisphere taking its turn at control, but it would appear that no serious conflict disrupts any given movement.

Something more akin to conflict between the separated hemispheres is occasionally seen in tests given the human patients. Incorrect responses by the left hand may so exasperate the more sophisticated dominant hemisphere that it reaches across with the right hand to grab the left and force it to make the correct choice. Or conversely, when the literate hemisphere and right hand fail in a block-arrangement test—one of the few things that the left hand and nondominant hemisphere generally do better—impatient twitches and starts occur in the left arm, which may have to be restrained to keep it from intercepting the right. As in split-brain cats and monkeys, however, one hemisphere or the other generally prevails at any given time. Any incompatible messages coming down from the other hemisphere must be inhibited or disregarded.

The experiments discussed in this article are a sample of the large variety of studies with the split brain that are being carried on by our group at Cal Tech and by others in laboratories elsewhere. Work with the split brain has enabled us to pinpoint various centers of specific brain activity, has suggested new concepts and new lines of thought and has opened up a wealth of new possibilities for investigating the mysteries of the mind.



RHESUS MONKEYS whose brains have been bisected perform well in most general play and exercise tests. These animals with split brains are hardly distinguishable from normal monkeys in their ability to move about, find and retrieve food and do acrobatics.

Kodak reports on:

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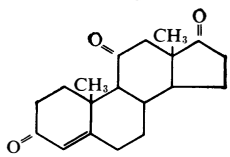

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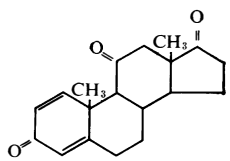

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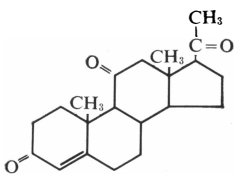

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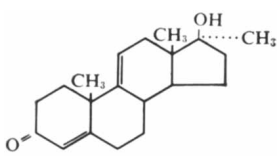

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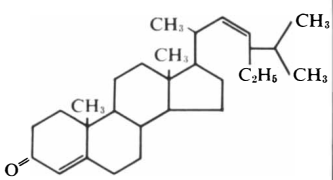

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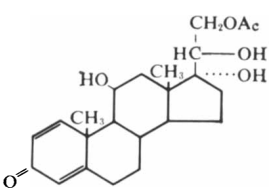

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We can now supply raw 16mm movie negative film with a magnetic stripe on it. This announcement is surprising only in its timing. You would have expected it *circa* 1949. We didn't make the announcement then because we didn't know how to put down a stripe that would stick for more than a few weeks, *then* carry through the photographic processing, and *then* remain in good condition on the negative for a long time. Neither, apparently, did anybody else. Now we know how.

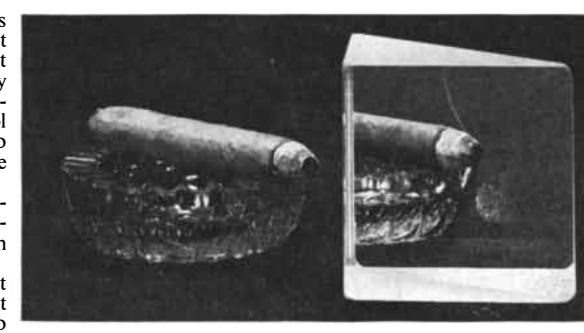
What's more, the stripe we now apply can withstand modern movie processing. Modern movie processing is not gentle. It is fast. It requires less than 2 minutes to turn exposed film into dry negative of better quality than hardly anybody in the business had ever seen in 1949. This happens inside a machine called an EASTMAN VISCOMAT Processor.

For putting both the picture and the sound on this magnetically striped movie film we recommend a KODAK Reflex Special Camera. We would appreciate an opportunity to show you that this is the finest 16mm *professional* camera that money can currently buy on the open market. If you already know that because you have one but didn't know we could adapt it for sound, you now know that, too.

Back in 1949, most movie film was intended for entertainment and most magnetic deposition was intended to record sound. Things change. If you are thinking more of analog or digital data corresponding to the event that is pictured on the film for the eye, you have just suffered a brilliant flash of insight and we have to talk to you about what kind of movie stock you want striped.

Get in touch with Eastman Kodak Company, Motion Picture Products Department, Rochester, N. Y. (Phone 716-562-6000, Ext. 6230), which is also in a position to sell you the processor and camera but may not even mention them unless you ask.

Thoughts while viewing a greasy thumbprint



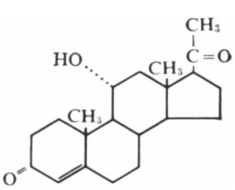
In the case of total reflection, such as is going on here, one is taught that 100% of the energy and not just 99.999+ % comes back. That may possibly be good enough an assertion for the average high school physics course, where one can also learn that scientists must never be sloppy.

It is instructive, however, to inquire what the grease of the thumbprint does: it ruins the perfection of reflection.

This is no news but comes out of James Clerk-Maxwell. The light penetrates a short distance into the lower-index medium. Only if not trapped there does the energy turn around and all come back. By sheer power of intellect without lifting a pinky labwise, one can prove that the spectral composition of the reflected light must be affected by the absorbance encountered during the brief skid outside. Penetration might be as much as 10 wavelengths very near the critical angle but quickly diminishes to a small fraction of a wavelength for incidence angles only a few degrees greater. As long as the absorbing substance is laid on thicker than that, the thickness doesn't matter. Get spectrophotometric curves. Who cares about cell thickness? Who needs cells? Why bother with tedious sample preparation? Just smear it on. Find out what mysterious ingredient in your competitor's brand of nail polish makes the ladies love it dangerously.

It would be well to do all this in the infrared, where absorption bands are numerous, strong, and enlightening. You could do process-stream monitoring. But you had better be sure you have a higher refractive index in the infrared than that of any sample you are likely to be examining.

Optical materials of high index and clean, extended infrared transmittance tend to be soft, soluble, both, or worse, or good for just one-time use. One, IRTRAN 4, offers high promise. We make it (from ZnSe). Excitement over the method—called ATR, for attenuated total reflection—had by September reached a pitch where ACS was able to put on a whole afternoon of papers about it. If you wish, you can use us as a sort of clearing house on the subject among the analytical instrument manufacturers and more specialized groups. Call 716 - 562 - 6000, Ext 5166. If patient, write Eastman Kodak Company, Special Products Division, Rochester, N. Y. 14650.



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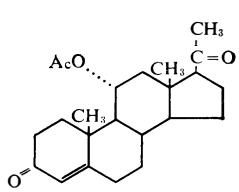

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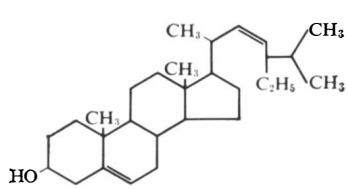
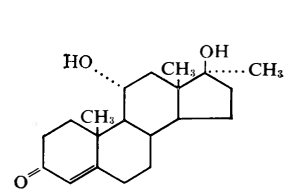


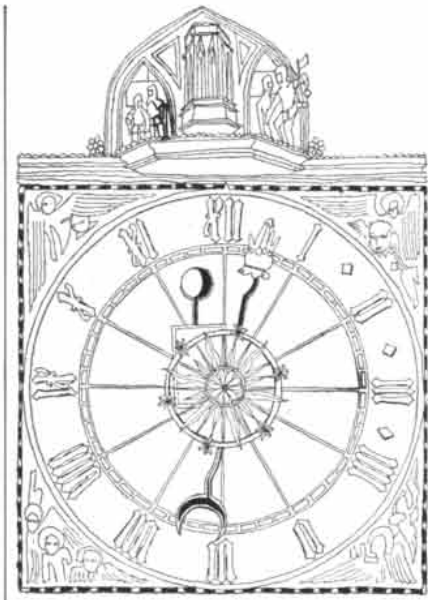
EASTMAN 9128, $3.00 for 1 g.



EASTMAN 9130, $4.50 for 1 g.

These are steroids but believed physiologically inert and thus different from very similar configurations of C, H, and O atoms in which very slight variations distinguish male from female and health from disease. To a small subset of the scientific community, these diagrams tell all, without need for stuttering non-words never intended to be framed by human lips To that subset and that alone is newly offered any of these compounds under the indicated EASTMAN Organic Chemical number at the indicated price from Distillation Products Industries, Rochester, N. Y 14603 (Division of Eastman Kodak Company). *Other stuff in this advertisement may bore that subset stiff. There are other subsets, however.* *Prices subject to change without notice.*

SCIENCE AND



Particle Schemes

In recent months much of the search for new "elementary" particles has been guided by a theoretical concept known formally as "SU_3 symmetry" and informally as "the eightfold way." The concept indicates how multiplets, or families of particles, that have approximately the same mass, such as the neutron-proton doublet or the pi-meson triplet, can be grouped into supermultiplets, or superfamilies. By specifying the composition of supermultiplets, the eightfold way makes it possible to predict the existence of missing members, their approximate masses and certain other properties. The scheme applies only to strongly interacting particles, the class that responds to the strong, or nuclear, force, and that has proliferated dramatically in the past half-dozen years. The class now includes well over 50 members, many of them originally described as "resonances" (see "Resonance Particles," by R. D. Hill; SCIENTIFIC AMERICAN, January, 1963).

The eightfold way was conceived independently in 1961 by Murray Gell-Mann of the California Institute of Technology and Y. Ne'eman, a colonel in the Israeli army. At that time Ne'eman was military attaché at the Israeli Embassy in London and a part-time student at the Imperial College of Science and Technology. Gell-Mann provided the informal name as an allusion to "the eightfold way that leads to the cessation of pain," a concept attributed to Buddha.

The term "eightfold way" refers to the various ways in which a group of eight elementary things can be mathematically related. An important part of the relation involves symmetrical transformations, which are of central importance in quantum mechanics. The particular mathematical relation used in the eightfold way is called SU_3 symmetry. The eightfold way explains how strongly interacting particles can differ in mass and in other basic properties (such as "isotopic spin" and "strangeness") and still be members of a superfamily.

A concept that antedates the eightfold way by about two years has also been fruitful in showing relations between different particles and in guiding experimenters in their search for new ones. Conceived by the Italian physicist Tullio Regge in 1959, it describes a mathematical function called a Regge trajectory. According to this concept certain particles that differ greatly in mass can be regarded as different "rotational states." The term "rotational" is employed because the states differ in the angular momentum of their spin.

Out of these and other theoretical concepts the belief has been growing that the proliferation of strongly interacting particles simply represents the discovery of a spectrum of energy states and that no state is more fundamental, or elementary, than any other. Speaking in October at the centennial celebration of the National Academy of Sciences, Geoffrey Chew of the University of California at Berkeley observed: "If there is no need for aristocracy among strongly interacting particles, may there not be democracy?"

New Birth-Control Devices

A number of simple plastic and metal devices that can be left inside the uterus without harm for years at a time are being tested in the U.S. and abroad as inexpensive and reliable aids to birth control. The devices, which must be put in place by a physician, include rings made of stainless steel or plastic or both, and various configurations of polyethylene such as a double-triangle "bow," a double-S loop and a spiral. All seem to have little effect on uterine function except for the prevention of conception, which all accomplish with high reliability. Accidental pregnancies have numbered slightly more than one per 100 patient-years of use, a rate that is much

lower than the rates achieved by traditional means of contraception and that also surpasses the record of the hormone birth-control tablets in groups other than closely supervised experimental ones.

The devices are descendants of an intra-uterine ring invented by a German physician, Ernst Gräfenberg, 35 years ago. Although the Gräfenberg ring, which was made of silver, was successful in early trials, wider experience with it indicated that it frequently caused bleeding and other difficulties; it was accordingly abandoned. Interest in it was revived, however, by studies in Israel and Japan. The Japanese studies, which involved a total of 19,000 women, showed that a Japanese modification of the Gräfenberg ring could be left in the uterus for as long as 20 years without detectable harm. The "bow," the spiral and the double-S loop are recent U.S. innovations. Together with variants of the Gräfenberg ring, they are now being investigated in a dozen studies coordinated by the National Committee on Maternal Health.

There is no agreement on how any of the devices work. They do not block the uterus; they are simply lodged inside it. The most widely held opinion is that they encourage peristalsis of the Fallopian tubes, with the result that the ovum makes the journey from ovary to womb in considerably less than the usual 72 hours. Thus even if the ovum has been fertilized, it is immature and the wall of the uterus is unprepared for its implantation. The new devices have caused no inflammation, few bleeding difficulties and, when a pregnancy accidentally occurs, no malformations or other apparent harm to the fetus. They can easily be removed if pregnancy is desired. Sheldon J. Segal, medical director of the Population Council, believes they are the most promising answer yet to the problem of overpopulation. The devices cost only a few cents each, and once in place they work without any further concern on the part of the couples using them.

Answers in Set Theory

Two central questions in the mathematical theory of sets have been answered by Paul J. Cohen of Stanford University. The questions have to do

with the "continuum hypothesis" and the "axiom of choice."

A set is a group of things considered together, just as the word is normally understood. The players on a baseball team are a set, as is the number of nickels in a dollar or the array of all whole numbers. Over the past century the study of sets, and of the relations between sets, has evolved into a theoretical structure that is one of the main branches of mathematics. Set theory is widely used in teaching to demonstrate how things can be grouped and how groups are related to one another; it has also proved useful in the definitions and investigations of all mathematics.

Every set has a cardinal number, which is the number of things in the set: nine for the baseball team, 20 for the nickels in a dollar and the name "aleph-null" for the infinite array of whole numbers. The German mathematician Georg Cantor, who was the originator of set theory, showed that there can be sets with a larger cardinal number than aleph-null, for example the set of points on a line. He used *c* (for continuum) to denote that cardinal number. Mathematicians have debated whether or not there are intermediate infinite sets, having cardinal numbers between aleph-null and *c*. The assumption that there are such sets has been known as the continuum hypothesis.

Kurt Gödel of the Institute for Advanced Study in Princeton, N. J., showed in 1938 that the continuum hypothesis could not be *disproved* with the existing axioms of set theory. One of the two long-standing questions in set theory has been whether or not the hypothesis could be *proved* with those axioms. Cohen has found a model of the axioms of set theory in which the continuum hypothesis is untrue. Therefore he argues that the hypothesis cannot be proved with the existing axioms of set theory.

The other question to which Cohen addressed himself was whether or not it is possible to prove the "axiom of choice." That axiom, an important mathematical tool, states that given any nonoverlapping collection of sets it is possible to form a new set containing one element from each. Gödel showed that this axiom, like the continuum hypothesis, could not be disproved with the existing axioms of set theory. Cohen has shown that set theory cannot prove the axiom. An important extension of Cohen's assertion is that even assuming that the axiom of choice is true, one cannot prove the continuum hypothesis from it.

Thus set theory, in spite of its value in mathematics, continues to lack the completeness that investigators seek in any theoretical structure. It appears probable that the lack can be supplied only by fundamentally new axioms, if such are indeed attainable.

A Viking Settlement in America

The first acceptable archaeological evidence that the Vikings reached America before Columbus has been reported by Helge Ingstad, a Norwegian explorer. Ingstad and his colleagues, working under the sponsorship of the National Geographic Society, have discovered in Newfoundland the ruins of what they believe to be a Viking settlement dating back to about A.D. 1000.

Icelandic sagas relate how Leif Ericson and other Norsemen sailed westward from Greenland at about that time and discovered a new land they called Vinland. Many searchers have claimed the discovery of a Norse settlement, at sites ranging from Chesapeake Bay to Hudson Bay. According to the National Geographic Society no previous claim of a pre-Columbian Norse site has had the support of ruins or burials, the only kind of archaeological evidence that could indisputably date from the time of settlement.

Ingstad had the idea, based on studies of the sagas and an old Icelandic map, that Vinland was farther north than any of the sites previously claimed. He examined the coast by airplane and boat, eventually finding traces of an ancient settlement at L'Anse au Meadow on the northwestern tip of Newfoundland. Excavations there turned up the remains of nine houses and a primitive smithy.

The discoverers cite three types of evidence for the authenticity of the site. Some of the house sites have ember pits, which were characteristic of Norse homes of the period in Greenland. Moreover, the smithy was apparently used to refine iron deposits found in nearby bogs; the technique was unknown to Eskimos and Indians and too primitive for Europeans of a period later than Ericson's. Finally, radiocarbon dating of charcoal from the ruins puts the date of occupancy at about A.D. 1000. A leading student of American archaeology, Junius Bird of the American Museum of Natural History, said that the site "is without question of pre-Columbian Norse origin."

St. Paul and the Computer

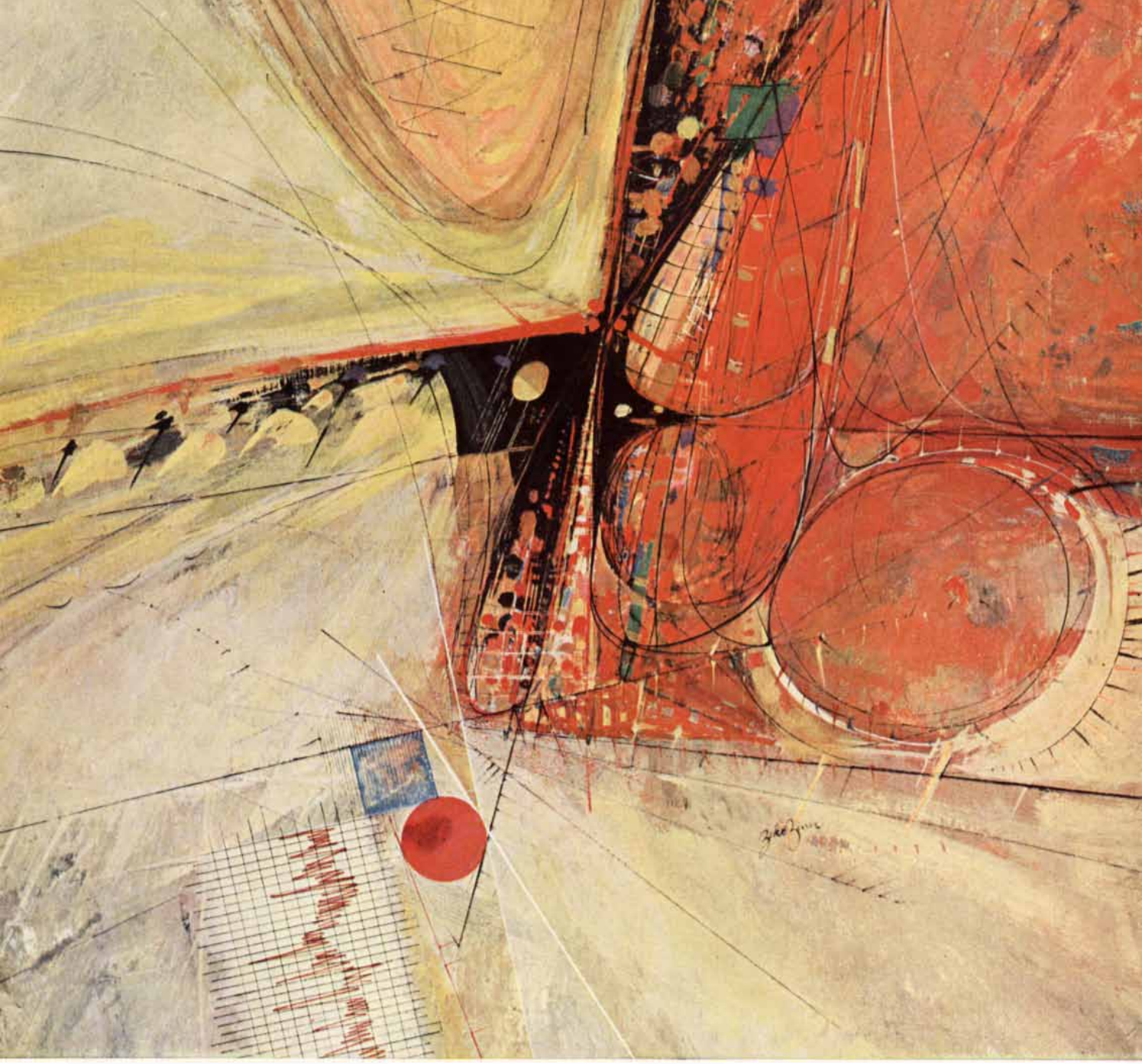
A Presbyterian minister who subjected the 14 Pauline Epistles of the New Testament to computer analysis has decided that St. Paul actually wrote only five of them and that the others were the work of at least five different authors. The Reverend A. Q. Morton of the Church of Scotland reported his findings in an article in *The Observer* and in lectures at the University of Chicago in November.

The authorship of many of the Epistles has been questioned for some time. In 1957 Morton and the late G. H. C. MacGregor of the University of Glasgow undertook to combine computer techniques with textual analysis in an effort to approach the problem objectively. They decided first to establish a number of literary habits so characteristic of an author that they would in effect fingerprint all his work, and then to test each of the Epistles for the occurrence of these habits. The habits they selected were simple and subject to counting: the frequency with which sentences of various lengths appeared and the frequency with which an author used six common Greek words (the Epistles were written in Greek)—the equivalents of "and," "but" and "in," the definite article, the personal pronoun and the verb "to be." Applying these seven tests to a number of Greek authors, Morton and MacGregor proved their hypothesis: they found that the tests would identify an individual's work regardless of subject matter or time of writing. Applied to the Epistles, all seven tests showed that only Romans, First and Second Corinthians, Galatians and Philemon were written by the same hand. Since Paul's authorship of Galatians seems to be firmly established, Morton said, "we concluded without any shadow of doubt that these are the genuine Pauline Epistles."

Morton's findings have been received with skepticism by many clerics. Some Catholic and Protestant scholars in this country said it was already generally accepted that at least three of the Epistles were not written by Paul and that Morton's evidence on the others is not conclusive—that it may reflect different circumstances of writing or dictation to different scribes. Morton, however, says his results are "quite open and shut" and constitute "a direct confrontation between science and religion every bit as far-reaching in its effects as the clash between T. H. Huxley and the bishops in the 19th century."

The Smiles of Men and Monkeys

"When men are amused, they draw back the corners of their mouth and emit a series of quavering grunts. Why should they make this quite arbi-



How to keep a Corporation Young

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The task of being a mature corporate citizen in a rapidly expanding technically-oriented economy entails several areas of responsibility.

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Polacolor film is now available in three forms. As a roll film, it fits all older model Polaroid Land cameras. It also comes in flat packs for our new Color Pack Camera and in sheets for 4x5 cameras. All of them give you the finished color print in 50 seconds.

Though it opens up enormous new opportunities for on-the-spot recording in full color, Polacolor film can't possibly replace the special capabilities of our seven other films.

Here is a primer on those films you may want to keep for future reference.

Type 42 is a panchromatic roll film rated at A.S.A. 200 and is used for scientific work as well as for snapshots. It produces a fine-grain print in just 10 seconds.

This same emulsion is also available as Type 52, a sheet film for any 4x5 camera which has a Graphic or similar back.

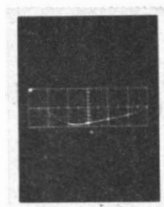
Type 55P/N is one of four kinds of Land film that can give you on-the-spot pictures with almost any 4x5 camera. This film, with an A.S.A. equivalent rating of 50, gives you a fine quality, usable *negative* and a positive print. Both develop outside the camera, outside the darkroom in 20 seconds. You can enlarge the negative up to 25 times original size with almost no evidence of grain.

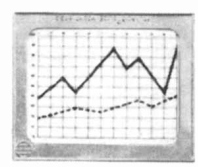
Type 57 is our 4x5 film for shooting in low light levels with fast shutter speeds. It is rated at 3200 A.S.A. and you get your finished print in 10 seconds. The same emulsion is available as Type 47 (roll film) and Type 107 (pack film) and is our most widely used general purpose film.

It is sensitive enough for virtually all scientific assignments.

Because it can be used indoors or out in unposed, natural light situations, it also makes wonderful pictures of the kids, around the house on weekends

Type 410 is the world's fastest film. It has an A.S.A. equivalent rating of 10,000. This is a high-contrast film which can record transient oscilloscope traces in the nanosecond range ... literally too fast for your eye to see. The prints develop in 10 seconds.





Type 146-L is one of a pair of Polaroid Land films which give you black and white transparencies instead of prints. Within moments after you click the shutter you can project them as lantern slides. This one, rated at A.S.A. 120, is best suited for line work and develops in 10 seconds.

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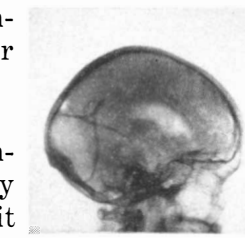

Exposed in a conventional X-ray machine, it produces a 10″x12″ positive X-ray image in just 10 seconds. The film not only develops faster than conventional X-rays, it's more sensitive. It requires 20% or less of the radiation normally required to make an X-ray picture.

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trary gesture, rather than some other one, to show friendliness and pleasure?" With these words R. J. Andrew, a Yale University biologist, begins an article in *Science* inquiring into the evolution of facial expression.

Andrew finds that man's basic repertory of facial displays is clearly related to that of the apes and that its evolution has been parallel to the evolution of similar displays in other primates. Whereas expressions do communicate information about an animal's motivations and intentions, expressions did not originate as reflections of drives or emotions. They stem rather from such simple responses as those associated with the protection of vulnerable areas of the head, preparation for biting, vigorous respiration, grooming and so on. In the course of evolution increased facial mobility due to changes in musculature, coupled with an increased need among social animals for displays conveying information, has "facilitated" these responses; they seem to have become less tied to a physical response and to have acquired more generalized meanings. Parting the lips and flicking out the tongue, for example, is a preliminary to grooming in social primates; in some advanced primates lip-smacking may become a generalized form of greeting.

Tracing the "grin," or retraction of the corners of the mouth, Andrew notes its occurrence in various primates and man. Originally it was apparently a protective response to a threat to the animal's head or a preparation for biting. In more advanced primates it becomes a generalized "startle" response. A man, Andrew writes, may grin while he is being criticized by a superior, while he is fighting or engaged in other physical exertion and even "during periods when some undesirable event seems likely to occur suddenly"—as when he is making fine adjustments in a delicate mechanism. Speculating on the connection between smiles and feelings of pleasure, Andrew reports that a large change in stimulation is generally considered unpleasant and evokes a protective response. With "facilitation" the grin—now a smile—may have come to be evoked by a small change in stimulation. Such a change, he points out, is considered pleasurable and is, indeed, one of the conditions of a successful joke.

Satellite Gravity Measurements

Measurement of the paths followed by man-made satellites may provide new evidence for the existence of con-

vection currents in the earth's mantle, the hot layer of rock immediately below the crust. Over the past several years satellite measurements have been employed to reveal irregularities in the earth's gravitational field The irregularities have generally been interpreted as signifying that the earth is slightly out of round on a plane through the Equator and slightly pear-shaped on a plane through the poles. S. K. Runcorn of the University of Newcastle upon Tyne believes, however, that the gravitational irregularities can be explained with equal ease and greater plausibility as resulting from convection currents in the mantle.

Writing in *Nature*, Runcorn notes that the maintenance of irregularities of shape over great periods of time would require the earth to have an extremely rigid mantle. If the irregularities date back three billion years or more (as has been suggested), the mantle would have to have a creep of less than a millionth of a millionth of a millionth (10^{-18}) of a per cent per second. Runcorn comments: "It is remarkable that our geophysical colleagues have not made widely known to engineers their technological breakthrough in discovering a material which, at elevated temperatures, has a creep rate only one millionth millionth of those encountered in the laboratory."

On the other hand, rising and descending convection currents in the mantle could produce changes in the density of various parts of the mantle sufficient to account for the irregularities in the earth's gravitational field. Moreover, when the satellite-observed irregularities are plotted on a map of the world, a remarkable coincidence is observed. All five areas of low gravity detected by satellite coincide quite closely with regions of the Mid-Ocean Ridge: the globe-girdling chain of mountains that is believed to be characterized by rising convection currents. Such currents mark zones of expansion in the mantle and could be expected to produce regions of low gravity. Satellite observations have also revealed four areas of abnormally high gravity. Two of them coincide with zones of compression and probable descending currents in southern Europe and the Andes. The other two regions of high gravity—below South Africa and in the Pacific north and east of Australia —are not so easily matched to the earth's present topographic features. But Runcorn, an advocate of the theory of continental drift, suggests that continental movements may provide a clue to these and related puzzles.

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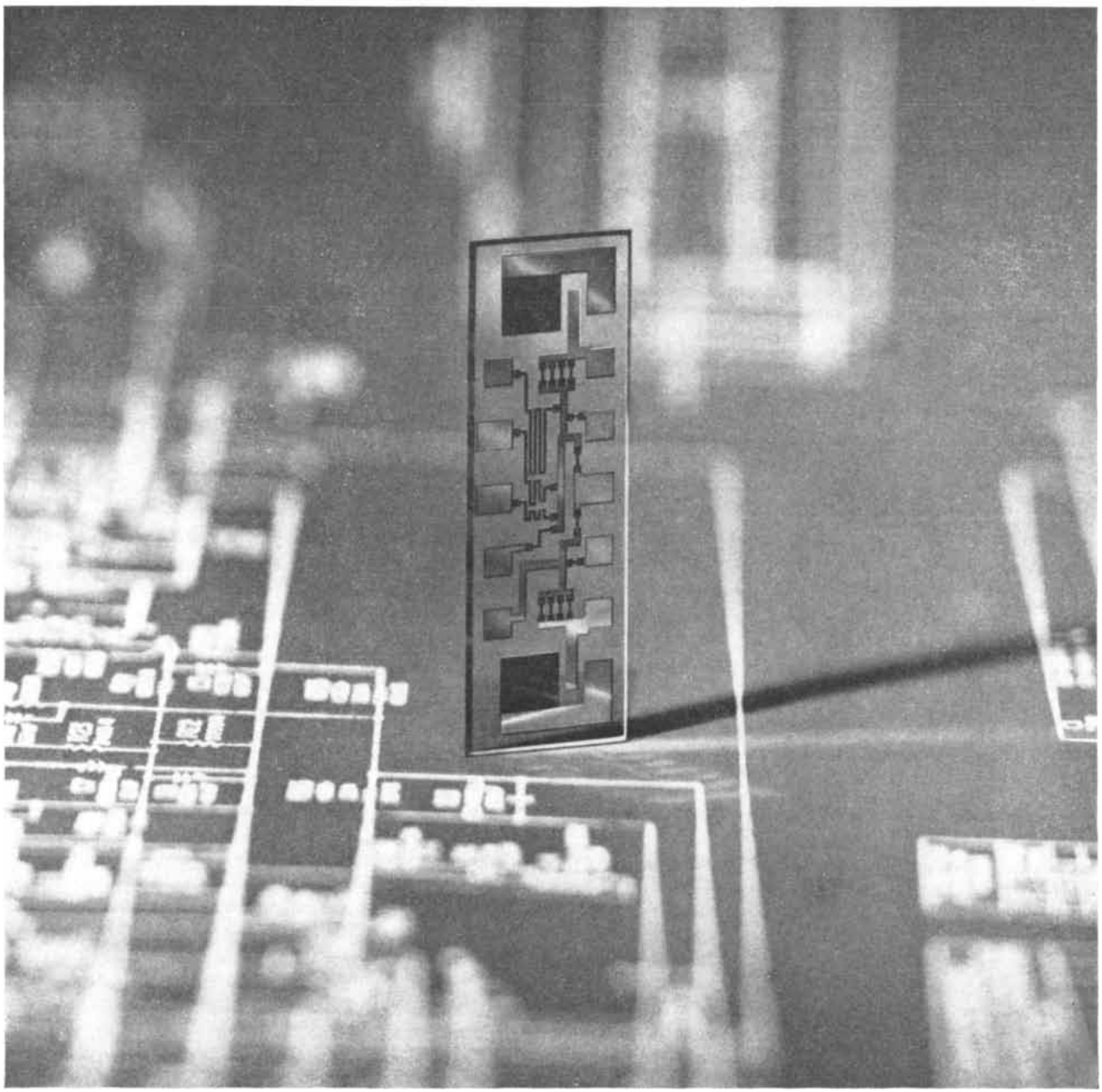


THE MITOCHONDRION

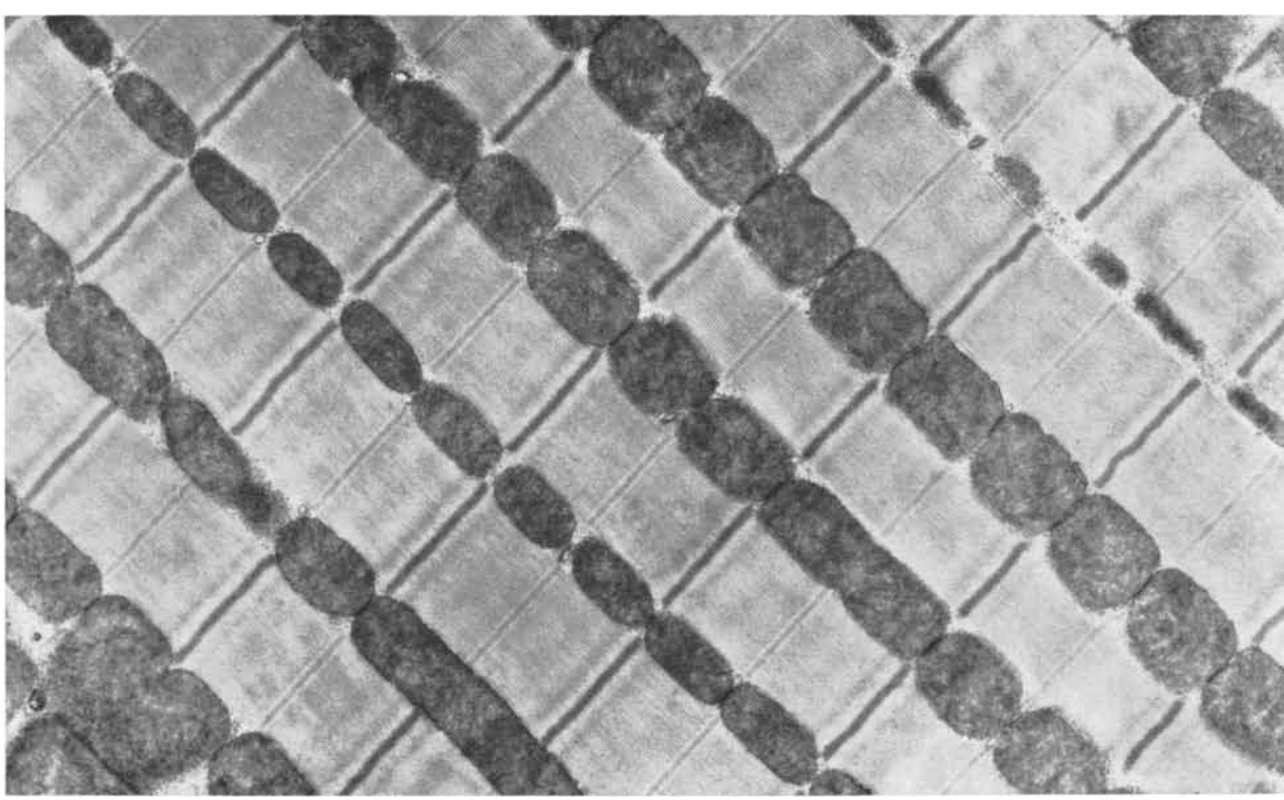
This small body within the living cell is the site of the chemical events that supply energy to the cell. The molecular architecture that underlies this function has recently been revealed in detail

by David E. Green

Although we do not know what the first forms of life on the earth were like, we do know the nature of the equipment that started them on the road to survival. Life was no more than an experiment of nature, in danger of being snuffed out at any time, until the proto-organisms developed dependable machinery to perform two basic functions: (1) reproduce themselves and (2) generate energy in a form usable for an organism's various requirements. It is clear what that machinery must have been even in the first successful living creatures some two billion years ago, because all forms of life on our planet have basically the same systems for these two purposes. They are summed up in the familiar initials DNA and ATP.

DNA stands for the genetic apparatus that is responsible for the replication of the key substances of life: proteins and the nucleic acids themselves—deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Fully as important as DNA is adenosine triphosphate, or ATP. This molecule supplies the energy for all the processes of life, including replication; in fact, as it is shaped by evolution, the replicating process is designed to be energized by ATP.

The energy-generating system of living things depends on two related actions: oxidation and the synthesis of ATP. The function of oxidation is to release electrons, which act as the agents for the storage and transformation of energy. In the absence of oxygen other methods of electron release can serve, and there are many cells and organisms that carry out "oxidation" in these substitute ways. In all cases, however, the goal of the process is the formation of ATP, which acts as a kind of storage



MITOCHONDRIA are the dark, oblong objects lined up end to end from top left to bottom right in this electron micrograph of a wasp's flight-muscle fiber, made by David S. Smith of the University of Virginia. Magnification is approximately 9,500 diameters.

battery feeding energy to the cell as it is needed.

Living organisms have developed three different systems for generating energy in the form of ATP: the various enzymes that catalyze the process of glycolysis and the intracellular particles known as the chloroplast and the mitochondrion. The most primitive of these is glycolysis; it is the breakdown of sugar by enzymes in the absence of free oxygen. The system is comparatively inefficient, yielding only one molecule of ATP for each pair of electrons released. The mitochondrion produces three molecules of ATP for each pair of electrons released by oxidation; the chloroplast possibly produces the same number of ATP molecules for each pair of electrons released by light. This threefold gain in efficiency makes the chloroplast and the mitochondrion the favored power plants of living things—the chloroplast in the world of green plants and the mitochondrion in the world of animal cells. In principle both are variations on the same theme.

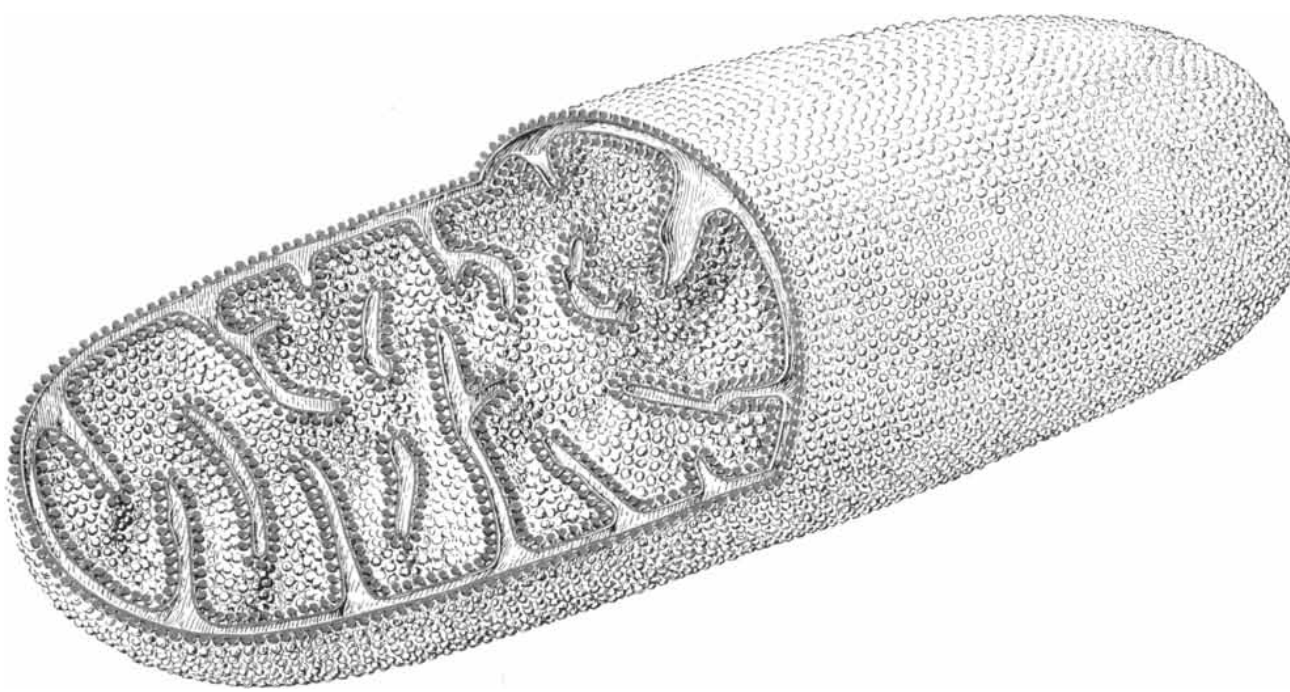
The mitochondrion is often called the powerhouse of the cell. It is a good deal more than that; it carries out functions other than generating energy. Indeed, its basic design seems to be copied by all other systems in the cell that have to do with the transformation or use of energy, such as those responsible for the transport of materials through membranes, for the contraction of muscle and so on. Thus the mitochondrion can serve as a Rosetta stone for deciphering the *modus operandi* of all the energy-transforming processes in cells. This article will discuss the mitochondrion's chemical structure and operations, now known in considerable detail, in that light.

The Structure of the Mitochondrion

Let us first look at the structure of this tiny body. In the average cell there are several hundred mitochondria. An average mitochondrion would be a sausage-shaped object about 15,000 angstrom units long and 5,000 angstroms in diameter. (An angstrom unit is a ten-millionth of a millimeter.) Rather like a Thermos bottle, it has a two-layered wrapping: an outer and an inner membrane with a watery fluid filling the space between them. Extending from the inner membrane into the interior of the sausage are a number of sacs called cristae. The surfaces of both membranes are sprinkled with thousands of smaller particles; they are anchored to the outside surface of the outer membrane and the inside surface of the inner membrane. These particles are the elementary units that carry out the chemical activities of the mitochondrion. The fluid between the membranes also participates, providing communication between the layers and supplying the enzymes in the membranes with the auxiliary catalysts known as coenzymes.

The two membranes serve as structural backbones for the mitochondrion. From the structural standpoint they have three notable properties: good tensile strength, stability and flexibility (The mitochondrion is by no means a rigid body.) One of the fascinating developments in the analysis of the mitochondrion was the discovery of the chemical arrangement that accounts for these properties.

Each membrane is made up of two materials apart from its attached particles. The principal material, accounting for about four-fifths of the weight of the membrane, is a structural protein that has recently been identified in our laboratory at the University of Wisconsin. In its usual form the protein is completely insoluble in water. Analysis of its constituent amino acids showed that half of them have paraffin-like side chains, that is, side chains insoluble in water. When such chains join together, they do so by virtue of what is known as a hydrophobic bond. The bond is fairly weak, but the large number of bonds involved in the joining of chains gives it a high degree of stability. As we shall see, the hydrophobic bond is a key to the structure and functions of the mito-



CUTAWAY DRAWING of a typical mitochondrion shows the two membrane layers separated by a fluid-filled space called the intrastructure space. The space within the inner membrane is called the interstructure space. The invaginations of the inner membrane are the cristae. The stalkless particles distributed over the outer surface of the outer membrane are involved in various oxidation reactions that supply electrons to the interior of the mitochondrion. The particles extending inward on short stalks from the inner surface of the inner membrane transfer the electrons along a chain of complexes that synthesize molecules of adenosine triphosphate (ATP).

chondrion; we can call it one of the motifs of the mitochondrial theme.

The structural protein can be broken down into monomers, or subunits, by various reagents such as lauryl sulfate, alkali or acetic acid. They weaken the hydrophobic bond, either by increasing the number of electrically charged groups on the molecules or by a detergent action. The monomer, whose molecular weight is 22,000, is soluble in water. If the reagents are removed from the solution, the smaller units spontaneously rejoin to form the insoluble polymer.

The second material in the mitochondrial membranes, constituting about a fifth of their weight, is lipid, or fatty material, almost entirely in the form of the molecules known as phospholipids. We can picture a phospholipid molecule as having the shape of a clothespin, the head consisting of an electrically charged group of atoms and the two legs made up of long-chain fatty acid [*see upper illustration on page 66*]. By itself this molecule is insoluble in water. In a structural combination known as a micelle, however, a group of phospholipid molecules becomes soluble. Imagine two rows of the clothespin-shaped molecules—hundreds or thousands of them—lined up back to back so that the heads of the clothespins all face outward. On the opposite, or inward, side of the rows the fatty-acid chains forming the legs of the molecules nest together and are joined by hydrophobic bonds. The resulting micelle is a stable structure, and the behavior of the phospholipid is determined by the properties of the micelle as a whole rather than by those of the individual molecule. By virtue of the fact that in water the electrically charged heads of all the molecules in the micelle face the water, the micelle is soluble.

It is a combination of structural protein and phospholipid micelles, then, that forms the membranes of the mitochondrion. We can picture the membrane as a network consisting of alternating protein and micelle units linked by hydrophobic bonds [*see lower illustration on next page*]. This model would account for the relative proportions of protein and phospholipid in the membrane and for the membrane's physical properties; its tensile strength presumably is derived from the structural protein, and its flexibility from the phospholipid micelle. The outer and inner membranes of the mitochondrion are not quite alike; the outer one shows some properties the inner one does not have. Probably components other than structural protein and phospholipid are responsible for these properties.

LONGITUDINAL CROSS SECTION of a beef-heart mitochondrion is magnified about 60,000 diameters in this electron micrograph made by Humberto Fernández-Morán, now at the University of Chicago. This particular mitochondrion is about 29,000 angstrom units long and 7,000 angstrom units in diameter, after having been flattened out on a grid for viewing.

The Mitochondrial Particles

Let us now examine the particles that perform the various functions of the mitochondrion. Electron micrographs show that each mitochondrion has many thousands of these particles; they are distributed, as we have noted, over the outside surface of the outer membrane and the inside surface of the inner membrane. The particles have three different

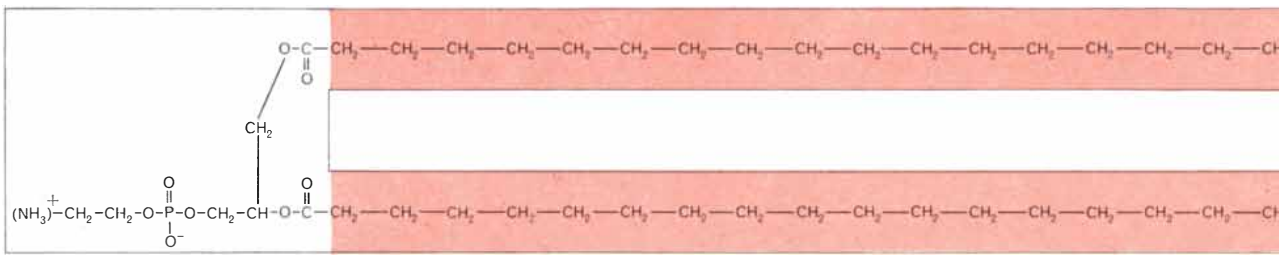
functions: (1) carrying out the oxidation reactions that supply electrons, (2) transferring the electrons along a chain of complexes that synthesize ATP, (3) catalyzing synthetic reactions that are powered by ATP.

The available evidence indicates that the particles concerned with the first and third of these functions are all located on the outer membrane, and that those concerned with electron transfers leading to the synthesis of ATP are on the inner membrane. (For example, bombardment of mitochondria with ultrasonic radiation does not disturb the electron-transfer particles but does dislodge most of the others, presumably because they are on the outer and more fragile surface.) It appears that the electron-transfer job is carried out by a particle of a particular kind that contains the entire set of catalysts that make up the chain.

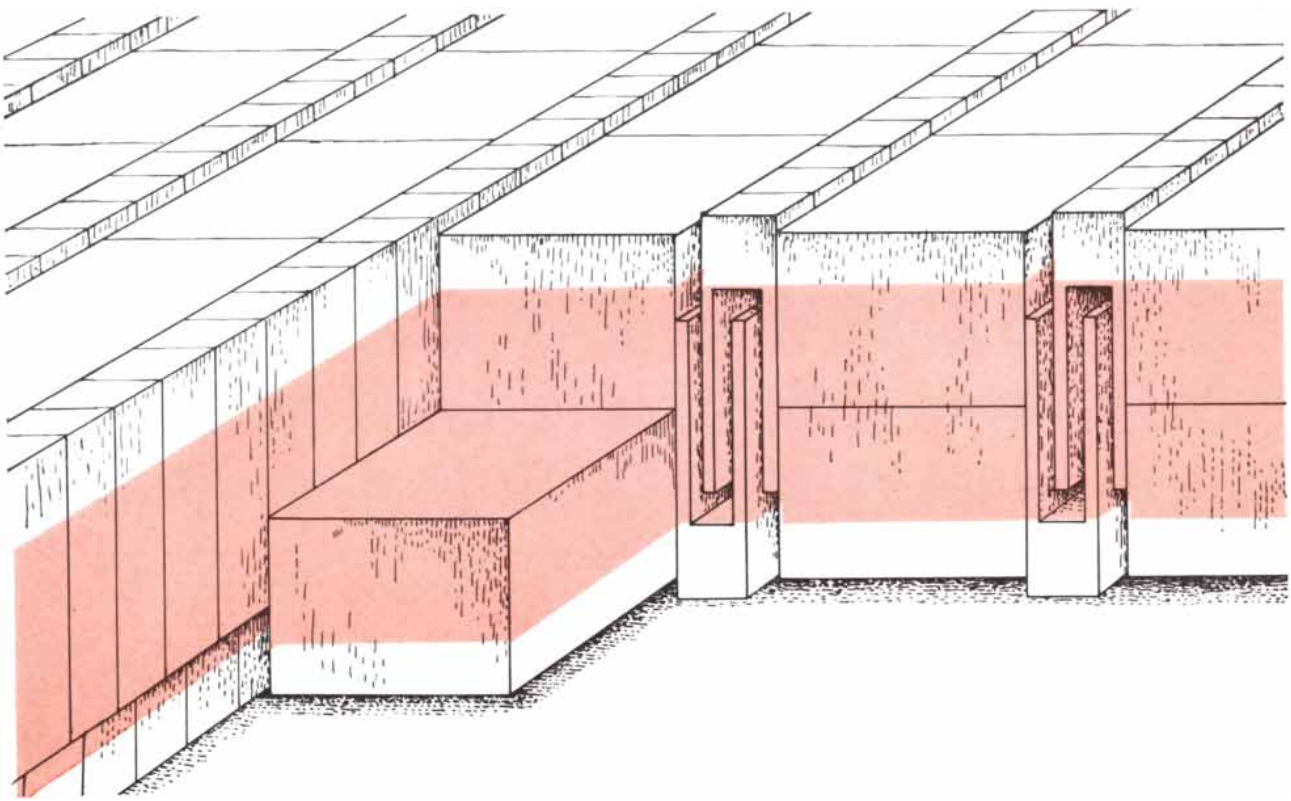
The general picture of electron transmission seems to be somewhat as follows. On the outer membrane certain particles responsible for providing "energetic" electrons (some four to six different particles are involved) do so by implementing oxidation reactions such as those of the so-called citric acid cycle and the oxidation of fatty acids. They pass on the released electrons to the coenzyme diphosphopyridine nucleotide, or DPN, which shuttles them across the liquid-filled space between the membranes to the particles on the inner membrane. In accepting the electrons the DPN molecule is reduced (and is then called DPNH); in turning them over to the inner-membrane particles it is oxidized.

The existence of a unit in which a single, complete electron-transfer chain is contained was implicit in studies conducted in our laboratory over the past 10 years. The physical unit, however, was first discovered by Humberto Fernández-Morán, now at the University of Chicago, during examination of mitochondria in the electron microscope. The electron-transfer particle has proved to be a momentous discovery, opening the door to investigation of the activities of the mitochondrion at the molecular level.

The chain traveled by the electrons in this particle consists of a series of catalysts arranged in a certain sequence, each of which can undergo oxidation and reduction. We can think of the chain



PHOSPHOLIPID MOLECULE, one of the two materials that make up the membranes of the mitochondrion, is shaped somewhat like a clothespin. The head (*left*) consists of an electrically charged group of atoms; the two legs (*right*) are long hydrocarbon chains.



MEMBRANES OF MITOCHONDRION contain networks of alternating protein and phospholipid units. The phospholipid molecules are lined up back to back with their heads facing outward in long rows known as micelles. The network is two protein molecules thick. The hydrophobic, or water-insoluble, bonding faces of both the phospholipid and the structural protein molecules are in color. This hypothetical model would account for the relative proportions of protein and phospholipid in the mitochondrial membranes.

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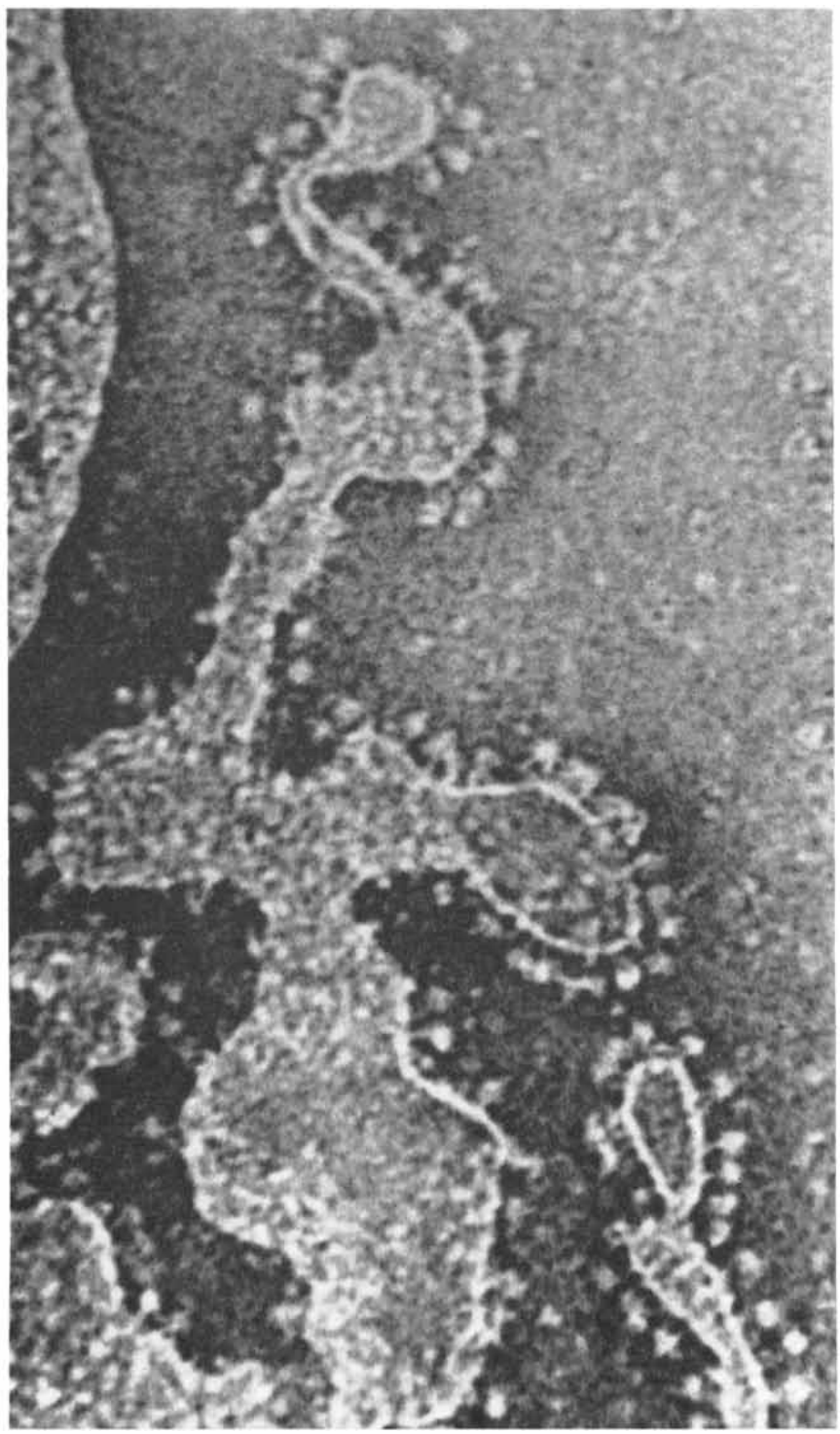
as a scale of notes that must be struck in regular order, except that the notes are struck not individually but in groups. There are 11 different components in the sequences (10 of them are proteins), and they are grouped in four complexes, or clusters. Complexes I and II are alternates: the chain starts with Complex I if the electrons come from the coenzyme DPNH; it starts with Complex II if the electrons are donated, as they may be, by succinate, a product of the citric acid cycle. In either case the electrons travel on from Complex I or II to Complexes III and IV, and eventually at the end of the chain they are carried off by molecules of oxygen.

The point of this arrangement is that each of the successive steps from Complex I to the end produces ATP. The transfer of a pair of electrons from DPNH to Complex I, then to Complex III and then to Complex IV results in the formation of a molecule of ATP at each site, or three molecules altogether. When ATP is synthesized, energy is stored in the molecule in the form of a high-energy bond, and this energy is provided by the transferred electrons because of differences in potential between the steps in the chain.



ENLARGEMENT of a small area at the upper left in the electron micrograph on page 65 shows the electron-transfer particles in greater detail. The base pieces of the particles form a continuous layer around the crista. Magnification is approximately 400,000 diameters.

The four complexes are stationary and are separated by lipid. From Complex I (or II) electrons are shuttled across a lipid layer to Complex III by a catalyst known as coenzyme Q, and from Complex III to IV the electrons are carried by cytochrome *c* [*see upper illustration on page 70*]. The complexes are arranged in a certain order; it has been found that if the four complexes are isolated and then dissolved in water, they will reassemble themselves in precisely the same arrangement they have in the mitochondrion.

This general scheme shows how electrons are transported from one complex to the next, but it is not easy to see how the traveling electrons can move within a complex. The proteins making up a complex are locked in fixed positions, which would seem to allow them no means of transferring electrons from one protein to another. Robert M. Bock of the University of Wisconsin and Richard S. Criddle of the University of California at Berkeley have proposed a brilliant explanation that seems to be borne out by the evidence so far, namely that the proteins make contact with one another by means of swinging groups of atoms, mounted on the respective proteins by flexible arms, that transfer and accept the electrons [*see illustration on pages 72 and 73*].

Models of the Complexes

We now know all the components of the electron-transfer chain (all except coenzyme Q are proteins), the number of molecules of each component, the amount of lipid associated with the chain (about 30 per cent of the total mass), the approximate molecular weight of each complex (between 250,000 and 600,000) and the approximate molecular dimensions of the various parts of the system and of the electron-transfer particle as a whole. With this information one can work out molecular models of the complexes and the entire particle. It appears that each complex, containing four to six protein molecules, must

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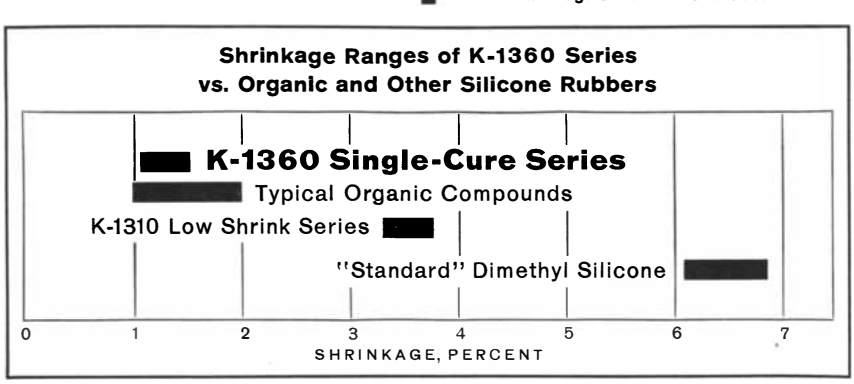

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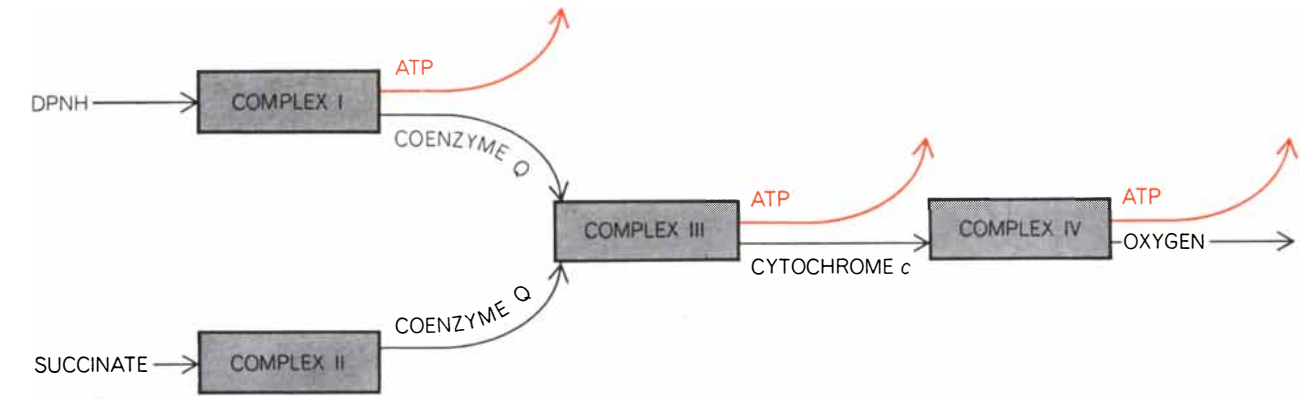
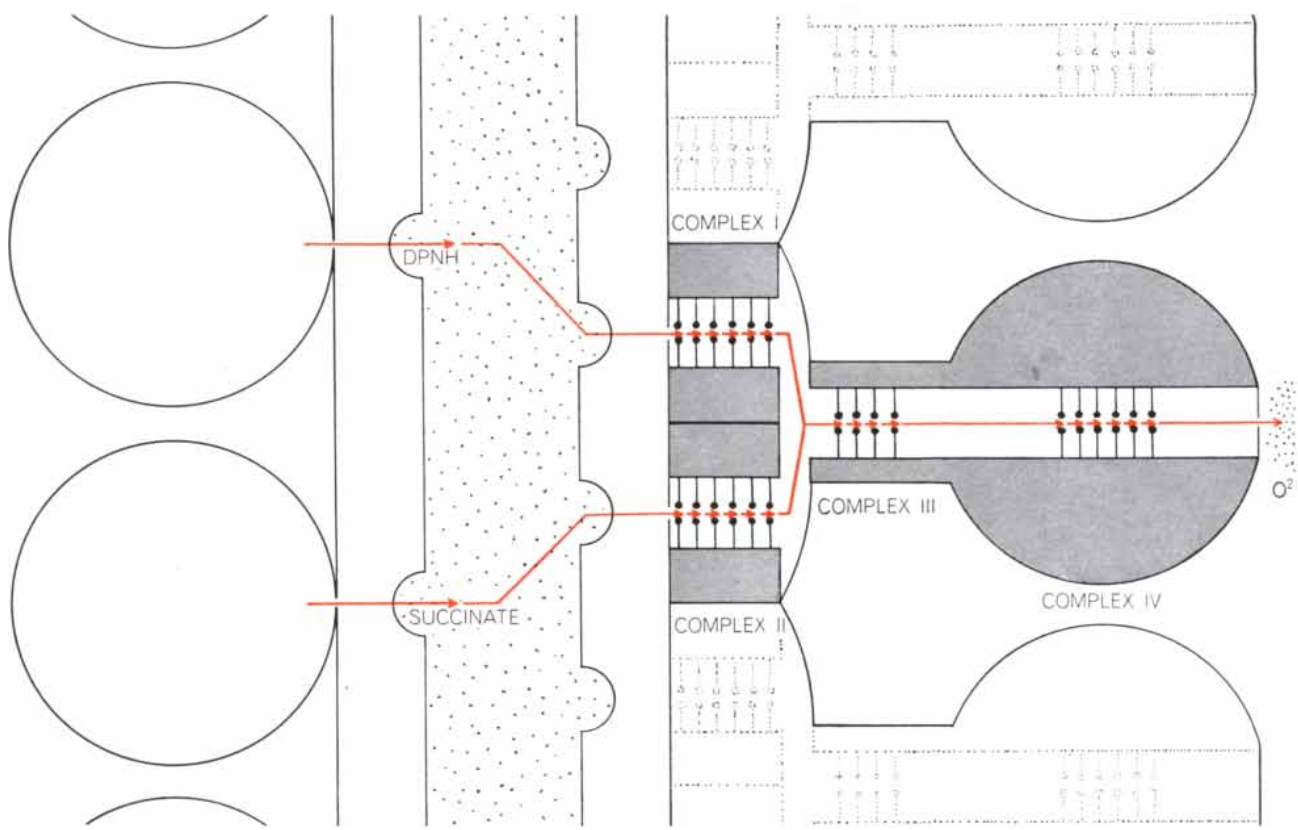
have roughly the shape of a doughnut, with the protein around the periphery and phospholipid in the center [*see illustration on pages 72 and 73*]. The proteins are linked to one another and to the phospholipid by hydrophobic bonds, as in the over-all membranes of the mitochondrion. The functional—that is, electron-transferring—groups in the protein molecules are probably directed toward the hydrophobic interior of the lipid core, which presumably is in the form of phospholipid micelles. Lipid also permeates the entire particle, providing a medium for the shuttling of electrons from one complex to another.

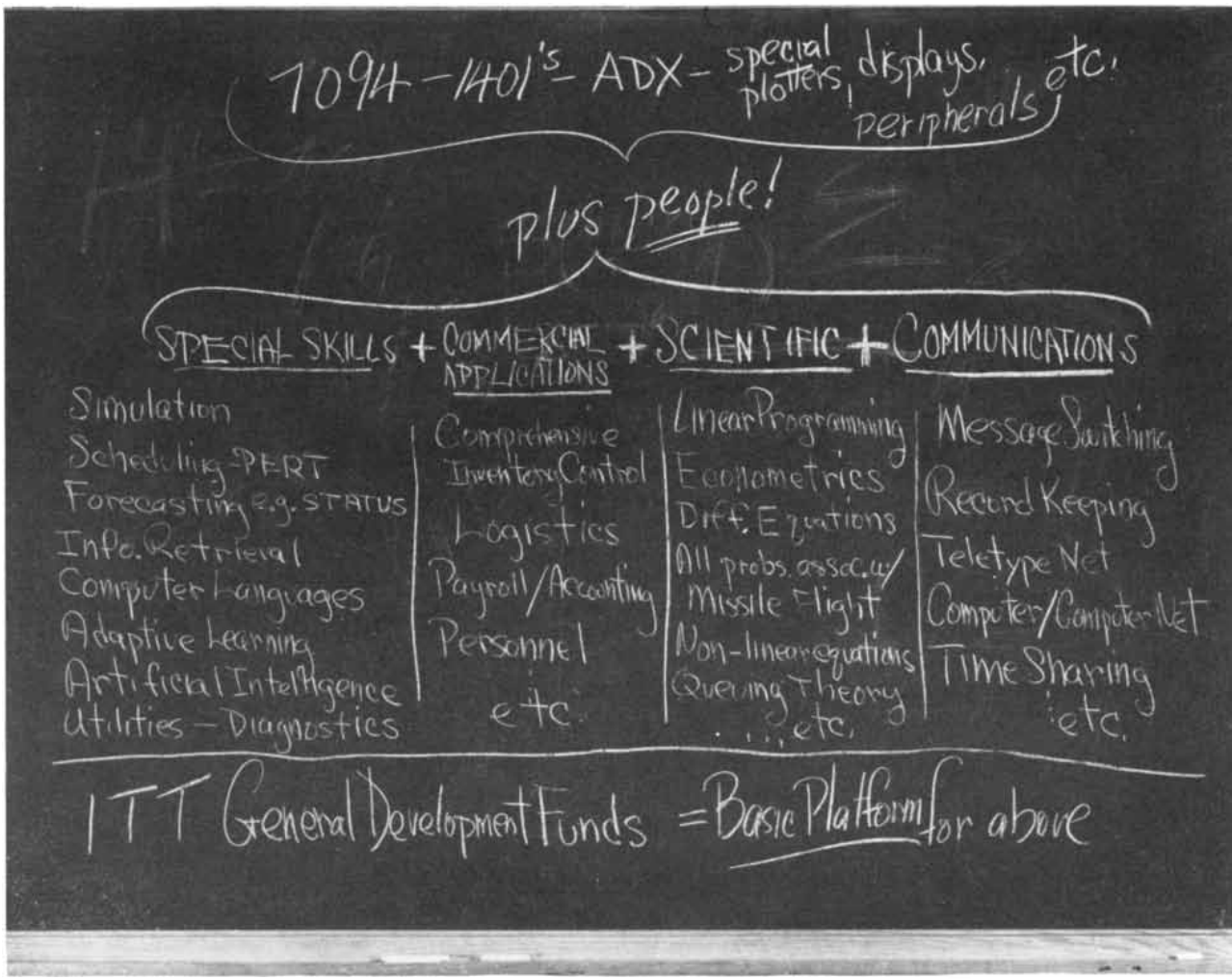
Sidney Fleischer and Gerald P. Brierley of our laboratory have elegantly demonstrated the essential role played by the lipid in the transfer of electrons. They delicately removed the lipid from electron-transfer particles, using a solvent composed of 90 per cent acetone and 10 per cent water at low temperature to avoid damage to the functional proteins. With the lipid extracted, the particles lost their ability to transfer



ELECTRON TRANSMISSION through a series of complexes inside the mitochondrion results in the formation of ATP, which stores the energy produced in the mitochondrion and supplies it to the cell when needed. Three molecules of ATP are formed in this process. DPNH and succinate are produced during the operation of the so-called citric acid cycle and also by the oxidation of fatty acids. Black arrows accompanying colored arrows denote oxidation reactions that donate electrons toward the formation of ATP.



HYPOTHETICAL ARRANGEMENT of the four energy-generating complexes within the electron-transfer particle would reconcile the disparity between the weight requirements of the proposed electron-transmission system and the observed weight of the particle. According to this hypothesis Complexes I and II are in the base piece, Complex III is in the stalk and Complex IV is in the headpiece. Electrons are supplied by the stalkless outer particles (*left*) to molecules of DPNH and succinate at the inner surface of the outer membrane. These coenzyme molecules then shuttle the electrons across the intrastructure space to the outer surface of the inner membrane, where they are donated to Complexes I or II. The gray parts of the electron-transfer particle at right are protein and the white parts are lipid. The fine structure of the electron-transfer mechanism within a single complex is depicted on pages 72 and 73.



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electrons. Fleischer and Brierley then restored the lipid by supplying phospholipid micelles in a form that readily entered the particles. Thus supplied, the particles recovered full activity in electron transfer. In short, lipid is an active partner, and there is accumulating evidence that phospholipid micelles take part in many catalytic activities in the mitochondrion, in addition to serving as a component of its membranes.

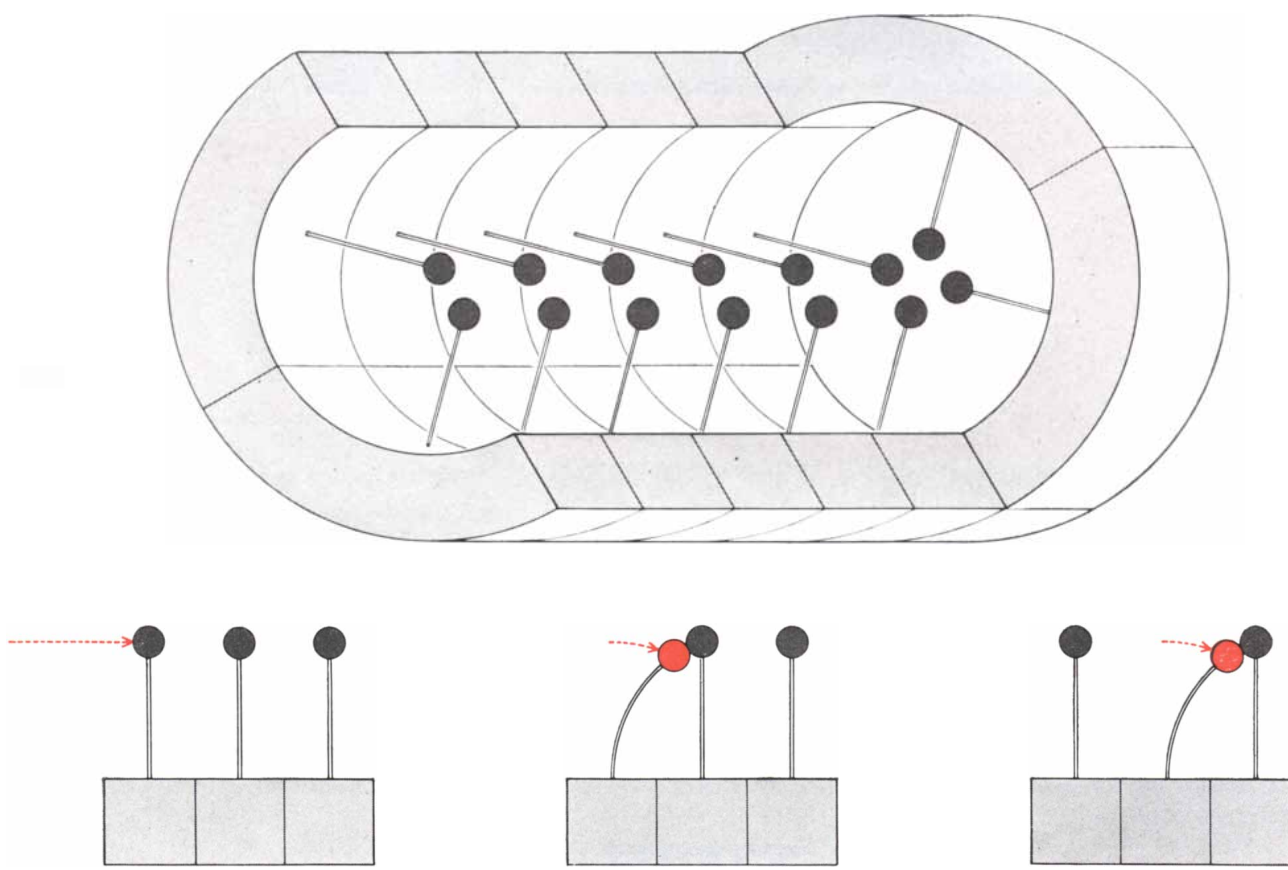
It is interesting to see that, structurally speaking, the mitochondrion has a striking resemblance to a virus. The virus particle consists of a protein coat and a nucleic acid core. When these two parts are separated, they are inactive; when they are combined again, the virus completely recovers its capacity for infection. In an analogous way the mitochondrion completely loses its ability to transfer electrons when its protein and phospholipid parts are separated and regains this ability when they recombine. In each case the partners are incompetent when alone and become active when coupled.

The Formation of ATP

How do the electron-transfer particles produce ATP? Essentially their function is to form ATP by joining a phosphorus atom in a high-energy bond to adenosine diphosphate (ADP). This is done in several steps by a rather intricate process. Let us examine how the process is carried out in the interaction of Complex IV and cytochrome *c*, where the details are best known.

The crux of the process is the formation of the high-energy bond. Energy for the bond is provided, as we have noted, by virtue of a drop in potential as electrons pass from one component in the chain to the next. In Complex IV these components are six protein molecules. The difference in potential between any one protein and the adjacent one is small—too small to supply enough energy for the high-energy bond. The total potential drop through the six molecules, however, is large enough. The set of six molecules does in fact function as if they were acting in unison, thereby assembling an energy package sufficient for the bond, as six men pulling on a rope together can move a weight that none of them could move singly.

How is the flow of electrons translated into a high-energy bond in Complex IV? George C. Webster of our laboratory has shown that the electron-bearing messenger, reduced cytochrome *c*, forms a compound with Complex IV; the two are joined by a high-energy bond, probably attached to the copper-containing group in the Complex IV protein molecule. Apparently one molecule of reduced cytochrome *c* donates its spare electron to the complex, and the reduced complex then interacts with another cytochrome *c* molecule and receives a second electron, which so to speak seals the bond. After the compound is formed it interacts with a comparatively small protein molecule called the coupling factor, which splits off Complex IV and forms a compound with cytochrome *c*, still using the same high-energy bond. Cytochrome *c* is in turn replaced by an inorganic phosphate group that attaches itself to the coupling factor by means of the high-energy bond. Then follows a final reaction in which a molecule of ADP bumps away the coupling factor and joins up with the phosphate group, still retaining the high-energy bond, to form ATP. In short, ATP is the end product of a series of reactions in which cytochrome *c* combines with Complex IV, the coupling factor replaces Complex IV, inorganic phosphate re-



ELECTRONS ARE PROPELLED through a single complex (in this case Complex I) from one protein to another by means of swinging groups of atoms (*black balls*) that extend into the lipid core of the complex from the surrounding protein sheath (*top*). The five-stage drawing across the bottom shows how an electron is transferred and accepted by three of these protein groups; the

places cytochrome *c*, ADP replaces the coupling factor and ADP and the phosphate addition at last come together with a high-energy bond that has survived all the substitutions.

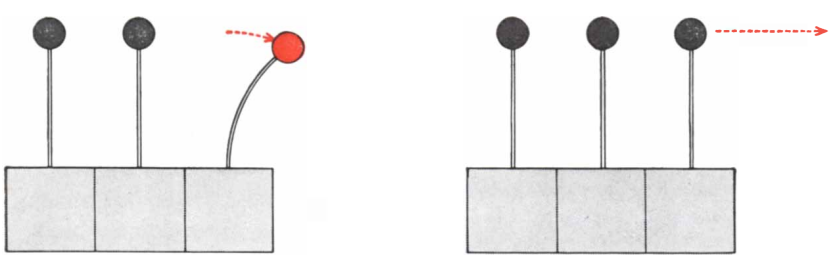
Imagine that the high-energy bond is a coiled spring, stretched by a molecule pulling at each end. Once it has been stretched, the tension can be maintained by other molecules replacing those pulling at the two ends, and the combination may wind up with a pair of partners entirely different from the one that originally did the stretching. This analogy essentially describes the process by which ATP is formed not only at Complex IV but also at the other complexes. Gifford B. Pinchot at Johns Hopkins University and Archie L. Smith and Marc F. Hansen in our laboratory have found that DPNH and Complex I form a compound with a high-energy bond; it can be assumed that coenzyme Q and Complex III likewise form a high-energy intermediate compound as a preface to the production of ATP.

The virtue of this roundabout method is that the series of substitutions serves to separate the enzyme systems taking part in the set of interactions so that they do not get in one another's way. As we shall see, the mitochondrion uses the same tactic (forming a high-energy intermediate compound) in generating energy for processes other than the synthesis of ATP, notably for moving substances through its membranes.

Before we leave the electron-transfer particle, let us note briefly the progress that has been made toward identifying it and locating its position in the mitochondrion. The particle, as first discovered by Fernández-Morán, seemed to be a minute spherical body about 100 angstroms in diameter, present in large numbers in the mitochondrion's inner membrane. A curious contradiction soon emerged. On any reasonable assumptions about its contents, a particle of that size would have a molecular weight of no more than 400,000. Two kinds of evidence later showed, however, that the electron-transfer system must be a great deal larger than that. In the first place, according to calculations based on the known components of the system their total molecular weight must be in the neighborhood of 1.3 million. This figure received strong experimental support when in our laboratory we isolated a particle that carried the electron-transfer activity and proved to have a molecular weight of about 1.4 million. It seemed that this unit could not be the same as the 100-angstrom particle seen with the electron microscope on the mitochondrion's inner membrane. How could a particle with a molecular-weight capacity of no more than 400,000 accommodate a system with a weight of about 1.4 million?

The situation was rescued from total mystery when electron micrographs of mitochondria were made at very high resolution, first by Fernández-Morán, and later by others, particularly David S. Smith, now at the University of Virginia. These showed that the particles in the inner membrane were actually made up of three parts: a spherical headpiece (the tiny sphere that had been seen earlier), a cylindrical base piece and a cylindrical stalk connecting the base and head. Together the three parts could total about 1.3 million in molecular weight.

The electron-transferring unit that our group had isolated did not have this shape; it was a sphere about 150 angstroms in diameter. It would not be surprising, however, to find that these spheres had lost their natural shape on being isolated; left alone, biological material, particularly lipid, has a tendency to round itself into a ball. Then Takuzo Oda of the University of Okayama, examining electron micrographs of mitochondria in the cells of human heart-muscle tissue, made the exciting discovery that there the particles are spherical and about 150 angstroms in diameter. Our micrographs had been of mitochondria in beef-heart cells. Apparently, then, the electron-transfer particles can take different shapes in different cells: extended in some, compressed into a ball in others. The three-part shape is not inconsistent with the four-complex picture of the electron-transfer chain: Complexes I and II may be in the base piece, Complex III in the stalk and Complex IV in the headpiece.



colored group in each stage is carrying the electron. This system of electron transfer within the complexes was first proposed by Robert M. Bock of the Enzyme Research Institute of the University of Wisconsin and Robert S. Criddle of the University of California at Berkeley.

The Larger Meaning of the Particle

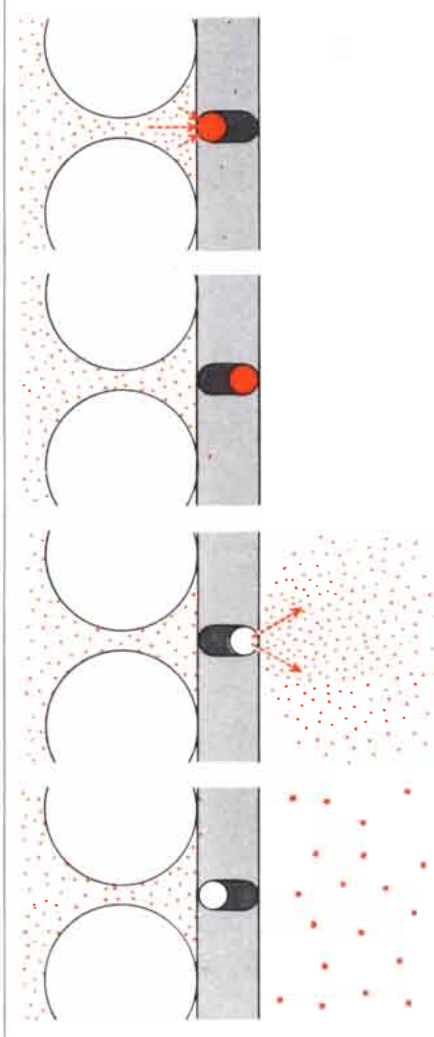
Let us now see what the electron-transfer particle has to offer as a Rosetta stone—that is, what it can tell us about other processes in the dynamics of the cell. Consider, for instance, the movement of substances through cell membranes, an act that calls for the application of propulsive energy. This activity has been extremely difficult to study at the chemical level; now the discoveries concerning the electron-transfer particle make it accessible to both theoretical and experimental investigation.

Among the materials that penetrate the mitochondrion and that play a role in its activities are magnesium, calcium and manganese. They make their entry into the mitochondrion, through its outer membrane, as divalent ions (Mg^{++}, Ca^{++} and Mn^{++}). In each case the entry is effected with a phosphate ion as an escort; in other words, the movement is by sets—a phosphate ion with a pair of magnesium ions or calcium ions or manganese ions. It turns out that this movement through the membrane is energized by a high-energy intermediate compound, of the same kind as the intermediates that lead to the synthesis of ATP. One molecule of the compound energizes the passage of one set of ions into the mitochondrion. Once the ions are there the high concentration they attain leads to their precipitation as metal phosphate, and as a result two hydrogen ions are released for each molecule deposited. Gerald P. Brierley of our laboratory, Albert L. Lehninger of Johns Hopkins University and J. Brian Chappell and Guy D. Greville of the University of Cambridge have independently documented this transport of ions through the membrane.

The synthesis of ATP and the movement of ions both require the same high-energy intermediate. What determines which of the two activities will have priority? Under ordinary conditions synthesis wins by overwhelming odds. For all practical purposes the movement of ions stops cold when synthesis of ATP is going on. Hector F. De Luca and Howard Rasmussen of the University

of Wisconsin have made the exciting discovery that one of the hormones of the parathyroid gland can switch off synthesis and turn on the movement of ions. We have here an instance of regulation by a hormone at the level of the mitochondrial membrane.

How, exactly, is the set of ions propelled through the membrane? The most attractive hypothesis put forward so far likens the propelling agent to a gun placed in the outer membrane. We may give this agent, presumably an enzyme, the name "translocase." To begin with, the translocase must be loaded with the right kind of projectile; only certain pairs of ions will fit this gun. When it is properly loaded, the translocase is fired by means of a detonating charge supplied by the high-energy compound. This firing causes the translocase to twist around, face the interior of the mitochondrion and propel its ion-pair shell through the membrane.



TRANSLOCASE "GUN" transports metallic ions and phosphates across the outer membrane of the mitochondrion from the external medium to the intrastructure space. The translocase molecule (*oblong shape inside membrane*) is loaded with pairs of ions (*top*) and is detonated, causing it to twist around and face the interior of the mitochondrion. It then fires the ion pair and returns to its original position (*bottom*). The ions combine with the phosphate groups in the intrastructure space to form crystals.

The features of the system have been investigated in a number of laboratories. These facts emerge. It has been shown that the high-energy compound that provides the charge can be generated either by the chain of electron transfers leading toward the synthesis of ATP or from ATP itself by reversal of the process. It has been shown further that the ion-moving agent (the assumed translocase) is in the outer membrane, because when the mitochondrion is broken into fragments by ultrasonic radiation, which destroys the outer membrane, the fragments are no longer able to move the ions, although they can still synthesize ATP.

What is translocase? Evidently it is a contractile substance, probably designed specifically for the propulsion of ions rather than for developing tension or the muscular type of contraction. Several laboratories have succeeded in extracting from mitochondria a contractile protein that on exposure to ATP undergoes changes in the shape and size of the molecule, which can catalyze the breakdown of ATP to ADP and which is greatly aided in this breakdown by calcium—the ion that is most easily propelled through the mitochondrial membrane. It remains to be determined if this protein is actually translocase.

On all sides evidence is piling up that the mitochondrion represents a general blueprint that is characteristic of all membrane systems—in fact, of all the energy-transforming systems of the cell. Membrane systems generally show the same features as those exemplified by the mitochondrion: two membranes separated by a space, a membrane structure composed of structural protein and phospholipid in a network arrangement, the presence of elementary functional particles in the membrane layers, the presence of a contractile protein system in the outer membrane and the possession of a system that can move ions. The basic elements—a double membrane with active, specialized giant molecules attached to the membranes—seem to be universal in all living systems.

Now that the energy-generating system of living things can be described in molecular terms, we can expect an accelerating tempo and revolutionary developments in all the fields of investigation bearing on this central problem of biology.

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A mile and a half of meridians, parallels, and orbit rings frame this stainless steel planet and support its continents. All told, more than 500 major structural pieces were assembled to mount a 120-foot diameter armillary sphere on a 20-foot base, at a total weight of 900,000 pounds.

All this stands as an open sculpture with virtually every part exposed: exposed to view, and exposed to rain, ice, salt-laden dampness, and the stiff gales that sweep across Long Island.

For permanent, weatherproof beauty, the designers chose USS 18-8S stainless steel (AISI 304). The three-point base that supports the sphere is USS COR-TEN Steel, a low-alloy high-strength steel that has unusual corrosion resistance. Each corner of the base is anchored to the foundation with ten 2¾-inch diameter bolts of USS "T-1" Steel, the remarkable constructional alloy steel with a minimum yield strength of 100,000 pounds per square inch that can create up to 50 per cent savings in weight.

Structural support presented unusual problems. The spherical shape would impose enormous loads on curving structural members. Yet these members could not be thick and could not be cross-braced without detracting from Unisphere's beauty. To fulfill the design concept, slim meridians and parallels had to be spaced according to map-making custom rather than engineering expediency and had to carry irregularly shaped, irregularly spaced land masses. Even the pedestal that would support the entire sphere had to be gracefully slender.

But the most formidable problem was wind load. In shaping convex land masses to fit the curvature of the earth, U.S.Steel knew that concave inner surfaces would trap wind like the spinnaker of a sailboat. Wind tunnel tests of a scale model confirmed the enormity of this problem: at wind velocity of 110 miles per hour, there would be a total drag of 396,000 pounds.

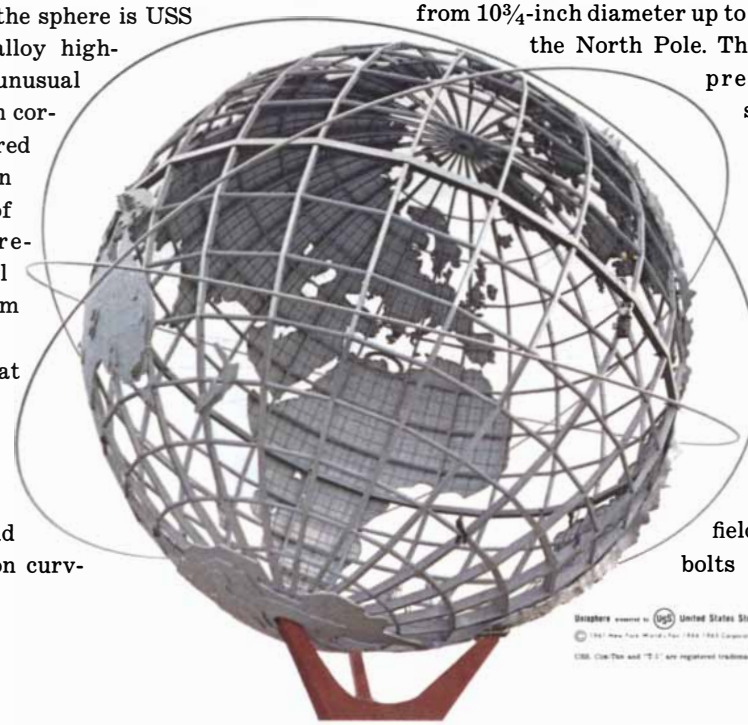
All of these wind and weight factors had to be translated into a stress distribution pattern that would indicate what structural strength each section would require: a computation so complex that 670 simultaneous equations had to be solved for just one of three sets of calculations. U.S.Steel called on advanced computing equipment to supply the answers in a matter of weeks; without high-speed computers, it would have taken years.

In its final design, Unisphere has ample strength and stability to stand up in a hurricane.

North-South meridians are hollow rectangular sections, 6 inches wide and 12 inches deep above the Equator, and 10 inches wide by 14 inches deep below the Equator. Parallels are round tubes from 10¾-inch diameter up to the Equator, to 6-inch near the North Pole. The Equator is an H-section prestressed by 15/16-inch stainless steel guys connected to a floating tension ring at the center of the Unisphere.

In the area surrounding the main supports, both meridians and parallels are heavy box sections which taper to meet the normal size members.

In the Northern Hemisphere, connections of parallels to meridians are field bolted with stainless steel bolts through shop-welded cap



plates. All connections for the Southern Hemisphere are field welded. Three stylized orbit rings that circle Unisphere are anchored by thin stainless steel aircraft cable, barely visible from the ground.

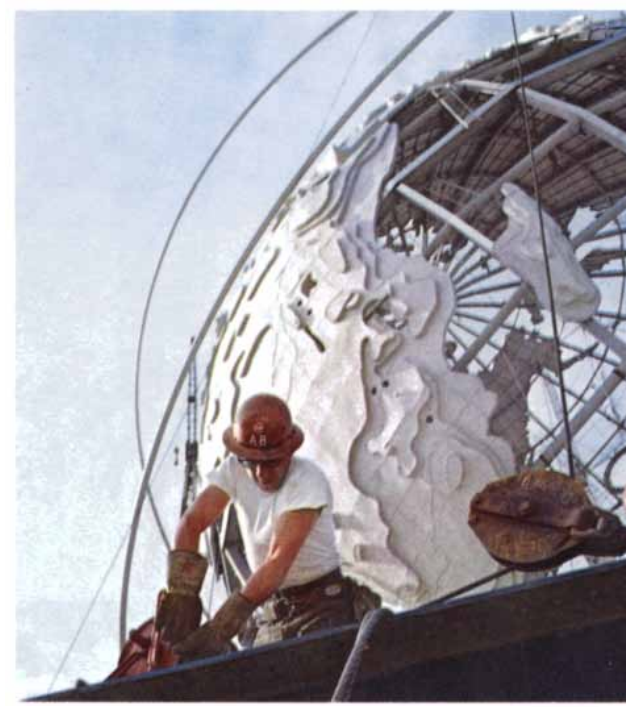
These structural sections were fabricated by U.S.Steel at Ambridge, Pa. Meridian pieces were butt-welded together in the shop, and each meridian quadrant—the quarter circle from equator to pole—was shipped in two sections. Already installed inside these members were tubular and plate diaphragms positioned for the 360 intersections of meridian and parallel.

Land masses were fabricated by U.S.Steel at Harrisburg, Pa., after careful studies to find what surface texture would look best at viewing distances of 90 feet and more. Continents and major islands are made of textured stainless steel sheets, mounted on a framework of channels and angles. Land elevations are built up in layer cake fashion, like a huge contour map. Since every coastline and contour line is irregular and every land mass must fit the earth's curvature, fabrication became a highly complex task in which no section was square in any plane.

From beginning to end, Unisphere demanded entirely new techniques to solve entirely new problems, even after the unprecedented design and engineering questions had been settled. A few examples:

Standard bending equipment wouldn't curve the orbital rings without crimping or defacing them, so U.S.Steel engineers designed a die that would do the job. Meridian sections had to be welded together *after* they were polished, so the engineers worked out a method to remove discoloration caused by welding. Working with polished sections during fabrication also required a whole new system of materials handling, using vacuum lifting equipment, protective tapes, and nylon slings.

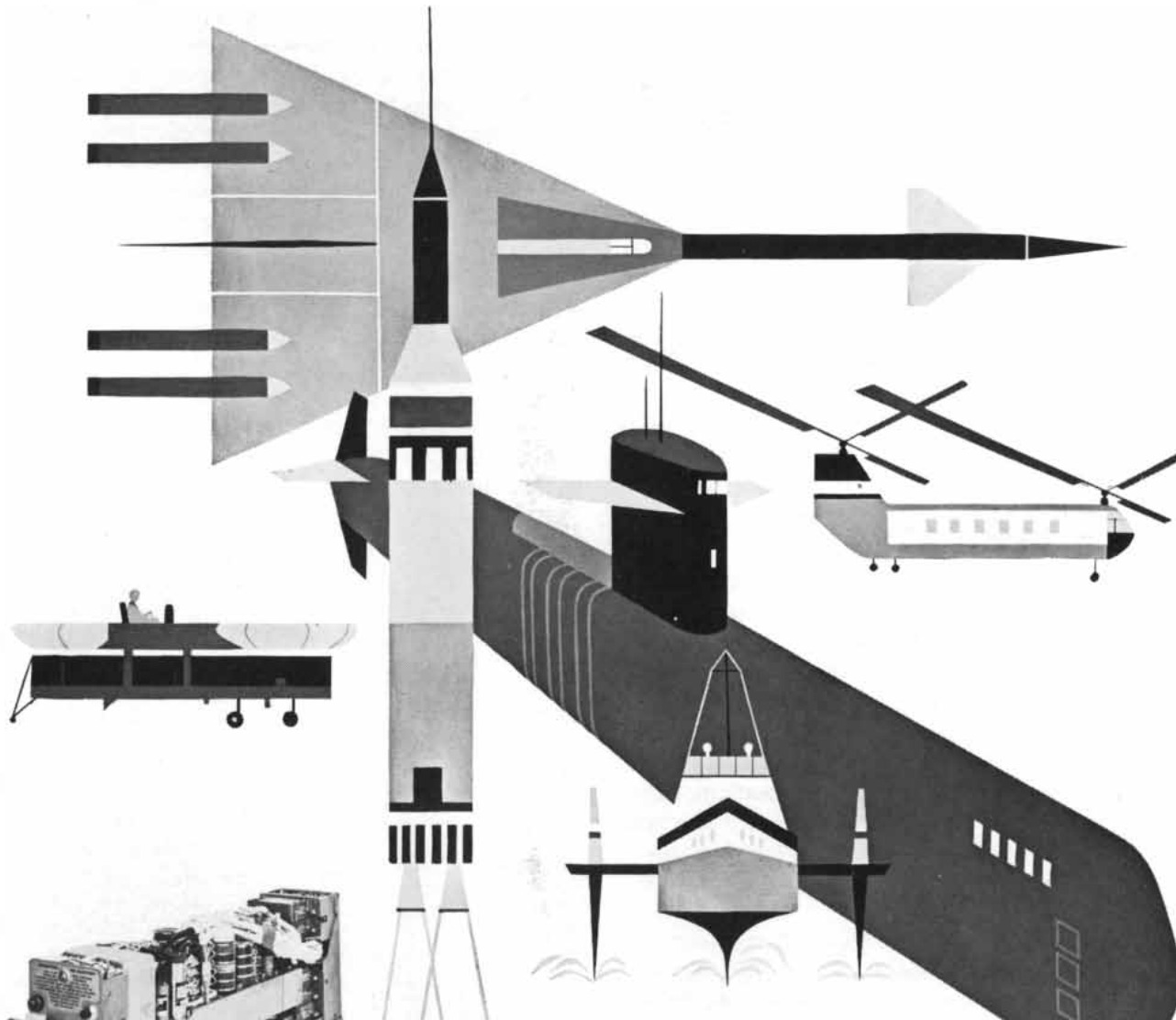
After tests of various surface materials including stainless steel mesh, land masses were made of a new nondirectional patterned stainless steel sheet designed especially for Unisphere. In construction, meridians and parallels were connected by what is probably the first application of inert gas shielded short-circuited arc welding to heavy stainless steel structural members in the field. And U.S.Steel construction engineers had to invent some new hoisting techniques: to raise large curved sections of the continents into place, they made a lift from a thirty-foot piling section, angles, clamps, and a rolling hitch; to position the huge orbital rings aloft, they welded each ring completely together, surrounding the sphere on the ground, then used four cranes to lift it in one piece and hold it until anchor cables were placed.

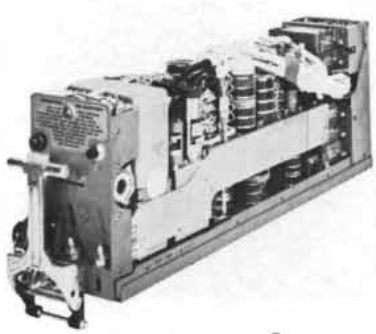


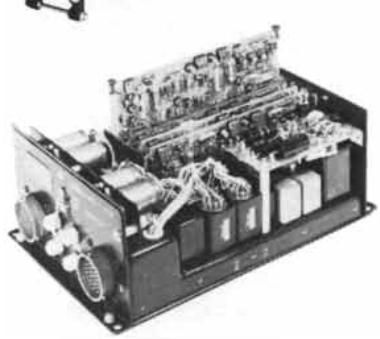
At no point could U.S.Steel engineers go to the book for their answers. There wasn't any book. But when the time came to put the pieces together, they fit. They fit each other, they fit the theme of the New York World's Fair, and they fit the modern notion that no structural design problem is too tough to solve, given the right technical know-how, the right facilities, and the right steels.

"To quote Mr. Robert Moses, president, 1964-1965 New York World's Fair: What stronger, more durable, and more appropriate metal could be thought of than stainless steel? And what builder more imaginative and competent than United States Steel?"

United States Steel USS







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TRACHOMA

This blinding eye disease afflicts nearly 500 million people in poorer parts of the world. Its virus-like agent was found only six years ago; today a practical vaccine is being sought

by Georges H. Werner, Bachisio Latte and Andrea Contini

Nearly 500 million people—more than a sixth of the world's population—are infected with the blinding eye disease known since ancient Greek times as trachoma. Trachoma is endemic in many parts of Asia, Africa, Europe, South America and among Indians in the U.S. Afflicting mainly the peoples of underdeveloped areas, the infection could probably be eliminated by the improvement of their hygiene, housing and nutrition. But the disease is a cause as well as a consequence of their poverty; it is part of the vicious circle that makes the development of the underdeveloped countries so difficult. A successful medical attack on trachoma would not only remove a vast burden of human suffering but also help to put the struggling nations on the road to a decent level of living.

It is only within the past six years that investigators have positively identified the cause of trachoma. The agent of the disease is a virus, or near virus, markedly similar to those responsible for psittacosis ("parrot fever") and the venereal disease lymphogranuloma venereum. This knowledge offers the exciting prospect that it may be possible to control the disease by vaccination and thus bring to an end its long career as a major scourge of mankind.

Trachoma was given its name by the first-century Greek physician Dioscorides in his famous *De Materia Medica*. The name comes from the Greek word *trachys*, meaning "rough," and this describes the most striking symptom of the disease: a roughening of the conjunctiva, the delicate lining of the eyelids. The disease starts with a mild inflammation of the conjunctiva of the upper eyelid. It proceeds to form many small follicles; these granulations may go on growing until the conjunctiva is as rough and pitted as the skin of an orange. Eventually the damage may extend to the eye's cornea and produce partial or total blindness.

In countries where the infection is prevalent it commonly attacks children at an early age. Trachoma is highly contagious, and it can be transmitted from person to person by flies, in water or, most often, by direct contact between the members of a family. Some ethnic groups seem to be more susceptible than others; Arabs, for example, have a higher incidence of the disease than Negroes in the same area. Climate also seems to be a factor: trachoma is most common in warm climates, near seacoasts and in windy desert areas, where irritation of the conjunctiva by sand particles in the air may sensitize it to infection. None of these conditions, however, plays a decisive role. The one common denominator that characterizes all the populations in which the disease is widespread is a low standard of living, with the accompaniments of undernourishment and insanitary conditions, such as ritual ablutions by many people with the same water and use of the same towel by all the members of the family.

Trachoma, easily identified by its symptoms, was described by the Sumerians in the fifth millennium B.C. and is reported in records of ancient China as early as the third millennium B.C. It was probably the most common eye disease in ancient Greece and in the Roman Empire. Armies and traders spread it from population to population. During the Middle Ages, Arab invaders and crusaders returning from the Middle East kindled epidemics of trachoma in Europe. Similarly, during the first half of the 19th century a new European outbreak of the disease was generated by Napoleon's soldiers on their return from his campaign in Egypt. Trachoma flared up again in some areas of eastern Europe during World War I and II.

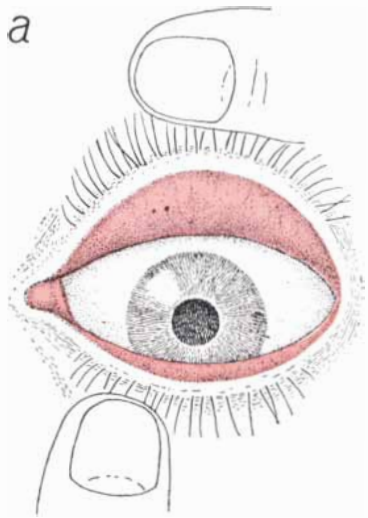
Egypt is still a virulent focus of the disease. The virus has infected most of the inhabitants of that country: practically all the children in the villages get it before they are a year old and 90 per cent of the children in the city slums are infected before the age of two. Egypt, however, is only one of many countries with a high incidence of trachoma [*see bottom illustration on next two pages*]. It is prevalent throughout North Africa; in Tunisia, for example, 40 per cent of the population have trachoma and 10 per cent of the desert people living in oases are totally or almost totally blind, mainly because of this disease. Trachoma is also common in the rest of Africa, particularly in the Bantu tribes of South Africa, which have the highest proportion of blind people in the world.

In China (according to available statistics, which describe conditions prevailing about 20 years ago) trachoma attacks nearly 50 per cent of the population: at least 100 million Chinese have had it in a severe form and 20 million are practically blind. In Vietnam the disease infects 30 per cent of the population and blinds nearly 10 per cent; in the Rajasthan province of India 50 per cent of the children are infected before they enter school; in some areas of Iran the entire population is affected. In Europe trachoma is still a problem in Portugal, southeastern Spain, Sardinia, Sicily, Yugoslavia and southern Greece. In the Western Hemisphere the disease has a high incidence in parts of Brazil, Argentina and northwestern Mexico, where 30 to 60 per cent of the school-age children are infected. In the U.S. the disease has all but disappeared from the "trachoma belt" that used to extend from West Virginia to Oklahoma, but the incidence is still high on some Indian reservations.

The classic symptoms of trachoma have been known for many centuries to physicians throughout the world. In a child who contracts the disease the first signs are a mild conjunctivitis, watering eyes, a feeling of heaviness of the upper eyelids, a slight aversion to light and frequent blinking. By turning out the inner side of the upper eyelids one can see small, whitish follicles in the lining and a network of capillary blood vessels forming around them. Sometimes the disease progresses no further and the conjunctivas heal spontaneously. In most cases, however, the infection, if untreated, steadily produces more and more damage, sometimes continuing throughout the sufferer's lifetime. The conjunctiva becomes rougher and rougher, with larger and more numerous follicles and nodules. The growing network of blood vessels invades the cornea and begins to form an opaque covering (called the pannus) over the eyeball. Scar tissue develops in the conjunctiva and cornea, further clouding the patient's vision. The eyelids become deformed and turn inward, eyelashes and all, so that they irritate the eyeball. Patients often suffer excruciating pain, and the disease ends in varying degrees of impairment of vision up to total blindness. Another unhappy aspect of trachoma is that recovery from an infection does not confer immunity: the virus may repeatedly attack the same individual with increasingly serious effects.

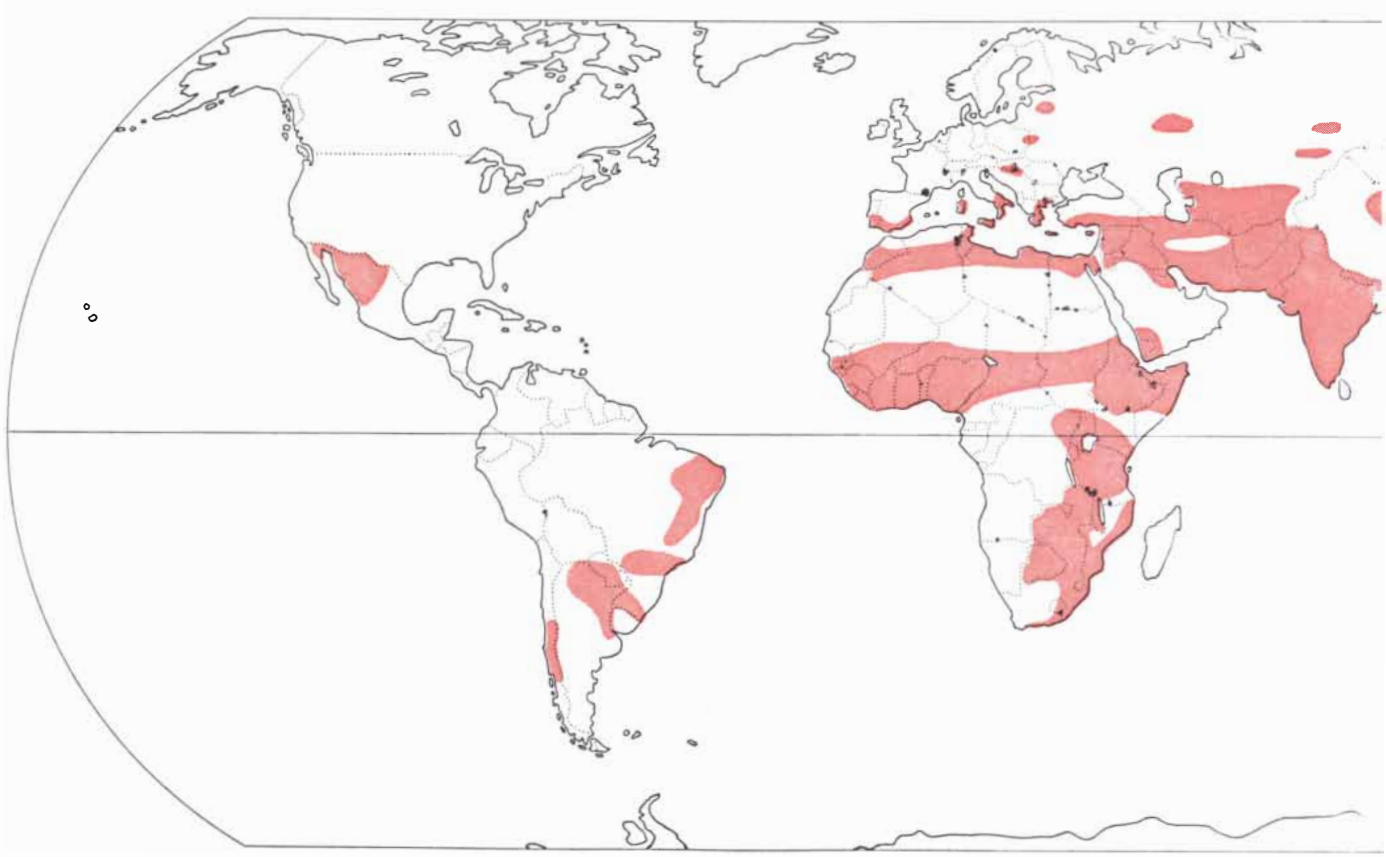
The first clue to the nature of the causative agent of trachoma was discovered in 1907 by two Austrian physicians named S. von Prowazek and L. Halberstaedter, who studied the disease in Java. They gently scraped some cells from the conjunctivas of trachoma patients and then stained the cells and examined them under the microscope. In the cytoplasm of the cells they found inclusions containing many tiny particles ("elementary bodies"), which they judged to be the organisms responsible for the disease. Their conclusion apparently was confirmed when they inoculated some of the scrapings from the patients into the conjunctivas of apes as an experiment: after a few days the apes' conjunctival cells showed the same elementary bodies. The infectious particles evidently had reproduced themselves in the new host.

The French bacteriologist Charles Nicolle followed up this finding. At the Pasteur Institute of Tunis, of which he was director, Nicolle and his associates set out in 1912 to try to identify further

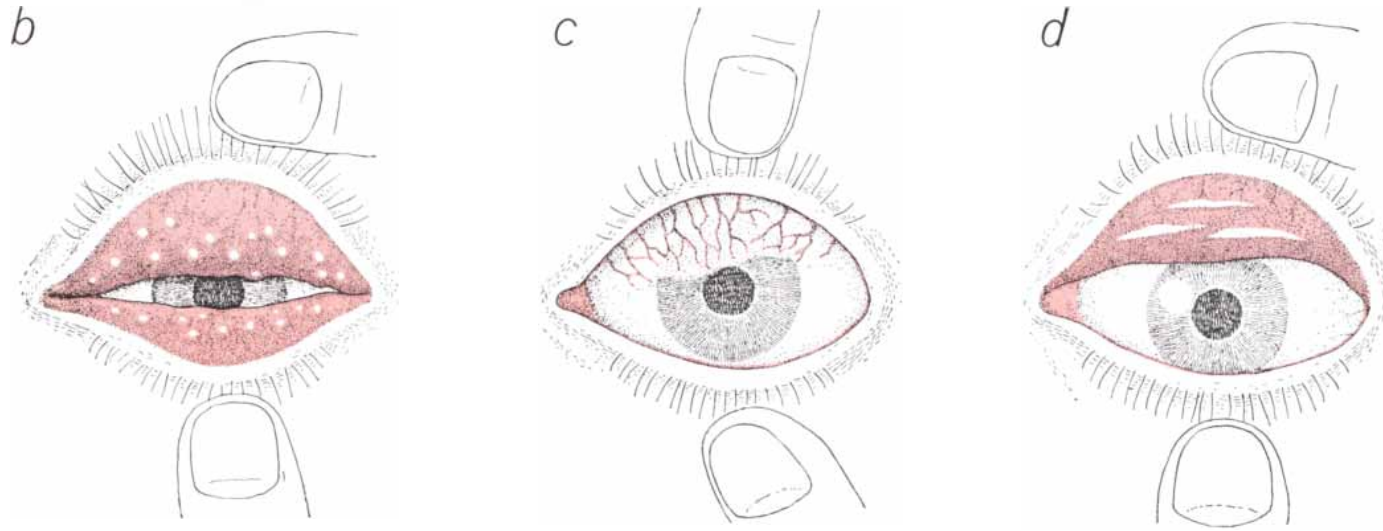


CHANGES IN EYE that accompany trachoma are illustrated. In *a*, *b* and *d* the eye-

the trachoma organism. Suspecting that it was a virus, they applied what was at that time the standard test to determine the question. They ground up the conjunctival scrapings from a trachoma patient, suspended the ground material in liquid and passed it through a porcelain filter. The pore size of the filter was small enough to stop bacteria and let



WORLD DISTRIBUTION of trachoma is indicated by color in areas where at least 10 per cent of school-age children are affected by the disease. Altogether nearly 500 million people of all ages throughout the world have trachoma. Many are blind from it. No



lids are turned back; in *c* the eye is merely held open. The eye in *a* is normal. In *b* typical trachoma follicles are shown. Pannus, a network of blood vessels, has begun to cover the eyeball in *c*. The white transversal scars of cicatricial trachoma are shown in *d*.

through only smaller particles such as viruses. Nicolle then inoculated the filtrate in the conjunctivas of a chimpanzee and a macaque monkey. It produced a mild conjunctivitis in both. When scrapings from the eyelid linings of these animals were inoculated on the conjunctivas of human volunteers, the human subjects soon showed the typical early symptoms of trachoma. The Prowazek-Halberstaedter particles turned up in profusion in the volunteers' conjunctival cells.

color shows in the area of the U.S. but the disease occurs on a few Indian reservations.

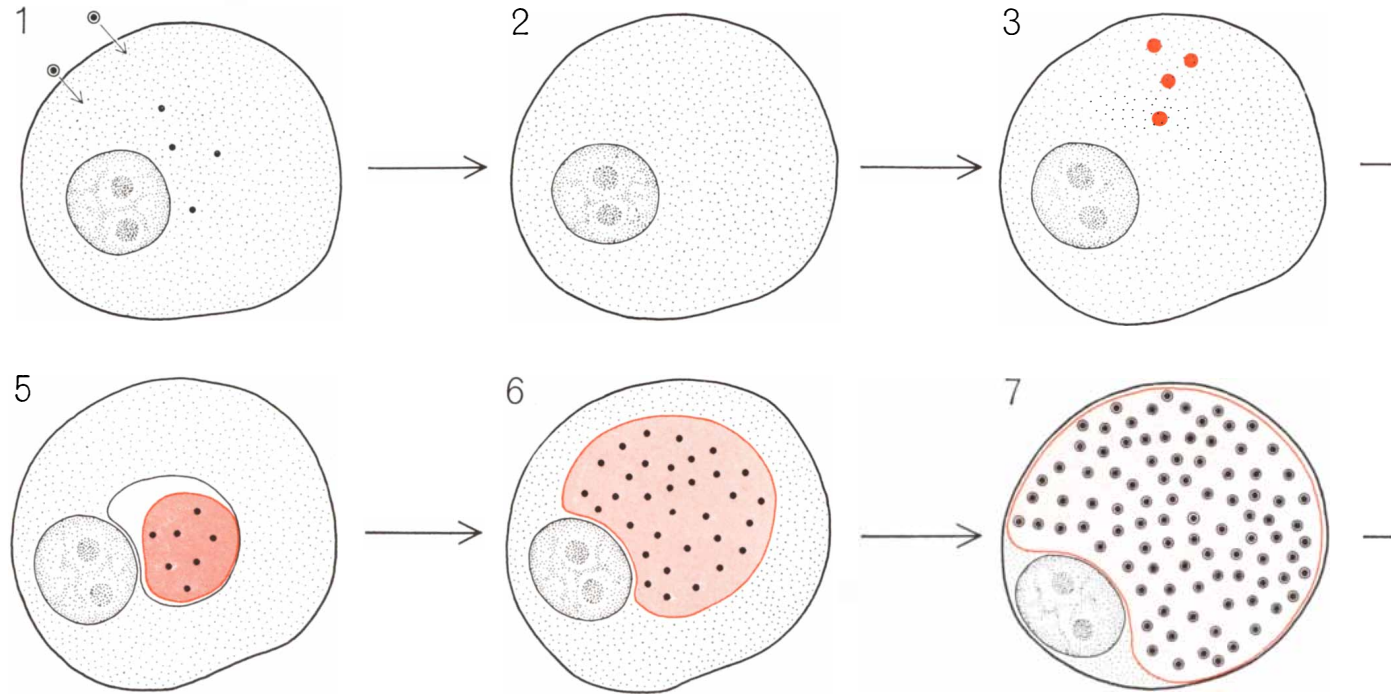
The passage of the infection by means of the filtrate from man to animal to man gave strong evidence that the agent of trachoma was a virus. Other experimenters later confirmed Nicolle's results. This, however, was still a long way from identification of the virus. As in the case of other viruses attacking only primate animals (for example the virus of poliomyelitis), little progress could be made in investigating the agent of trachoma until it could be grown in cell cultures in the test tube or in relatively simple systems such as the developing chick embryo.

In the 1930's and 1940's virologists, notably Sir Samuel Bedson of the London Hospital and Karl F. Meyer of the San Francisco Medical Center of the University of California, learned that the agents of psittacosis and lymphogranuloma venereum multiplied in cells in much the same way as the agent of trachoma, producing similar bodies in the cytoplasm. They also found ways to cultivate those viruses in the yolk sac of fertilized chicken eggs. For many years, however, all attempts to grow the trachoma agent in the same way failed. Then in 1957 four virologists at the National Vaccine and Serum Institute in Peking finally succeeded. These workers, whose accomplishment can be ranked in importance with that of John F. Enders and his colleagues in achieving the test-tube cultivation of the polio virus, were F F T'ang, H L. Chang, Y. T. Huang and K. C. Wang

The key to the success of the Chinese workers was their precaution in eliminating bacteria and other organisms in the culture that would mask or prevent the propagation of the trachoma agent itself. Various bacteria are commonly present in the human conjunctiva. T'ang and his co-workers, after taking conjunctival scrapings from trachoma patients, treated the material with streptomycin to inactivate the bacteria. They then inoculated the scrapings into the yolk sac of chick embryos that had been incubated for six to eight days. From a total of 93 such cultures they managed to produce three that gave positive evidence of propagation of the trachoma agent in the cells of the yolk. The typical Prowazek-Halberstaedter bodies, characteristic of the trachoma infection, showed up clearly in the cytoplasm of these cells [*see illustrations on next two pages*]. Furthermore, this material, after a series of passages in chick embryos, produced conjunctivitis in rhesus monkeys.

The following year two British bacteriologists, H. L. Collier and J. Sowa of the Lister Institute of Preventive Medicine in London, confirmed and extended the Chinese workers' discovery Using the same technique, they cultivated the virus present in scrapings from trachoma patients in the West African country of Gambia. The material they cultured, when tested in a blind human volunteer, produced the characteristic clinical and microscopic signs of trachoma.

Since 1958 many workers have isolated the same agent from trachoma patients in Israel, Saudi Arabia, Egypt, Sardinia, California, Taiwan, Tunisia, South Africa, Australia, Portugal, Japan, India, Yugoslavia and other areas where the disease is endemic. Armed with the

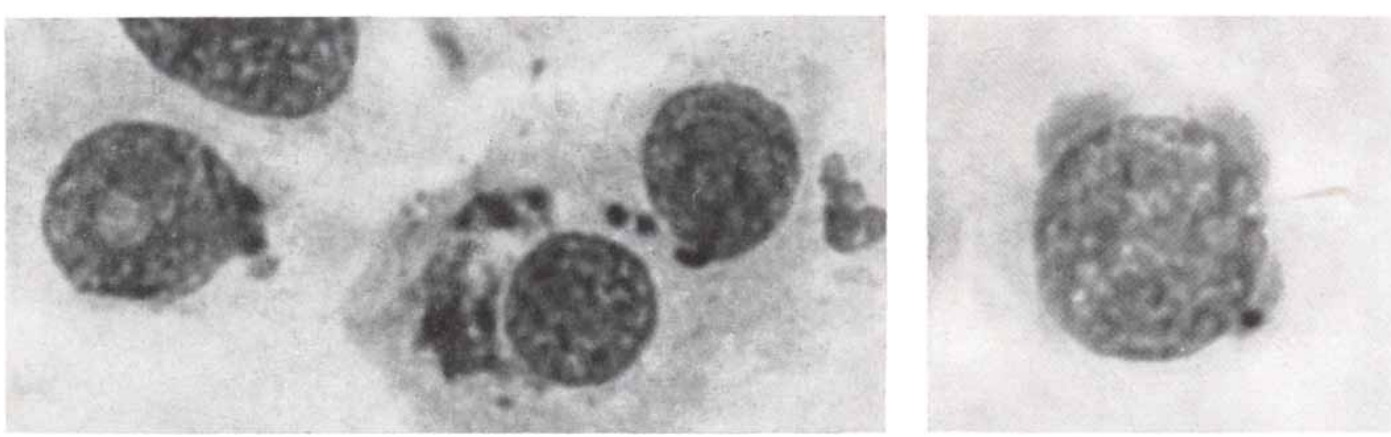


TRACHOMA-AGENT LIFE CYCLE requires living host cell. Cycle begins when agent sheds protein coat as its DNA enters cell (*1*). An "eclipse phase" follows, when no infectious particle can be recovered from the cell (*2*). After about three hours RNA particles begin to appear in the cytoplasm (*3*); they grow until they form a mass (*4*) called an inclusion body, which is found within a vacuole that appears in the cytoplasm. Some 25 hours after infection new DNA particles begin to appear in the inclusion bodies (*5*). Their number increases, the inclusion body grows (*6*) and finally the body fills the whole cell (*7*); it crowds the nucleus against the

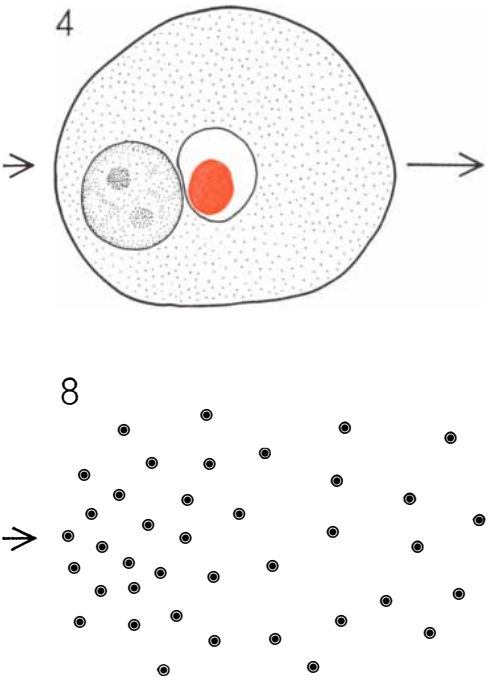
discovery that the organism can be grown not only in the yolk sac of fertile chicken eggs but also in human cells in vitro, a number of laboratories are pursuing an intensive study of the biology of the trachoma agent. In the past three years investigations at the Lister Institute, the Hadassah Medical School in Jerusalem, Tokushima University in Japan and the medical schools of the University of California, the University of Texas, the University of Chicago and Notre Dame University have shed much light on the nature of the organism and the way it multiplies in the living cell.

The trachoma agent has been found to belong to a family of virus-like agents called Bedsonia (after Bedson, who did pioneering work on them). This group includes both the organisms causing psittacosis and lymphogranuloma venereum and those responsible for certain pneumonias and other diseases of animals. The Bedsonia agents meet the definition of a virus because they can multiply only in living cells. They are, however, somewhat larger than any other animal virus and, unlike other viruses but like bacteria, they are sensitive to the effect of sulfonamide drugs and antibiotics.

In its proliferation in the cell the trachoma agent shows all the characteristic behavior of a virus. The organism consists essentially of a core of deoxyribonucleic acid (DNA) enclosed by a coat of protein. In the act of penetrating the cell the agent divests itself of its protein. The naked DNA then initiates a sequence of chemical syntheses in the cell's cytoplasm. Particles of ribonucleic acid (RNA) arise near the cell nucleus. As they grow they form an "inclusion body" that eventually engulfs practically all the cytoplasm and produces a number of new DNA particles. The DNA particles



INCLUSION BODIES in cells from eyelids of trachoma patients are shown in photomicrographs by the authors. At left, they are the black spots near nuclei of cells. Next, three larger crescent-shaped bodies are growing around a nucleus. The third photomicro-



cell wall. The DNA particles acquire protein coats at this stage, and then, 70 hours after infection, they burst out of cell (*8*) and go on to infect adjacent cells in a similar manner. The process is typical of virus infections.

then clothe themselves in protein coats and, some 70 hours after the invasion of the original single particle, burst out of the cell as viruses ready to infect adjacent cells. Presumably the original DNA acted as a template for the synthesis first of RNA and then of the full-fledged DNA-plus-protein virus.

Although the agent produces trachoma only in man, experiments have shown that it can develop toxic or pathological effects of one kind or another in various animals. For instance, Samuel D. Bell, Jr., and his associates at the Harvard Medical School have shown that some strains of the trachoma agent will kill mice within 24 hours after being injected into the bloodstream and within a few days after being injected into the brain. In our laboratory at the Rhône-Poulenc Research Center we have noted that injection of a very small dose of the agent into the brain causes the mice to lose weight rapidly. In white rabbits the inoculation of some strains of the agent into the skin causes inflammatory nodules to form there.

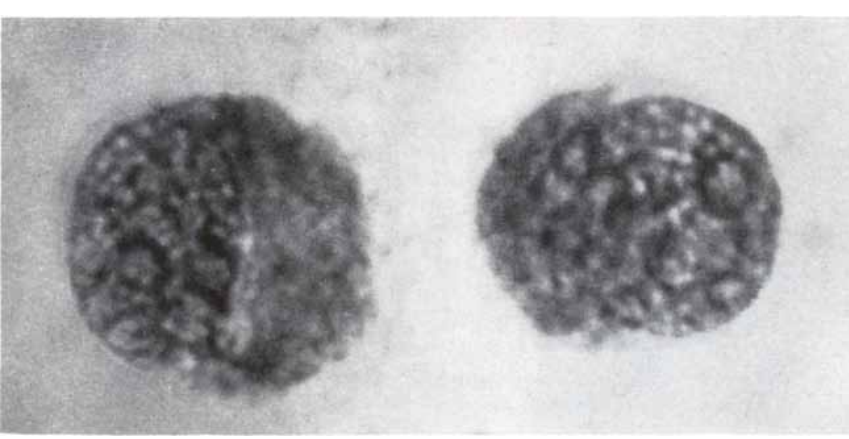
Before 1938 the only treatment of any value for trachoma was the application of a solution of copper sulfate as a wash for the conjunctiva. Since then clinical investigators, following the pioneering work of G. B. Bietti of the University of Rome, have discovered, and laboratory studies of the agent have confirmed, that the organism is vulnerable to sulfonamide drugs, to tetracycline antibiotics (aureomycin, terramycin and others) and to some other antibiotics (erythromycin and spiramycin). The sulfa drugs, taken orally, inhibit the multiplication of the agent, and the antibiotics rapidly kill it when applied locally to the eye in the form of drops or ointment. The combined sulfonamide-antibiotic treatment is highly successful in curing the disease if it is caught early, particularly in children.

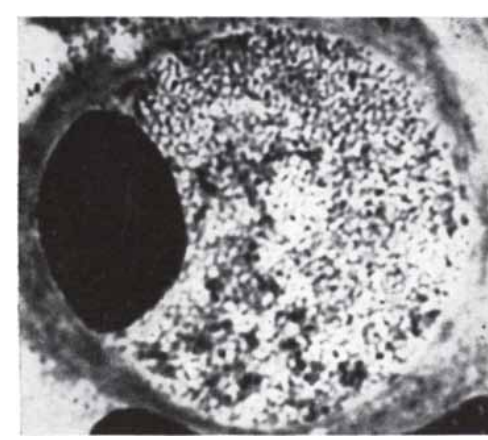
In Sardinia and other areas with sufficient medical resources trachoma has been all but halted by systematic treatment of all infected school children with the drugs. The World Health Organization has undertaken to assist 15 countries in programs of chemotherapeutic control of the disease. The treatment of a patient takes several weeks, however, and a community-wide campaign is costly—too costly for underdeveloped areas and too difficult for nomadic populations. Moreover, it is doubtful that even a massive effort, assuming that funds are available, could cope effectively with the disease in countries where the standard of living remains low. In such an environment a child is cured only to be reinfected by his continuing contact with the contaminated population.

Thus chemotherapy, effective as it is, offers little hope at present for any marked reduction of trachoma on a world-wide basis. Immunization, on the other hand, would surmount the problem of exposure to the agent and could be applied on a large scale without great cost. Much of the present research therefore is directed toward the goal of finding an effective vaccine against trachoma.

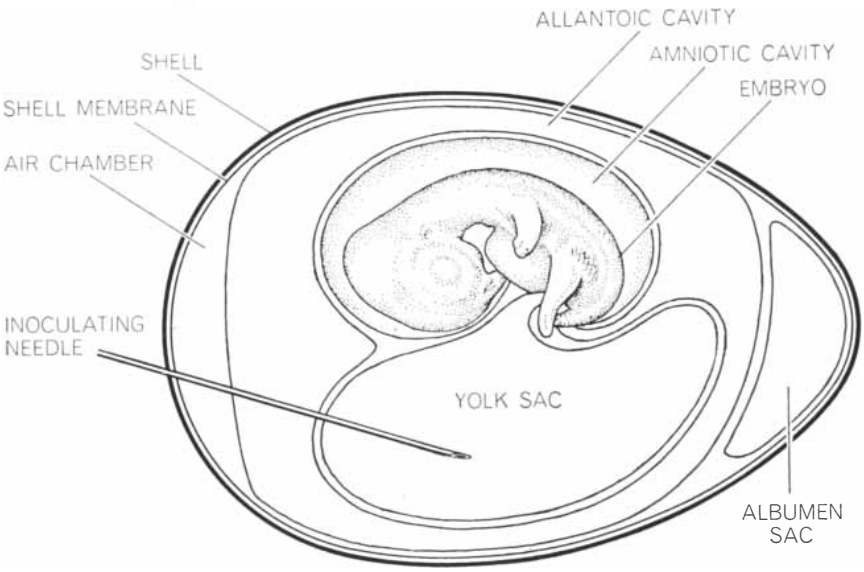
This might seem a vain hope in view of the fact that the infection normally gives a patient no immunity against repeated reinfection. The common human experience in this respect has been borne out by experiments with other primates: monkeys can be infected with the trachoma agent again and again, and each time their conjunctivitis is no less severe than the time before.

Yet such a situation need not discourage searchers for a vaccine; indeed, it adds interest to the challenge. In the case of trachoma the normal lack of immunity is open to at least two possible explanations that offer loopholes for attacking the problem. First, the trachoma agent may fail to evoke the manufacture of defensive antibodies by the host because it is a local infection confined to the tissues of the eye. In that case it might be possible to stimulate the formation of antibodies by injecting the trachoma antigen intramuscularly or subcutaneously. Second, there may be several varieties of the trachoma organism, each unaffected by the antibodies against the others, so that each in effect is a new infection. Indeed, it has been established that the agent has several strains and that there are at least two

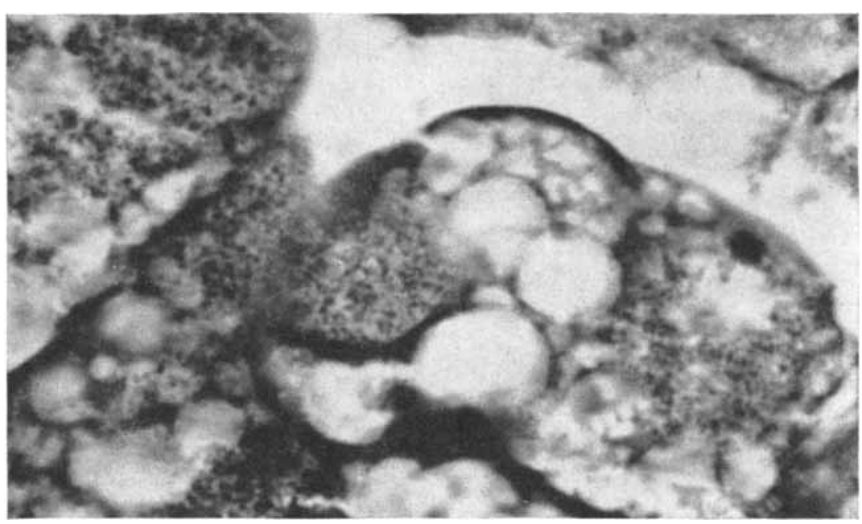




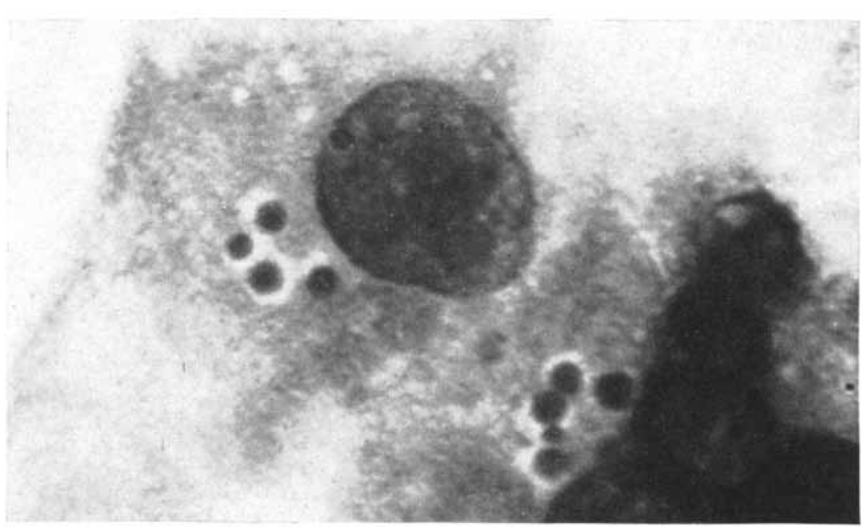
graph shows large bodies surrounding nuclei like skullcaps. At right a mature inclusion body, packed with new trachoma agents, fills a cell. Staining has made nucleus appear black. Magnification in all four photographs is approximately 2,000 diameters.



CHICK EMBRYO is widely used as culture medium for viral agents. The trachoma agent grows well in the cells of the yolk sac. In this diagram the sac is shown being inoculated.



INFECTED CELLS (granular areas) of chick embryo are seen in this section of yolk sac. Trachoma agents produce the grainy appearance. Magnification is about 1,700 diameters.



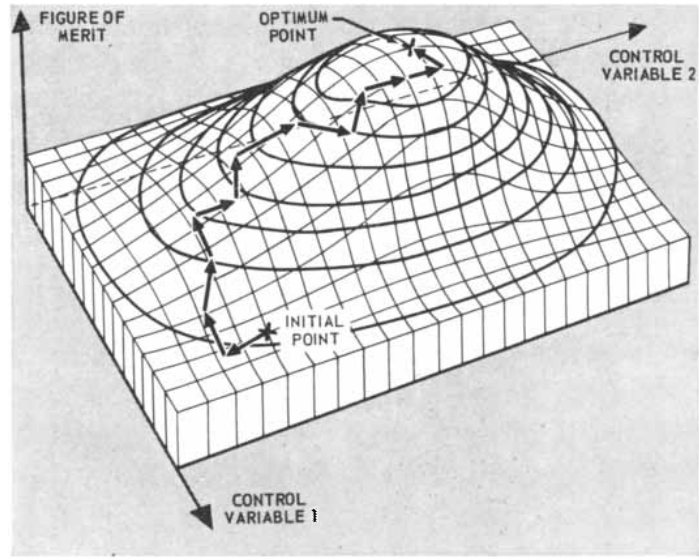
TRACHOMA INFECTION of cultures of human cancer cells has also been achieved in the laboratory. The large ovoid is a cell nucleus; the small round spots, inclusion bodies.

distinctly different types from the standpoint of antigenic structure.

By various stratagems investigators have in fact succeeded in experimentally immunizing animals against the trachoma agent. Bell's group at Harvard inactivated the organism with formalin, injected this vaccine intravenously in mice and found that it protected the mice against later injections of lethal doses of the live agent. We have made mice similarly immune to lethal or toxic doses in the brain by vaccinating them first with small intracerebral injections of the live agent; we were able to protect the mice, although less effectively, even with injections of the formalin-inactivated agent in the abdominal cavity. Chandler R. Dawson and his associates at the San Francisco Medical Center of the University of California have successfully vaccinated monkeys with the live organism injected into muscle. And Collier at the Lister Institute has been able to weaken some strains of the trachoma agent (by a series of passages in chick-embryo cultures) so that they produce no sign of disease when inoculated in the conjunctiva of a baboon.

Some vaccination attempts against trachoma have already been made in human patients with encouraging results. John C. Snyder and his co-workers at the Harvard School of Public Health made a small test with two volunteers. They gave one a subcutaneous injection of the formalin-inactivated organism, and six months later they inoculated the conjunctivas of both subjects with the live agent. The trachoma symptoms of the vaccinated individual were definitely less severe than those of the unvaccinated one. In a similar trial in Ethiopia A. Felici and R. Vozza of the Istituto Superiore di Sanità in Rome also found that vaccinated volunteers were more resistant to the agent than unvaccinated controls. J. Thomas Grayston and his co-workers in a medical research unit of the U.S. Navy in Taiwan applied a post-infection vaccination to six volunteers. All six were experimentally infected in one eye with the live agent; two months later three of the six were given an intramuscular injection of the formalin-inactivated organism, whereas the other three received only a placebo injection. In the latter group the trachoma progressed and eventually involved both eyes; in the vaccinated group it remained limited to the one eye originally infected.

Along with trachoma, a somewhat similar infection known as "swimming-pool conjunctivitis" has been clarified in



Typical representation of figure of merit for a system with two adjustable variables. The path shows how the figure of merit is maximized as the two variables are adjusted by an automatic controller.

Control Techniques for Optimizing Multi-variable Systems

A large number of important systems or processes involve goal-seeking in the presence of constraints. A system may be defined as goal-seeking if, in the process of performing a given task, it has the additional objective of maximizing or minimizing some figure of merit, such as cost, yield, or error.

The controller for such a system must be capable of automatically adjusting the value of each input parameter according to some strategy in order to maximize or minimize the figure of merit. Mathematically, the problem faced by the controller is equivalent to maximizing a function of n variables, where n is the number of adjustable parameters involved. Geometrically, the function may be thought of as a surface in $n+1$ dimensional space, consisting of an n-dimensional parameter space plus an additional dimension along which the figure of merit is measured. The two-parameter case leads to an easily visualized three-dimensional surface or hill, as shown in the figure above. All possible operating points of the system are represented by points on the surface of this hill.

Systems involving goal-seeking in the presence of constraints encompass a wide variety of practical situations. Many examples may be found in the manufacturing and process industries where it is desired to produce some part or substance according to predetermined specifications. In such cases the goal might be to minimize the manufacturing cost or to maximize the yield of the process. Constraints would be chosen to insure the desired physical or chemical characteristics of the output, as well as compatibility with any limitations on physical capacity of the plant or machinery. Adjustable parameters might include feeds and speeds in a machining operation, compositions and flow rates of inputs to a chemical process, etc.

Ultimate realization of a goal-seeking controller is clearly dependent upon the development of advanced control techniques. Such a controller would be most useful in complex situations for which the system input-output relationships are either unknown or ill-defined, and are changing with time and environment. In these situations straightforward computing and control techniques are impractical, and advanced techniques such as self-adaption and experimental learning must be applied.

Recent research programs carried out at the Bendix Research Laboratories have entailed investigation of control techniques applicable to such goal-seeking systems. This work has uncovered a number of engineering and mathematical problems, and has resulted in the formulation of basic concepts for the development of a generalized goal-seeking control system.

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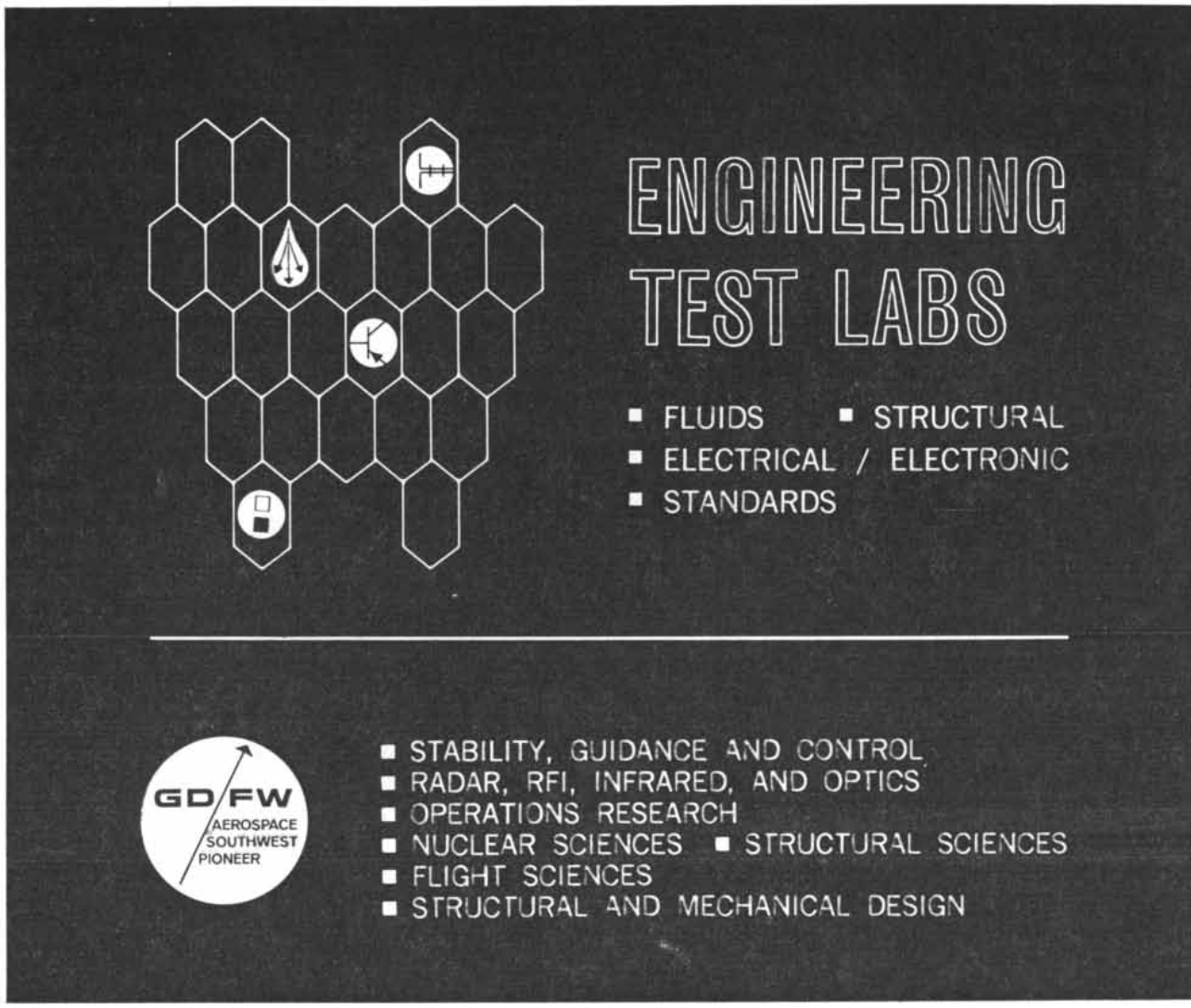
WHERE IDEAS UNLOCK THE FUTURE

DECREASE OF TRACHOMA in Finland accompanied advent of modern sanitation and better standard of living. Vertical scale represents per cent of patients at the Helsinki Ophthalmologic Clinic treated for trachoma. Disease disappeared from Finland in the 1950's.

recent years as a by-product of the trachoma investigations. As its name suggests, it is not particularly a disease of underdeveloped areas or of populations with a low standard of living; it is most commonly picked up in contaminated swimming pools. The infectious organism is sometimes present in the genitourinary tract (as the trachoma agent never is) and is passed on from mothers to newborn babies in that way. The disease is quite different from trachoma. it produces no scars or blindness and is self-limited and self-healing. And yet this conjunctivitis, technically called inclusion blennorrhea, turns out to be caused by an agent remarkably like that of trachoma. The Lister Institute workers, who first isolated this organism, have found that under certain experimental circumstances it can produce trachoma and that it is neutralized by trachoma antibodies! How two agents so closely related to each other can behave so differently in their effects on the host is a question that is currently fascinating virologists.

The investigation of trachoma has now reached an exciting stage. Several field trials of vaccines are under way in areas where the disease is prevalent The Harvard School of Public Health is conducting such trials among American Indian school children and among infants in Saudi Arabia. Grayston's group in Taiwan has found, in the first year of a program of vaccinating preschool children with formalin-inactivated material, that the rate of trachoma infection among these children is only half to a third that among the unvaccinated. It remains to be seen how long-lasting the immunity will be and how effective such programs can be in immunizing large and differing populations. So far all that can be said is that the outlook is not discouraging.

Meanwhile it should be remembered that trachoma is essentially a disease of poverty, overcrowding and ignorance. Wherever living conditions improve, the prevalence of the infection declines dramatically. A good case in point is Finland. At the beginning of this century the Finnish people had one of the highest rates of trachoma in Europe. Thanks to their industry and elevation of their living conditions, they eliminated the disease as a problem long before any effective medical treatment became available. The 500 million trachoma sufferers who remain in the world are a vivid reminder of the opportunities that lie ahead for the application of science and technology.



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BORON

Although first identified as an element more than 150 years ago, boron has only recently come to be appreciated for its many useful properties. Several of its prospective applications are outlined

by A. G Massey

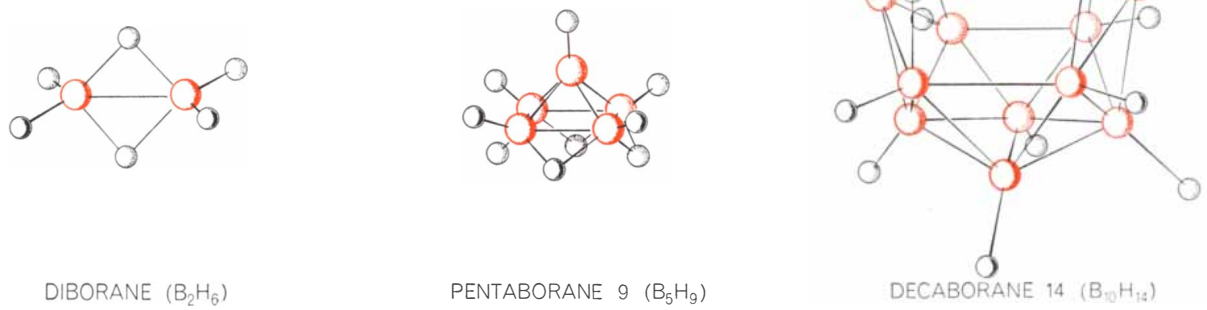
In 1901, when the young German chemist Alfred Stock was just setting out on a long and distinguished career in chemical research, he chose the compounds of boron as his field of special interest because, as he later wrote, "it was evident that boron, the close neighbor of carbon in the Periodic System, might be expected to form a much greater variety of interesting compounds than merely boric acid and the borates, which were almost the only ones known at that time." Stock's intuition soon proved to be well founded. Over the next 30 years he successfully synthesized all but one of the important compounds of hydrogen and boron, now called boranes, and laid the foundation for the discovery of a myriad of other boron compounds. Today boron and its compounds are used in high-energy fuels for rockets and jet aircraft, in neutron shields for nuclear reactors and in heat-resistant lubricants and glasses, to mention only a few of its diverse applications. Borax and boric acid are familiar in a variety of household products, and one boron compound is being investigated as a treatment for cancer. What is more, modern X-ray-diffraction techniques have shown that many compounds containing boron form unusually complex crystals; these studies promise to yield new insights in structural chemistry and new applications in incipient technologies. The future of boron seems certain to confirm further Stock's original appraisal.

The relative anonymity of boron before Stock's time can be attributed in part to its dominant affinity for oxygen; in nature boron occurs exclusively in combination with oxygen. In addition to boric acid (H_3BO_3), which is sometimes found naturally in volcanic steam jets, the most important borate minerals include borax ($Na_2B_4O_7 \cdot 10H_2O$), kernite ($Na_2B_4O_7 \cdot 4H_2O$), colemanite ($CaB_3O_4(OH)_3 \cdot H_2O$), boracite ($Mg_7B_{16}O_{30}Cl_2$), borocalcite ($CaB_4O_7 \cdot 4H_2O$) and boronatrocalcite ($Na_2B_4O_7 \cdot Ca_2B_6O_{11} \cdot 16H_2O$).

The discovery of borax, the commonest ore of boron, is lost in antiquity. Medieval alchemists apparently used borax as a flux in metal smelting and soldering; they often referred to "borach" or "baurack," which was possibly derived from the Persian or Arabic word *borak*, meaning white. The name "boron" itself is a portmanteau word derived from borax and carbon, an element with which boron shares many properties.

Elemental boron was first obtained in 1807 by Humphry Davy by the electrolysis of boric acid. Soon afterward Joseph Gay-Lussac and Louis Jacques Thénard independently succeeded in isolating boron by heating boric oxide with potassium. The free element resembles crushed dark brown or black earth and has no mechanical or structural strength. It lies between beryllium and carbon in the periodic table of the elements; it is thus the fifth lightest element.

It was the close proximity of boron and carbon in the periodic table that first led Stock to consider the possibility of a series of boron hydrides (compounds of boron and hydrogen) analogous to the hydrocarbons (compounds of hydrogen and carbon) of organic chemistry. At that time the metallic carbides were



SIX BORANE MOLECULES (compounds of boron and hydrogen) on these two pages were all discovered and identified before 1930 by the German chemist Alfred Stock. The three at the left have the general formula B_nH_{n+4}; those at the right have the general

known to yield gaseous carbon derivatives when subjected to hydrolysis. For example, on treatment with water calcium carbide readily produces the hydrocarbon acetylene (C_2H_2). It was therefore quite natural for Stock to attempt the preparation of his hypothetical boron hydrides by the hydrolysis of metallic borides. Although he soon found that both magnesium boride and beryllium boride successfully served this purpose, his experiments were temporarily frustrated by the fact that the conventional methods then employed for handling organic compounds in open flasks and beakers were not suitable for containing his new hydrides, which spontaneously burst into flame in the presence of air. He overcame this obstacle by conducting his entire experiment in an evacuated glass system [*see bottom illustration on next page*].

In so doing he also succeeded in overcoming another major difficulty. By cooling any part of the vacuum apparatus in liquid air he could cause the newly synthesized hydrides to condense at that point. Thus by a suitable arrangement of valves and tubes gaseous and liquid hydrides could be manipulated to any point in the system and pure hydrides withdrawn.

Another of Stock's ingenious innovations in the design of laboratory apparatus arose out of these experiments. Because boron hydrides reacted with the grease used for lubricating conventional glass stopcocks, he invented a mercury float valve that was the prototype of many such valves in service today. Throughout the experiments there was the constant danger that the fragile soda-glass apparatus might crack under the strain of being immersed in the coolant; in this event the highly reactive hydrides within could mix with the liquid air and cause a violent explosion.

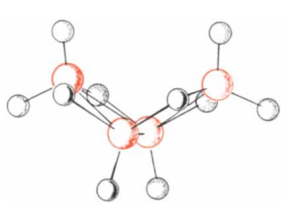
As his work progressed Stock realized that the boron hydrides could be fitted into two distinct series, one with the general formula B_nH_{n+4} and the other with the general formula B_nH_{n+6}. The molecular structures of several boranes of each type are shown on these two pages. Altogether Stock discovered eight of the "common" boranes; a ninth, enneaborane (B_9H_{15}), was not identified until 1958.

Since the time of Stock's initial experiments there has been considerable debate about how electrons are arranged in the boron hydrides, or boranes. Until 1949 it was generally accepted that the familiar covalent bond of chemistry involved the sharing of an electron by two atoms, but in that year it was shown by H. C. Longuet-Higgins, now at the University of Cambridge, that for diborane (B_2H_6) this concept had to be broadened. In a molecule of diborane two electrons must be shared by three atoms to form a "three-center," or "banana," bond [*see upper illustration on page* 92]. More recently X-ray-diffraction studies have unraveled the complex structures of other boranes; apparently these also contain multicenter bonds with the bonding electrons spread over several atoms.

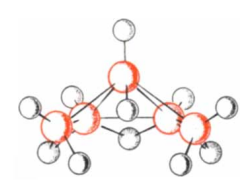
Stock's experiments yielded only about four grams of mixed boranes from the hydrolysis of two kilograms of magnesium boride. In recent years much better yields have been obtained from the reduction of boron trichloride (BCl_3). The impetus for this improvement has come from research on the possibility of using boranes in high-energy fuels for rockets and jet aircraft.

Theoretically the range of a rocket is established by the ratio of the heat evolved by the oxidation, or combustion, of its fuel and the density of the fuel. According to this dual standard it would appear that liquid hydrogen is the ideal rocket fuel; it has both a high heat of combustion and the lowest density of any substance. The low boiling point of liquid hydrogen (minus 252 degrees centigrade) tends to cancel these advantages. The refrigerated storage system required to maintain liquid hydrogen below its boiling point means that an equal weight must be sacrificed in the payload.

In this respect the boranes are potentially superior to liquid hydrogen as efficient rocket fuels. Although they have heats of combustion considerably lower than liquid hydrogen, they still produce 50 per cent more energy per unit of mass than any of the liquid or solid fuels now in use. Unfortunately the low spontaneous-ignition temperature of most boranes makes their direct use as fuels somewhat hazardous. It seems reasonable to suppose that these hydrides of boron could be combined with compounds of carbon to produce more tractable organoboranes, but owing to the secret nature of this kind of research no indication of what borane derivatives have been studied has yet appeared. It can be calculated, however, that in order to retain the high heat value of the parent borane the derivative must contain as much hydrogen and as little carbon as possible; this could be done by adding to the molecule a small number of methyl groups (CH_3). It is known that after much difficult and expensive processing exotic organoborane fuels have in fact been produced that have a heat value 40 per cent higher than conventional kerosene fuel. The use of such fuels could result in 40 per cent greater range for a rocket, but rockets consume such vast amounts of fuel that even for a short journey the cost of boron-based fuels—about $2,000 per gallon—would be prohibitive. Accordingly interest in liquid-



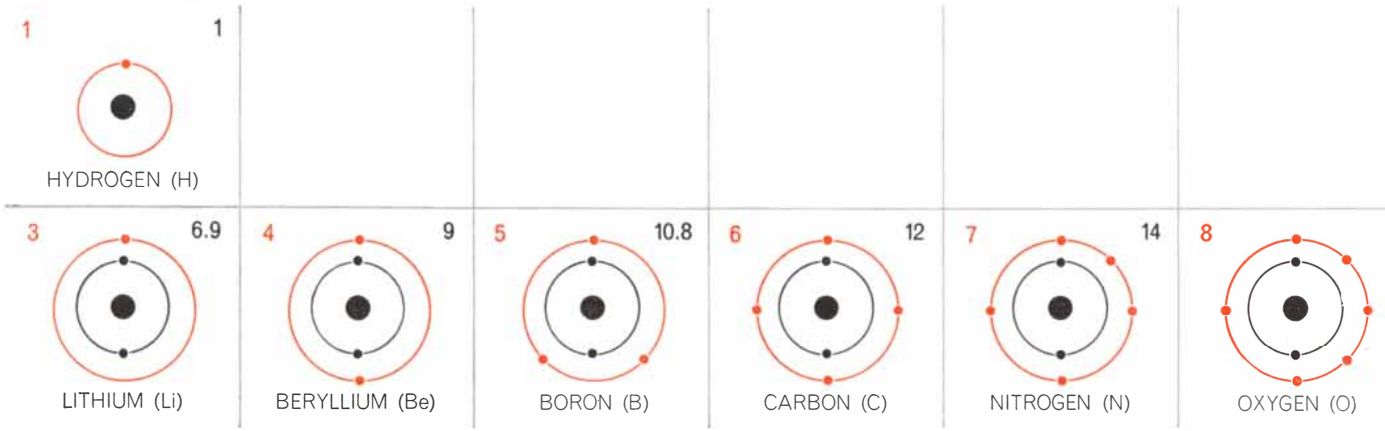
TETRABORANE (B_4H_{10})



PENTABORANE 11 (B_5H_{11})

DECABORANE 16 ($B_{10}H_{16}$)

formula B_nH_{n+6}. The large colored balls represent boron atoms; the smaller balls are hydrogen atoms. At room temperature and atmospheric pressure diborane is a gas, decaborane 14 and decaborane 16 are solids and the other three compounds are liquids.

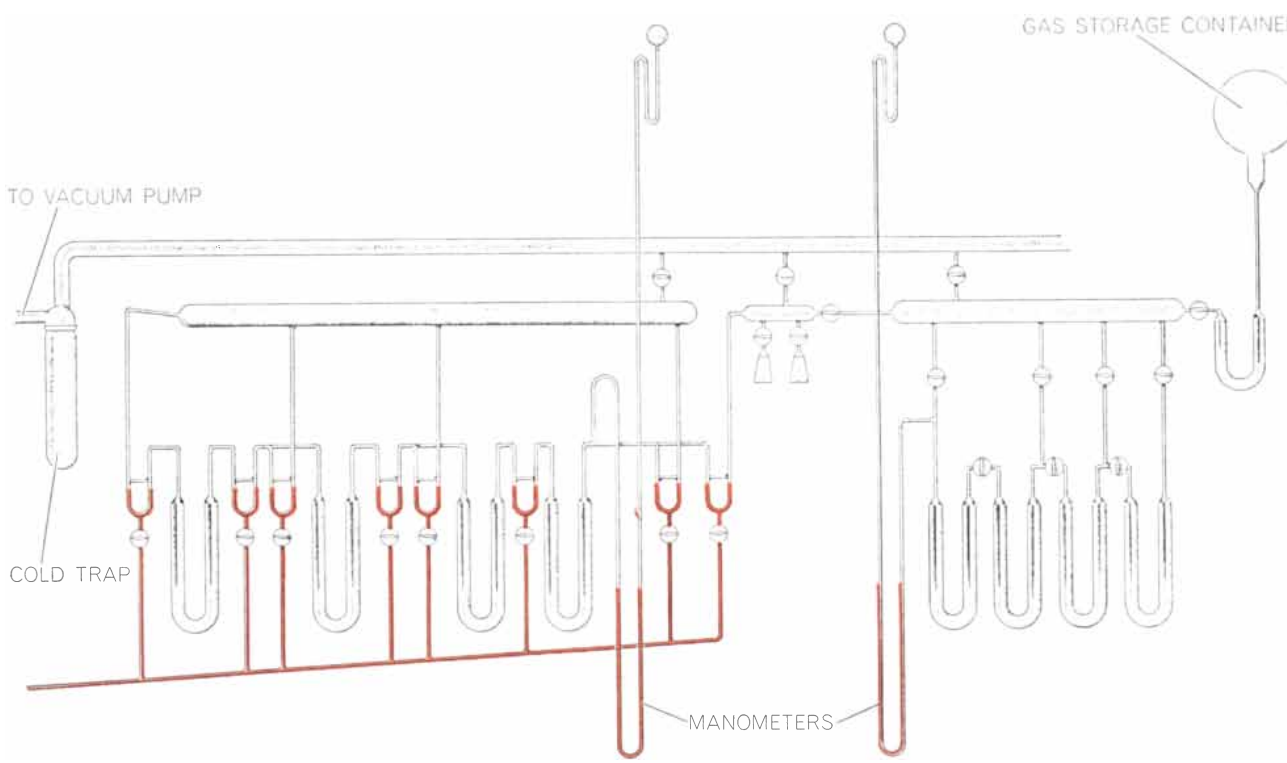


FIRST PART OF THE PERIODIC TABLE of the elements shows boron in the fifth box, between beryllium and carbon. Rings and dots represent electron shells and electrons. Valence electrons, which are responsible for chemical reactions, and their shells

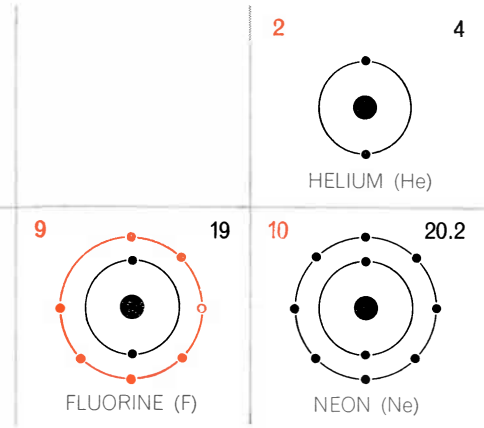
boron fuels has faded recently, although derivatives of decaborane ($B_{10}H_{14}$) apparently continue to find favor as solid propellants.

Organoboranes are also used as additives in fuels for jet aircraft and automobiles. When added to a kerosene-rich jet fuel, they greatly increase the velocity of the jet flame and help to reduce the danger that the flame will be extinguished at high altitudes, where the atmosphere (and hence combustion-supporting oxygen) is greatly rarefied. In the automobile industry a small proportion of organoborane is added to leaded gasoline. An engine that burns such a fuel has a lower octane requirement and a higher resistance to premature ignition than an engine that burns normal leaded fuel. The mode of action of these borane additives is not yet clear, but it may well be that the boron poisons the cylinder-head deposits that catalyze premature ignition. The boric acid formed by the combustion of the fuel has the unusual property of being nonvolatile when it is heated alone but volatile when it is heated in steam; therefore much of the boric acid residue is swept out of the cylinder by the water vapor in the hot exhaust gases.

In the late 1940's H. I. Schlesinger and Anton B. Burg of the University of Chicago discovered a novel boron-hydrogen system in which BH_4 units



VACUUM APPARATUS depicted in this schematic drawing is similar to the arrangement used by Stock to isolate the common boranes. The pressure within the system is less than a millionth of an atmosphere. The large U-shaped tubes across the bottom are used to separate mixtures of gases and volatile liquids by fractional condensation at low temperatures. The smaller U-shaped tubes across the center are mercury float valves. The cold trap at left is cooled with liquid nitrogen. Mercury is in color throughout the system.



are in color. Atomic numbers are also in color; black numbers are atomic weights.

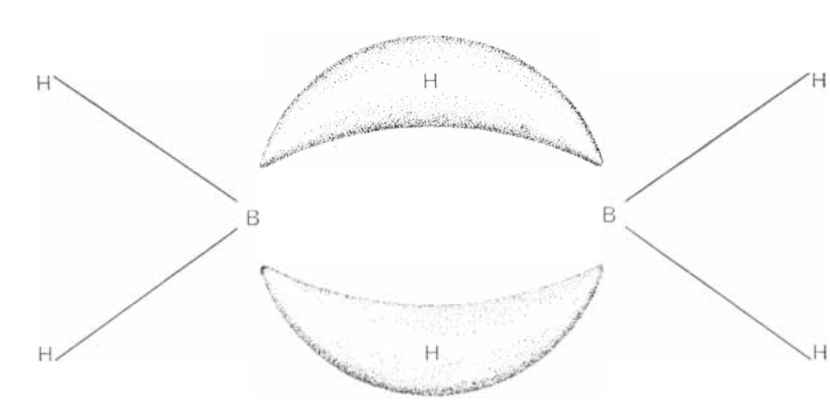
were attached to metals to make compounds called borohydrides. Some of these compounds, notably sodium borohydride ($NaBH_4$), have turned out to be valuable reducing agents in synthetic chemistry. The borohydrides are among the most volatile known derivatives of metals. During World War II the volatile uranium borohydride $U(BH_4)_4$ and its methyl derivative $U(CH_3BH_3)_4$ were used in attempts to separate the uranium isotopes by the method of gaseous diffusion. Being somewhat unstable, they were finally discarded in favor of the only other uranium compound of greater volatility: uranium hexafluoride (UF_6).

There are two isotopes of boron in nature, one with an atomic mass of 10 and the other with an atomic mass of 11. Boron 10, which constitutes about 20 per cent of natural boron, has an unusual capacity for absorbing slow neutrons. The capture of a low-energy neutron by a nucleus of this boron isotope results in the immediate expulsion of a high-energy alpha particle, or helium nucleus, which rapidly loses its energy in collisions with the surrounding molecules. An obvious application for this property of boron 10 is the manufacture of neutron-absorbing materials for control rods in reactors and for protective radiation shields. Elemental boron itself cannot be used for this purpose; since it is a typical nonmetal it has no ductility, tensile strength or other fabricating properties. Instead a substance called boral is made by suspending boron carbide (B_4C) in molten aluminum. Ingots of this mixture, after being wrapped in an aluminum jacket, can be rolled out, at about 700 degrees C., into sheets a quarter of an inch thick. In this way a thin, lightweight neutron

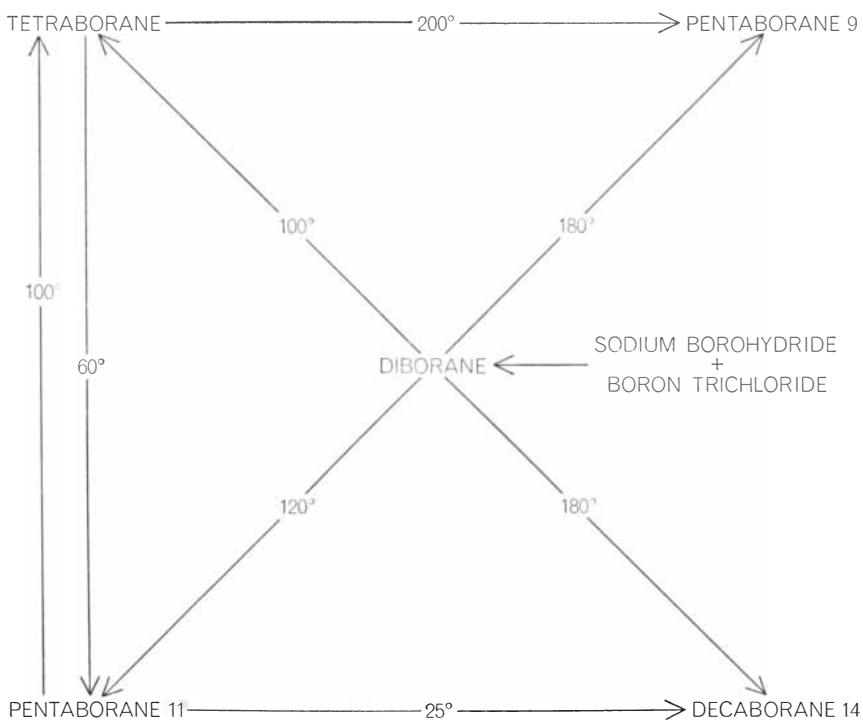
shield is formed; such shields would fill an obvious need in the nuclear-powered aircraft of the future.

Pressure-molded bricks of finely powdered boron carbide and water, when baked in air at 600 to 1,000 degrees, are also effective neutron absorbers. During baking some of the boron is oxidized to boric oxide (B_2O_3), which is liquid at that temperature; on cooling, the boric oxide becomes glassy and binds the brick together. A similar technique, involving the pressure-molding at 1,500 degrees of mixtures containing 5 to 20 per cent boron with a metal such as copper or nickel, also produces neutron absorbers suitable for nuclear reactors. The efficiency of these neutron-absorbing materials is of course increased (as is the cost) if the boron source is artificially enriched in boron 10 before fabrication.

Because neutrons have no electric charge, they normally pass unchecked through vast amounts of matter before they are captured by a nucleus; this makes them more difficult to "count" than other types of radiation. Efficient neutron counters can be made from simple Geiger counters, however, by filling the counter tube with a mixture of argon and boron trifluoride (BF_3) enriched in boron 10. When a slow neutron passes through the tube, it is captured by a boron 10 nucleus and an alpha particle is emitted; the alpha particle, being electrically charged and having a high energy, ionizes the gas in the tube and triggers the counter. A less sensitive counting device employs a mixture of boron 10 and zinc sulfide spread evenly over the surface of a photomultiplier tube. The alpha particles emitted by the boron 10 nuclei on neutron capture cause scintillations in the zinc sulfide that are detected and amplified by the photomultiplier.



"BANANA BONDS" are formed in a molecule of diborane when pairs of electrons must be shared by three atoms (in this case two borons and one hydrogen). The bonds are represented by "electron clouds"; the cloud is thickest where the electrons spend the most time.



BORANES CAN BE INTERCONVERTED using the vacuum apparatus at bottom of page 90 by controlling heat and other factors within the system. This chart shows the heats required to convert some common boranes; other techniques are needed to prepare the rarer hydrides of boron. Hydrogen must be added to convert pentaborane 11 into tetraborane.

These nuclear properties of boron 10 are also advantageous in research on the treatment of brain tumors. It has been observed that when an inorganic boron compound such as borax is administered intravenously to a patient suffering from a brain tumor, boron accumulates in a higher concentration in the tumor than in normal, healthy brain tissue; this differential lasts for about 30 minutes. If the tumor is irradiated with a beam of slow neutrons during this period, the boron 10 nuclei emit tissue-killing alpha particles on neutron capture. Since alpha particles are known to travel only a few thousandths of a millimeter in tissue, more damage will be done to the tumor than to the healthy parts of the brain. For many compounds the ratio of "boron in tumor" to "boron in brain" is low, only of the order of two or five to one, although a figure of 28 to one has been reported by one investigator. Research is continuing on the synthesis of boron-containing organic molecules that might be more readily absorbed by tumors. One report of such work states that boron derivatives of dyes such as Evans blue or trypan blue are absorbed with a differential of 100 to one in the growing edge of brain tumors in mice. This opens up the exciting possibility that boron-containing analogues of biologically active compounds may be found that could carry boron preferentially to other cancerous sites in the body.

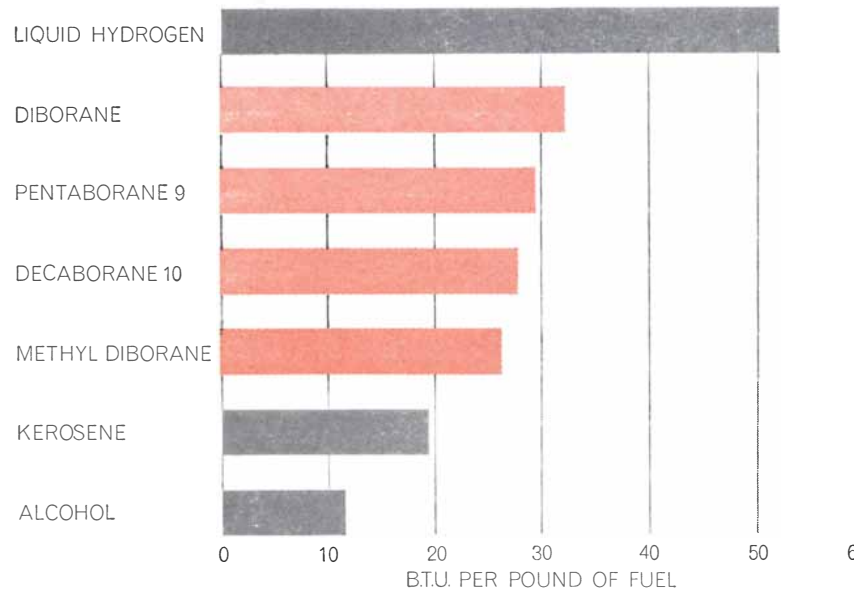
These analogues are likely to be compounds of boron and nitrogen. Since these two elements straddle carbon in the periodic table, they respectively have one electron more and one electron less than carbon does. Thus a boron-nitrogen bond has the same number of electrons as a carbon-carbon bond. It follows that some compounds of boron and nitrogen are chemically analogous to certain hydrocarbons. A good example is bora-

zine ($B_3N_3H_6$), the molecule of which resembles the ring-shaped molecule of benzene (C_6H_6). Borazine, which is sometimes referred to as inorganic benzene, is very stable, but at 500 degrees in a vacuum it slowly loses hydrogen as its molecules begin to link up. From the products of this reaction it is possible to isolate the multi-ring boron-nitrogen compounds biborazinyl ($B_6N_6H_{10}$) and borazanaphthalene ($B_5N_5H_8$), which are analogous to the hydrocarbons biphenyl ($C_{12}H_{10}$) and naphthalene ($C_{10}H_8$) respectively.

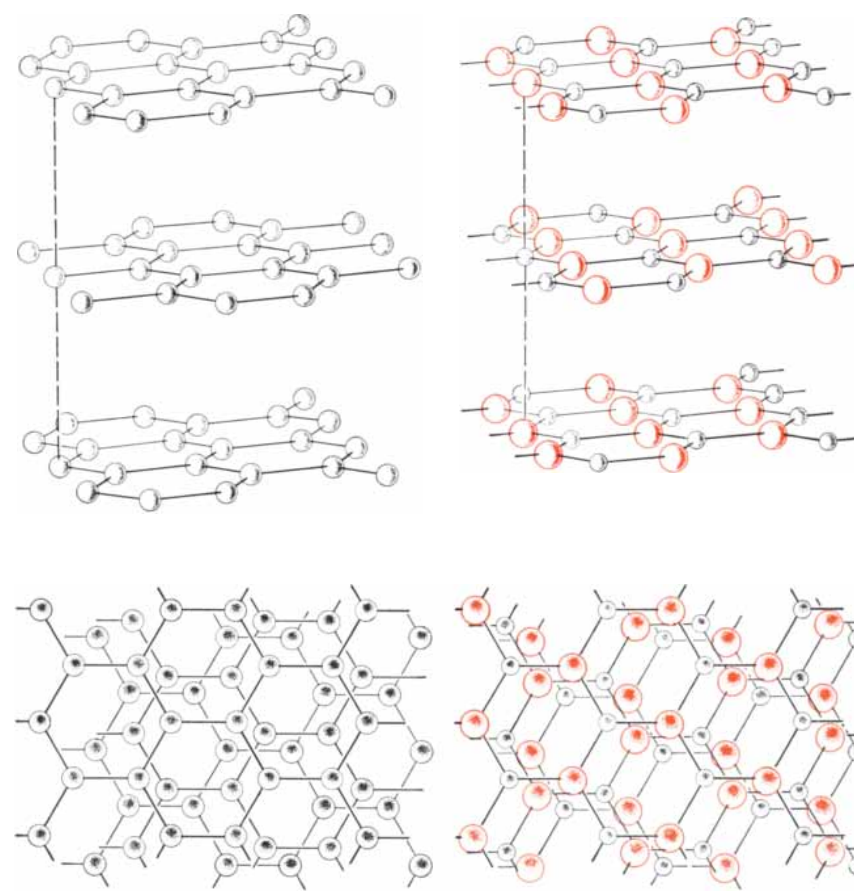
At very high temperatures borazine, like most other boron-nitrogen compounds, yields boron nitride, which can exist in two forms. Hexagonal boron nitride has a layer structure much like that of graphite but with the hexagonal rings of successive layers lying directly on top of one another [*see bottom illustration on this page*]. The electrons in hexagonal boron nitride are not "free" in the sense that they are in graphite; this causes boron nitride to have inferior lubricating properties compared with graphite because its layers do not slide over one another so easily. Nonetheless, the superior heat resistance of boron nitride has stimulated much research into its possible use as a high-temperature lubricant.

An even more remarkable form of boron nitride is borazon, the cubic, or diamond-like, crystal form that results when a boron-nitrogen compound is subjected to about 85,000 atmospheres of pressure at 1,800 degrees—conditions sufficient to convert graphite into diamond. Only small fragments of borazon have so far been made, but its properties seem particularly intriguing. It is harder than diamond and surpasses it in heat resistance; it is affected by temperatures only in excess of 1,500 degrees. (Diamond reverts to graphite at about 900 degrees.) Oxidation by air is slight even at this temperature, making the use of borazon in high-speed cutting tools possible. At about 1,650 degrees borazon changes to a hexagonal variety of black boron nitride with physical properties very similar to the graphite formed by heating diamond. What will the lubricating, electrical and other properties of this graphite-like substance be? Such tantalizing questions can only be answered when the parent borazon becomes more readily available.

Borazon, although supreme, is only one of several exceedingly hard boron compounds; boron carbide and crystalline elemental boron are both harder



HEATS OF COMBUSTION of several potential rocket fuels are indicated in this graph. Although liquid hydrogen has a high heat of combustion and the lowest density of any substance, its low boiling point tends to cancel these advantages. The four boranes shown all produce more energy per unit of mass than the kerosene- or alcohol-rich fuels now in use.

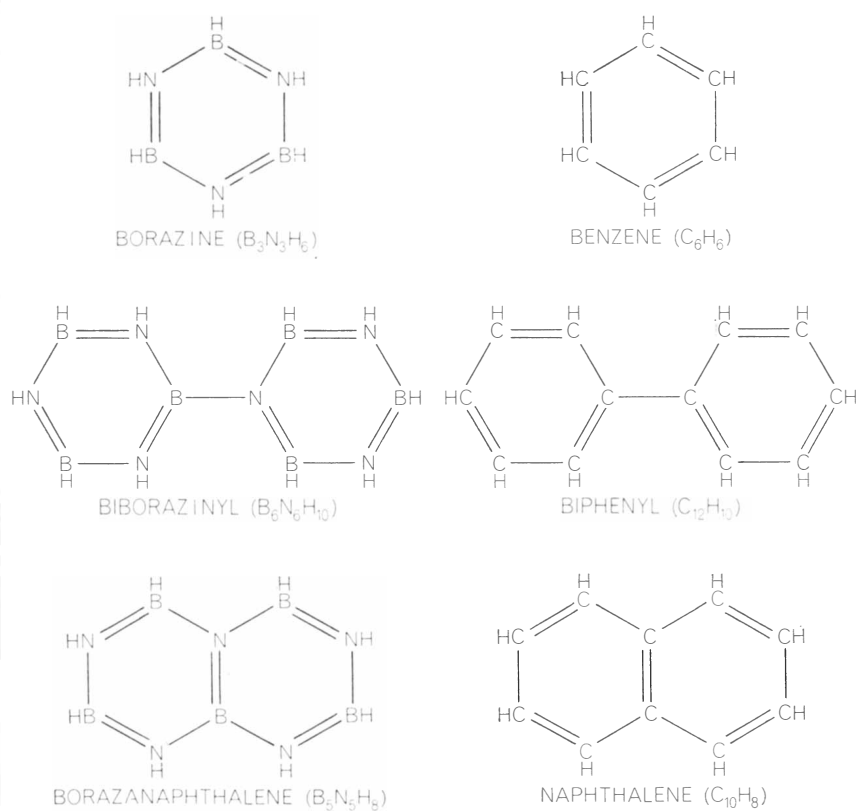


LAYER STRUCTURE of hexagonal boron nitride (*right*) resembles that of graphite (*left*). In boron nitride, however, the layers are in phase, whereas in graphite they are staggered. Although graphite layers slide over one another more easily than boron nitride layers do, the superior heat resistance of boron nitride could make it a better high-temperature lubricant. Boron atoms are in color, nitrogen atoms (*right*) and carbon atoms (*left*) are not.

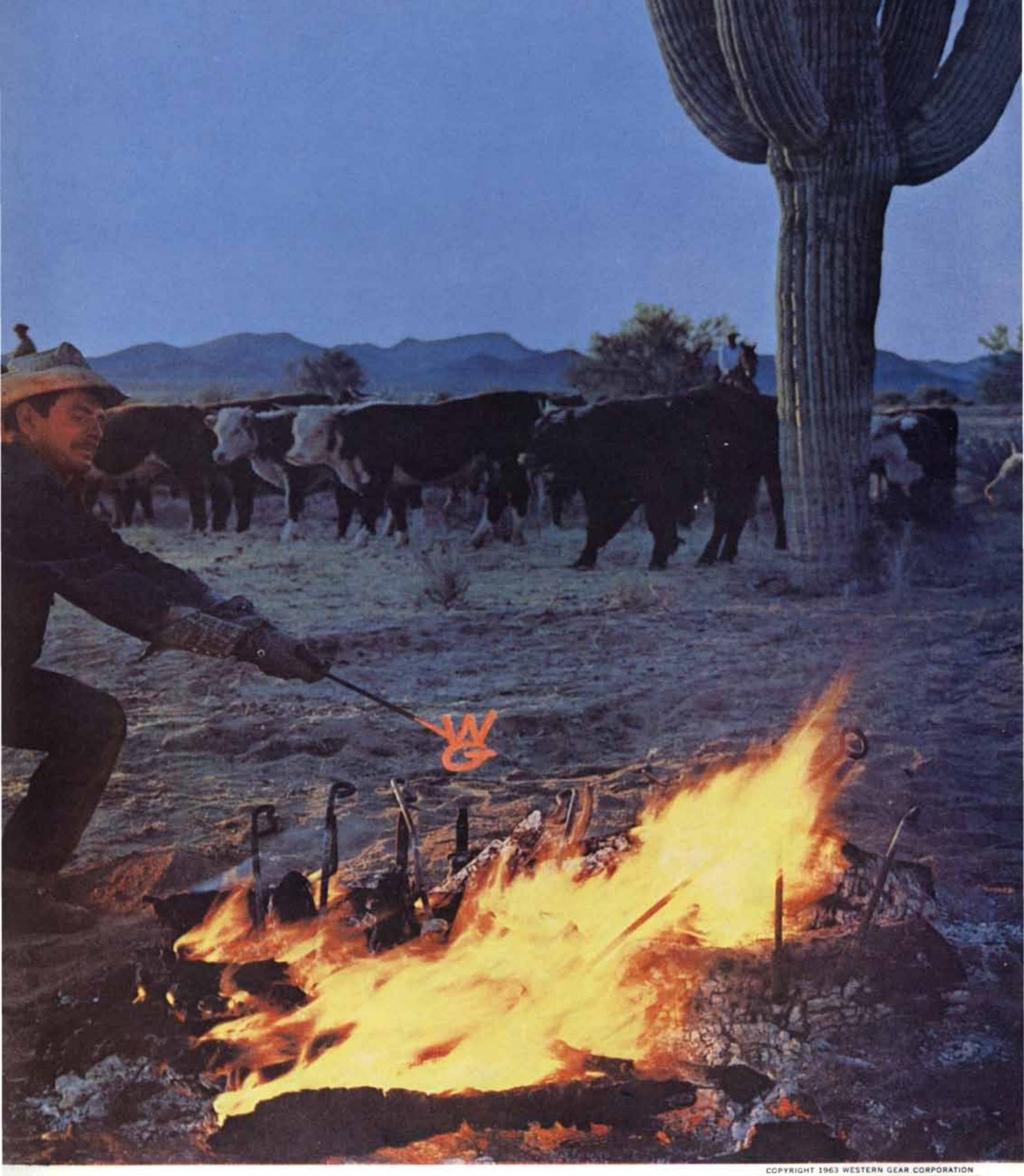
than Carborundum. To be of practical use, however, the nonmetallic elemental boron must be bound to some other substance to give it mechanical strength and shape. For example, boron-coated iron is used to make knife sharpeners, bearings and dies. To deposit the coating the iron is heated in an atmosphere of diborane at low pressure. The thermally unstable borane decomposes to yield elemental boron, which at about 300 degrees is deposited on the metal as a smooth, uniform layer. If the temperature is allowed to rise to about 900 degrees, the boron rapidly diffuses into the metal and the coating, now containing some metal boride, is much more firmly bound but rougher in appearance.

The possibility that the chainlike molecules called polymers can be made of inorganic substances has been closely scrutinized during the past few years in the hope that heat-resistant substances with all the properties normally associated with plastics might be discovered. Ordinary organic (carbon-containing) polymers tend to burn or char when subjected to heat; one way to combat this disadvantage is to employ noncombustible, largely inorganic (containing no carbon) building blocks. Carbon, the neighbor of boron in the periodic table, is renowned for its ability to form long chains. A perfect example of such catenation is polyethylene, in which many hundreds of ethylene molecules (C_2H_4) are linked to form long chains of CH_2 units. So far, however, no similar compounds containing straight boron chains are known. The maximum possible number of boron atoms linked together in such a way appears to be two. Boron has a much greater tendency to link with itself in well-defined three-dimensional polyhedrons—a configuration as yet unknown in organic chemistry. A simple example of this is tetraboron tetrachloride, in which the four boron atoms constitute a regular tetrahedron [*see illustration on page 96*]. A search for boron polymers based on boron-oxygen-boron bridges resembling the silicon-oxygen-silicon links in the substances called silicones has so far failed to yield useful material.

Boron-nitrogen compounds, since they often mimic their carbon-carbon analogues, would also seem to be likely candidates for inorganic polymers. Stable, thermoplastic polymers result when nitrogen compounds such as dimethylamine or trimethylamine are heat-



SOME BORON-NITROGEN COMPOUNDS (*left*) are chemically analogous to organic hydrocarbons (*right*). These boron-nitrogen bonds have the same number of electrons as the analogous carbon-carbon bonds. Borazine is sometimes called inorganic benzene.



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Johnny knows more because science knows more. And that's because a lot of people like Johnny took thousands of years to learn one small fact after another. In ancient days all learning, science included, was philosophy. Aristotle, in fact, was the first person to separate the two. By classifying and relating all the small bits of information, he established as distinct disciplines the first scientific specialties. Among them were anatomy, biology, meteorology, physics and physiology. In addition, he invented logic and psychology.

Even so, scientific progress was pretty haphazard. But in the early 1900's there were enough scientists to produce what might be called a "critical mass of ideas." Then, with the help of improved communications, these ideas interacted to form new ones. A chain reaction began. Today, science is literally exploding with new ideas and attacking a lot of ignorance, poverty and disease in the process. It happened none too soon. For example, it is estimated the world population will increase from its present 3 billion to 50 billion in fewer than 70 years. Think of the food and energy we'll need. Fortunately, science is already beginning to produce it.

Science takes these great strides with the help of specialization. But if specialization is the seven-league boot, industry is the cobbler. For just as the cobbler fits the boot to the foot, companies like Cyanamid fit knowledge to human needs. Today, for example, 33 different scientific specialties are represented at Cyanamid alone. They range from analytical chemists, who find out what things are made of, to zoologists who determine which animals help man, which ones hurt him, and how.

Between these alphabetical extremes are bacteriologists, electrical engineers, mycologists, pharmacologists, textile engineers and virologists and others. They work in such diverse areas as health, industrial chemicals, dyes and pigments, fibers, resins and plastics.

Today, the scientist is finding that he must know a lot about several specialties to avoid duplicating the work of others. This has led to another alphabet soup of "interdisciplines" starting with astrophysics and biochemistry.

Now where does Johnny fit into science? Everywhere. He can't escape it. As medicine it touches him at the very moment of birth. Under other names, it affects him every day of his life. He studies it in school, and we at Cyanamid hope he will at least consider it as a career. It's exciting, rewarding work and we want to help make sure that Johnny knows it.

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To bring science to the classroom several hundred Cyanamid people visit science clubs and classes to talk with students about science and engineering, and to counsel them if they show an interest.

And like most responsible companies, Cyanamid also comes across with cold cash, three quarters of a million dollars a year to university departments of agriculture, chemistry, chemical engineering and medicine.

Finally, a number of Cyanamid's top scientists have returned to the colleges full time. As professors, department heads and deans, they can draw upon their practical experience in industrial chemistry and administration.

Thanks to scientists and scholars like these, all of us know more than the ancients did. Our knowledge is paying off in greater productivity, less suffering, a longer life. To make sure that Johnny's son enjoys this too, we at Cyanamid are doing our best to see that Johnny knows more than we do.

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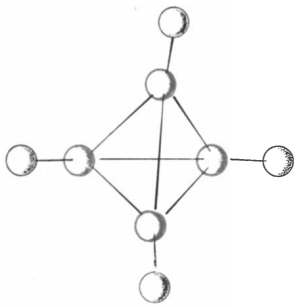


TETRABORON TETRACHLORIDE (B_4Cl_4)

POLYHEDRAL STRUCTURE characteristic of many boron compounds is evident in this drawing of a tetraboron tetrachloride molecule, in which four boron atoms form the vertices of a regulartetrahedron. Boron atoms are in color; chlorine atoms are in black.

ed with pentaborane (B_5H_9). Unfortunately their structures are not yet known, and the control of their molecular weight (and hence physical properties such as solubility and softening point) has proved difficult to achieve. Another system at present under study contains boron-phosphorus bonds formed by reacting diborane with certain phosphine derivatives. These boron-phosphorus polymers have high heat resistance but their mechanical strength is poor. Some of these polymers are so light that when they are dropped, they float down as gently as a feather and shatter on impact with the floor. The future may well show that the best boron-containing polymer we are likely to achieve is heatproof glass, which is predominantly a three-dimensional network of boron, silicon and oxygen atoms.

Although this article is intended to describe boron in its more exciting aspects, there are many more mundane uses for its compounds in the glass and ceramic industries, in metallurgy, in pharmaceutical preparations and in weed killers. Moreover, today, as in Stock's time, research into the structural chemistry of boron is very active. One interesting possibility that arises from this work involves derivatives of the new borohydride ions $B_{10}H_{10}^{--}$ and $B_{12}H_{12}^{--}$, which contain polyhedrons of boron atoms. Unlike normal boron compounds containing boron-hydrogen bonds, these borohydrides are remarkably stable and may well lead to useful polymers if the boron polyhedrons can be linked together in a controlled manner. In any event, boron appears certain to remain in the public eye in one or another of its diverse roles.

The Origins of the Steam Engine

Fifty years before James Watt came on the scene Thomas Newcomen built practical steam engines to pump water out of mines. What is known of these engines and how did they influence later ones?

by Eugene S. Ferguson

If one had a handbook of human history with a synoptic chart that opened out at the back, one might expect the chart to reduce the industrialization of England in the 18th century to the words "James Watt," "steam engine" and "textile mills." This familiar view is misleading on two counts. Watt did not invent the machine that supplied power to the looms of the textile mills. Steam engines had been put to work 50 years before Watt appeared on the scene, and the industry that created the demand for them was not weaving but mining. At the beginning of the 18th century two Englishmen from Devonshire, Thomas Savery of Shilston and Thomas Newcomen of Dartmouth, built steam-powered pumping machinery for the drainage of mines. The need for a way to remove water from mines had become more and more pressing as the mineral resources of England were exploited during the 17th century. The operators of tin mines in Cornwall and lead mines in Derbyshire were waging a losing battle against water seepage as their mines were dug deeper, and many coal mines around Birmingham and Newcastle were threatened with flooding as the inflow of water overcame the pumps then available. Savery's engine never succeeded as a mine pump, although it was useful for other purposes; Newcomen's did provide the power to lift water from mines.

The Newcomen engine also succeeded, two generations later, in stimulating the curiosity and imagination of James Watt. In 1769 Watt patented an engine soon brought to commercial status by industrialists who realized that its superior thermal efficiency would enable them to make greater practical use of steam power. The Newcomen engine should not, however, be considered a mere taking-off point for the genius of Watt. Its impact on the technology and economics of mining is today symbolized by the monotonous bobbing of the pivoted "walking beams" of oil-well pumping rigs, a familiar sight in the southwestern U.S. The vertical pump shaft is guided at its upper end by an odd protuberance on the beam called, in the graphic language of the industry, a horsehead. Whether or not the builder of the first such oil-pumping rig was aware of his source, he had borrowed these elements from a Newcomen engine originally used to pump water [*see illustration on opposite page*]. In 250 years the power unit has evolved from a steam cylinder to an electric motor, but its function—to pull one end of the beam down—has not changed at all.

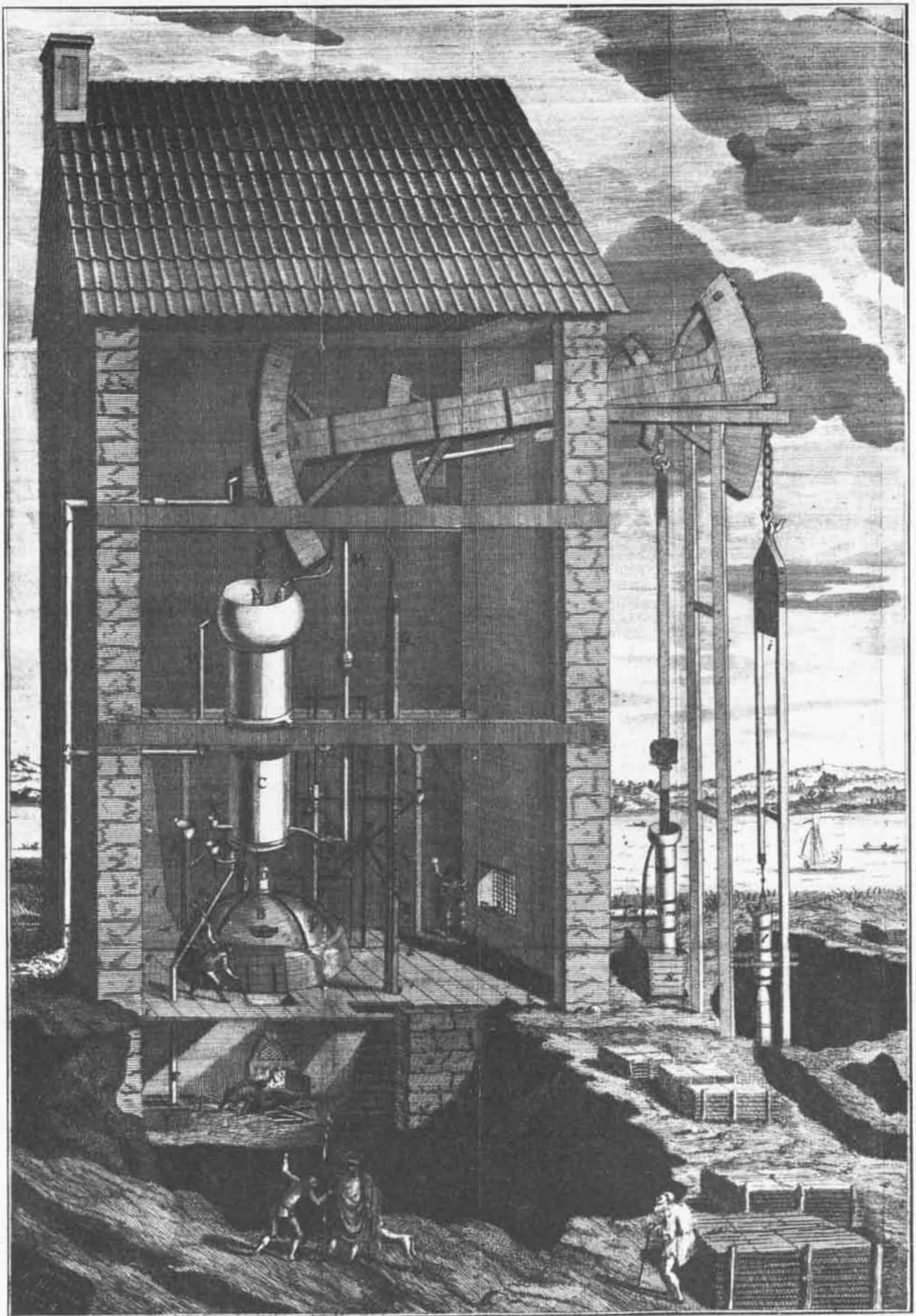
In Newcomen's design one end of the beam was secured to the pump shaft and the other end was chained to a piston that fitted into a vertical steam cylinder. When steam supplied to the cylinder from a boiler directly below it was condensed by the injection of water, the resulting vacuum enabled the pressure of the atmosphere to force the piston down, thus drawing the beam down on one side and the pump rod up on the other. Long after the steam engine was being used for purposes other than pumping it retained the overhead beam of Newcomen's design. Watt himself experimented in 1770 with turning the cylinder upside down in order to eliminate the beam, but he quickly and permanently abandoned the idea.

Little is known about Thomas Newcomen, the man whose innovations were so original, influential and enduring. He was born in Dartmouth in 1663, made a living as a seller and perhaps small-scale manufacturer of iron products and died in London in 1729. The recent tricentennial of his birth gave impetus to the study of his life and work; such study, including this critical review of the Newcomen engine, would scarcely have been possible were it not for the dedicated men who in 1920 in London organized the Newcomen Society for the Study of the History of Engineering and Technology. The members of this group, the first to take a serious interest in Newcomen as an individual, combed the records for the origins and later history of the steam engine, publishing their findings in the *Transactions* of the society.

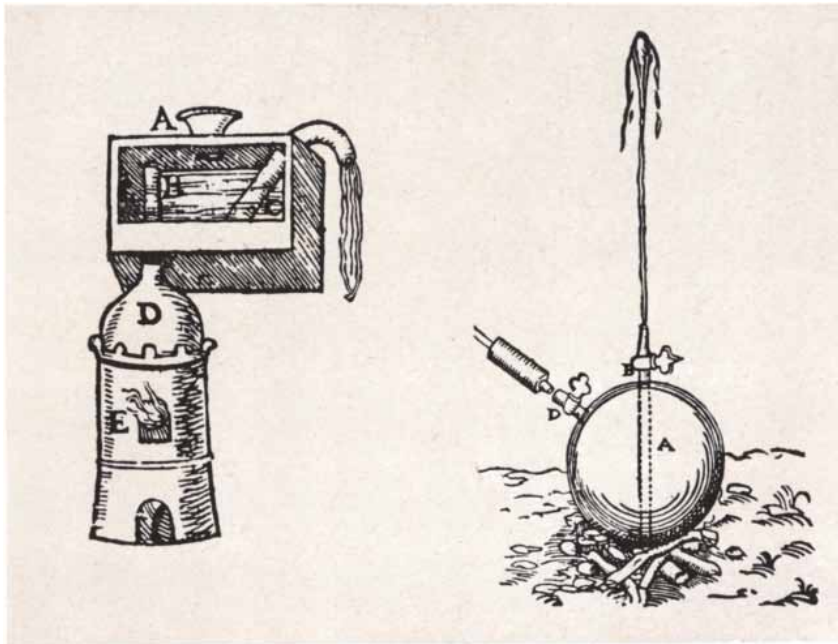
The source materials they uncovered tell us more about the state of technology at the time than about the events of Newcomen's life; nothing is revealed of his formal and informal education, the actual sources of his ideas and the steps by which his major innovations were thought out. It is unlikely that we shall ever learn the details of the steps taken by Newcomen during the 10 years he spent developing his engine. He was not prominent during his lifetime, and although his engine won immediate acceptance, it was seldom linked with his name, being known merely as the "fire engine" or "atmospheric engine." In this article I shall review the antecedents of the engine he designed and, as far as I am able to reconstruct it, the period of development immediately preceding its appearance.

A glance at the dozens of well-illustrated books devoted to machines that were published in Italy, France and Germany from the time of Georgius Agri-

NEWCOMEN ENGINE at a mine at Dannemora in Sweden was illustrated in a book of 1734 on Newcomen's principles; the illustration is reproduced on opposite page. The author was the Swedish engineer Mårten Triewald. Illustration describes the engine as the "Dannemora fire and air machine."



Dannemora Eld och Luft Machin,
Kongl. Majts och Rikens Högloflige Bergs Collegio
Underdånigst Dedicerad af Mårten Triewald.



STEAM DEVICES of 16th century raised small amounts of water. At left is an apparatus of Giambattista della Porta; water poured into chamber *B* through funnel *A* is raised through pipe *C* by steam generated in flask *D*. At right is a device of Salomon de Caus adapting same principle to produce a fountain through the generation of steam in a copper sphere (*A*).

cola's *De Re Metallica* (1556) onward indicates that the problem of water-raising was one that occupied many mechanics and mechanical philosophers in the advanced countries of Europe. Except for Agricola's treatise on mining, which gave details of 14 kinds of pump for removing water from mines, the books were concerned less with mine drainage than with pumping water for town and castle water supplies and for the operation of fountains. Nevertheless, the techniques of pumping were well known and widely discussed. Some of the devices employed were an endless chain of buckets, the Archimedean screw and the rag-and-chain pump, in which a series of rag-wrapped balls, spaced a foot or two apart on a continuous chain, were drawn vertically upward through a wooden pipe, each forcing some water ahead of it. There were many alternative machines using manpower or horsepower for the hoisting of ordinary tubs of water. During the 17th century the possibility of using steam or gunpowder as a motive power was also being explored.

It has been said that science owes more to the steam engine than the steam engine owes to science. Such a generalization seems particularly inappropriate with respect to a machine that exemplifies the overlap between the empirical and the theoretical stages of the Industrial Revolution. Although it is true that a clear understanding of the thermodynamic phenomena in the steam engine was not attained until around 1860, it is equally true that the sequence of ideas apparent in the work of Galileo, Torricelli and Pascal in establishing the fact of atmospheric pressure, and of von Guericke, Huygens and Papin in devising ways to make atmospheric pressure do work, was an indispensable prerequisite of the Newcomen engine.

Close to the Newcomen engine chronologically but not conceptually was the steam-powered machine patented by Thomas Savery in 1698. This engine, which promised to solve the problem of mine flooding, incorporated elements and principles not shared by the Newcomen engine and can be traced to a wholly different line of development. Savery, a gentleman of leisure and Fellow of the Royal Society of London, exhibited a model before the society in 1699. His engine consisted of a vessel in which steam was condensed to produce a vacuum, whereupon the vessel was filled by water rising through a suction pipe [*see illustration on opposite page*]. Steam at high pressure was then admitted to the same vessel, forcing the water to a higher elevation. The machine was a combination of steam pumping devices built or suggested earlier by Salomon de Caus and R. d'Acres and probably well known in Savery's circle.

In 1702 Savery expanded his patent application in a small book entitled *The Miner's Friend*. Here he addressed himself to the "Gentlemen Adventurers in the Mines of England: I am very sensible a great many among you do as yet look on my invention of raising water by the impellent force of fire a useless sort of a project that never can answer my designs or pretensions; and that it is altogether impossible that such an engine as this can be wrought underground and succeed in the raising of water, and dreining your mines.... The use of the engine will sufficiently recommend itself in raising water so easie and cheap, and I do not doubt but that in a few years it will be a means of making our mining trade, which is no small part of the wealth of this kingdome, double if not treble to what it now is."

In spite of Savery's optimism, the metalworking techniques at his command were inadequate to solve the problem of containing steam at several atmospheres of pressure. Hence the Savery engine was practical only in situations other than the one for which it was originally intended. The most successful application of the engine was in pumping water into building or fountain reservoirs that were no higher than about 30 feet, which called for only moderate steam pressure.

The Newcomen engine soon preempted the role of draining the mines, but the Savery engine was the first to be employed (around 1750) to turn machinery. For this purpose the engine pumped water into a reservoir some 15 or 20 feet above that supplied a conventional water wheel. Throughout the latter part of the 18th century the Savery engine was built in considerable numbers and used by manufacturers who could not or would not afford the larger, more efficient but initially more expensive Newcomen and Watt engines. As late as 1833 at least five Savery engines were at work in France; the engine was reinvented about 1870 in Germany, perhaps also in England. Now known as the pulsometer, it went on to a new career of pumping water containing solids in such applications as the drainage of shallow excavations.

The problem of following the sequence of events in the development of the Newcomen engine points up the meagerness of available source materials. What little information Newcomen's contemporaries have left us requires careful interpretation. One popular scientific lecturer of the early 18th century, John Theophilus Desaguliers, described him

as an "ironmonger" and "Anabaptist." This is the way he has been described by modern writers oblivious to the fact that "ironmonger" has come to imply "peddler," or perhaps "junkman," and that "Anabaptist" suggests the outlandish. Thus Newcomen is likely to be thought of as a ragged, gaunt pusher of a handcart, waiting for Dickens to be born so that he could get into one of his books.

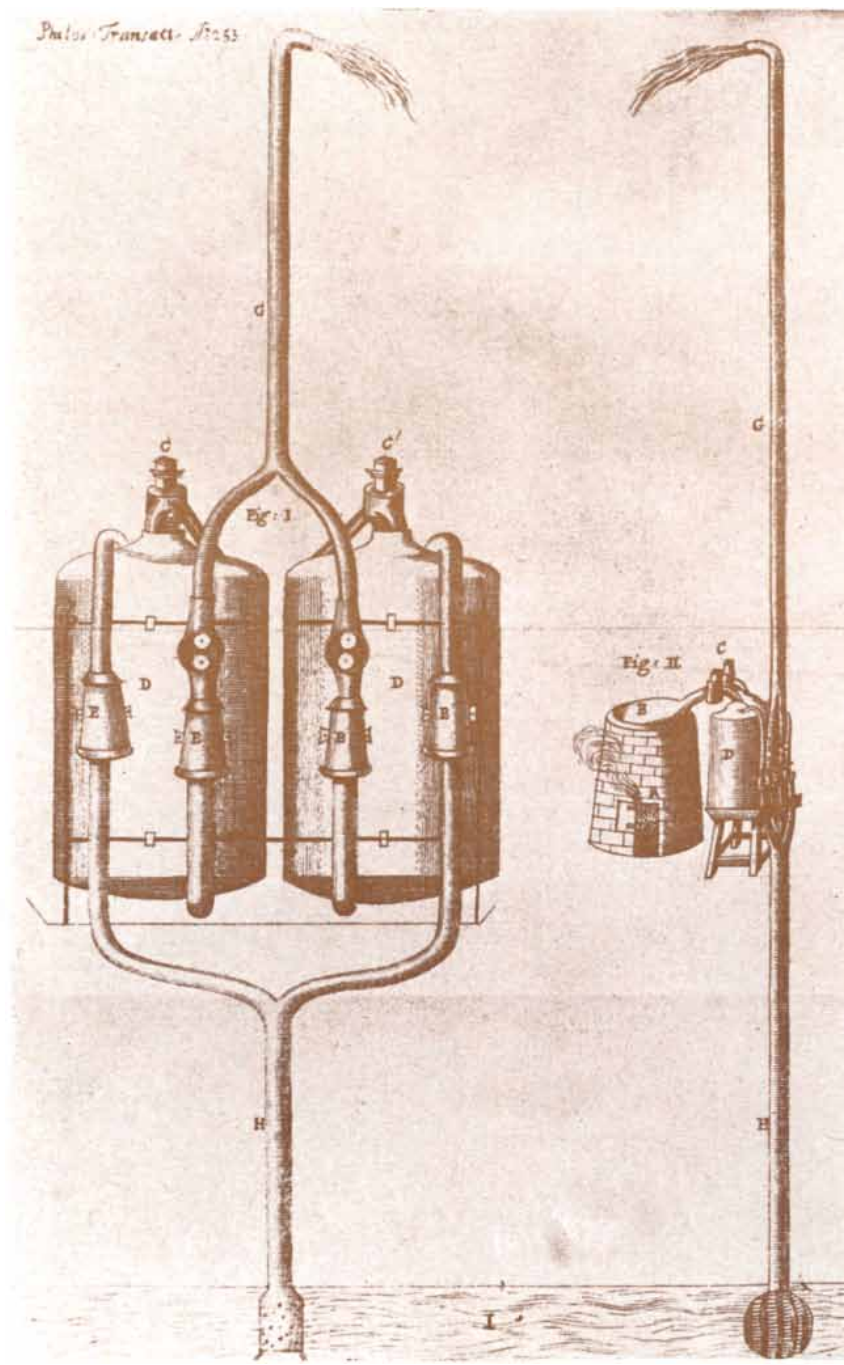
The background of his assistant, John Cawley, is even less distinct. Desaguliers called him a glazier; another man who could have known him said he was a plumber. Elsewhere he is referred to as a brazier or coppersmith. This description seems proper because an ironmonger was a dealer in hardware and industrial supplies, sometimes manufacturing what he sold. He might have had an iron foundry as part of his establishment; he usually employed braziers and tinsmiths; he was likely to have a lathe and a smithy. It has been suggested, I think reasonably, that the ironmonger rather than the millwright (who generally built in wood) was the predecessor of the mechanical engineer. So we can forget the picture of Newcomen the indigent peddler and accept the more plausible likeness of a man well skilled in the machinery trade.

As for the significance of the work Newcomen did in developing the steam engine, Desaguliers states: "If the Reader is not acquainted with the History of the several Improvements of the Fire-Engine since Mr. *Newcomen* and Mr. *Cawley* first made it go with a Piston, he will imagine that it must be owing to great Sagacity, and a thorough Knowledge of Philosophy, that such proper Remedies for the Inconveniences and difficult Cases mention'd were thought of: But here has been no such thing: almost every Improvement has been owing to Chance."

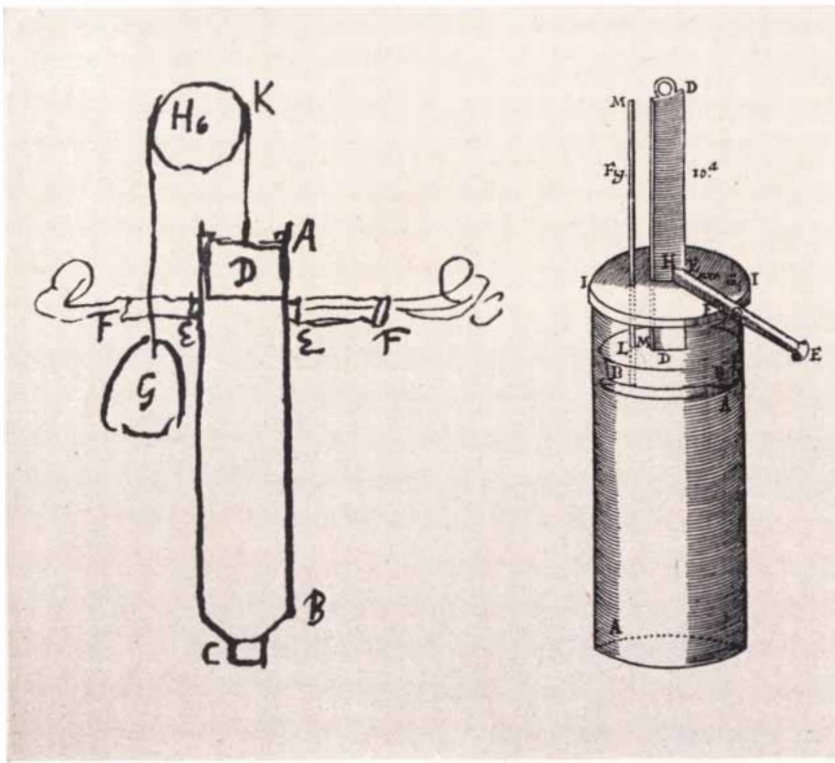
Further detraction—or inverted praise—came from Mårten Triewald, a Swedish engineer who took plans for a Newcomen engine back to Sweden with him in 1726, attributing the design to the Almighty, who "presented mankind with one of the most wonderful inventions that has ever been brought into the light of day, and this by means of ignorant folk who had never acquired a certificate at any University or Academy." Triewald did mention, however, that Newcomen worked on his machine "for ten consecutive years."

Since Desaguliers and Triewald, our principal sources, were contemporaries of Newcomen's, it is perhaps presumptuous to question their judgment. But contemporaneousness does not ensure accuracy, and Desaguliers is known as a kind of press agent of science and the arts. He was the first to publish the absurd story about Humphry Potter, the boy who, while attending a manually controlled Newcomen engine, invented the automatic valve gear in order to keep the engine running when he went fishing. The work of both authors shows them to be vain and opinionated, and it is natural to wonder on what occasion Newcomen had pricked their pompous balloons.

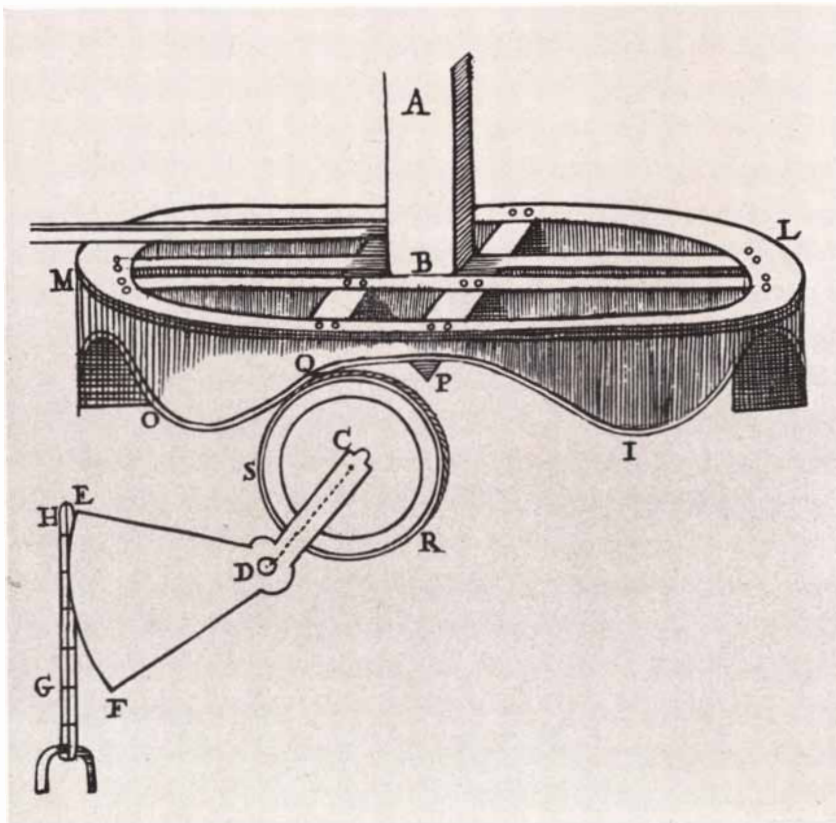
The scant biographical information does not tell us unequivocally that Newcomen's design was complete when the engine was set to work near Birmingham in 1712. L. T. C. Rolt has recently assembled evidence that suggests the exist-



MINE PUMP designed by Thomas Savery in the late 17th century envisioned condensation of steam in vessels *D* to produce a vacuum, which would create suction to draw water up from the mine to fill the same vessels. High-pressure steam would then be introduced to dispose of the water through pipe *G*. The pump did not work in mines because metalworking techniques to contain high-pressure steam were not available. It did serve to pump water into low reservoirs for use in buildings and fountains; steam pressures for that were moderate.



PRECURSORS OF NEWCOMEN ENGINE included (*left*) an idea sketched in a letter by Christian Huygens for using gunpowder to force air out of a cylinder; as remaining air cooled, piston *D* would drop. At right is design by Denis Papin using steam to make vacuum.



CAM ARRANGEMENT of a pump in 1696 was a precursor to the arch head devised by Newcomen. Horsepower turned scalloped cam, which raised and lowered wheel *C* around fixed pivot *D*, producing a pumping action by blade-shaped device attached to a lift pump.

ence a few years before 1712 of one or more unsuccessful Newcomen engines in Cornwall, near the inventor's home in Dartmouth. This would certainly make more credible the appearance of a definitive machine in 1712. In any case, a virtually anonymous ironmonger working in Dartmouth would hardly travel 175 miles to Birmingham, as Newcomen apparently did, to erect an engine unless he had connections farther afield than his home city. Although I cannot be certain, it seems probable to me that Newcomen was no stranger to London and that he quite possibly had traveled to the Continent, where he might have seen some of the great water-driven pumping engines around Paris. Just as Americans in the early 1800's went to England to learn the latest techniques in engineering, so in the 1700's Englishmen went to the Continent.

The design of the engine built by Newcomen in Birmingham in 1712 was, if not definitive, remarkably near completion. Certainly by 1717 it had been given its final form; we have an engraving made of the engine in that year. Fifty years later John Smeaton was to improve Newcomen's machine by determining after methodical empirical investigation the optimum operating conditions and proportions of parts of the engine, but Smeaton did not tamper with the inventor's essential design.

Even in its earliest manifestations the Newcomen engine was simple enough so that observers could understand its operating principle and cyclical sequence of events as soon as an explanation was provided. A vertical steam cylinder, fitted with a piston, was located under one end of the large, pivoted working beam; the piston rod was hung on a flat chain secured to the top of the arch-shaped head of the beam. Steam was supplied to the cylinder by the boiler directly below it. A vertical lift pump was located under the other end of the beam and the pump rod hung on a flat chain secured to the arch head just above it. Thus both the piston rod and the pump rod moved vertically, always tangent to a circle whose center was at the pivot of the beam.

A working stroke began after the steam cylinder had been filled with steam, at a pressure just slightly above atmospheric, from the boiler. The pump end of the working beam was held down by the weight of the reciprocating pump parts, which extended down into the mine. The steam-admission cock was closed, and water was then injected into the cylinder in order to condense the

steam and produce a vacuum. The atmosphere, acting on the top of the piston, pushed the piston down into the evacuated cylinder, which caused the pump rod to be lifted by the other end of the beam. The cycle of operation was completed by again admitting steam to the cylinder in order to allow the pump end of the working beam to go down. As soon as the cylinder pressure reached atmospheric, the spent injection water was discharged into a sump.

The cylinder was large. The first engine cylinder was 21 inches in diameter and had a working stroke of more than six feet. The effective vacuum was about half an atmosphere, enabling a 21-inch piston to lift unbalanced pump parts and water weighing one and a quarter tons. Operating at 14 working strokes a minute, the engine would develop about six horsepower. Later engines increased in size to a cylinder diameter of seven feet and a stroke of 10 feet and developed well over 100 horsepower.

The late Henry W. Dickinson, author of the current standard history of the steam engine and a principal founder of the Newcomen Society, recognized that Newcomen's contribution was the "first and greatest step" in the development of the modern steam engine, but he diluted the effect of this judgment by writing: "When we look into the matter closely, the extraordinary fact emerges that the new engine was little more than a combination of known parts."

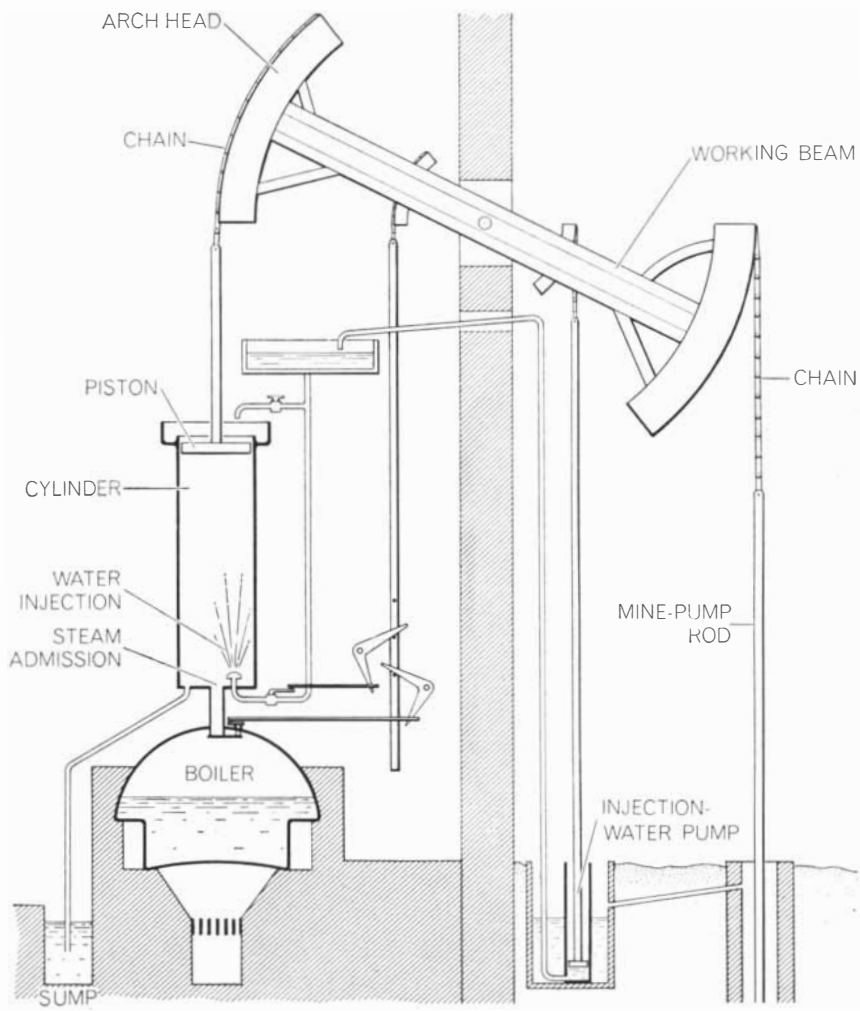
This statement brings to mind a remark made in 1853 by a correspondent of *Silliman's Journal:* "It appears that the human mind cannot arrive at simplicity except by passing through the complex; it is like a mountain more or less elevated, whose heights must be overcome before the plain at the opposite base can be reached: and when reached, the level seems to be that of the plain left behind. So when a simple solution of a problem is arrived at, we think it an easy natural thought and almost self-evident."

This, it seems to me, describes the problem we have in looking at the innovations of Thomas Newcomen from a 20th-century vantage point. In retrospect the idea of the steam engine is a natural thought, modified only by our occasional impatience with Newcomen's inability to see some obvious further development, such as the addition of a crank and flywheel, which came two generations later (shortly after having been rejected as impractical by so capable and forward-looking an engineer as John Smeaton). It is not easy for the human mind to put what is now obvious back into the box labeled "Unknown."

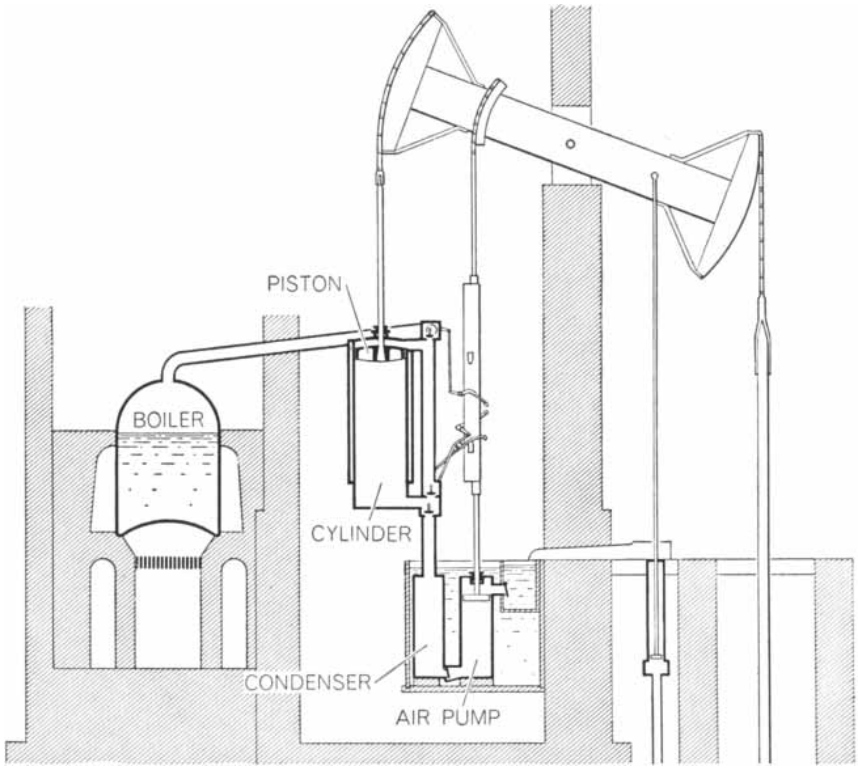
In discussing Newcomen's achievement with reference to the "known parts" of the engine it should be noted that he was not simply a clever compiler of mechanical elements. He did not employ many devices, including the crank and flywheel, that were vastly better known than some he made use of in his "combination of known parts," and most of those he did use he modified in such a way as to make the distinction between adaptation and invention seem artificial.

Consider Newcomen's use of the steam cylinder and piston. The line of development leads straight from von Guericke through Huygens and Papin to Newcomen. The cylinder fitted with a piston and evacuated by the condensation of steam was clearly present in Papin's design published in 1690 and republished in 1695, and we ought to assume that Newcomen knew at least as much about Papin's work as had been published. The steam in Papin's cylinder, however, was to be condensed by cold water dashed on the outside wall. Newcomen's essential improvement was to inject water directly into the cylinder, which sped the condensation and enabled the engine to operate at 12 or 14 strokes a minute instead of three or four.

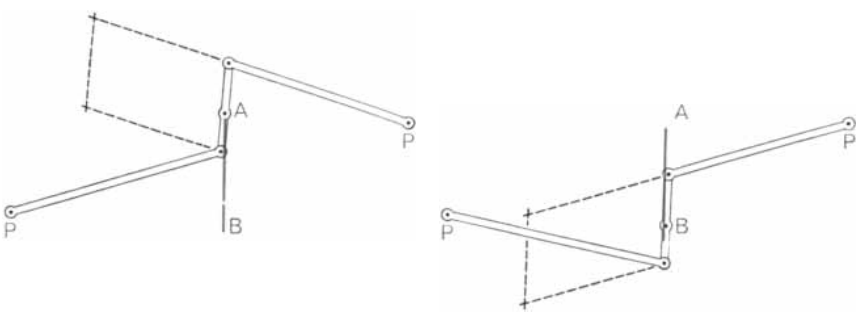
One of Newcomen's experimental engines had employed a water jacket around the steam cylinder for cooling, and it may be, as Triewald reported, that the change from external to internal cooling resulted from the accidental leakage of jacket water into the cylinder, which "immediately condensed the steam, creating such a vacuum that... the air, which pressed with a tremendous power on the piston, caused its chain to break and the piston to crush the bottom of the cylinder as well as the lid of the small boiler." Even if this report is accurate, Newcomen was still faced with the nice diagnostic problem of determining from the wreckage what had caused the



SUCCESSFUL ENGINE by Newcomen introduced steam into a cylinder that was then cooled with injection of water, creating partial vacuum. Atmospheric pressure forced piston down to achieve pumping; weight of mine-pump rod and equipment then raised piston for new cycle.



CONTRIBUTIONS BY WATT to the steam engine included the development of a separate condenser, as depicted here. Newcomen had effected the condensation in the main cylinder.



PARALLEL MOTION was another major contribution by Watt; it kept piston rod vertical as beam end moved in an arc. Three key elements (*solid lines*) worked from fixed pivots *P* so that rod end, at center of vertical element, moved along line *A-B*. Watt's final version made use of a parallelogram linkage (*broken lines*) that made whole apparatus more compact.

sudden smash. Serendipity in no way diminishes Newcomen's role in the innovation of injection condensation.

In his use of the boiler Newcomen was adopting a thoroughly developed "known part." Made of copper, the boiler probably was derived directly from the brewer's kettle. Since the steam pressure was low—Newcomen set his safety valve to open at about 1.5 pounds per square inch above atmospheric pressure—the difficulties of design and construction were few. Indeed, the boiler was similar to the one built by Savery.

The full synthetic ability of Newcomen, and his judicious critical sense, are revealed in his treatment of the working beam, the pump and the valve gear. The working beam and pump can be examined together, because their appearance is that of a greatly enlarged pump handle or well sweep attached to a common reciprocating lift pump. Before Newcomen's day few, if any, mines in England were drained by lift pumps attached to beams, pump handles or sweeps. Where the topography of the mining district permitted, long drainage tunnels called adits were dug from the lowest mine level to a lower open valley in the vicinity. Although the adits were small in cross section, some of them extended for two miles or more. Even after a mine was deepened beyond its adit level, water had to be pumped only as high as the adit. When surface water was available, an underground water wheel, receiving its water from ground level and discharging into the adit, would operate a lifting device of some kind, usually a chain of buckets.

In some larger works, where horses could be used, the water was lifted in great tubs by a whim, or horse gin. The hoisting rope was wound on a horizontal drum geared to a vertical shaft. The vertical shaft, fitted with a hub with radiating arms, was dragged around by horses hitched to the ends of the arms. In smaller mines, where only manpower was available, a horizontal drum turned by hand cranks was used to hoist buckets or drive a rag-and-chain pump.

If Newcomen had seen a copy of Agricola's mining book, he would have found reciprocating lift pumps in profusion, but he would have come away from the treatise with the distinct impression that the proper way to move the rod of the lift pump up and down was to hang it on a crank arm, that is, to employ a crank and connecting rod. There is one simple beam pump in Agricola, but it is a small one operated by the power of a single man.

Among the actual devices that Newcomen might have seen was a large overhead pivoted beam, without arch heads, in the horse-driven water pump at York House in London. The London Bridge waterworks, although they employed cranks and connecting rods, had the lower third of a large pulley cut away in a manner that faintly suggests the arch heads at the ends of the Newcomen engine beam. The almost complete absence of the arch head from pump beams in the illustrations that Newcomen might have seen is most striking. A sketch in Leonardo da Vinci's notebooks could hardly have been known to Newcomen because the notebooks were effectively buried until the 19th century. Only one illustration remains as the possible—or probable—source of Newcomen's arch heads. In a book by Venturus Mandey and James Moxon—*Mechanick-Powers: or, the Mistery of Nature and Art Unvail'd,* published in London in 1696—there is a cam-operated pumping device that clearly shows the sector-and-flat-chain arrangement adapted by Newcomen, who changed the shape of the beam from curved to straight. The drawing in the Mandey and Moxon book was copied directly from an earlier work edited by Philippe de la Hire, a French mathematician and member of the Académie des Sciences, who had directed

the building of such a pump to supply water to a castle near Paris.

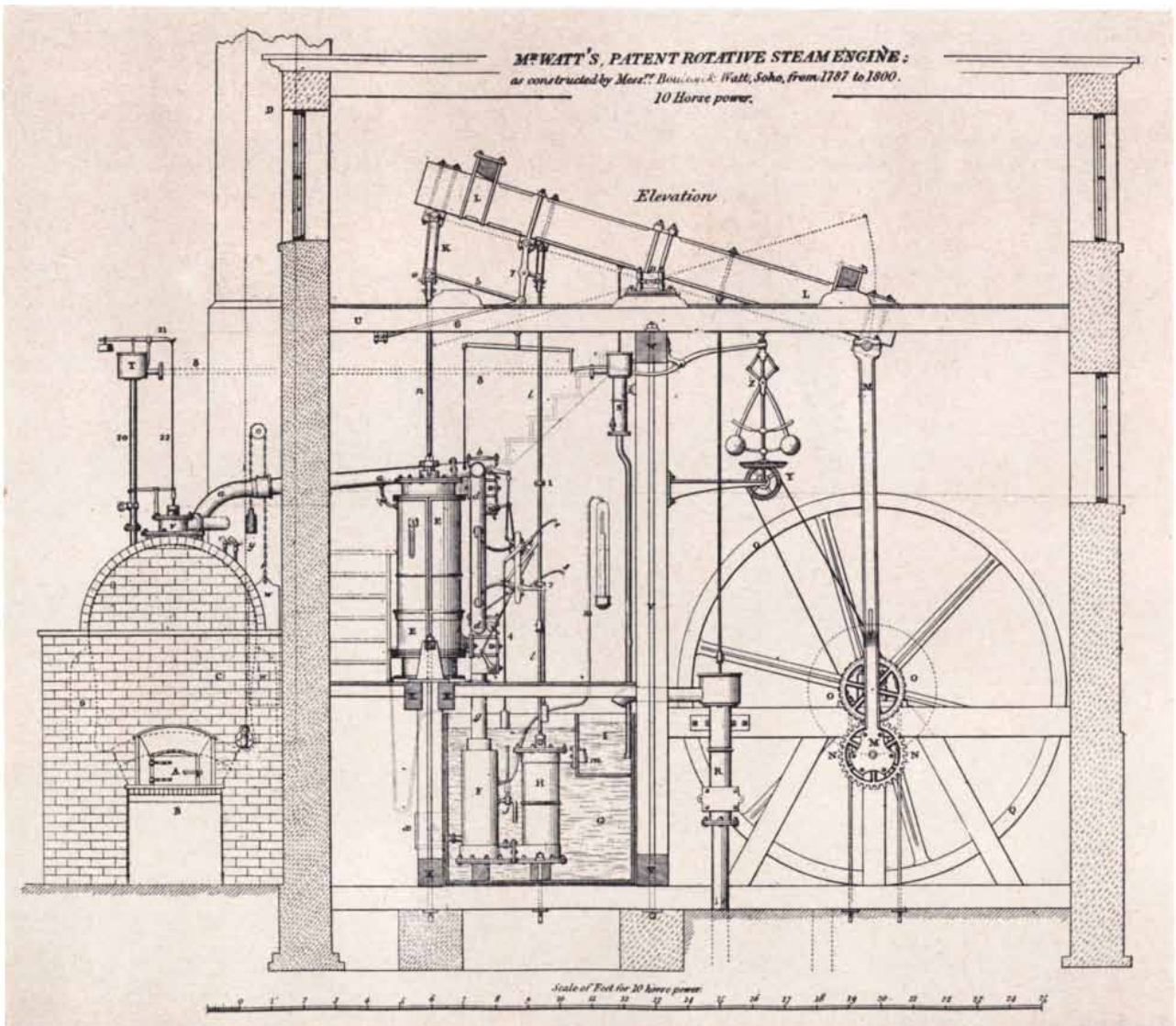
Thus the working beam of the Newcomen engine appears to be an elegant adaptation, not a copy, of ideas that existed before he designed his engine. I have labored this point in order to emphasize the fact that Newcomen was not merely adapting the steam cylinder to a widely used system of water-raising. His engine was a new and original system in itself.

The origin of the valve gear, which enabled the engine to operate automatically—opening and closing valves as required for the sequence of operations—is similarly obscure. The idea may have been suggested to Newcomen by a control mechanism of the automata—knights, maidens and animals—that performed at an appointed hour in the great medieval clocks. The Newcomen engine valve gear was a sequential control; it remained for Watt to supply a regulatory feedback control system. Newcomen's system, however, was much more involved than, for example, the control of the rate of a common clock.

Even after all the elements of the steam pumping engine had been settled on, however, there was still the problem of the physical arrangement of the elements. Pictures of the gaunt and unsymmetrical profile of the Newcomen engine set against the English landscape, with its awkwardly tall stone enginehouse and its outlandish protruding beam threatening to topple the whole assemblage, make it difficult to believe that there was anything about the arrangement that could not have been built differently if the "right way" had not been shown boldly by Newcomen. As an assemblage of elements, some adopted but most adapted, the engine was a clear statement of the builder's personal style of invention.

The genius of James Watt was of a different kind, and to discuss the difference in terms of superiority smacks of useless historical partisanship. Newcomen selected the components of a steam engine and gave to each its proper place and function. Watt, on the other hand, originated at least two new major components, and in making a brilliant adaptation of a third he introduced the world to the notion of feedback for automatic control.

Watt began his work on steam engines in 1763, when, as an instrument maker at the University of Glasgow, he undertook the repair of a teaching model of



WATT ENGINE was depicted in this 1826 illustration. The engine transformed the vertical action of the piston rod *n* into rotary motion through the flywheel *Q*. Watt's special contributions included condenser *F*, parallel-motion linkage at left end of beam, centrifugal governor *Z* and "sun and planet" gear mechanism at center of flywheel, causing wheel to turn at double the speed of the engine.

a Newcomen engine. His careful and sustained study led him in 1765 to recognize that he might increase the thermal efficiency of the engine, as well as its capacity and operating speed, by condensing the steam in a chamber attached to, but separate from, the main steam cylinder. This was the first of his most important innovations.

His earliest patent, which included the separate condenser, was granted in 1769, but his first successful full-sized engine was not completed until 1775, the year in which Matthew Boulton became his partner. Parliament granted a patent extension to Watt that year, providing a virtual monopoly on the condensing steam engine for 25 years.

After Watt had devised a double-acting engine, in which steam moved the piston first in one direction and then in the other as it was admitted alternately to each end of the cylinder, the arch head and flat chain no longer sufficed to guide the upper end of the piston rod, because the chain transmitted force in tension only. Accordingly in 1783 Watt brought forth his second major innovation: the straight-line linkage that bears his name. Refining further his first ideas, Watt combined the straight-line linkage with a pantograph, a linkage system in parallelogram form, to produce the so-called "parallel motion" [*see bottom illustration on page 104*].

In these two inventions we find a measure of Watt's capacity: the separate condenser was neither anticipated nor invented independently by anyone else, and the parallel motion solved a problem whose existence was not even suspected until Watt overcame it. For the next 100 years mechanics and mathematicians occupied themselves in a search for alternative solutions.

Finally, in 1788 Watt adapted the centrifugal "flyball" governor to control the speed of his engine by linking the governor to the steam-inlet valve. The flyball governor had been used in grain mills to increase the distance between the flat grinding stones as their speed increased. Watt's use of the governor, however, added the far-reaching principle of feedback that made possible self-regulating, rather than merely automatic, machines. The ordinary steam engine and the Watt engine were built, in the words of Boulton, "with as great a difference of accuracy as there is between the blacksmith and the mathematical instrument maker." Thus the few astonishingly sophisticated Boulton and Watt engines in service toward the end of the century hurried a generation of machine builders to a higher order of accuracy, which in turn called for a whole new array of large, rugged and precise machine tools. The influence of the new tools on mechanization was profound and can be traced directly to the present. The effect of the separate condenser and self-regulating speed control on the direction of industrial technology can be appreciated if we recognize that their invention was an essential step toward the modern steam turbine. Undeniably Watt opened doors whose very existence might have gone unnoticed for 100 years after his time.

The Watt steam engine was twice as efficient, from the standpoint of fuel consumption, as even the best Newcomen engine. A recent study by two English economic historians, A. E. Musson of the University of Manchester and E. A. G. Robinson of the University of Cambridge, has shown, however, that both Savery and Newcomen engines were being built long after they had been

WORKING PUMP of Newcomen design is shown at a colliery in England. The pump was in use from 1791 until 1918. Subsequently it was taken down and re-erected at the Science Museum in London. Part of the working beam is visible below catwalk at top center.

made obsolete by Watt's improvements, and that Boulton and Watt supplied only about a third of all steam engines built during the 25-year period of the patent monopoly (1775–1800). It is also clear that a two-cylinder Newcomen engine capable of turning machinery was in existence, and that the high-pressure engines operating without condensers of any sort were soon to be built by Richard Trevithick in England and Oliver Evans in the U.S.

Since hindsight is one of our best-developed faculties, it has been possible for writers for more than 200 years to dismiss the appearance of the Newcomen engine of 1712 as well as the Watt engine of 1775–1788 as being merely normal responses to industrial demands. The well-established axiom of simultaneous but independent discovery, which can be interpreted to mean that a particular invention is inevitable, has been applied to suggest that if Thomas Newcomen had not built his engine, somebody else would have done so at about the same time.

This seems no more accurate in the case of Newcomen than in the case of Watt. In looking carefully at the Newcomen engine, it has become increasingly evident to me that it represents a unique solution to the problem the inventor set out to solve. There was no anticipation of the completed engine, and nobody came forward to contest Newcomen's priority of invention. The first radical modification occurred no sooner than 50 years later, when Watt conceived the separate condenser.

Newcomen was not the first man to "discover" the correct way to build a steam engine; there is no correct way. It is conceivable, for example, that he might have made the cylinder horizontal rather than vertical, that he might have supplied steam above atmospheric pressure (only eight pounds per square inch would have sufficed to do the work), or that he might have used a crank, connecting rod and flywheel. Any of these variations would have been possible if he had approached the problem differently. But by producing a machine that was a pumping engine, not easily adapted to the turning of wheels, Newcomen limited the options that lesser engineers could exploit in the future. He did the job his way, and he gave the world such a convincing statement of rightness in the machine he put together that he exerted an enormous influence on the direction in which English technology would proceed for the next several generations.

Photographic interpretation by William Thonson

Advances in Field Emission

A needle-shaped cold cathode in an electric field can emit a beam of electrons. The large current density and high power available from a small field emitter have many applications in electronics

by W. P. Dyke

Much of electronics depends on the emission of electrons from metals and the manipulation of those electrons to perform various tasks. Electrons can be induced to leave a metal in a number of ways, most of which involve supplying them with additional energy. In an ordinary radio tube, for example, a negatively charged filament—the cathode—is heated so that free electrons "boil" out of the metal and are accelerated by an electric field toward the positively charged anode. In recent years another kind of electron emission that has interested physicists for some time has gained technological significance. It is called field emission because it requires no input of energy to the cathode but simply the presence of a strong electric field between cathode and anode. Its advantage is that it can deliver a high-density stream of electrons from an unheated cathode of extremely small dimensions. To the electrical engineer this large current density suggests several lines of application: miniaturization of components, very high power levels or—perhaps most interesting—a means of attaining the high "information rates" required in electronic devices ranging from fast oscilloscopes to compact X-ray machines for studying high-speed phenomena.

Field emission was discovered by R. W. Wood of Johns Hopkins University in 1897, but it was not much studied until the 1920's, when a number of physicists tried to exploit it for the generation of X rays. Although 30 years were to elapse before cold-cathode X-ray tubes became practical, these investigations did confirm Wood's finding that electrons could be emitted without any input of energy. During this period Robert A. Millikan and Charles C. Lauritsen of the California Institute of Technology also noted another important property of field emission: the emitted current is an exponential function of the field or the applied voltage. Neither of these properties could be understood in terms of classical physics and the physical model that had explained electron emission until then.

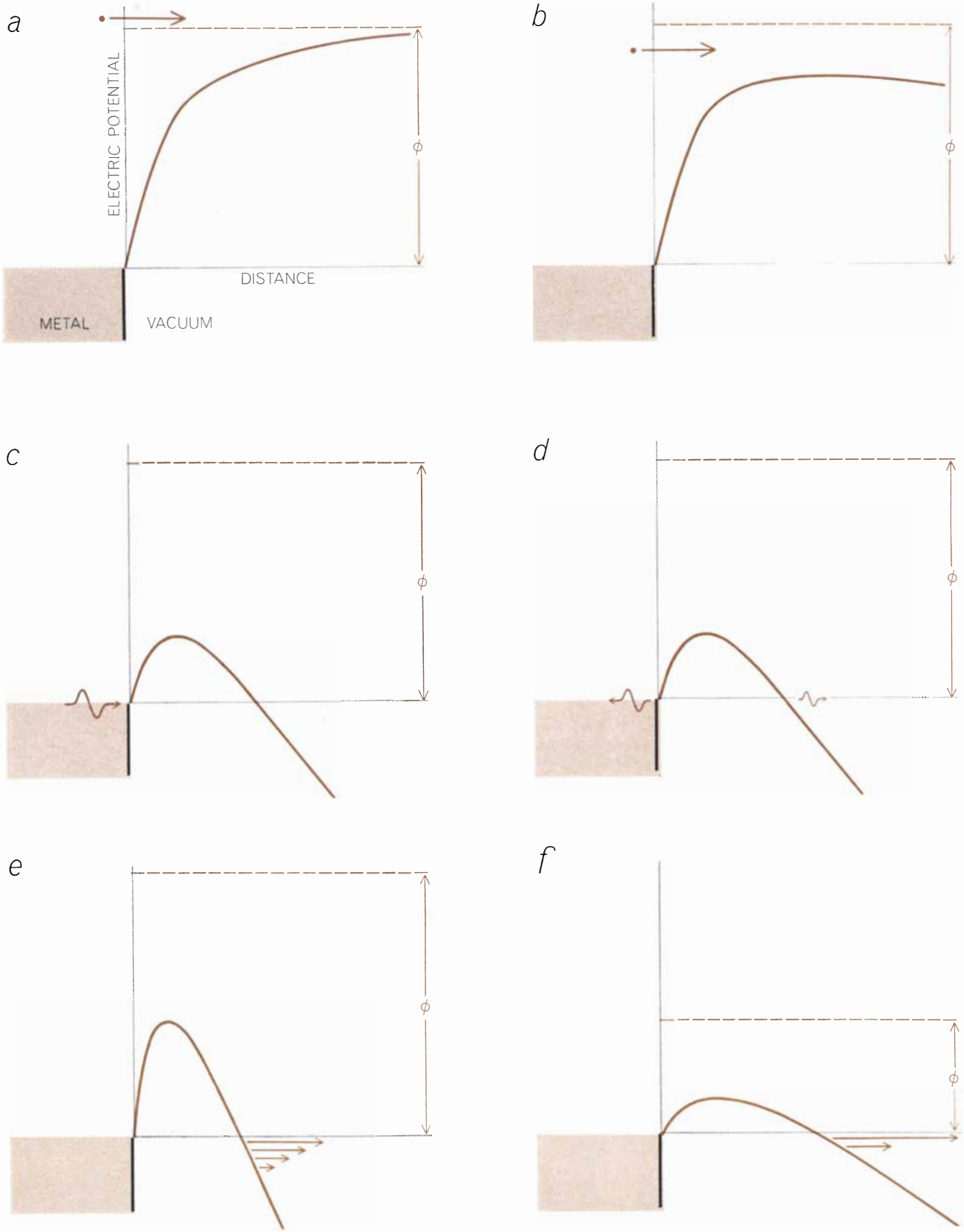
According to that model the free electrons in a metal are contained at the surface by an electric potential barrier; the electrons cannot surmount the barrier unless they are raised to an energy level at least as high as it is [*see illustration on opposite page*]. The minimum energy required is called the work function, and it is designated by the Greek letter phi. This energy can be supplied by heat (thermionic emission), light (photoelectric emission) or bombarding particles, usually other electrons or positive ions (secondary emission). There must, however, be an input of energy.

The German physicist Werner Schottky had shown that the presence of a strong electric field modified this energy requirement by thinning the potential barrier and reducing its height. The Schottky effect had explained the small increases in thermionic emission that were attained when fields of about 100,000 volts per centimeter were applied. Some physicists suggested that still stronger fields might lower the barrier sufficiently for the most energetic electrons in the cold metal to escape over the top without any added energy. They calculated, however, that this should occur only in fields of the order of 100 million volts per centimeter—and they detected field emission in fields 10 to 100 times weaker. Clearly some other explanation was needed.

It was soon supplied by the new concepts of quantum mechanics, according to which an electron behaves like a wave as well as like a particle. A wave could "tunnel" right through a thinned potential barrier instead of hurdling it. In 1928 R. H. Fowler and Lothar W. Nordheim of the University of Cambridge developed a wave-mechanical theory for field emission that still appears to be essentially correct. It accounted for the known effects of the phenomenon and predicted other effects that have since been confirmed by experiment.

First of all, the Fowler-Nordheim equations made it clear that field emission currents depend on the applied electric field and on the work function of the cathode; no heat energy is required. This effect was specifically verified by G. Fleming and J. E. Henderson of the University of Washington in 1940. Robert Gomer of the University of Chicago recently demonstrated that the emission process persists even at very low temperatures by obtaining field emission from a cathode immersed in liquid helium at 4 degrees Kelvin (4 degrees centigrade above absolute zero). The practical significance of this effect is that a field emitter needs no heating element or heating circuit; this makes it a simpler device that can respond instantly without warming up.

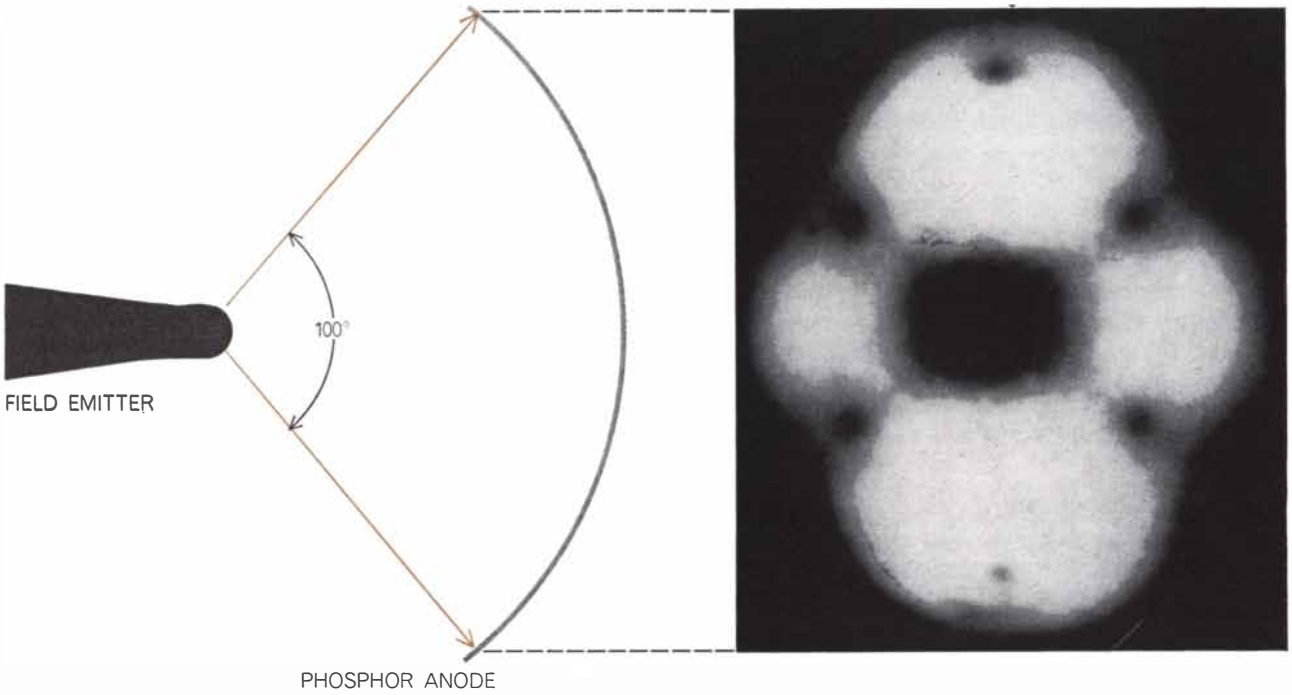
The Fowler-Nordheim theory also showed that the emitted current should increase exponentially with the applied electric field in just the manner observed earlier by Millikan and Lauritsen. As the increasing electric field thins the barrier, the emitted current builds up rapidly, a 1 per cent change in field causing about a 10 per cent change in current. As a highly nonlinear device the field emitter is a suitable component for certain amplifiers, frequency multipliers, modulators and voltage-control and -measurement devices. Experimental models of



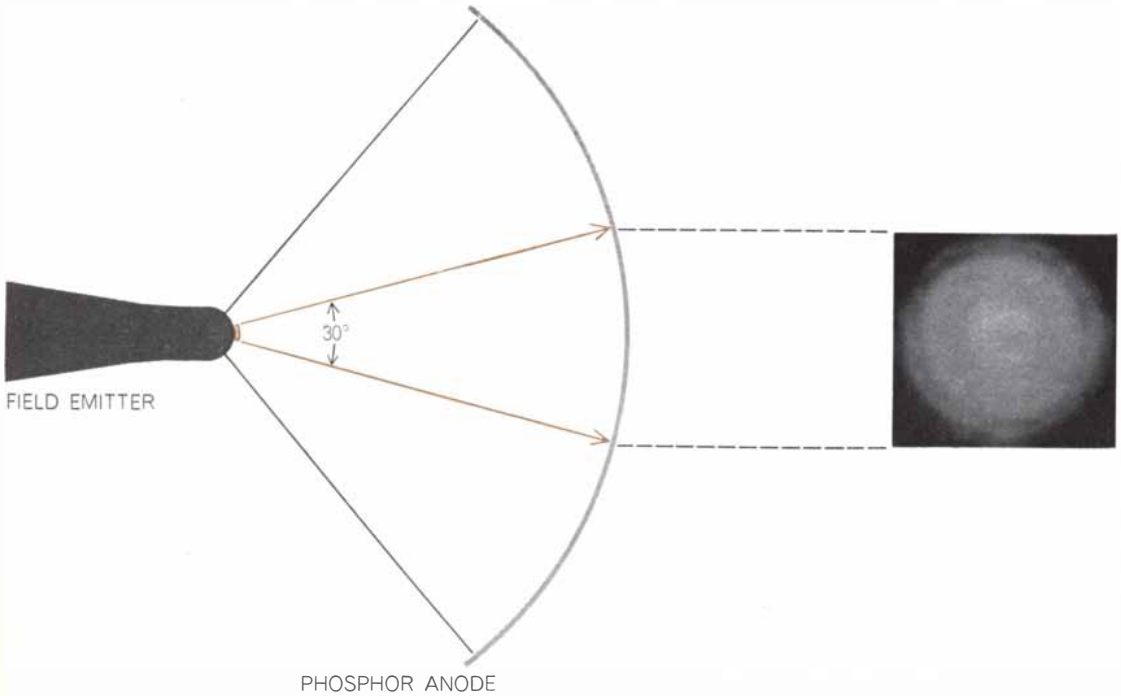
POTENTIAL BARRIER confines the free electrons in a metal at the surface (*black bar*). The barrier (*colored curve*) varies in potential (*vertical axis*) with distance from the metal (*horizontal axis*) according to the electric field near the metal. In the absence of a field (*a*) an electron (*colored dot*) can escape only if it is given energy in the amount of the work function (φ) to enable it to surmount the barrier. The presence of a moderate electric field produces the Schottky effect (*b*), in which the barrier is thinned and lowered. Field emission occurs when a stronger field thins and lowers the barrier more. An electron, visualized as a wave (*c*), strikes the barrier and is in part reflected and in part transmitted by tunneling: through it rather than over it (*d*). The energy distribution of field-emitted electrons is related to the work function of the emitter metal. When it is high (*e*), electrons (*colored arrows*) at various energy levels penetrate the barrier; when it is low (*f*), the escaping electrons are all at about the same energy level.

each of these devices have been built and operated.

Another prediction of the wave-mechanical theory was that field emission electrons would have a nearly uniform energy. The physical basis for this narrow energy distribution is the relation between the energies of the electrons in the cathode and the slope of the potential barrier. Only electrons at or near the conduction level, the most energetic occupied level in the cold metal, encounter a thin barrier and have a high probability of transmission; electrons of lower energy strike a thicker barrier and are usually reflected. The slope of the barrier and therefore the energy spread depend on both the work function and the electric field; for tungsten, with a work function of 4.5 electron volts, the energy spread is about .2 elec-



ELECTRON BEAM diverging from a field emitter forms a pattern when it strikes a phosphor screen. This is the principle of the field emission microscope. The photograph is of the emission pattern for tungsten; its details are related to the structure of the emitter crystal. Dark areas correspond to regions where atoms are closely packed, the work function is high and there is little emission.



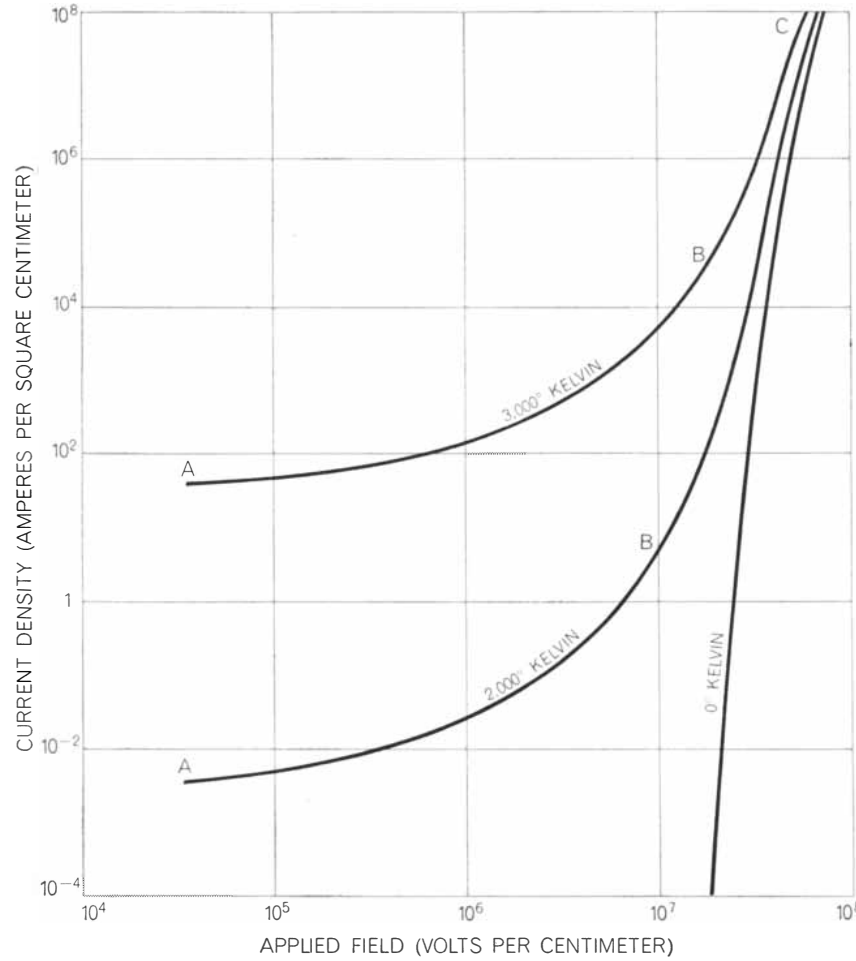
NARROWER BEAM can be attained by coating the tip of the emitter with a metal that has a lower work function than tungsten, such as zirconium. It adsorbs in a small region (*colored*) and creates a "hole" through which electrons are emitted preferentially. The beam is thereby confined to a narrow cone (its emission pattern is shown at the right) and can be collimated or focused.

tron volt; for tungsten coated with cesium it is only .07 electron volt. The practical advantages of narrow energy distribution are the reduction of "noise" and of optical aberrations in the beam.

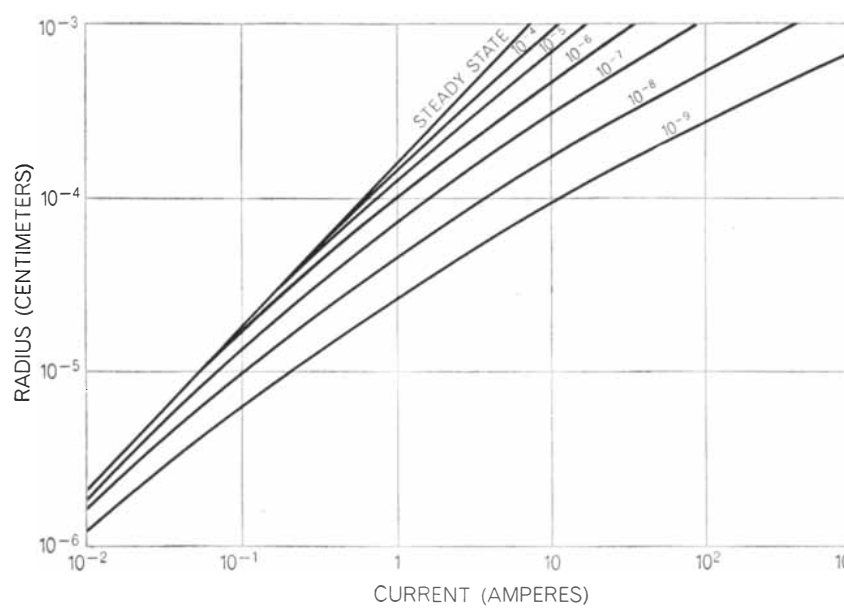
The most significant prediction of the new theory was the very large current densities: of the order of 100 million amperes per square centimeter of emitter surface, or about a million times larger than the current densities in thermionic emission. This is the case because in field emission a large fraction of the conduction electrons that strike the barrier have a chance of emission; in a heated cathode only a few of the electrons can acquire sufficient energy to leave the metal. Since there are about 10^{22} free electrons in each cubic centimeter of a metal, the number of electrons striking the potential barrier is enormous, and at a high enough field about one in 100 incident electrons can escape. What was a real barrier becomes a semitransparent sieve. The current-density prediction was confirmed in Germany in 1940 by R. H. Haefer, who obtained a million amperes per square centimeter. It was primarily the promise of high current densities that impelled our group, then at Linfield College in McMinnville, Ore., to undertake an intensive study of field emission in 1946. We have obtained steady currents of 10 million amperes per square centimeter and intermittent pulses 10 times higher.

One property of field emission that was not predicted by the original Fowler-Nordheim theory and that becomes significant at large current densities is the effect of the emitted electrons themselves on the field that causes their emission. What happens is that the charge on the emitted electrons opposes the electric field and tends to reduce it; this in turn limits the density of the electron beam. The result is that beam density is found to increase rather less rapidly than expected with applied voltage. Fowler and his colleagues predicted this "space charge" effect in 1929 but could not draw large enough currents to demonstrate it. At Linfield College we observed the effect in 1953. As a result it was possible to modify the basic theory and express emitted-current density as a function of applied voltage rather than of the field, with allowance for the space-charge effect.

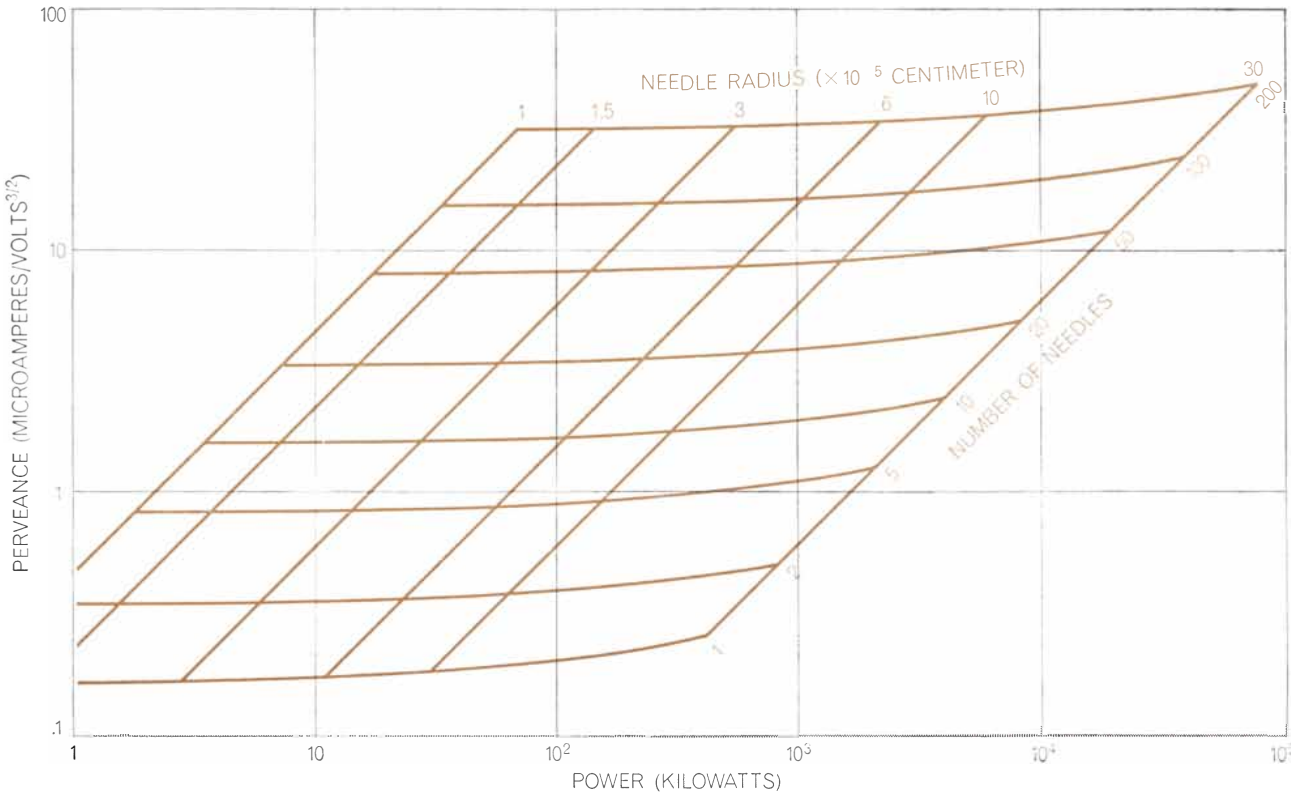
The effect is a mixed blessing. On the one hand, it functions as a partial feedback that tends to protect the emitter against excessive current densities caused by accidental increases in the



CURRENT DENSITY in relation to field is shown for tungsten emitters, two of them heated and one a cold-cathode field emitter. When the field is moderately high (*A-B*), electrons in the heated cathodes are emitted primarily over the potential barrier (Schottky effect); at very high fields (*B-C*) emission is primarily by tunneling and increases, as it does in the case of cold-cathode field emission, very rapidly with an increase in the electric field.



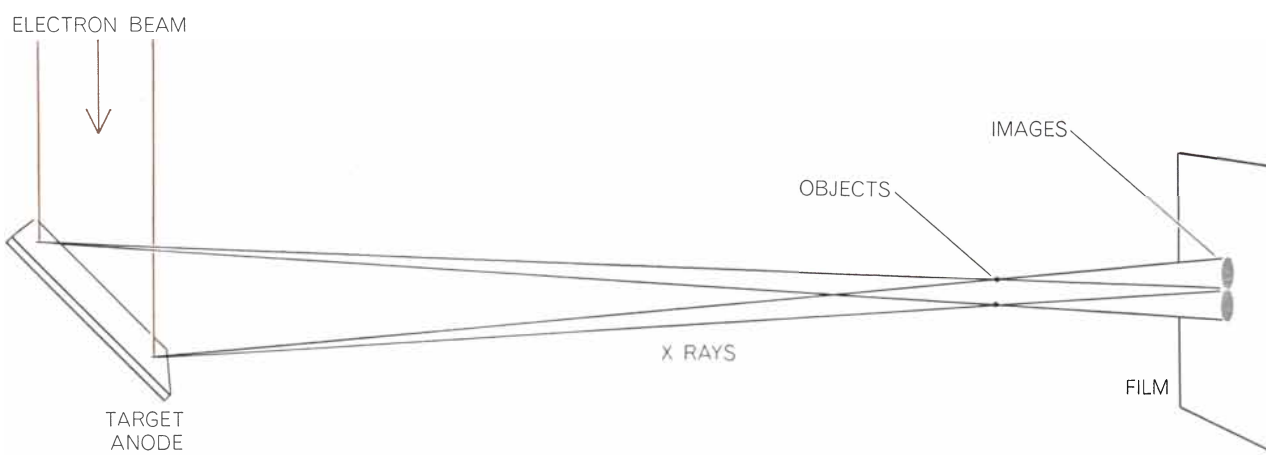
SINGLE-NEEDLE CATHODES of various sizes can emit the maximum practical currents shown here. Each curve is for an emission pulse of a different duration (in seconds).



MULTIPLE-NEEDLE CATHODES perform, according to theory, as shown in this graph. Perveance is a measure of conductance that takes into account the "space charge" effect; here it is equal to the current in microamperes divided by the voltage raised to the 3/2 power. For example, 10 needles with tip radii of .00006 centimeter should deliver a perveance of about 2 and a power of about 100,000 watts. Output is actually somewhat lower because needle shapes may vary slightly and each needle reduces its neighbors' fields.

field or voltage, and to smooth out small differences in the energies of the emitted electrons. On the other hand, space-charge effects can increase the divergence of the electron beam and reduce the sensitivity of the emitted current to applied voltage. Fortunately the emitter can in many cases be operated satisfactorily at current densities below the level at which space-charge effects become serious.

A field emitter is commonly made of tungsten fashioned in the shape of an extremely fine needle, primarily to take advantage of the intense field that surrounds a sharply pointed conductor and so to hold the necessary voltage to a reasonable level. A typical cathode has a hemispherical tip from one micron to a hundredth of a micron (10^{-4} to 10^{-6} centimeter) in radius—many times smaller than the point of an ordinary pin. The tip usually includes only a single crystal of the metal, so that the hemispherical surface includes all faces of the crystal. Since the field decreases with distance



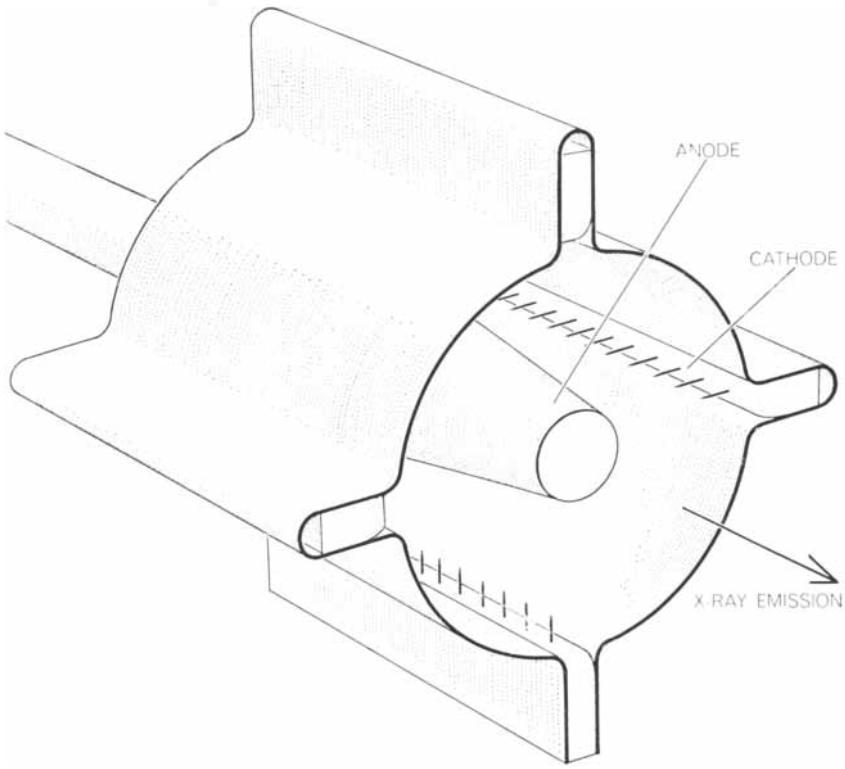
X RAYS are formed when an electron beam strikes a target anode, the X-ray source. An object that absorbs X rays casts a shadow image on a photographic plate or film. The image is enlarged, or blurred, as shown. In this case the two objects are just far enough apart to be resolved. Resolution improves with small source size, which the large current densities of field emission can provide.

from the tip, significant current densities are emitted only from a small area at the tip. Because of the curvature of the emitter surface the electron beam diverges to form a cone. The vertex angle at the emitter tip is, in the case of tungsten, about 60 degrees at low current densities and about 100 degrees at high densities.

When such a beam is allowed to fall on a phosphor screen concentric with the cathode surface, a visual emission pattern is formed [*see upper illustration on page 110*]. The higher the current density emitted from a point on the cathode, the brighter the corresponding image on the screen. The emission nulls, or dark spots, correspond to crystal faces where the atoms are closely packed, the surface is relatively smooth and the work function is therefore high. This is the principle of the field emission microscope invented in the 1930's by Erwin W. Müller, now at Pennsylvania State University [see "A New Microscope," by Erwin W. Müller; SCIENTIFIC AMERICAN, May, 1952]. The microscope, which for many years was the only practical field emission device, visualizes the effects of various phenomena at the surface of metallic crystals on what is nearly an atomic level. It has become an increasingly useful tool for analyzing physical and chemical phenomena that affect the work function or surface configuration. Various investigators have used the field emission microscope to study such phenomena of metal surfaces as catalysis, adsorption, desorption and epitaxy.

A rather unusual property of a field emitter, then, is that it is its own microscope. We have been able to learn a great deal about changes affecting the life and stability of emitters by examining their emission patterns, and to apply the resulting data to further development. It is interesting to note that the effectiveness of the field emission microscope depends on the high information rate derived from its large current densities. The large current makes it possible to photograph an emission pattern in a hundred-millionth of a second; the resolution allows a minimum of 1,000 discrete "bits" of information in the pattern. The information rate (10^3 bits in 10^{-8} second) is therefore 10^{11} bits per second.

Whereas the field emission microscope benefits from the divergence of the electron beam, many electronic devices require a parallel or finely focused beam. This can be attained with field emission by first limiting the divergence of the



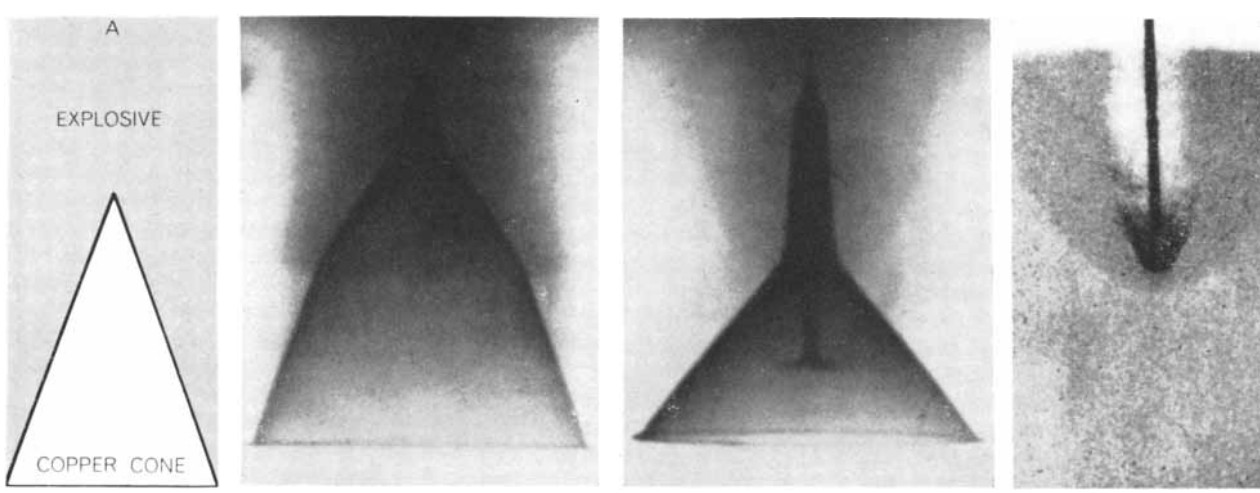
X-RAY TUBE using field emission is shown in an enlarged, highly schematic diagram. Electrons emitted from four comb-shaped cathode arrays strike the conical anode where X rays are formed. A small tube is six inches long; the diameter of the truncated end of the anode is about a millimeter and the dose is about 10 million rads per second at the tube face.

beam at the emitter. We coat a portion of the emitter surface with a low-work-function material such as zirconium. The coating, which conveniently adsorbs in a very small area around one face of the tungsten crystal, lowers the potential barrier in the area so that electrons escape only through a small "hole" and the vertex angle of the beam is restricted to about 30 degrees [*see lower illustration on page 110*]. Such a beam is narrow enough to be collimated or focused with electrostatic or magnetic lenses.

Although the performance of field emission devices generally improves with increasing beam density, there is a level beyond which the current cannot be pushed without creating a vacuum arc. At densities higher than 10^8 amperes per square centimeter the emitter temperature increases to a point at which surface material evaporates, is ionized rapidly in the electron beam and becomes a plasma. This tends to neutralize the space charge and thereby to increase the electric field, the current density and the heating of the emitter. The end result of this cycle is a sudden surge of current; an arc develops that consumes emitter material and changes the shape of the cathode. To prevent such arcs one must limit the current density to a safe level—around 10 million amperes per square centimeter. This is accomplished by controlling the applied voltage and the condition of the cathode surface.

Although the arc is generally to be avoided, its ability to consume metal has its uses. A controlled arc can remove undesired surface projections (on the shank of the emitter needle, for example) that would otherwise cause field emission in the wrong place. The arc is also a tool with which to shape emitters by dulling and rounding their tips, or with which to clean the tips by vaporizing adsorbed contaminants.

The arc even has certain advantages as a source of electrons. It can produce current densities considerably higher than those available from field emission, and do it very quickly. The serious problem, of course, is that the arc changes the shape of the emitter and so affects the geometry on which its initiation de-



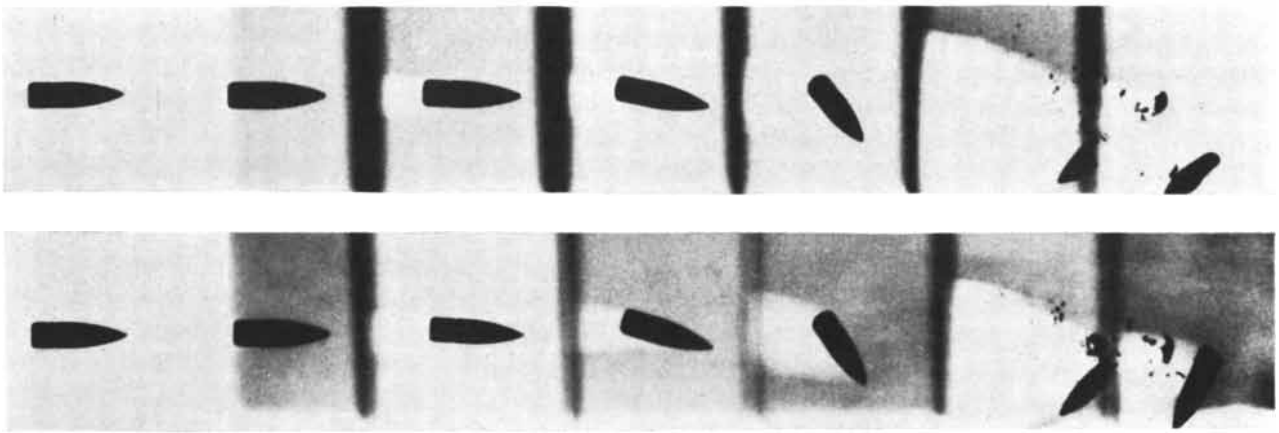
SHAPED EXPLOSIVE CHARGE (*diagram at left*) has a conical depression lined with a thin sheet of copper. Radiographs made at the U.S. Army Ballistic Research Laboratory show what happens when the explosive is detonated at *A*. As the detonation front advances the cone breaks down; a thin jet of molten metal forms in the center. Striking a polyethylene target (*right*), the jet digs a cavity and sets up a shock wave. Exposures were .2 microsecond for the first two pictures and .05 microsecond for the third one.

pends, making it difficult to maintain the arc's current-to-voltage relation from one pulse to another. No complete solution for this difficulty has yet been found, but C. M. Slack of the Westinghouse Electric Corporation was nevertheless able to utilize the arc in a triode flash X-ray tube that performed reliably for a few hundred shots. Some arc X-ray tubes now last for more than 100,000 shots.

The high current densities of field emission can be exploited, as indicated earlier, in various ways. Single-needle cathodes have been used mainly in devices that operate at relatively low power levels, such as cathode-ray tubes or voltage-measurement and -control tubes. Single needles operating at low power can be introduced into extremely small structures, which suggests that field emitters may in time be employed as active elements in miniaturized circuits. An electron source small enough to fit inside a standard hypodermic needle, for example, can easily deliver a peak power of 100 watts. A single needle can, on the other hand, deliver considerable power if a high enough voltage is applied. A needle with a tip radius of 6×10^{-4} centimeter can emit a current of 140 amperes if it is pulsed at 300,000 volts for 10 billionths of a second [*see bottom illustration on page 111*]. The beam power is 42 million watts—from a cathode that can be seen clearly only with a high-power microscope.

Some devices such as microwave tubes, however, require a high conductance—large currents at relatively low voltages—and this a single needle cannot yet provide. The solution we have worked out is to arrange several needles in a comb-shaped configuration and operate them in parallel. By varying the size and the number of the needles it is possible to obtain a wide range of conductances and power levels [*see top illustration on page 112*].

It might appear almost impossible to fabricate a group of tiny needles sufficiently uniform to operate in parallel, since in order to keep the emitted currents within 10 per cent of one another the cathode geometries must be held to a tolerance of about 1 per cent. Actually it is quite feasible. The needles are first sharpened by electrolytic polishing to a radius of about a millionth of a centimeter and then the tips are dulled by being heated in a vacuum. The rate of dulling depends on surface forces that vary with tip radius, so that the sharper needles dull faster and the radii



.30–'06 BULLET is seen penetrating a block of gelatin in these filmstrips made by two arrays of X-ray tubes that recorded the event from two directions. The stereoscopic radiographs provided an accurate record of the trajectory and also showed how the bullet tumbled and broke up. The pictures were timed in advance on the basis of the bullet's approximate velocity. Exposures were .1 microsecond.

become nearly equal. Manipulation of the temperature and the electric field during this procedure provides further control of the shape of the tip. In practice a group of needles can be made to emit in parallel at a common voltage with between 70 and 100 per cent efficiency.

At the end of World War II the best performance available from field emitters was an average power of a few watts drawn stably for about an hour. Through field emission microscope studies we were able to identify the principal causes of instability and short life: surface contamination and "sputtering," which occurs when an emitter is buffeted and pitted by positive ions, usually gas ions that are present even in fairly high vacuums. We were able to reduce both of these effects by improving our vacuums, and after a while we obtained from a single needle a steady-state current density of 10 million amperes per square centimeter that persisted for 1,000 hours at an average beam power of 35 watts. Later, using a group of 20 needles, we increased the average beam power to some 300 watts and the operating periods to more than 20,000 hours. Even longer emitter life should be attainable in the future.

These tests were conducted with simple diode tubes in ultrahigh vacuums. Pressures of less than 10^{-12} millimeter of mercury were attained by ion pumping and the use of special materials to prevent the diffusion into the vacuum of atmospheric helium, which is a particularly effective sputtering agent. These vacuums have been successfully applied in some commercial X-ray tubes. In certain applications, however, it is impossible to maintain such high vacuums. We have found that a field emitter will operate for reasonable periods in lower vacuums if the needle is periodically reconditioned by a flash of high temperature that smoothes and cleans its surface. Because of the emitter's microscopic size very little energy is needed and a flash duration as short as a millisecond may suffice; the interval between flashes depends primarily on the vacuum and power level and varies from a few minutes to a few hundred hours.

The most successful application of the field emitter to date has been in flash X-ray tubes characterized by small size and a high information rate. We developed our first X-ray tube in 1953 at the suggestion of Floyd A. Odell, then a ballistics worker at the Edgewood Arsenal. Although it had sufficient intensity only for microsecond radiographs of small animals, it caught the attention of Colonel H. S. Morton and Eugene Nooker at the Applied Physics Laboratory of Johns Hopkins University. Their interest led to support from the U.S. Navy's Bureau of Ordnance for the development of field emission flash X-ray devices.

In its simplest form an X-ray tube includes an electron-beam source and a metallic anode, or target. The electrons strike the target at high velocity and form X rays that leave the tube through a window and are directed at the object under study. A point object on which the rays fall casts an enlarged shadow on a photographic plate; the smaller the X-ray source (the target), the smaller the shadow and the more such bits of information can be resolved in a given area [*see bottom illustration on page 112*]. Maximum resolution therefore requires the smallest possible X-ray source. Moreover, the larger the current in the electron beam, the shorter the time required for a photographic exposure. To obtain a high information rate, therefore, one wants a large electron current striking a small area, that is, a large current density. It can be shown that the information rate of an X-ray tube is proportional to the current density of its electron beam.

Conventional X-ray tubes have a source size of about one millimeter and a beam current of a few milliamperes, and they normally require an exposure time of the order of one second—quite satisfactory in the case of static objects. Many of today's high-speed mechanisms and phenomena, however, call for much shorter exposure times in order to avoid the image blur resulting from motion during the exposure. The jet of a shaped explosive charge, for example, moves at approximately seven millimeters per microsecond. In order to keep the motion blur down around a tenth of a millimeter the exposure time must be of the order of a hundredth of a microsecond (10^{-8} second). This requires a current in excess of 1,000 amperes. That current, compressed into a beam one millimeter in diameter in order to maintain high resolution, corresponds to a current density of more than 100,000 amperes per square centimeter. It is the field emitter's ability to provide and even exceed such current densities that is its basic advantage in flash radiography.

A typical field emission arc X-ray tube has several comb-shaped electron sources arranged around a conical anode [*see top illustration on page 114*]. The anode provides a large enough surface area to dissipate heat while presenting a small

Software

Modern Galatea

System software brings the ancient Pygmalion-Galatea legend up to date, for it is software that gives the breath of life to the Galatea of hardware. Add software to a general-purpose computer and the result is a highly sensitive and specialized information system. Its virtuosity is a direct reflection of the creative software concept that goes into it. System software, of course, involves far more than computer programming; and at SDC, system software is our only business. Here, system software development is total, including the planning of the system, analyses of its requirements, its design, production, installation and, finally, its use, evaluation, and a system training program. By our own definition and methodology, the prime objective of system software is to make man the senior partner and decision maker in the man-machine relationships of today and tomorrow. At every stage of SDC's system software design, the principle of evolution is fundamental... which means that inherent in every SDC system is the flexibility to anticipate the needs of the future.

To date, the scientists and engineers of SDC have participated in the creation of 18 systems for various governmental organizations. Each new project, with its unique requirements, presents new challenges to the men and women of SDC. As each day sees more knowledge added to this rapidly expanding technology, challenging new career opportunities occur. Human factors scientists, operations research scientists, systems-oriented engineers, and computer programmers interested in the new field of information systems are invited to write Mr. A. L. Granville, Jr., SDC, 2430 Colorado Ave., Santa Monica, California. May we send you a new brochure—"Software System Development"—on the command/control aspects of software? It will give you added new insight into the step-by-step phases of system software, from planning to development to operations. Please write Mr. Granville at our Santa Monica address above. "An equal opportunity employer."

System Development Corporation

SDC

X-ray source. A high-voltage pulser applies a square wave (constant voltage for a short time) of from 100,000 to 600,000 volts in pulses of from 30 to 100 billionths of a second. The tubes are small and can be connected to the pulser by a coaxial cable, so that several tubes can be clustered around a small object or strung out along the path of a moving body and energized successively to obtain sequential radiographs of a fast-moving event. This makes it unnecessary to move the X-ray film, which can therefore be made large enough to record the image at life size and avoid the loss of resolution associated with optical systems. As a result high-resolution radiographs can be made at frame rates exceeding a million per second with an exposure time as short as 30 billionths of a second for each frame.

This new cineradiographic technique has been applied in biological and physical investigations. In one experiment a series of radiographs visualized the displacement of internal organs in animals subjected to 30 times the acceleration of gravity. Flash radiography has also recorded the complex sequence of events associated with an exploding wire, all of which take place in a few microseconds. By arranging two sets of tubes at right angles to each other along the path of a bullet penetrating a block of gelatin, experimenters have produced a series of stereoscopic pairs that trace the projectile's trajectory and attitude in three dimensions and yield accurate data on its velocity and deceleration [*see illustration on page 116*]. Ballistics workers at the U.S. Army's Aberdeen Proving Ground have adapted flash radiography to studies of the dynamic-yield points of various materials. They work with shaped explosive charges that emit jets of molten metal at some 20,000 feet per second. Radiographs show the formation of the jet and its degree and speed of penetration [*see bottom illustration on page 114*].

Field emission has also proved valuable in the study of radiation effects, particularly those that depend on high dose rates rather than on total dosage. A field emission X-ray tube can produce dose rates of 10^7 to 10^9 rads per second, and the effect of such rates on materials is striking. For example, an insulator normally insulates because it contains no free electrons. Irradiation with pulsed X rays supplies it momentarily with enough free electrons for a current to flow. Since the induced current can cause malfunction of electronic circuits, the study and prevention of such effects are receiving considerable attention. They can now be observed on a laboratory scale because of the small size of the X-ray source.

The effects of ionizing radiation can also be studied by irradiating an object directly with an electron beam. The field emitter can provide such a beam, functioning, in effect, like a Van de Graaff generator but at much higher dose rates—up to 10^{13} rads per second, or five million rads per pulse. The advantage of getting a large dose delivered very quickly is that it helps to separate the cause of radiation from the effect—to administer a dose in a time that is short compared with the reaction time of the object or organism under study. Initial applications have been confined to small biological specimens such as bacteria, but with higher voltages the increased penetration of the electron beam will extend the technique to larger, denser specimens.

In general terms one of the important contributions of field emission seems likely to be the development of high-performance instruments in small packages. The first such instrument is an X-ray machine that weighs only 48 pounds and has a volume of only about half a cubic foot. It is already extending medical diagnosis into hitherto inaccessible regions, such as the hinterland of Haiti, where it has made possible a chest X-ray survey. It has also proved to be convenient for guidance in the course of surgical procedures; in hip-pinning operations, for example, it can be placed between the patient's legs. The instrument is small first of all because the cold cathode requires no heating element and secondly because its short pulse length makes it possible to cut down on the amount of insulation.

Field emission technology is still at a very early stage of development. With continued research it should be possible soon to reduce operating voltages so that field emitters can be combined with transistors and other solid-state electronic devices to extend ultraminiature circuits and instruments to higher performance levels. Improvements in beam optics will make it possible to collimate and focus the electron stream with more precision. This should lead to X-ray machines with smaller source sizes and therefore higher resolution. It should also adapt the field emitter to a number of electron-beam devices, including oscilloscopes and other display tubes and even high-resolution television tubes.

We can't redesign him

But we can improve man-machine efficiency by designing vehicles "around" him. One major obstacle—replacing man's subjective impressions with quantitative test data—has been overcome by a new achievement of Caterpillar research.

Human memory was too unreliable.

Even our best test drivers couldn't exactly record their reactions during field tests. And precise data was what we needed.

Our first project was to develop instrumentation for recording the effects of motion, vibration, balance, noise and seat position on vehicle operators.

Step Two: Controlled Testing

When these devices were operational, we tackled the job of developing testing methods which would duplicate identical conditions in a controlled laboratory environment. The result was the Caterpillar Ride Simulator.

This device has three basic elements: a ride platform, including seat and controls; a servo drive mechanism which controls the platform; and an analog computer which directs the servo drive unit.

We can record on tape vertical acceleration measurements of a vehicle in the field... and then recreate them exactly on the ride platform in the lab.

No Memory Problem

Now we can study the effects of vehicle parameter changes more closely. And we can judge two versions of a vehicle in immediate sequence—eliminating the ride memory problem completely.

Step 3 of our human engineering project was even more ambitious. Could we shortcut vehicle development by evaluating prototype designs with pre-hardware paper testing?

Using the analog computer, our research engineers simulated a mathematical "model" of a vehicle concept. A taped road profile was used as input data to the model with the computer output actuating the ride simulator.

Thus we reproduced both the bounce and pitch of the concepted vehicle as it "traveled" a taped terrain.

Instant Design Changes

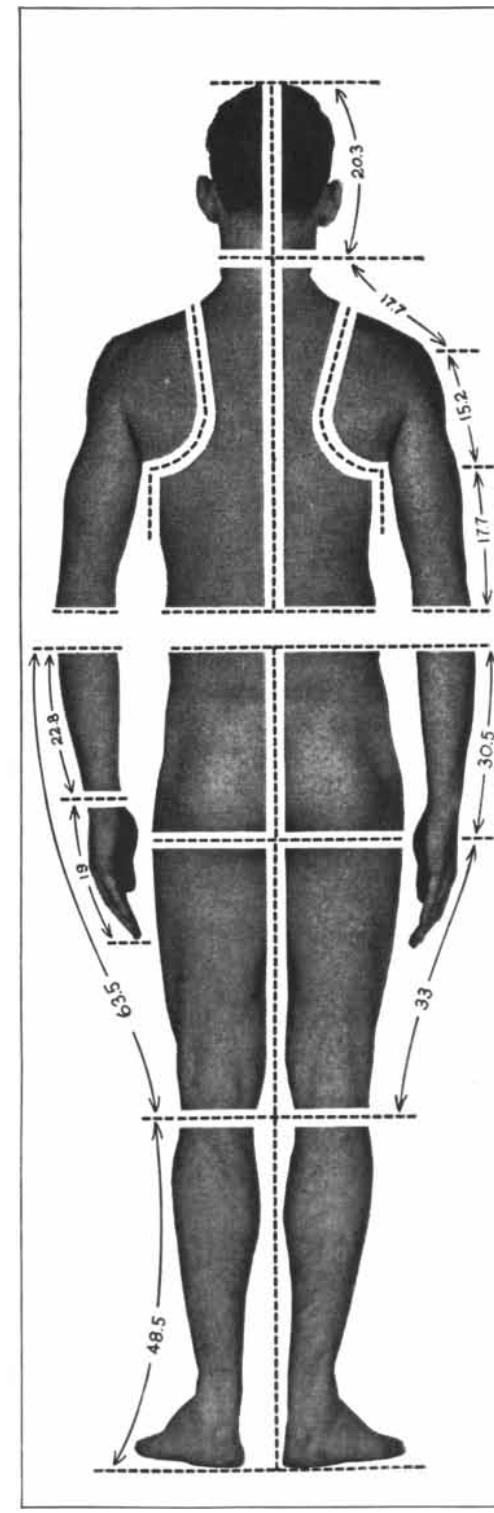
We can pinpoint the need for design modifications immediately. And by programming changes through the computer, we can evaluate the revised concept in moments instead of days.

Accuracy? No problem.

How important will the Ride Simulator be in our future R & D work?

The time saved in evaluating existing hardware alone will be highly rewarding—to say nothing of its potential in the evaluation of new vehicle concepts.

The Ride Simulator is only one example of Caterpillar's continuing study of Human Engineering as a means of perfecting the man-machine relationship. The vehicle specialists at Caterpillar can apply this special knowledge to your military vehicle projects. Contact Defense Products Department, Caterpillar Tractor Co., Peoria, Illinois.



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MATHEMATICAL GAMES

Presenting the one and only Dr. Matrix, numerologist, in his annual performance

by Martin Gardner

Readers may recall last January's interview with the renowned numerologist Dr. Matrix. He was in Sing Sing at the time, having been incarcerated for a foolish experiment with U.S. currency. In the fall of 1963, partly as a reward for cryptographic services to the Government, he was paroled. Washington refuses to divulge details, although I suspect Dr. Matrix' intimate knowledge of Oriental languages was involved.

I did not learn Dr. Matrix' whereabouts until early December, when I received a post card from Iva Toshiyori, his attractive Eurasian daughter (her mother had been Japanese). The pair were in Chicago. The old mountebank, finding it hard to earn a living as a numerological consultant, had worked up a night-club act and was booked to open on Saturday, December 14, at the Purple Hat Club. This was too good to miss. I wired Iva that I would be in Chicago the following Wednesday.

The Purple Hat is a popular cabaret in the Rush Street section of Chicago's near North Side. One can see its floor show from the bar. I arrived shortly before Wednesday night's first show, found an empty stool, ordered a drink, then rotated 180 degrees to survey the scene.

Behind a small stage, at one end of the dance floor, was a black backdrop on which large red and white numerals formed the order-three square shown on page 122. Dr. Matrix had clearly intended to indicate the coming year by the way he had placed the digits of 1964. I was trying to determine what curious properties the matrix possessed when the lights began to dim and the Purple Hatters, a small group of musicians wearing lavender top hats, began to play soft strains of Oriental music.

A spotlight followed Dr. Matrix from a side entrance to the center of the stage. He was in full evening dress, tall and unsmiling, his green eyes glittering ominously above his prominent, convex nose. An enormous blood red jewel glowed at the front of his snow white turban. He bowed with a maximum of dignity, then turned to introduce his assistant, Miss Toshiyori. Iva bowed with a minimum of costume. "Good Lord," whispered the man sitting on my left (a New York booking agent, I learned later), "where did he find *her*?"

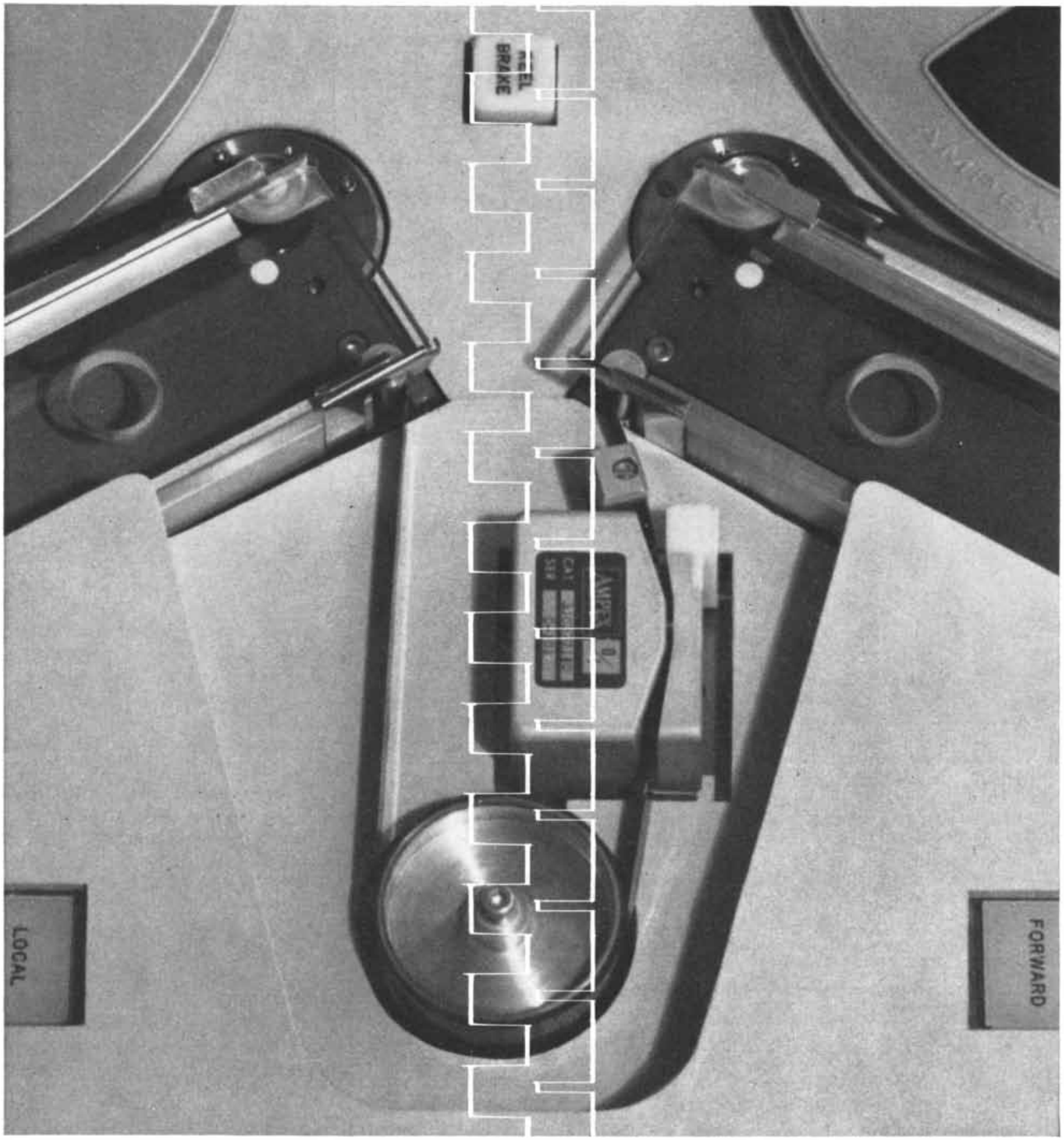
Iva slithered gracefully among the tables, gathering green cards on which patrons had been asked to write questions and sign their full name and date of birth. She tossed the cards into a big glass bowl and poured a purple liquid over them. When Dr. Matrix snapped his fingers, the contents of the bowl burst into flames. Speaking in low, guttural tones, the dancing flames illuminating his bony features from below, he began his "readings."

It was a brilliant performance. Shrewd guesses and predictions were cleverly interwoven with anagrams and other word plays on the patrons' names or initials, with curious numerological speculations involving birth dates, and with a masterful display of what is known in the fortunetelling trade as "cold reading." (A cold reading is a reading given without prior information about a subject. "Mrs. C. G.," Dr. Matrix would say, "the vibrations of your handwriting suggest that you recently received a phone call that was most disturbing." Mrs. C. G. would scream with astonished confirmation.) He received a good hand when he finished.

The lights went on. I saw Iva—she had slipped into a dress—approaching the bar. "Hi!" she said. "I thought I recognized you during the act. Come along. We have two hours until the next show."

I slapped some change on the bar. "Old friend," I explained to the bug-eyed man on my left.

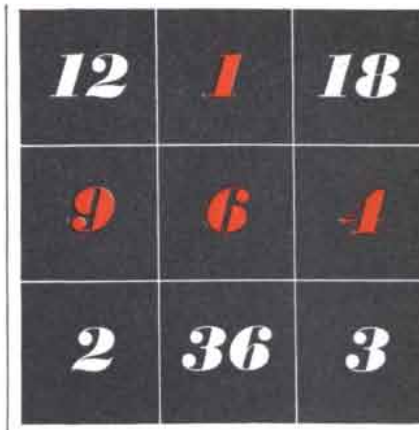
The three of us took a taxi to Dr. Matrix' apartment in a nearby lake-front hotel. Dr. Matrix was surprisingly cordial. "Yes," he said, "I chose that order-three square because it contained 1964



What has a drive concept so simple it's revolutionary? AMPEX TM-7

Here's a transport that's far in advance of anything in its class—the all new Ampex TM-7. It's a low-cost tape transport designed for less maintenance, less tape wear. And its most advanced feature is the revolutionary single capstan drive system. The new drive system has three major moving parts—a capstan and two reels. As a result, most of the components found in this type transport have been eliminated. Maintenance is far less. And tape wear? Virtually none. The two vacuum chambers keep a uniform tape tension on the capstan. There is nothing to smear the tape; nothing to stretch it. Tapes last and last. Even the old soft-binder tapes can be used with very little wear. The new Ampex TM-7 is completely compatible with IBM tape formats and with other Ampex equipment. It has a packing density of 200 and 556 bpi. A tape speed of 36 ips. A start and stop time of 10 ms with tape distance held within ±10%. Also, Ampex designed a new series of data and control electronics for the TM-7 to provide low-cost tape memory systems. The TM-7211 is a complete memory system enclosed in a 19 inch rack cabinet. And the TM-7212 is a complete shared system with four TM-7 transports in one cabinet. Write to the only company providing recorders, tape and core memory devices for every application: Ampex Corporation, Redwood City, California. Worldwide sales and service.

AMPEX



Dr. Matrix' magic multiplication square

so symmetrically. It is the simplest magic multiplication square. The product of the three numbers in any row—horizontal, vertical or diagonal—is 216. It is the lowest possible product for such a square, assuming, of course, that each cell contains a different positive integer."

He paused until I had finished jotting down this information. "There is a pretty puzzle connected with this square. You might ask your readers to see if they can rearrange the same nine numbers to make a magic division square."

When I looked puzzled, he explained: The two end numbers of any line of three are multiplied, then the product is divided by the middle number. The final result must always be the same.

"Excellent," I said. "I'll put that in my column and give the answer next month. Any other curiosities connected with 1964?"

Dr. Matrix nodded gravely. "From a military point of view, the year is potentially explosive. The Boer War ended in 1902. If we add each of those four digits to 1902, we obtain 1914, the year World War I began. That war ended in 1919. Add 1, 9, 1 and 9 to 1919 and the result is 1939, the start of World War II."

"I dig it," I said. "World War II ended in 1945. Let's see..." I added 1, 9, 4 and 5 to 1945. The result: 1964!

"It would be foolhardy," said Dr. Matrix, "to ignore this obvious pattern. Of course, the numbers merely impel, they never compel."

"It occurred to me," I said, hoping to change the subject, "that because the new year ends with 4 it might be an appropriate time to introduce my readers to the old pastime of the four 4's. Do you know the game?"

Dr. Matrix sighed painfully. "I know it well."

Let me first explain the recreation.

VARIAN INSTRUMENTS AT WORK

VARIAN associates
INSTRUMENT GROUP, PALO ALTO, CALIFORNIA
IN EUROPE: VARIAN A.G., ZUG, SWITZERLAND

Frequency and time measurements have progressed toward greater and greater precision

through the development of the pendulum, tuning fork, resonant electronic circuits, and crystal oscillators.

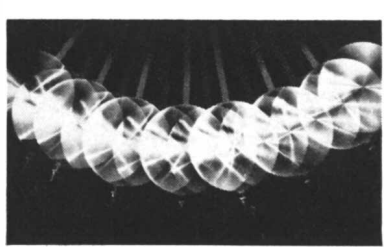
In the past decade, the study of quantum electronics has led to an understanding of the inherent stabilities associated with atomic resonance. As a result, several practical "atomic clocks" have been developed which provide the most accurate frequencies yet known—against which the most accurate measurements yet known can be made. Varian Associates produces three different devices of this nature.

Cesium beam tubes have provided the reference for the first practical atomic standard. Their acceptance and widespread use has revolutionized measurement concepts. At Beverly, Massachusetts, Varian makes tubes of this type which incorporate the most recent designs.

At Palo Alto, California, Varian has combined solid-state electronic circuitry with rubidium optical packages to create small, highly reliable, portable instruments.

Most recently, hydrogen masers have been developed at Beverly and are now being evaluated to determine the extent of their accuracy and stability. These devices have proven that the hydrogen maser furnishes the most stable reference yet discovered.

If frequency or time control is part of your work, Varian would like to help you. Contact Earle Benson in Beverly, Massachusetts or Gordon Harper in Palo Alto, California.



Superconducting magnets which operate at temperatures near absolute zero (–273°C) have intrigued scientists for several years with their promise of generating very intense magnetic fields with extremely small amounts of power.

Until now, superconducting magnets have not proved practical for research applications requiring useable volumes of highly homogeneous magnetic fields. Now, with the successful development of the X-4120, Varian has taken a giant step forward in this exciting new technology. The X-4120 is a superconducting magnet that can generate a magnetic field of 65 kilogauss which is homogeneous to within 0.1% over a volume ½" in diameter and one inch in length. And the entire field is accessible to a room temperature probe.

The X-4120, combining previously unattained field intensity, volume and homogeneity, opens up new areas of research in materials studies, susceptibility measurements, and magnetic resonance work.

Varian is now offering complete superconducting magnet systems, complementing its line of precision iron magnets. The new systems include the X-4120 magnet, dewar, dewar cap and magnet support mechanisms, plus a special power supply which allows a programmed control of magnet power input.

Further details may be obtained by writing Bob Abler, Magnet Products.

The chemistry of a product often determines how durable it will be, how effective, even how safe for human use. Hundreds of examples immediately come to mind in the areas of food products, drugs, paints, oils, insecticides, and fertilizers.

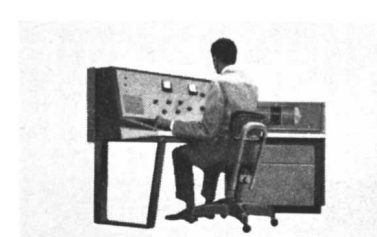
Manufacturers must strive constantly to eliminate any chance of error in chemical composition. Ethics, competition, certain patents, and often government regulation demand rigid quality control.

Research chemists have long used the analytical capabilities of Nuclear Magnetic Resonance (NMR) to identify the precise chemical structure of compounds by determining the number and location of hydrogen atoms within the molecule.

Scientists recognized that the same techniques could be used to monitor finished products, but that this would put too large a work load on the research instrument. Varian therefore developed the A-60 Spectrometer as a less expensive instrument designed specifically to handle fast, routine, non-destructive analyses.

With the easy-to-operate A-60, results are reproduced on pre-calibrated charts, so that technicians can perform hundreds of analyses a day and check the readings against known spectra.

You can see the A-60 at work in any of our three Applications Laboratories located in Pittsburgh, Pa.; Zurich, Switzerland; and Palo Alto, Calif. For more information briefly describe your interest in a letter to LeRoy Johnson, Analytical Instruments.



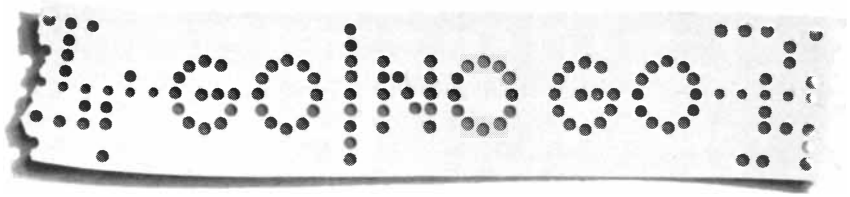
One seeks to form as many whole numbers as possible, starting with 1, by using only the digit 4 four times—no more, no less—together with simple mathematical symbols. Naturally one must establish what is meant by a "simple" symbol. This traditionally includes the arithmetical signs for addition, subtraction, multiplication and division, together with the square root sign (repeated as many finite times as desired), parentheses, decimal points and the factorial sign. (Factorial n is written $n!$ It means $1 \times 2 \times 3 \ldots \times n$.) A decimal point may also be placed above .4, in which case it indicates the repeating decimal .4444 . . . , or 4/9.

The numbers 1 through 10 are easily expressed, in many different ways, by using no more than the symbols for multiplication, division, addition and/or subtraction [*see illustration on page 126*]. By adding the square root sign, numbers 11 through 20 (except for 19) are readily obtained. By allowing the factorial sign and the dot used as both a decimal point and a repeating decimal sign, one can go on to 112. There seems to be no way to express 113 within these restrictions unless one employs highly bizarre combinations of the above symbols, such as the combined square root, decimal and repeated decimal signs in the denominator of the first term in the following equation:

$$\frac{4!}{.\sqrt{4}} + \frac{\sqrt{4}}{.4} = 113$$

The pastime was first mentioned in the issue for December 30—in the palindromic, invertible year 1881—of a lively London weekly that had been founded that year by the astronomer Richard Anthony Proctor. He called his periodical *Knowledge: An Illustrated Magazine of Science, Plainly Worded—Exactly Described.* A letter to the editor expressed astonishment at the fact (shown to the writer by a friend) that all integers from 1 through 20, except 19, could be expressed by four 4's and simple signs. Factorials and dots were not allowed. Readers were asked to try their hand at it before solutions were given in a later (January 13) issue. (With the help of the factorial sign, 19 can be expressed: $4! - 4 - 4/4$. Can the reader of *this* periodical find a way to do it by using only the four arithmetical signs and the decimal point?)

Since 1881 the game has enjoyed occasional revivals. A lengthy article on the topic, by W. W. Rouse Ball, appeared



DATA PROCESSING SYSTEMS FOR SPACE

Advanced STL digital telemetry units, decoders, and command distribution assemblies are now being used on NASA's OGO and Pioneer, and the Air Force's Nuclear Test Detection spacecraft. STL hardware and experience with on-board data processing equipment is being applied in the development of new systems which will perform checkout and maintenance functions in space. This advanced technology requires circuit designers, logic designers, and digital systems engineers. For Southern California or Cape Canaveral opportunities, write Professional Placement, One Space Park, Dept. J-1, Redondo Beach, California, or P.O. Box 4277, Patrick AFB, Florida. STL is an equal opportunity employer.

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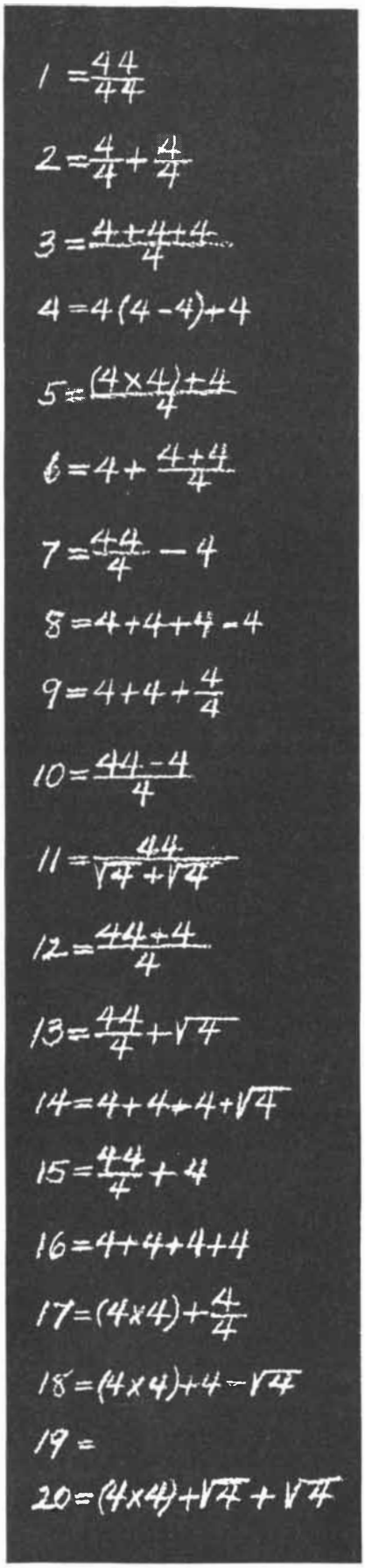


The game of four 4's

in the *Mathematical Gazette* for May, 1912, and there have been scores of subsequent articles, including tables that go above 2,000. Even now the mania will suddenly seize the employees of an office or laboratory, sometimes causing a work stoppage that lasts for days.

"Is it possible," I asked Dr. Matrix, "to express 1964 with four 4's and the traditional symbols?"

He shook his head vigorously. "Of course many important dates *are* possible. 1776 is 4 times 444. But 1964 is not one of them. With five 4's, yes." He jotted on my note pad:

$$44^{\sqrt{4}} + 4! + 4$$

"But four 4's, no."

"How about 64?"

"That," said Dr. Matrix, "is not difficult. Oddly enough, 64 can also be expressed—under traditional restrictions, of course—with three 4's and also with two."

The reader is invited to try his skill on all three problems; that is, to express 64 with four 4's, with three 4's and with two 4's. No symbols may be used other than those that have been mentioned. The task is middling hard with four 4's, ridiculously easy with three, extremely difficult with two. Next month I shall give the best solutions known to Dr. Matrix.

Dr. Matrix gazed sadly off into space when I spoke to him about the coming election campaign. In an interview that I reported in January, 1961, he had called attention to the grim pattern of death in office for every president who had been elected in a year ending in zero, beginning with 1840. Lincoln (elected 1860), Garfield (1880), McKinley (1900) and now Kennedy (1960) had been killed by an assassin. Harrison (1840), Harding (1920) and Roosevelt (1940) had died in office.

"Yes," he said finally, "the names and birth dates of the leading candidates deserve careful analysis. In the past 22 elections, beginning in 1876, the only occasion on which the man with the shorter last name won the popular vote was in 1908, when Taft defeated Bryan. This gives Rockefeller an edge over all his competitors. Of course Nixon, Romney and Johnson are eliminated because their names lack a double letter such as the two *L*'s in Rockefeller." (Dr. Matrix was here alluding to the now-well-known law that all U.S. presidents of the 20th century must have a double letter in their name. So far Eisenhower has been the only exception, but because his opponent, Adlai Ewing Stevenson, also lacked the double letter there was no real contest.)

I was scribbling furiously. "That makes Rocky a stronger candidate than Goldwater, I suppose. Both men have the double letter, but Rocky's last name is longer."

"In that respect, yes. Rocky's height, of course, is a liability. In the past 15 elections, beginning in 1904, the only time the shorter candidate won the popular vote was in 1940, when Roosevelt, at six feet two inches, defeated Willkie, six feet two and a half. By the way, did you know that both Rockefeller and Romney, the two *R*-initial men, were born on July 8?"

I shook my head.

"In fact, all five leading Republican candidates—Rockefeller, Romney, Goldwater, Nixon and Scranton—were born in months that begin with *J*. Goldwater and Nixon were born in January, Scranton in July. *J* is the 10th letter of the alphabet. Note that 'Republican' has 10 letters and that the digits of '64 sum to 10."

"Is that a good omen?"

"To a certain degree. The digits of 1964, however, sum to 20. The only candidate with exactly 20 letters in his full name is Barry Morris Goldwater. On the other hand, the president will not be inaugurated until 1965, which sums to 21, the number of letters in the name of William Warren Scranton."

"Your numerology is confusing," I said.

"No more than politics. I regret to report that Scranton, the governor of Pennsylvania, was not born in Scranton, Pa., or in its anagrammatic cousin, Cranston, R.I. He was born in Madison, Conn. But 'Madison' is a presidential name, so that should be counted a favorable sign."

"Someone has suggested," I remarked, "that Rockefeller should open a campaign speech by saying: 'I come to Barry Goldwater, not to praise him.' "

Dr. Matrix looked as solemn as an owl. "It is possible to devise many appropriate puns on the candidates' names. Nix on Nixon, for example. Aldrich Rockefeller sounds like 'old rich rocky feller,' and one might say that his views on certain issues are enough to rock a feller. Nixon's straightforward Republicanism is indicated by the fact that the first and last letters of 'Republican' are his initials; the same letters backward are Rockefeller's. The governor's full initials, backward, may be prophetic: the

Honeywell Presents
"Science All Stars"
Sundays 4:30 E.S.T.

abc TV

Nationwide TV Program to Discuss the Sciences in an Engaging and Rewarding Fashion

"Science All Stars" presents brilliant achievements by gifted teenagers in every field from biology to electronics—with on-the-spot participation by the nation's leading scientists

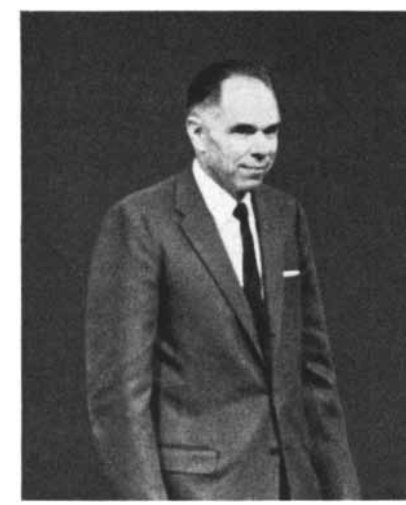
A different approach to the discussion of science forms the basis for an entirely new kind of network television show being presented by Honeywell. First, there is the enthusiastic, adventuresome spirit and actual scientific contributions typified by winners in Science Fairs who will show and explain their ingenious experiments. Second is the mature evaluation and valuable insights offered by world-famous leaders in science, education and government.

Using this combination of viewpoints, science comes alive in an exciting and meaningful adult program rich in value for the inquiring mind. Among the fields to be explored on "Science All Stars" are:

- Radio Astronomy
- Generation of electricity from biological systems
- Theory of numbers including logic systems
- Gyroscopic stabilization
- Microwave sensing and signal transmission
- Crystalline materials – lasers and control of light
- Hydroponics
- Cardiology
- Rocket propulsion dynamics

All the exhibits slated for use on the program are technically excellent, and some have an engagingly lighthearted quality. A young scientist offers the services of his live fish in generating power (choose from one-fish, two-fish, or three-fish batteries!) ... two boys pit their computers against each other in a game of ticktacktoe ... you'll watch an oscilloscope pattern of the heartbeat of a flea as a 12-year-old-boy records the flea's electrocardiogram.

Appearing in the premiere show in mid-January are Dr. Glenn T. Seaborg, Nobel Prize winner and chairman of the Atomic Energy Commission, along with Colonel Charles Yeager, commandant of the Aerospace Research Pilot School and first man to fly a plane through the sound barrier. Subsequent programs will feature Dr. Jerome Wiesner, advisor on science and technology to the U. S. Government and soon to be Dean of Science at M.I.T.; Col. John Paul Stapp, Assistant for Aerospace Medicine; Dr. Nan Deiter, Research Astronomer at Cambridge Research Laboratory, and others who will participate in the exhibits of nearly 65 different young scientists from all over the country.



DR. GLENN T. SEABORG, AEC Chairman and winner of the 1951 Nobel prize in chemistry, will appear on the first program in the "Science All Stars" series. A television camera built by a 16-year-old boy for $40 will be used to televise Dr. Seaborg's part in the program.

By emphasizing the inherent excitement of scientific exploration, "Science All Stars" creates an aura of drama and fascination that not only makes science more understandable to the average person but is bound to intrigue young viewers everywhere. In sponsoring the program, Honeywell hopes to stimulate more of our youth to consider careers in science.

You are invited to watch "Science All Stars" Sundays at 4:30 EST on the ABC TV Network starting January 12. (Check your local TV listings.) Your comments will be appreciated. Address Dr. John Dempsey, Honeywell Research Center, Hopkins, Minnesota.

ONE OF THE YOUNGEST licensed ham radio operators in the country, 13-year-old Michael Schatzlein of Knightstown, Ind., discusses the theory of sound, carrier waves and the speed of light with Col. Charles Yeager. Michael will also "talk" the pilot of a supersonic jet through the sound barrier on "Science All Stars" using his home-made ham radio.

Honeywell

Republican who RAN in 1964. Crossword puzzle experts will recognize that Roc/kef/el/er are respectively the words for a fabled bird, dreamy tranquillity, an elevated railroad and an Irish god of the sea."

Iva, who had left us to ourselves while we conversed, returned to the living room to remind her father that he was due back at the Purple Hat in half an hour. I paid the taxi fare and walked them around to the club's back entrance.

"When is the last show over?" I asked Iva.

"Two-thirty," she said, smiling.

"Will you, perhaps, feel like eating somewhere?"

"I'll be ravenous."

How does a man in middle age kill three hours in the middle of a freezing, snowy night, in the middle of the week, in mid-December, in the middle of the Windy City? I decided to return to my hotel and spend the time in the middle of my bed.

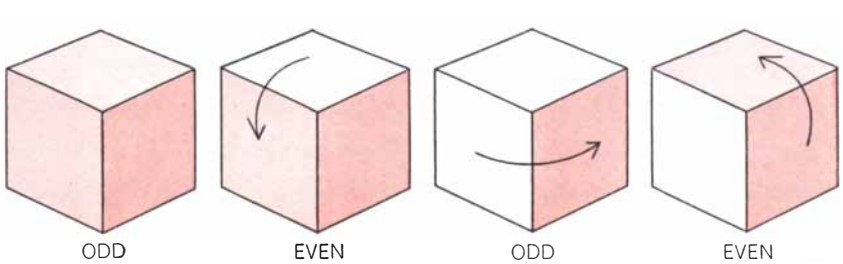
Readers were asked last month to identify which one of five alphabet blocks in a row on a chessboard had been the center block in a previous formation before the blocks were moved by tipping them over an edge from square to square. It is obvious that if a block is moved an even number of times, it will rest on a square that is the same color as the square on which it started. An odd number of moves puts it on a square of opposite color. Not so obvious is the way in which odd and even apply to the orientations of each block.

Imagine a block painted red on three sides that meet at one corner and placed so that you can see three of its sides. There are four possibilities: you see no red side, one red side, two red sides or three red sides. If you see one or three red sides, we say the block has odd parity; otherwise, it has even parity. Whenever the block is given a quarter-turn in any direction, it is sure to change parity. (This follows from the fact that opposite sides of the block are different colors. Each quarter-turn takes one side out of your line of vision and brings its opposite side into view. Thus a quarter-turn always alters one of the visible colors.) Think of a block as a die instead of a block with colored sides. In this case its parity is indicated by whether the sum of the three visible faces is odd or even.

Because each move of the block gives it a quarter-turn, it changes its parity with each move. After an even number of moves it will be on a square of the same color as the square from which it started, and it will have the same parity. After an odd number of moves it will have changed both color of square and parity. The center block originally rested on white. If it moved an odd number of times, it will be in the second formation on a black square, its parity altered. But all the blocks on black squares in the second formation have the same parity, therefore the center block is not among them. It must have moved an *even* number of times. This would put it on a white square, with its parity the same as before. Of the two blocks on white squares, only the second from the right has unaltered parity. Therefore it is the block we seek.

To prove that Frank Lloyd Wrong's shoe-box house has an even number of outside doors, we consider first the fact that every door has two sides. If there are n doors, the total number of sides is $2n$, an even number. We are told that every room has an even number of doors. Assume that all doors are closed. An even number of *sides* will face into each room, therefore the total number of sides facing into rooms will be even. We subtract this even number from the total number of sides, also even, to obtain another even number: the number of sides *not* facing into a room. These sides must, of course, be on the exterior doors. Therefore the number of doors leading to the grounds is even.

The decoded Christmas message is "The compliments of the season to you" (the complements of the C's on $2u$).



How a quarter-turn changes the parity of a cube

SCIENTISTS and ENGINEERS

Some facts about Xerox to help you evaluate our capabilities

How good is the Company's potential for growth?

Each year FORTUNE ranks the 500 largest U.S. industrial corporations in order of sales. In 1962 Xerox had the fifth biggest *increase* in sales over the previous year: $104,472,214, up from $61,384,372 (70% higher than 1961). The thirteenth straight year in which a record has been set.

By 1967, Xerox and its affiliated companies should attain world-wide sales and profits three times what they were in 1962. If this objective sounds bold and impractical, let it be said that Xerox has already achieved some of the growth expected in 1964 and 1965. (Nine months figures for 1963 show Net Income up 65.1%).

Indeed, you would not be reading this advertisement if we were not a company determined to reach our goal of continuous growth at a rate averaging not less than 20% a year. Such growth constantly creates key positions in the Xerox organization for scientists and engineers with exceptional ability.

What about R & E?

One of our basic policies is to maintain a creative, strong research, development and engineering organization and program.

By the end of 1962, the rate of research and engineering expenditure had reached the level of $1,000,000 per month. Or approximately 10% of 1962 sales. The company's profit for the entire year 1957 was only $1.6 million.

Five years ago there were 200 people in research and engineering at Xerox. Now there are over 800, and we are vigorously seeking to add to this staff.

Not simply men experienced in the fields of physics, engineering and chemistry. Xerox seeks top-level *creative* scientists . . . men with penetrating minds and a fresh point of view, to unlock doors in the dozens of disciplines in which Xerox is engaged.

To attain these objectives, Xerox grants its engineers and scientists a large measure of academic freedom, encourages them to explore new imaging techniques within the broad discipline of graphic communications. And, in an expanding, campus-like setting, provides the creative climate to help its scientists and engineers keep our various research and development programs on target.

Is the work challenging?

There is literally no end to graphic communications. 47 new patents were awarded to Xerox in 1962 alone.

Xerox scientists and engineers, employing our xerographic and electronic techniques, are today at work on advanced projects in data storage, transmission, retrieval and display systems . . . print-out from analog and digital inputs . . . development of a photographic coating without gelatin for rapid processing . . . a method of forming micro-miniature electronic circuits which incorporate given capacities and resistances . . . equipment which can transmit and record information more than 20 times as fast as conventional facsimile systems.

To be working alongside leading professionals in this rapidly evolving, dynamic field of graphic communications . . . to be given freedom to exercise initiative . . . not only offers opportunity for the highest order of professional fulfillment. It is a challenge of the first magnitude. If you are equal to this continuing challenge, a rewarding and satisfying career can be yours at Xerox.

What's the living like?

Like this. Webster, New York, home of Xerox Corporation's modern, expanding facilities, is a pleasant suburban community situated to the east of Rochester—as are the city's most attractive suburbs. You drive to and from work leisurely, across open country. In a matter of minutes.

Recreational facilities abound here. There are 42 golf courses in the greater Rochester area, a number of them championship courses. From the shores of Lake Ontario on the north to the scenic beauty of the famed Finger Lakes vacationland area to the south, opportunities for skiing, skating, swimming, boating, summer cottage living, weekend outings, and wholesome family fun are unmatched.

Secondary schools in Rochester and its suburbs are among the finest in the nation. Rochester is proud of its reputation as an academic community. And so is Xerox; in 1963 a contribution of $380,000 was made in support of higher education. It is the intention of Xerox to donate annually a fixed percentage of profit before taxes to privately supported colleges and universities.

Is this the life for you?

That depends. On your life goals. And whether you can reasonably expect to achieve them in your present job and location. And how soon.

You may wish to read this page aloud to members of your family. Then take a close look at upstate New York on a map. Then throw the meeting open to discussion. If you agree that it's time for a change in your career . . . time for you and your family to turn over a new life—

MAJOR ASSIGNMENTS ARE OPEN right now at Xerox in the following areas:

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for fundamental studies in materials science, gaseous electronics, electrostatics, and solid state research.

Organic Chemists
for development of novel photoconductive materials and devices.

Paper Chemists
Ph.D., to do exploratory studies in paper technology.

Engineers
B.S. or M.S. in chemical or electrical engineering to work on data storage, transmission, display and retrieval systems.

If your interests and experience qualify you, please send resume and salary history to Mr. Lee B. Sundsted, Xerox Corporation, Dept. SA-1-1, P.O. Box 1540, Rochester 3, New York. An equal opportunity employer.

Doctor's Office

A little untidy? That's okay. He'll straighten it out later. He doesn't have time right now.

His time is taken up with space exploration. He's a Ph.D. at Caltech's Jet Propulsion Laboratory. He and 1300 other scientists and engineers are planning unmanned spacecraft and deep space probes to areas 220,000 miles up and up.

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THE AMATEUR SCIENTIST

The dynamics of a golf club and the aerodynamics of air-supported vehicles

Conducted by C. L. Stong

With the aid of a slow-motion movie camera and a co-operative friend any golf player can easily explore the dynamics of his club head during the split second of the drive that separates the sheep from the goats of golfdom. The procedure, as applied by Louis A. Graham, a consulting engineer in Naples, Fla., analyzes the travel of the club head throughout the swing, including its velocity and acceleration at the critical moment of impact—factors that determine whether a squarely struck ball will merely topple off the tee or go a history-making 445 yards to match the performance of E. C. Bliss in August, 1913.

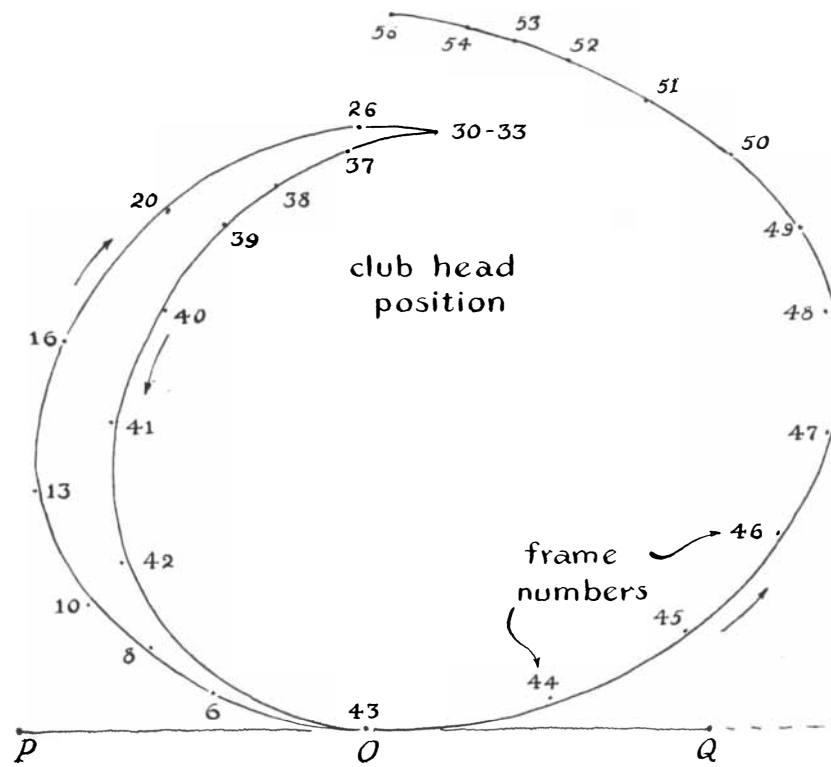
"The procedure is essentially simple," writes Graham, "but the reliability of the results will reflect the care with which certain measurements are made. I pick a sunny day for the experiment and, having arrived at the golf course with my co-operative friend and accessories, tee my ball. Then I place a tee marker precisely four feet in front of the ball and another four feet behind it to make a line that points toward the first green. My friend stations the tripod-mounted camera for a medium close-up shot on a line that intersects the ball at right angles to the tee markers. I address the ball, facing the camera. My friend photographs the complete drive from address to follow-through at the rate of 48 frames per second. The known distance between the tee markers and their position in relation to the club head scales the pictures with respect to distance. The exposure rate—the number of frames per second—of the camera provides the time dimension. (If the exposure rate is not known accurately, it can be calibrated by photographing a phonograph turntable marked with a chalk line and turning at 45 or 78 revolutions per minute.)

"The film is developed and analyzed. One can use either a film-editing device that projects an enlarged image of each frame or a set of enlarged prints of each frame, mounted serially and numbered for identification.

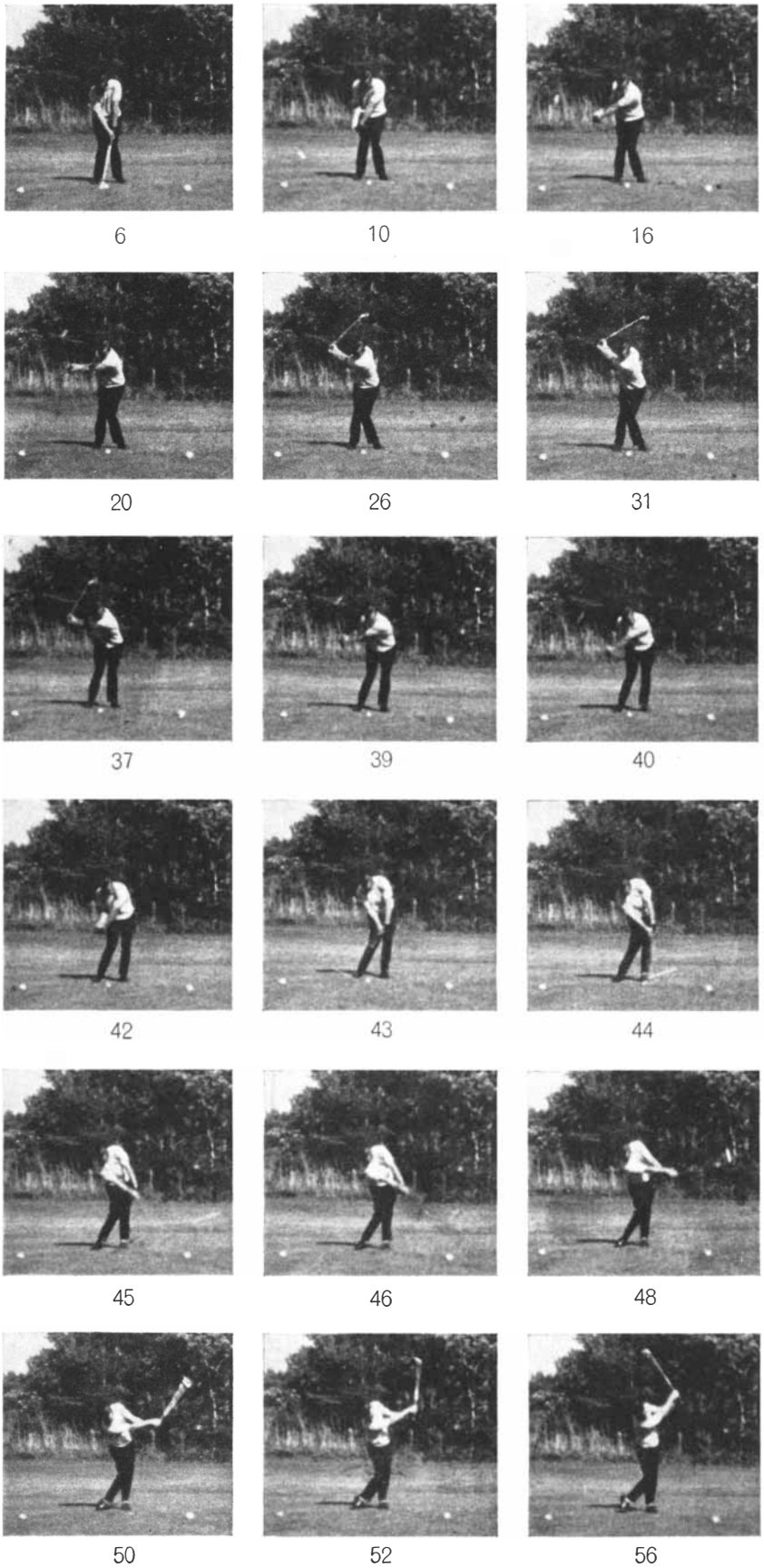
"The next step is to plot the position of the club head during the course of the swing. Since a point in a plane is determined by its distance from two other known points, the position of the club head can be plotted in relation to that of the two tee markers [*see illustration below*]. First, I draw a base line near the bottom of a sheet of graph paper ruled with rectangular co-ordinates and on it locate three equally spaced points: the tee marker *P*, the ball (*O*) and the tee marker *Q*. I usually space these points four inches apart, thus establishing a scale of 12 inches of club head travel per inch of graph paper.

"The location of the club head (*C*) with respect to that of the tee markers can be transferred to the graph by one of three methods. Proportional dividers are handy for transferring the scaled distance from *P* to *C* and from *C* to *Q*. Alternatively, the angles *CPQ* and *CQP* can be measured with a protractor and reconstructed on the graph, point *C* being located at the intersection of lines projected from *P* and *Q*. If no protractor is at hand, the vertical and horizontal distances between *C*, *P* and *Q* can be measured with a square and ruler and similarly transferred to the graph.

"Plot enough points to establish a reasonably smooth track, skipping several frames during slow portions of the



Graph of successive club head positions



Selected frames from slow-motion film of a golf swing

swing. The resulting graph is of course not extremely accurate. The plane in which the club head swings, for example, is inclined to the plane of the film. The track plotted from the image therefore differs slightly from the true excursion of the club head, but the error is not large and can be ignored. By the same token, the travel of the club head from point to point is subsequently measured along straight lines, whereas the club head actually follows a curved path. Error introduced by this source can be minimized by speeding up the camera. My camera, an inexpensive one, is limited to a maximum speed of 48 frames per second, a rate that records the event adequately for the objectives of this experiment.

"The total distance traveled by the club head and its velocity and acceleration are derived from a second set of graphs prepared from the graph of club head position. On a second sheet of graph paper ruled with rectangular coordinates divide the abscissa into a series of uniform increments equal to the total number of frames occupied by the swing and note the corresponding time intervals in seconds as well as the frame numbers. The ordinate will carry two scales: club head travel in feet and club head speed in miles per hour. The scales of the ordinate should provide for a total club head travel of 36 feet and a maximum velocity of about 80 miles per hour. Graphs of convenient proportion result when the length of the ordinate representing 36 feet equals the length representing one second on the abscissa. The maximum velocity of 80 miles per hour need not occupy more than half of the ordinate scale, as shown in the accompanying graph [*upper illustration on opposite page*].

"Data for plotting club head travel against time are derived by measuring the graph of club head position. Make a table of three columns, for frame number, time and distance. Beginning with the point on the graph of club head travel that shows the head addressing the ball, scale the distance to the next point and convert to equivalent feet by referring the measurement to the base line that includes *P*, *O* and *Q*. Measure and tabulate the remaining position points in the same way. When the table is complete, add the distance increments progressively, plot distance against time and draw a smooth curve through the points.

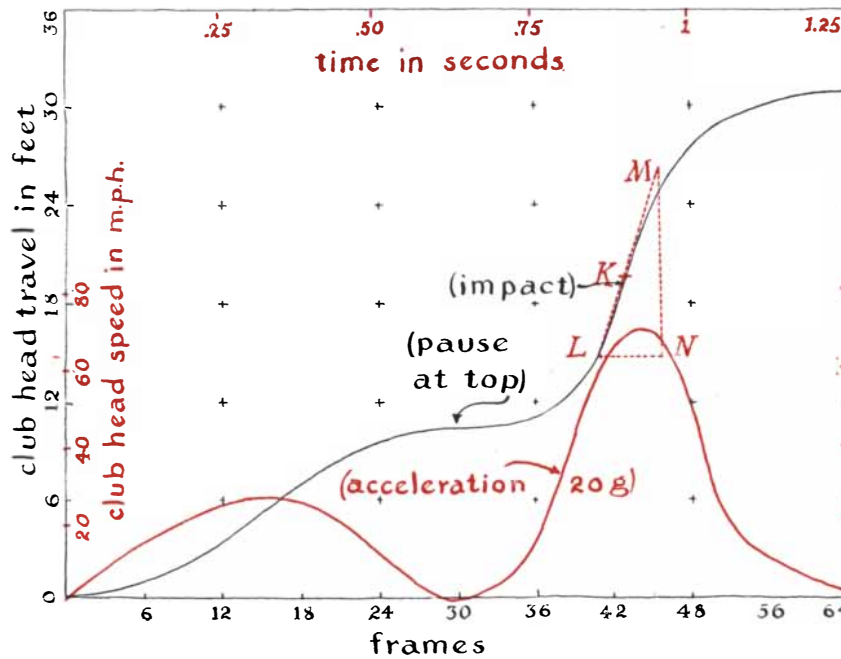
"The speed of the club head at any point is found from this graph by the familiar graphical method of slopes. To find the speed of the club head at about

the point of impact (frame No. 43), draw a tangent *LKM* of arbitrary length through *K*. The sides *MN* and *LN* are found by referring to the scale to equal 11.2 feet and .11 second respectively. The speed of the club head at this instant is equal to the ratio 11.2/.11, or 102 feet per second. The result can be expressed in miles per hour by multiplying it by the number of seconds per hour and dividing the product by the number of feet per mile: $102 \times 3{,}600/5{,}280 = 70$ miles per hour. Repeat the procedure for each of the frames, tabulate the results, plot speed versus time and draw a smooth curve through the points.

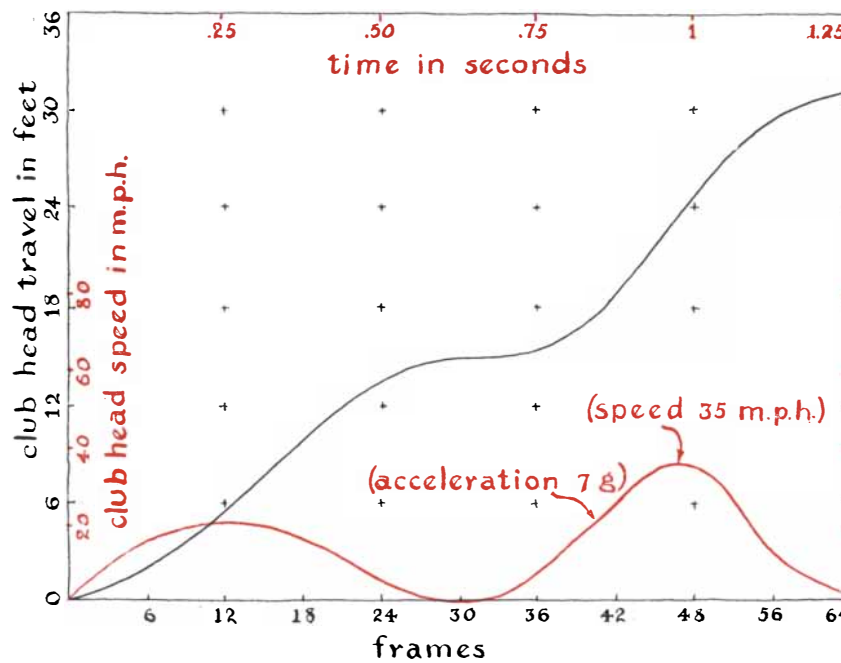
"Club head acceleration can be graphed in the same way or merely computed from the graph of club head speed at frames of particular interest, such as the frame showing the moment of impact. For example, to determine the acceleration of the club head depicted by frame No. 38, draw a tangent to the graph at this point. Then, at some arbitrary point above, say at the point corresponding to a velocity of 56 miles per hour, drop a perpendicular *MN* from the tangent. At another arbitrary point below, say at the point corresponding to a velocity of 12 miles per hour, draw a line *LN* parallel to the abscissa and intersecting both the tangent and *MN*. Inspection of the abscissa discloses that the length *LN* is analogous to a time interval of .1 second. Acceleration is defined as the rate of change of velocity and is equal to the difference between the final velocity and initial velocity divided by the time interval between the two. In this example the velocity difference is 56 miles per hour minus 12 miles per hour, or, expressed in feet per second: $(56 - 12) \times 5{,}280/3{,}600 = 64$ feet per second. The acceleration is $64/.1 = 640$ feet per second per second. The acceleration of gravity (g) amounts to 32 feet per second per second. The acceleration of the club head at frame No. 38 in terms of g is accordingly 640/32, or 20 g!

"Having performed this rainy-afternoon portion of the procedure, what reward awaits the duffer? For one thing, he can see at a glance why his drives do not match those of a professional golfer. The graphs discussed so far show the performance of golf professional Dick Bull using an iron. His swing from address to follow-through required 1.17 seconds. The club head traveled 31 feet. His backswing occupied .6 second. He paused at the top about .1 second. More interesting than these figures, in my opinion, are those of the club head speed and acceleration Bull achieved: the increase in club head speed during the .1 second before impact from 15 miles per hour to an amazing 70 miles per hour, representing an acceleration of slightly over 20 g. Graphs of Bull's performance with a driver, although different in many respects from those of his irons, show exactly the same figure for speed, 70 miles per hour, and an acceleration of 22 g, a remarkably uniform performance. Similar analysis of the performance of a fairly good amateur using a driver shows precisely half the velocity of Bull's club, 35 miles per hour, and an acceleration at impact of only seven g [*see lower illustration below*].

"Although these methods of analyzing motion are routine in engineering cir-



Speed and acceleration graph for a professional's swing



Similar graph for an amateur's performance

The Lincoln Laboratory, a research center of the Massachusetts Institute of Technology, conducts a program of general research with applications to urgent problems of national defense and space exploration. Scientists and engineers of many disciplines are engaged in fundamental investigations and technological development in selected areas of advanced electronics. All qualified applicants will receive consideration for employment without regard to race, creed, color or national origin. Lincoln Laboratory, Massachusetts Institute of Technology, Box 18, Lexington 73, Massachusetts.

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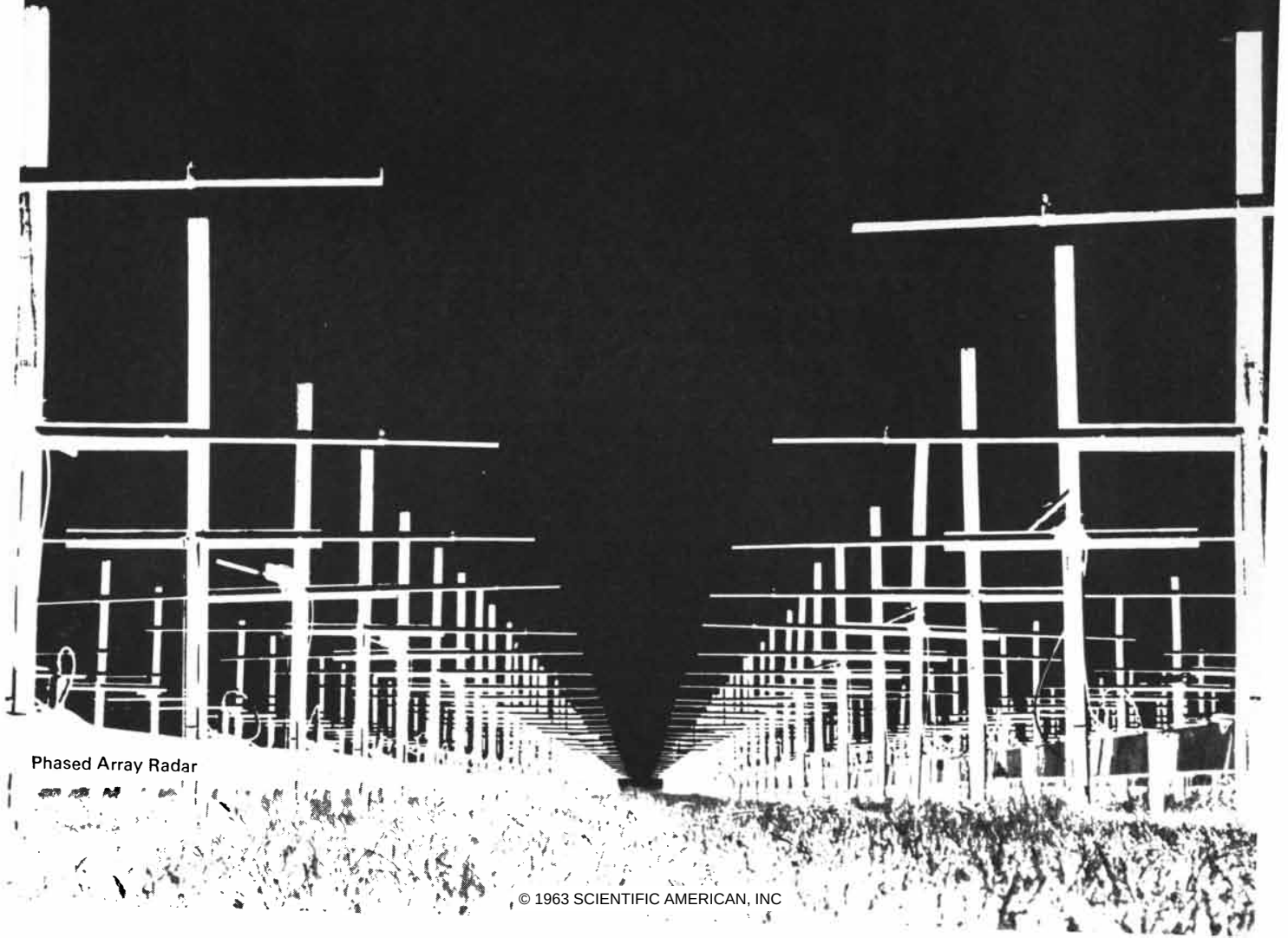
Space Communications

A description of the Laboratory's work will be sent upon request



Phased Array Radar

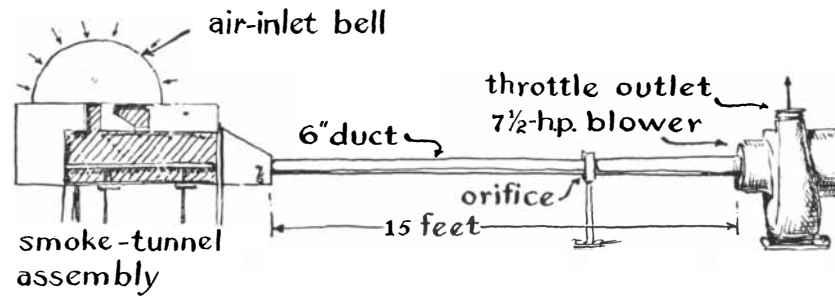
cles, I am not familiar with their prior application to the game of golf. As with many procedures, they are easier to apply than to describe. I find them interesting because they clearly reveal why Bull and other professionals achieve their long drives. Duffers with movie cameras may well begin asking each other, 'How's your v and g?' "

Interest in "ground effect" aircraft—machines that ride a few inches above the surface on a cushion of low-pressure air created by a vertical jet—led Robert W. Moffat, a graduate student at Wayne State University in Detroit, to design an inexpensive smoke tunnel with which he can make remarkably accurate aerodynamic measurements. The most novel feature of the tunnel is the use of a high-fidelity loud-speaker powered by ordinary 110-volt, 60-cycle house current to produce precisely timed pulses of smoke that, when photographed against the black background of the tunnel's interior, resemble a series of dotted lines. The shape of the lines depicts the pattern of the air flow; the spacing between the timed smoke puffs enables the experimenter to compute the velocity of the flow.

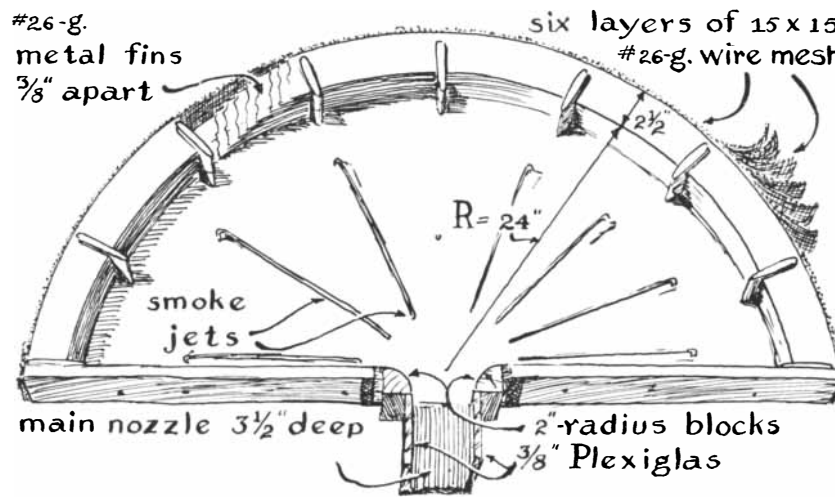
"The tunnel has seven principal sections," writes Moffat, "an air-inlet bell, the smoke system, the test nozzle, the tunnel body, the lighting system, the blower and air controls and the flow-measuring station [*see top illustration at right*]. Because the tunnel was designed to investigate the aerodynamics of hover craft, the apparatus was fitted with a single nozzle that directs air at right angles against the floor of the tunnel. The floor, which simulates the ground, can be fixed at any distance between two and 20 inches from the jet for investigating the behavior of air flow in the range of low altitudes within which these craft normally fly.

"To achieve the stable flow of air required for the accurate measurement of air flow in two dimensions, the apparatus was equipped with a semicircular inlet chamber, resembling half of a shallow cheese box, for smoothing the turbulence of the air in the room. The curved edge of the chamber is made of eight semicircular strips of 26-gauge sheet metal spaced 3/8 inch apart. The sheets are supported by eight slotted, streamlined struts four inches long. The sides are closed by two semicircular sheets of 1/4-inch plywood and the bottom by a straight piece of one-inch plywood with a rectangular outlet for the test nozzle, as shown in the accompanying illustration [*middle illustration below*]. The sides must be braced externally to prevent bowing that would disturb the flow. Air enters the sheet-metal slots through six layers of fly screening. This construction limits the velocity of air flowing from the room into the screening to about 15 per cent of the jet velocity at the point where air enters the tunnel.

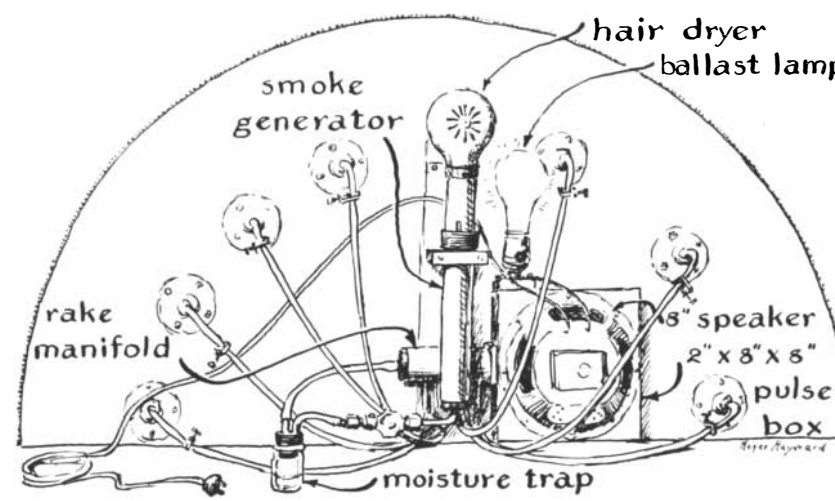
"The smoke system is supported on the front face of the air-inlet unit. It consists of a forced-draft burner that admits tobacco smoke to a pulsing apparatus from which puffs of smoke are delivered



General view of smoke-tunnel apparatus



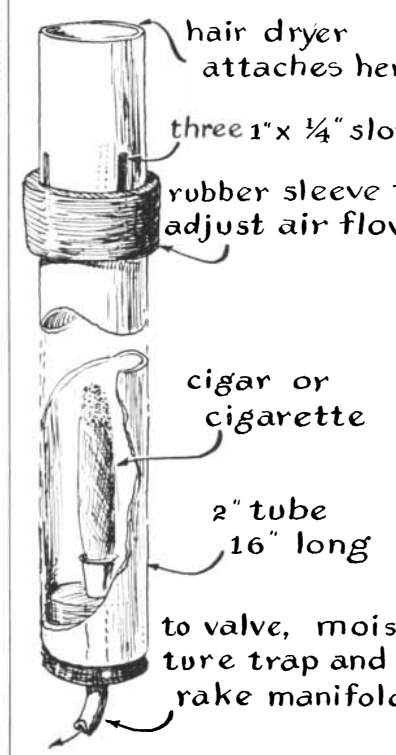
Internal details of the air-inlet bell



External view of the air-inlet bell

by Tygon tubing to a set of seven 1/8-inch copper tubes mounted in a radial array inside the inlet bell, as illustrated. The smoke generator consists of a straight metal tube two inches wide and 16 inches long closed at one end by a rubber stopper drilled for a cigarette or cigar holder and supplied with air at the other end by an electric hair dryer. Pressure inside the smoke generator is adjusted by a controlled leak—three slots that can be adjusted in size by a sliding rubber sleeve.

"The tubing that connects the smoke generator to the pulsing vessel includes a wide-mouthed bottle closed by a screw cap fitted with an inlet and an outlet. The bottle acts as a moisture trap for condensate that would otherwise collect at low points in the tubing and interfere with the even distribution of smoke to the rake assembly. (The design of the trap could be improved. My trap increases the running intervals between cleanouts, but considerable moisture condenses in the tubes.) The smoke, passing through the trap, enters one end of a 1½-inch manifold and leaves through seven individually controllable smoke lines tapped into the side of the manifold. The smoke lines are made of transparent tubing so that the presence of condensate can be checked before the start of each run. The flow through the individual lines is regulated by pinch



The smoke generator

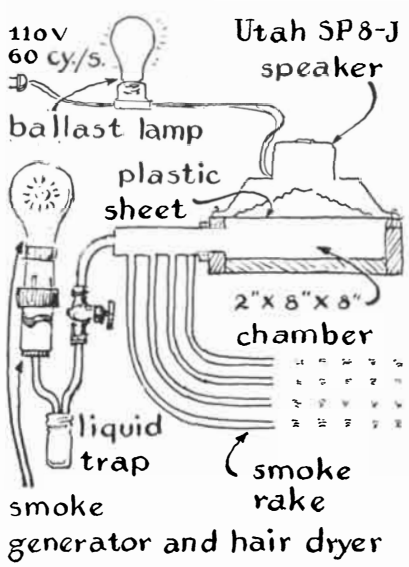
valves. The other end of the smoke manifold opens into one side of the pulsing chamber.

"The pulsing chamber consists of a box two by eight by eight inches made of one-inch plywood. The lid of the box is a square of plywood with a circular hole for mounting an eight-inch high-fidelity loud-speaker. The loud-speaker is sealed to the plywood around the perimeter. A thin plastic diaphragm separates the loud-speaker from the pulsing chamber to prevent smoke from diffusing through the porous paper of the speaker cone, as shown in the accompanying illustration [*right*].

"The speaker is energized from the 110-volt, 60-cycle power line. A resistance must be connected in series with the loud-speaker circuit to limit the current. A transformer equipped with a variable secondary winding, such as those used to power toy trains, could be used, but I found that a three-way lamp (30, 70 and 100 watts) worked nicely with a speaker rated at an impedance of eight ohms. The lamp is inexpensive and its three resistance values provide an adequate selection of adjustments. Sound intensity, and hence pulse amplitude, are controlled by selecting the desired resistance (wattage) of the lamp. The amplitude of the pulses varies in proportion to the wattage. The vibrating diaphragm of the loud-speaker periodically increases and decreases the pressure of the air inside the smoke system. This causes the smoke to discharge from the copper tubes as a series of smoke rings that, when viewed from the side, appear to consist of twin puffs that clearly mark the streamlines. The pattern is photographed by a single exposure. I use a shutter speed of 1/500 second for recording velocities on the order of six feet per second. My camera is equipped with a leaf shutter; those with focal-plane shutters might not prove satisfactory because of their relatively slow scanning speed.

"Air is conducted to the test nozzle through a rectangular tube of plywood that flares at the entrance to the inlet bell to prevent separating of flow at a sharp corner. The flare is made by butting the tube against a pair of radius blocks. The smoke is injected into the air by the nozzles of the seven copper tubes, grouped in a semicircular array of five-inch radius symmetrical with respect to the outlet tube.

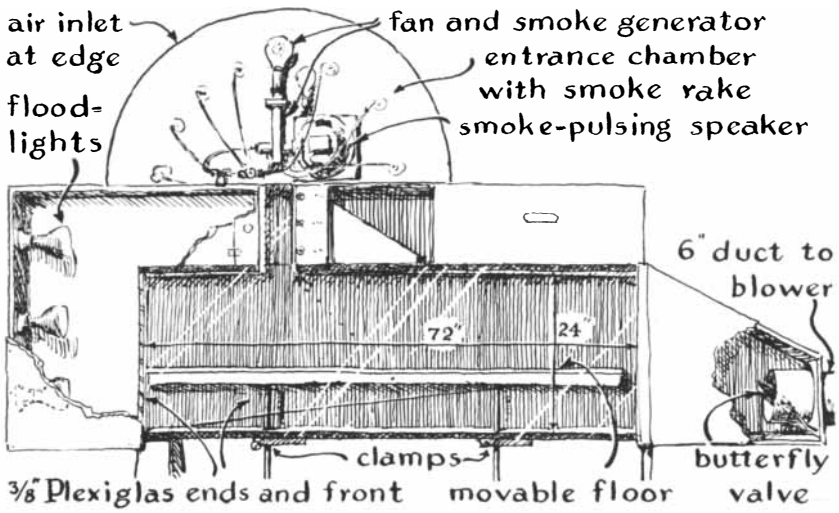
"The entire front and the left end of the tunnel, as well as the left wall of the nozzle duct, are made of transparent plastic so that air flow can be observed and photographed. A light box



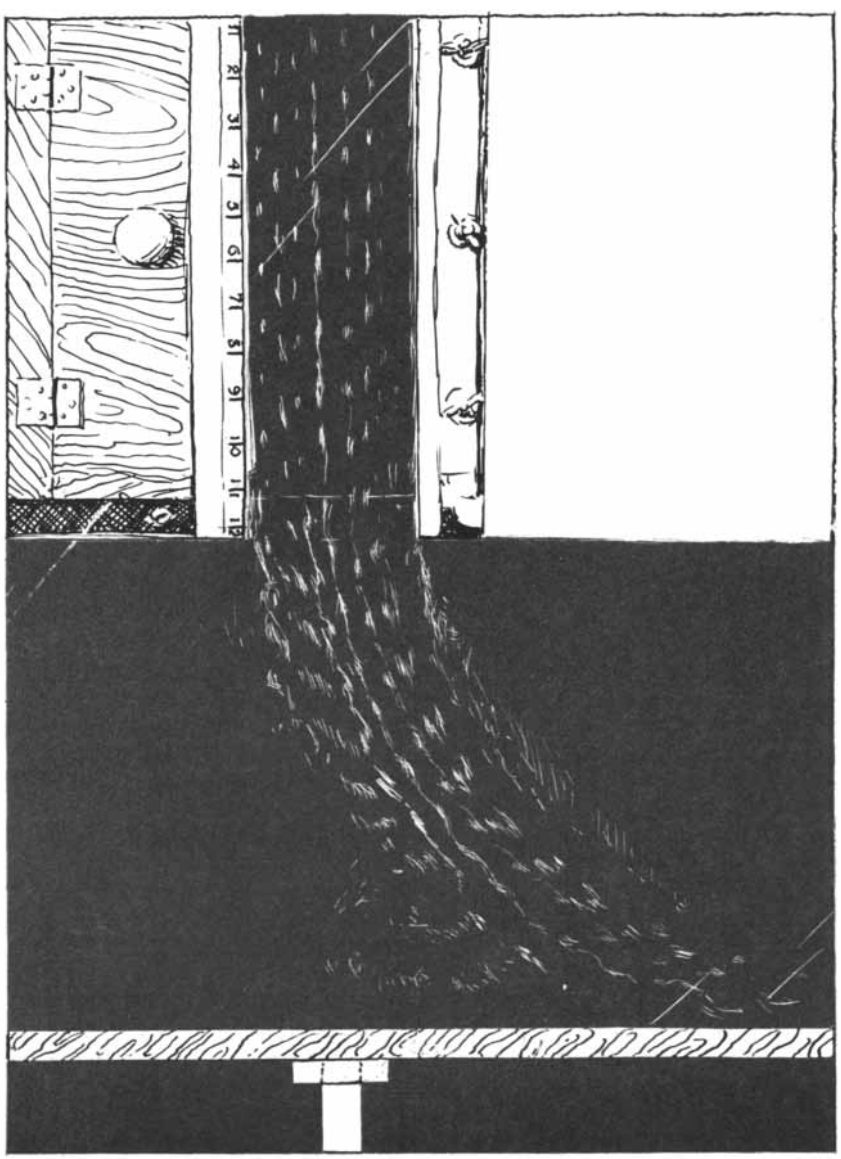
The pulsing apparatus

fitted with three floodlights illuminates the nozzle and the tunnel from the left. The tunnel is 3½ inches deep, 24 inches high and 72 inches long. The inside back wall is painted flat black. The movable floor is sealed by weather stripping at the sides and the left end. It can be raised or lowered as necessary by means of wooden dowels that pass through rubber grommets in the bottom of the tunnel, and it can be fixed at any level by clamps that secure the dowels. Air leaves the tunnel at the right through a duct six inches in diameter and 15 feet long containing a square-edged orifice station at which the flow is measured. Air is pulled through the system by connecting the exhaust duct to the inlet of a 7½-horsepower blower that moves 920 cubic feet of air per minute at a reduced pressure of about two inches of mercury. I control the flow by throttling the discharge from the blower.

"Pressure measurements were made by means of vertical U-tube manometers, partially filled with oil, connected to taps in the system by flexible tubing at desired points. (Colored water can be used in the manometers but I prefer oil because of its lower rate of evaporation.) I installed a series of pressure taps in the nozzle duct and in the back wall of the tunnel at the left of the nozzle, as well as a diagonal row of taps that slopes downward from the right of the nozzle. Pressure measurements are of particular interest in the area at the left of the nozzle, which corresponds to the underbody region of a hover craft where compressed air accumulates to support the weight of the machine. The area at the right of the nozzle, which represents the



Cutaway view of smoke tunnel



Pulsed jet of smoke in tunnel

environment into which the jet discharges, is of similar interest.

"If the experimenter wants to investigate conventional aerodynamic effects, such as the forces that are developed on wing sections and the like, the construction can be modified so that the jet is directed into the tunnel from the left end. The apparatus should then be lighted either from the front or the top (see "The Amateur Scientist," SCIENTIFIC AMERICAN, May, 1955).

"In a properly functioning tunnel the smoke streams flow as thin, continuous lines from the jet to the exhaust port, their separation and curvature determined by the geometry of the apparatus. The same smooth flow is observed in the case of pulsed smoke, except that the streamlines are depicted by puffs of smoke instead of lines, as shown in the accompanying illustration [*bottom of this page*]. In this example the flow is smooth inside the duct that leads to the nozzle but becomes turbulent as the jet bends into the tunnel proper. The duct carries a scale divided in inches for measuring the separation of the puffs. Because the interval between the puffs is known to be 1/60 second and the distance between puffs can be measured, the velocity of the flow is easily computed.

"This tunnel was constructed to confirm mathematical predictions that the ratio of the innermost radius of the jet to the thickness of the jet controls air flow in the case of ground-effect vehicles. Comparison of the measured and predicted values of pressure and flow agreed within 7 per cent. All measurements made with the tunnel during a series of experimental runs were in close agreement.

"The stratagem of using a loud-speaker as an inexpensive generator of timed puffs should have application to smoke tunnels of many types. Doubtless the technique can be improved. For example, time did not allow me to investigate the effect of electrical wave form on the shape of the puffs. Perhaps a triangular wave, instead of the sine wave I applied to the speaker, would improve the discreteness of the puffs because the motion of the speaker cone would then drive the smoke at constant velocity. My choice of an eight-inch speaker was arbitrary. The size of the speaker and the cone displacement for best performance are clearly related to the volume of the chamber, the manifold and the smoke rake. An interesting series of experiments could be devised for determining the optimum proportions of these components."

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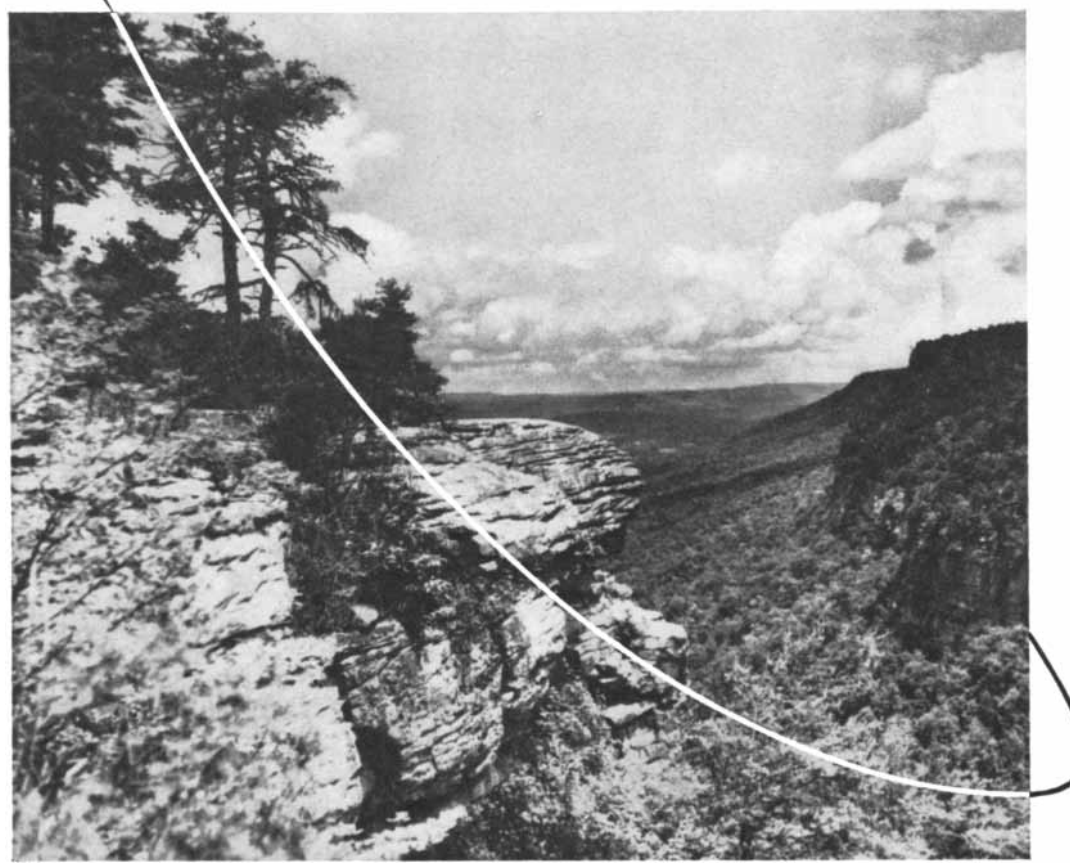

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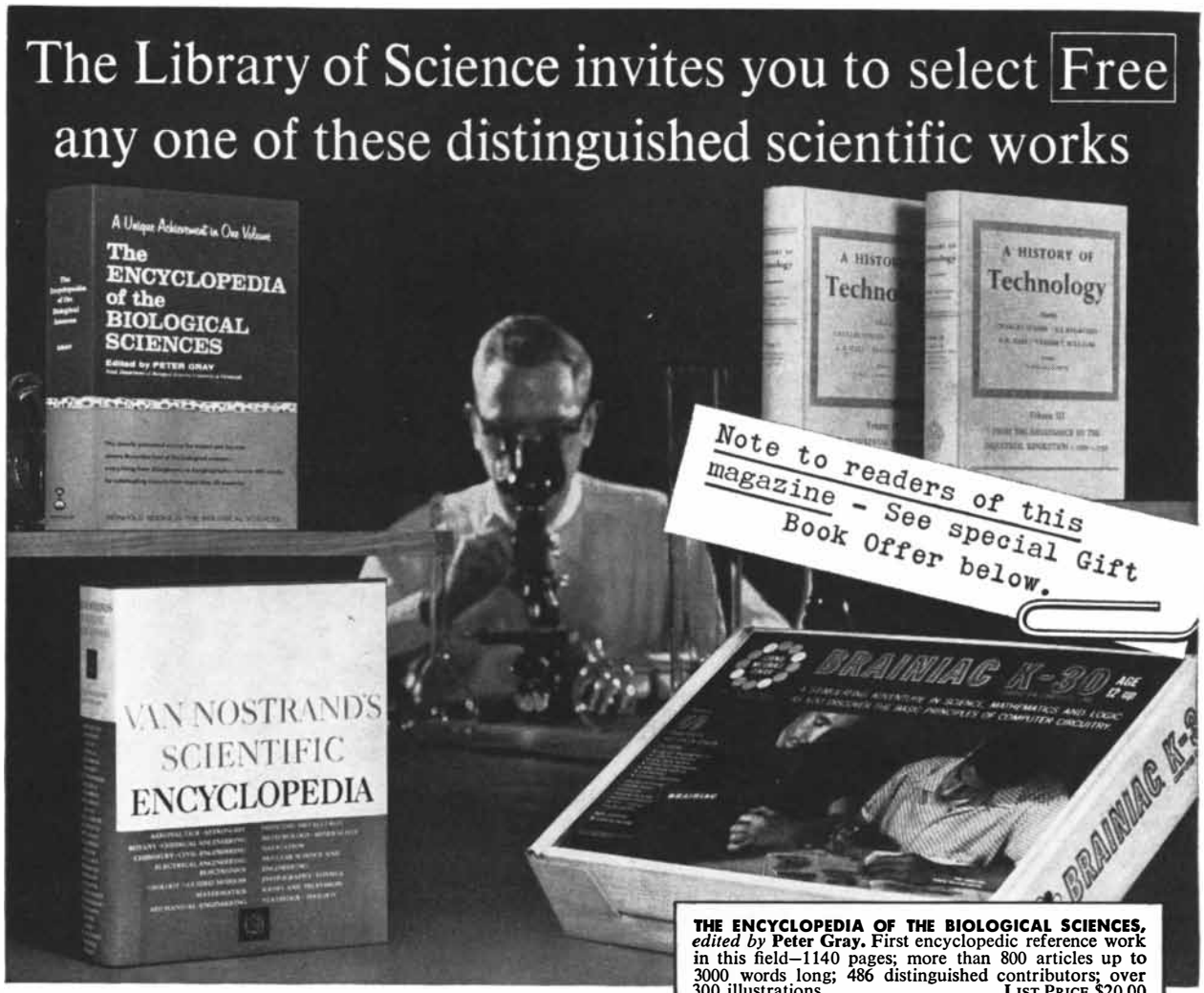

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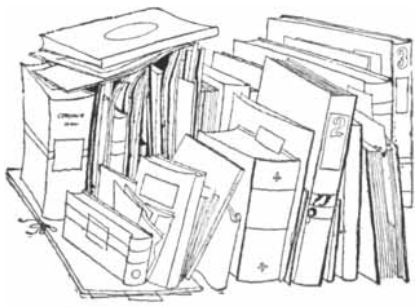


BOOKS

Concerning the slow rate of growth of the U.S. economy

by Leon H. Keyserling

CHALLENGE TO AFFLUENCE, by Gunnar Myrdal. Pantheon Books ($3.95).

Most U.S. economists have failed to analyze with reasonable accuracy the causes of the highly unsatisfactory performance of the U.S. economy during the past decade, and the inadequacies of our national economic policies reflect this default and others. Gunnar Myrdal's new book diagnoses the trouble with unerring precision and sets forth the full remedy with both vision and practicality. The current poverty of U.S. economics is poignantly revealed by most American reviews of this great work, which slight or entirely ignore the author's central theme and wander off into minor criticisms largely based on misinterpretation. Any evaluation of the book must be set in the context of U.S. economic problems and the measures now under consideration to meet them.

From the beginning of 1953 to the present our economy has moved in a fairly rhythmic pattern of recessions, sharp upturns of insufficient pace and duration to bring us even reasonably close to the full use of our resources, and periods of stagnation or abnormally slow economic growth that lead into the next recession. As a result the average annual growth rate of the U.S. economy, measured in total real output of goods and services (gross national product, or GNP), during the past decade has been only about 2.8 per cent. This contrasts very poorly with the at least 4.2 per cent—and possibly 5 per cent—required to maintain the reasonably full use of resources by absorbing the annual increase in the civilian labor force and in productivity or output per man-hour.

The upturn that started early in 1961 has not been appreciably better than the entirely unsatisfactory upturns that followed the earlier recessions subsequent to the Korean war. The reason the upturn is tending to last longer this time is that at first its pace was slower than on earlier occasions, and that the period of stagnation came even sooner. What has really been stretched out is the duration of a progressively weakening "recovery" movement, and we should not boast too much about taking so long in not getting back to full prosperity. To illustrate, if we consider 12-month periods from the first quarter of 1961 to the first quarter of 1962, from the second quarter of 1961 to the second quarter of 1962 and so forth, each succeeding period through the second quarter of 1963 registered a declining rate of economic growth (7.7 per cent from the first quarter of 1961 to the first quarter of 1962, and only 3.3 per cent from the second quarter of 1962 to the second quarter of 1963). There has been some quickening, but not much, in the third quarter of 1963. Moreover, an annual growth rate of well below 4 per cent from the fourth quarter of 1961 to the present should be contrasted, not with the growth rate of 5 per cent or better that would be required annually to absorb the increase in the labor force and in productivity *after* the full use of resources is restored, but rather with the growth rate of 8 or 9 per cent required annually for about two years to lift us *from where we are now* to the full use of resources. Most forecasters expect at best a continuation of the stagnation pace in 1964, and some fear another recession this year.

The roller-coaster performance of the economy from the beginning of 1953 through the third quarter of 1963 has meant a deficiency of about $475 billion (measured in 1962 dollars) in total national output, accompanied by some 30 million man-years of lost opportunities for employment. Meanwhile the true level of unemployment (taking into account full-time employment, the full-time equivalent of part-time employment and the concealed unemployment resulting from the repressed growth of the civilian labor force due to shortage of job opportunities) rose from less than 5 per cent of the civilian labor force in 1953 to about 9.3 per cent during the first three quarters of 1963 (seasonally adjusted). Full-time unemployment rose from 2.9 per cent to 5.7 per cent.

Myrdal will have none of the blandness that is now manifest in many quarters. He says: "I have seen no evidence that would render it probable that the American economy by itself—i.e., as a result of the forces now at work in that economy, including Government policies currently to be anticipated—would get out of this rut." He finds that "the creeping complacency that America is now an affluent society... that allows it to slow down its economic progress is patently wrong... a basically defeatist view... static and not geared to a rational approach of public responsibility and policy." He is concerned not only for the U.S. but also for the world; he feels that only a much improved U.S. economic performance would enlarge the motivations both here and abroad for the reduction of armaments and restore optimum U.S. influence in other countries.

Empirical observation of the U.S. economy during the past decade makes this clear: The periods of rapid upturn have been aborted, and the periods of stagnation and recession have set in, because of a confirmed tendency to generate periodically a nonsustainable rate of growth in our productive facilities compared with our effective ability to distribute and consume. During the relevant period preceding the 1957–1958 recession private investment in plant and equipment grew more than three times faster than total private consumption plus private outlays for goods and services at all levels of government (which are really public consumption); during the period preceding the 1960–1961 recession the former grew about 3.5 times faster than the latter; and even from the first quarter of 1961 to the fourth quarter of 1963 (estimated), in spite of the repressive effect on investment of idle plant capacity in the neighborhood of 15 per cent, the former grew very much faster than the latter. The

investment cutbacks resulting in due course from these imbalances in the two earlier periods, coupled with the more enduring deficiencies in demand for ultimate products, brought on the periods of stagnation and recession. These imbalances now threaten us again.

It is particularly noteworthy, from the viewpoint of public policy, that the nonsustainable investment binges have all along been sustained by more than ample profits, retained earnings and other sources of investment funds, and that they are entirely unimpeded by any excessiveness in the tax burden on corporations or on individuals who save a large part of their income for investment purposes. Meanwhile, over the decade and even now, the deficiencies in demand for ultimate products have been due to deficiencies in private incomes and in public outlays, with the latter arising in part from the adverse effect of low economic growth on public revenues at any given tax rates and in part from highly unsuccessful attempts to balance the Federal budget at the expense of the national economy.

My estimate is that the deficiency of about $475 billion in total national production from the beginning of 1953 through the third quarter of 1963 has been accompanied by a deficiency of about $315 billion in private consumer spending and a much larger deficiency in total personal income (allowing for taxes and saving). The deficiency in such income and the periodic excesses in saving and investment have been aggravated by the poor distribution of income. If one considers all multiple-person families in the U.S., those with incomes of less than $4,000 (who spend all their income and usually go into debt) received in 1961 only 7.2 per cent of the total family income although they constituted 22.6 per cent of all families. Meanwhile families with incomes of $15,000 and more (who save and invest at high rates) received 23.7 per cent of the total family income although they represented only 7.3 per cent of all families. Federal outlays for goods and services have annually averaged several billion dollars too little, and the adverse impact on the economy has several times exceeded this figure because of the high "multiplier" effect of such outlays.

The central task of national economic policy is to help restore and maintain the economic equilibrium that would result from a sustainable relation between, on the one hand, the expansion of our ability to produce, which arises largely from investment in plant and equipment (which in turn has an important bearing on the productivity of workers) and, on the other, the expansion of the ultimate demand for goods and services that flows from the size and composition of private incomes and from levels of government spending. Moreover, the very programs that would enlarge personal incomes and improve their distribution would be a major attack on private poverty, and the adequate enlargement of public spending would help both to liquidate private poverty and to overcome the poverty (measured against our resources and needs) of goods and services in the public sector.

On all these points Myrdal delivers accurate fire. He rejects the notion (pushed repeatedly by many U.S. economists in private and public life) that the economic stagnation of the U.S. is caused by an excess of current consumption and leisure and a deficiency in saving and investment. He adds that the "lag in consumer demand is a basic factor behind the low economic growth rate" and warns of the danger of the serious lag in wage-rate increases (the largest single element in the expansion of private incomes and consumption) behind productivity gains. He finds the beckoning opportunity to lift U.S. standards of living in the fact that a fifth of all Americans still live in poverty and another fifth in deprivation.

Myrdal advocates "public expenditures which in the first place will improve the lot of the poor in America." He says that "the situation is overripe for a radical reform of the old age security system," urges large improvements in minimum-wage legislation and advocates much larger public investment in education, medical care, slum clearance and urban renewal. Indeed, Myrdal insists that "redistributional reforms should be looked upon as equally important as a basis for the achievement of rapid and steady expansion of the American economy and high employment as from the point of view of social justice."

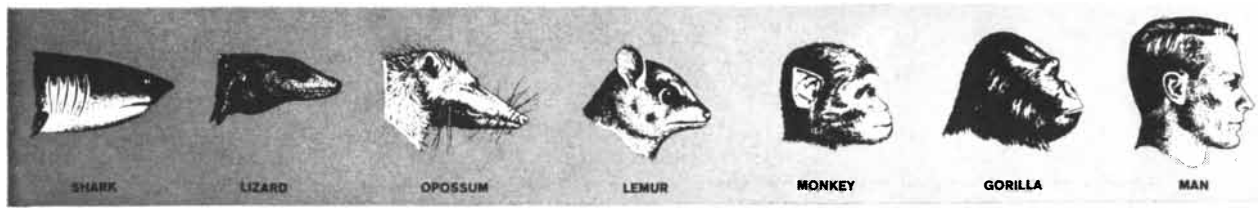
The national economic policies now in being (and those under active consideration) to get the U.S. moving again are in sharp if not diametric contrast with those that Myrdal rightly advocates. The pending tax bill (viewed properly in conjunction with the 1962 tax cuts for corporations) would allocate (according to my estimates) about $7 billion to investment purposes, taking into account both the corporate tax cuts and that portion of the personal tax cuts for the top eighth of the incomes, which in large measure would be saved for investment purposes. These types of cut, for reasons already stated, are wholly or preponderantly wasteful, even as economic stimulants. Only about $6 billion of the current tax bill (again according to my estimates) would be allocated to the consumption function. The distribution of this allocation is economically and socially unsound because between 40 and 45 per cent of the personal tax cuts would go to the top eighth of the income-tax payers. Under the pending measure the taxpayer with an income of $3,000 would receive an increase of only 2 per cent in his after-tax income; the taxpayer with an income of $200,000 would receive a 16 per cent increase.

Most important of all, the tax program neglects the obvious truth that the rate of technological change in much of industry and agriculture is so rapid that even the increase in the demand for their products that would result from tax reduction would make only a slight contribution to the 22.5 million new jobs we need over the next decade to reduce unemployment, to absorb the growth of the labor force and to create new jobs for those forced out of their current ones by such technological change. A properly devised tax-reduction program therefore needs to be accompanied, as Myrdal insists, by a huge expansion in such fields as slum clearance and rehousing, urban renewal, health and education, public works, mass transportation and resource development. All of these require a large, immediate and progressive expansion of domestic public outlays.

Yet, as a *quid pro quo* for a dubious kind of tax reduction, our national economic policies have been tending toward a freeze, if not an actual reduction, of these vital domestic public outlays in the years immediately ahead. Even a freeze is actually a reduction in view of the growth of the population. Meanwhile too little has been said, and much less attempted, with respect to the vast needed expansion of social security and improvement of minimum-wage legislation. And in its "guidelines" addressed to the private economy the Council of Economic Advisers has been a powerful influence in bringing on the lag of wage rates behind productivity gains that is so important a factor in the total consumption deficit.

The policy of tight money and rising interest rates, substantially adhered to even recently, is highly repressive in its economic effects and highly regressive in its effects on income distribution. Myrdal is entirely correct in his advocacy of a much more selective application of monetary restraints in order not to feed the fat and starve the lean.

In the lively debate about whether



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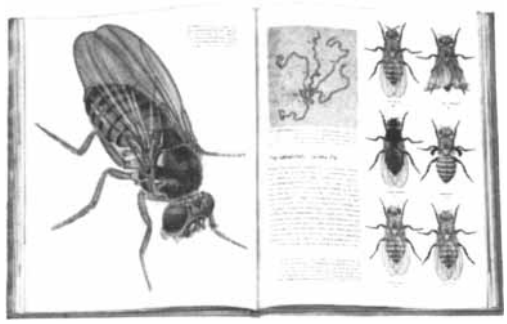

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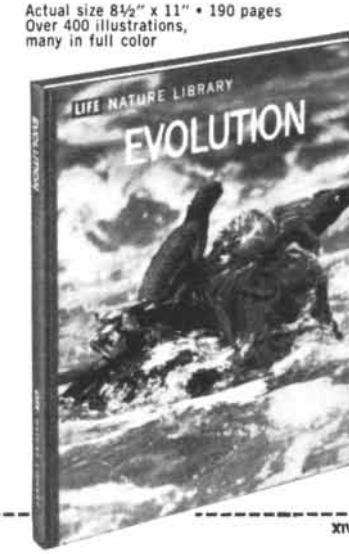

MALE FRIGATE BIRD displays bright red gular pouch to attract females. Attractive sex characteristics increase mating success, are more likely to be passed on.

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the excessive level of unemployment is caused by structural maladjustments in the labor force (the unadaptability of potential workers to new types of jobs) or by an insufficiency of aggregate demand, I side with the Council of Economic Advisers. With enough of an aggregate demand, workers in the main quickly adjust to new job opportunities and can be trained largely on the job; this was demonstrated by our experience during World War II. Moreover, although some training and educational programs are desirable at all times, we cannot know what jobs to train people for until the jobs are created.

The statement that an adequate aggregate level of demand will provide full employment is, however, merely a truism. The real problem is how to get enough demand. Because of technological factors and the relative urgency of competing needs and consumer desires, it will be impossible to create an adequate level of demand without paying far more attention to the structure of this demand, without so restructuring the demand that much more of it takes the form of those activities requiring expanded public spending, and also new admixtures of private and public spending requiring, among other things, ampler credit and lower interest rates.

Some reviewers have attributed to Myrdal an excessive stress on the structural approach. I agree that he appears to give too much weight to this aspect of the problem. He covers himself quite well, however, by pointing out that structural, or selective, policies to prevent unemployment must be preceded by a full-employment policy that maintains a general scarcity of labor. Throughout the whole book he underscores above all the public programs required to change the structure of demand.

Going all out for long-range economic planning, Myrdal says that it involves much more than technical plans in specialized fields, because "the main thing in long-range planning is that all these technical plans have to be integrated into an over-all plan for the development of the economy as a whole." He notes with discernment that what is most needed is "a much better co-ordination of already existing Government policies" that would make it "possible to scrap a lot of specific regulations and policy interventions which have spuriously grown up *ad hoc*.... Indeed, successful planning should free the citizens from a lot of nuisance public intervention of which there is an astonishing amount in the U.S.... I find American Government offices appallingly big in relation to the functions they perform. And many functions themselves would disappear in a more perfect planning."

Although these comments square with my own 30 years of experience in Washington, I think that Myrdal, in discussing the deficiency in U.S. economic policy and its execution, tends to blame this too much on the attitudes of large business enterprises and on the defective economic education of the average U.S. citizen. Allowing for this, I feel that there is much room for improved policy action at leadership levels of official responsibility. The Employment Act of 1946, if fully utilized, offers an opportunity and even sets forth a mandate for the very kind of planning Myrdal advocates. Such planning, by the very techniques of its utilization, would avoid some of the policy aberrations discussed here.

The tendency to blame the failure to get the U.S. economy moving again on so-called "political" difficulties beyond the reach of national leadership cannot be said to be pointless. To a considerable degree, however, the economics of any national administration reflects—perhaps with some cultural time lag—the prevalent stream of professional economic thinking. To bring home the extent to which the differences between Myrdal's economic thinking and that made manifest in our national economic policies reflect recent trends in our professional economics, it is helpful to recall the content of perhaps the most widely read and influential book written by a U.S. economist in recent years.

John K. Galbraith's *The Affluent Society* appeared in 1958, when we had just suffered two recessions within five years, when slow economic growth and chronically rising unemployment had become so clearly our dominant economic problem that this reviewer had from 1954 on published several studies on this subject, and when we had suffered much selective price inflation in the years immediately preceding in spite of considerable economic slack. Yet Galbraith lampooned the nationwide concern about economic growth, urged "winning a measure of release from our present commitment to full employment," said that poverty is no longer "a massive affliction" in the U.S. and declared that in the U.S. economic security (except in times of depression) is "finished business, or largely finished business." Correspondingly, urging "much expanded use of the sales tax," Galbraith said that "in the affluent society no useful distinction can be made between luxuries and necessities" and that "argument for equality" can get us nowhere; he urged a "truce" on this issue "because of its comparative lack of social urgency." And in a letter to *The Washington Post* on August 3, 1960, Galbraith urged policies to inhibit "consumption rather than investment."

The following question arises: Does Galbraith's worthy theme that more of our resources should be directed into the public sector conflict with the recent trend toward holding back on domestic Federal public outlays in return for a tax reduction proposal that would provide more spendable income for taxpayers in the private sector in direct correlation with how affluent they already are? Not entirely. Galbraith did not advocate more Federal domestic spending; he urged more state and local public spending, financed by more sales taxes, which are profoundly regressive. In fact, most of Galbraith's book fits in well with much of national economic policy in recent years: the regressive tenor of tax and monetary policies, the misplaced stress on investment rather than consumption, the dampening attitude toward wage increases, the dearth of direct action against massive poverty and the viewpoint that a top priority for ethical and social problems is old hat.

Much of Myrdal's rejoinder to these ideas has already been set forth here. Most important of all, however, is his eloquent attack on the dichotomy between economics and ethics that now has a virtual strangle hold on dominant economic thought in the U.S. He urges above all that "the moral issue" be pressed through "eradication of poverty" and "a redistributional economic policy," and he concludes with ultimate validity that "never in the history of America has there been a greater and more complete identity between the ideals of social justice and the requirements of economic progress."

I have become convinced that a substantial portion of the "political" obstacles to more effective national economic policies arises precisely because the policies *ab initio* do not project in their content or presentation the galvanizing force of sufficiently appealing ethical and social objectives. In our system, as it has evolved in the 20th century, this galvanizing force is unlikely to begin at random points among the people or in the Congress; it usually must start with Executive articulation. Woodrow Wilson, who during his first term put through what may have been for its time the greatest program of economic and social reform in U.S. history (without the benefit of a war or a depression), said the last word on this subject in an

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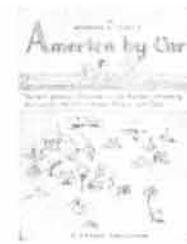

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essay he wrote at the age of 22: "Leadership makes principles; principles make parties."

I believe that President Kennedy, with his native endowments and pragmatism, would have moved toward this progressive reshaping of our national economic policies as evidence of the inadequacies of the current approaches accumulated (as I believe they will). I feel also that President Johnson, a man of great realism and genuinely committed to the economics of human well-being, will generate momentum in this same direction. Meanwhile, it would be very helpful for all thoughtful citizens, and particularly those in positions of high public leadership, to read and ponder Myrdal's book.

Short Reviews

THE COLUMBIA ENCYCLOPEDIA, edited by William Bridgwater and Seymour Kurtz. Columbia University Press ($49.50). The third edition of the *Columbia Encyclopedia*, which has been revised, updated and reset, is an improvement over its predecessor, which was a work of great merit. More than 6,500 new subjects are covered, from national and world affairs to science, philosophy, literature, the arts and sports. You can now read about Barry Goldwater and James Hoffa, the CIA and DNA, Nikita Khrushchev and Sonny Liston, space satellites and J. D. Salinger, the John Birch Society and the desalination of water, Maria Callas and tranquilizers, lasers and Leonard Bernstein, Martin Buber and the Common Market, the IGY and Edward Albee, open-heart surgery and Yevgeny Yevtushenko, Roger Maris and abstract expressionism. Also new are 20 maps and 40 pages of illustrations. (The second edition had neither maps nor illustrations.) In all there are 7.5 million words, 75,000 articles and 35,000 titles in reference bibliographies. There are also inaccuracies, curious omissions and odd preferences. Every reviewer and user will have his own complaints reflecting special knowledge and special needs, but the Columbia can withstand criticism. It is a fine reference book, dependable and indispensable whether or not you have the money and shelf for larger encyclopedias.

STUDIES IN FRONTIER HISTORY, by Owen Lattimore. Oxford University Press ($12). A group of essays published between 1929 and 1958, mostly in learned journals, dealing with frontiers and recent problems of peoples who live in frontier regions, in particular those of China and Central Asia. By experience, temperament and training Lattimore is uniquely equipped to discuss the questions to which the essays are addressed. In an engrossing autobiographical preface, which is all too short, he sketches his adventures and observations over many years as a traveler in inner Asia. Often with only a single companion, his servant, he journeyed for thousands of miles on foot and horseback over lonely trails and wild wastes. He encountered merchants, nomads and brigands, learned their different languages, shared their campfires, their food, their pleasures, their weariness. As a sympathetic and gifted student, he sought to know and to understand rather than to prove a theory. This is a first-class book from which there is much to learn about matters that are today in the forefront of world affairs.

VANISHED CIVILIZATIONS OF THE ANCIENT WORLD, edited by Edward Bacon. McGraw-Hill Book Co., Inc. ($28.50). A continuation of the series begun by this publisher with the volume *The Dawn of Civilization*, this book consists of 15 articles by different contributors dealing with various cultures that time has consigned to limbo and that modern archaeology has at least partly rescued. Henri Lhote writes of the neolithic rock painters of the Sahara, who flourished at a time when the land that is now desert was wet and fertile enough to support many people; Roger Summers describes the Zimbabwe of Southern Rhodesia, whose cultural high point came between A.D. 1000 and 1200; L. P. Kirwan, the "X-group enigma" of a little-known people of the Nubian Nile; William Watson, the ancient Ainu, fair-skinned aborigines of Japan whose descendants still occupy the southern island of the Kuriles (Ainu people of today are thought to be the first inhabitants of the Japanese islands, but they are not "conscious of any past glory," having long been reduced to underdogs by the Japanese invaders); Christopher Pym, the empire of the Khmers; Donald Strong, the Etruscans, "an historic people who left no history"; J. B. Segal, the Sabians of northern Mesopotamia, who won renown in astronomy, medicine and the exact sciences and who helped to transmit classical learning to the Arabs; J. Eric S. Thompson, the Mayans; E. D. Phillips, the highland people of Luristan, Mannai and Urartu, who were on the fringe of Mesopotamian empires; T. Sulimirski, the Sarmatians, "a once mighty folk scattered among the nations" (they were of Iranian stock, were influential in "reshaping the ancient European order at the turn of Antiquity and the Middle Ages" and made considerable contributions to medieval art). Maps, charts and photographs.

THE ATLAS OF BRITAIN AND NORTHERN IRELAND, planned and directed by D. P. Bickmore and M. A. Shaw. Oxford University Press ($100). This folio volume, with some 200 map pages, is a record in pictorial form and on a geographic basis of the resources of the United Kingdom. It is not primarily topographical; instead it presents a vast body of facts and statistics relating to many different subjects. Ingenious and colorful maps furnish information on bacon factories and bicycle manufacturers, national parks and nuclear reactors, biscuit bakeries and breweries, sawmills and scrub woodlands, sheep farms and local death rates, tidal movements and inland waterways, Paleozoic systems and parliamentary-constituency boundaries, potato fields and fog dispersion, green crops and housing conditions, dry days and dressmaking establishments, fresh-water fish and Gaelic-speaking populations, slaughterhouses and wind conditions. Many countries have issued similar national atlases, but this is the first for Great Britain. The work, which has had the co-operation of leading scholars and experts from Oxford and Cambridge as well as from government departments, commercial firms and other organizations, has been more than a decade in the making. An unfortunate but perhaps unavoidable consequence of this long period of preparation is that many of the statistical and other data are five to nine years old. The maps are clearly executed; the treatment of legends, symbols, color and statistical details deserves high praise; the format is both elegant and practical. This is an unusual publication that deserves to be honored by use.

BIRDS AND TREES OF NORTH AMERICA, by Rex Brasher. Rowman and Littlefield, Inc. ($200). Rex Brasher was born in Brooklyn in 1869 and died in 1960. From boyhood—at the age of 12 he already had a collection of 155 mounted birds—he was a passionate ornithologist. He knew what he wanted to do and he devoted his entire life to doing it in spite of adversity, frustration and repeated disappointment. His goal, on which he had resolved at the age of 16, was to paint all the birds of North America. To prepare himself he left school in his teens to become an apprentice copper engraver at Tiffany, worked as a photo-

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engraver in Maine, lived in the barest possible circumstances to save his money against the day when he would begin painting, and in 1895, at the age of 26, began his field observations. He sailed along the Atlantic coast, shipped out of Gloucester in a fishing boat to see the birds of the north, crisscrossed the continent. Later he bought a farm in the Berkshires of Connecticut and settled down to complete his task. By 1928 he had painted more than 3,000 separate birds and 383 species of trees. He could not, however, find a publisher for his work and so decided to issue it himself. This required, among other things, painting by hand 93,000 individual plates for the 100 sets of the four books, which were published at $2,400 a set. The paintings are here reproduced in full-color facsimile from the originals, now owned by the State of Connecticut. The text itself is brief, consisting of Brasher's own notes as to habitat, range and breeding, and of other odds and ends of commentary. It is said of Brasher that he lived in the "huge shadow" cast by Audubon. It is true that his paintings do not compare with Audubon's in brilliance, but they have a soft quality, a gracefulness and a fidelity of their own, and they have been much admired by leading ornithologists and collectors. Their appeal is enhanced by the knowledge of the painter's incomparable devotion and dedication to so gentle and unworldly a task.

PASSENGER CAR DESIGN AND HIGHWAY SAFETY. Association for the Aid of Crippled Children and Consumers Union of U.S., Inc. ($2.75). The proceedings of a conference, held in 1961, in which representatives of automobile manufacturers, insurance companies, engineering firms, the U.S. Public Health Service and other Federal and state institutions participated. The papers and the discussions deal with such topics as highway safety strategies, the methods of evaluating safety measures, the vehicle-design aspects of safe handling, vehicle-handling research and its influence on automotive engineering practice, driver-vehicle fit, the usefulness of periodic safety inspections, the effects of vehicle aging and mileage on accident rates, crash protection for children, economic aspects of automobile safety devices, the legal regulation of automobile design. One is struck by how much is known about the causes and prevention of accidents, how little of what is known is used, how widespread are the misconceptions about highway safety and how great the need is both to gain more knowledge of this complex subject and to enforce its application.

NORTH FACE IN WINTER, by Toni Hiebeler. J. B. Lippincott Company ($3.95). An account of the first winter climb of the notorious north face of the 13,000-foot Eiger in the northern Alps by one of the four members of the successful team. The story suggests that the famous and somewhat meaningless cliché on the reason for climbing a mountain ("because it is there") can now be changed; men who do the sort of thing reported here do it because they are crazy. Still, this is an exciting story.

BIRDS OF WISCONSIN, by Owen J. Gromme. The University of Wisconsin Press ($22.50). A lively, attractive display of 328 species of Wisconsin birds (including some that are now extinct) in 105 color plates, together with brief notes as to range, numbers and so on. In addition to the identification portraits there are 16 color plates showing birds in their natural habitat or in relation to other birds or animals. The artist, who is curator of the Milwaukee Public Museum's Division of Birds and Mammals, has a deep feeling for his subjects, a clean line and sound sense of color. This is altogether a pleasing book.

MAN AND THE LIVING WORLD, by Karl von Frisch. Harcourt, Brace & World, Inc. ($7.50). A graceful, popular survey of biology by the eminent Austrian zoologist best known for his discovery of the dancing language of the bees. Von Frisch looks into every corner of the subject, from the life of one-celled creatures to genetics and biochemistry. His presentation is so lucid and relaxed that, having once begun, the reader is delighted to follow the story through to the end. Good illustrations.

QUANTUM MECHANICS, by Edward U. Condon and Philip M. Morse. McGraw-Hill Paperback ($2.95). Reprint of a now classical monograph, first published in 1929, that gives an outline of the results obtained by the use of quantum mechanics. The authors recount developments between 1924 and 1929, a period they call "the most exciting in the history of theoretical physics."

THE ART OF THE HITTITES, by Ekrem Akurgal. Harry N. Abrams, Inc. ($25). A sumptuously illustrated survey of the art, society, language and religion of this warlike people, who between 2300 and 800 B.C. built hilltop palaces,

made their sculptures by carving directly into rocky cliffs and produced remarkable vases, jewelry and other ornamental objects. Handsome photographs in color and black and white, maps and ground plans of excavations.

Notes

ON FORMALLY UNDECIDABLE PROPOSITIONS OF PRINCIPIA MATHEMATICA AND RELATED SYSTEMS, by Kurt Gödel. Basic Books, Inc., Publishers ($3). An English translation by B. Meltzer of Gödel's famous paper, with an introduction by R. B. Braithwaite.

MIDDLETOWN IN TRANSITION, by Robert S. Lynd and Helen Merrell Lynd. A Harvest Book ($2.45). A paperbacked reprint of the second of the two notable studies by the Lynds, this volume is concerned with the cultural conflicts of Middletown during the great depression.

AN ACCOUNT OF THE ASTRONOMICAL DISCOVERIES OF KEPLER, by Robert Small. The University of Wisconsin Press ($5.50). A reprint of a book published in 1804 that, as William D. Stahlman points out in his introduction, is the best description in the English language of the planetary systems that preceded and led up to Kepler's work and of Kepler's own mathematical demonstrations in the *Astronomia Nova.*

MAN ON HIS NATURE, by Sir Charles Sherrington. Cambridge University Press ($1.95). A soft-cover edition of Sherrington's famous Gifford Lectures, given at the University of Edinburgh in 1937.

PAPERS ON HUMAN GENETICS, by Samuel H. Boyer IV. Prentice-Hall, Inc. ($9). Gathered from technical journals, these papers—which in time run from the early part of the century to 1961 and in subject matter from mathematical analyses of genetic problems and blood-group genetics through biochemical genetics, cytogenetics and mutation—furnish a sound sampling of the rapid development of human genetics since Mendel's epochal discoveries were brought to full light some 60 years ago.

THE URBAN CONDITION, edited by Leonard J. Duhl. Basic Books, Inc., Publishers ($10). Some 30 contributors—among them lawyers, sociologists, city planners, public health officials, psychiatrists and psychologists—contribute articles to this volume, which deals with the many complex problems of the modern

city, from delinquency to sanitation, from overcrowding to public housing.

RESOURCES IN AMERICA'S FUTURE, by Hans H. Landsberg, Leonard L. Fischman and Joseph L. Fisher. The Johns Hopkins Press ($15). This large and comprehensive monograph is mainly concerned with the projections of demand and supply of natural resources—products, services, basic land, water and minerals—in the U.S. to the year 2000.

DANGEROUS PROPERTIES OF INDUSTRIAL MATERIALS, by N. Irving Sax and others. Reinhold Publishing Corp. ($25). The second edition of a huge reference work that gives concise information about the hazards associated with the manufacture, use, handling, storage and shipping of more than 10,000 common industrial laboratory materials. The hazards range from allergies to blowing oneself up.

THE SCIENTIFIC PAPERS OF SIR GEOFFREY INGRAM TAYLOR: VOLUME III, edited by G. K. Batchelor. Cambridge University Press ($17.50). The third volume of this collection of Taylor's papers consists of contributions to aeronautics, wing theory, gas dynamics, detonation and blast waves, ballistics and the effects of explosions in the air and under water.

DIRECTORY OF BRITISH SCIENTISTS. St Martin's Press, Inc. ($24). The first edition of a directory that lists some 30,000 persons who hold a degree in science from a British university. In most cases the main sphere of work of each individual is given, together with titles of his principal publications; also listed are scientific societies and their journals and research establishments.

FROM A LOGICAL POINT OF VIEW, by Willard Van Orman Quine. Harper Torchbooks ($1.35). A paper-backed reissue of nine of Quine's logico-philosophical essays, several of which make stimulating reading.

MATHEMATICS AND THE PHYSICAL WORLD, by Morris Kline. Anchor Books ($1.95). A paper-backed version of Kline's lucid, historically oriented study of the interaction of mathematics and the physical sciences. Kline's book is valuable not only as a survey of mathematical concepts but also as a counterpoise to the recent emphasis in primary and secondary schools on the more abstract approaches to mathematics.

INDEX OF ADVERTISERS

JANUARY 1964

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Pelorus Ring (American—19th Century)—Courtesy Dossin Great Lakes Museum.

from pelorus ring to spacecraft guidance

In 203 B.C., when Hannibal was recalled from Italy to defend Carthage against Scipio's legions, an alleged pirate named Pelorus served as his navigator. His name now graces the Pelorus Ring, an instrument for taking bearings and celestial azimuths.

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