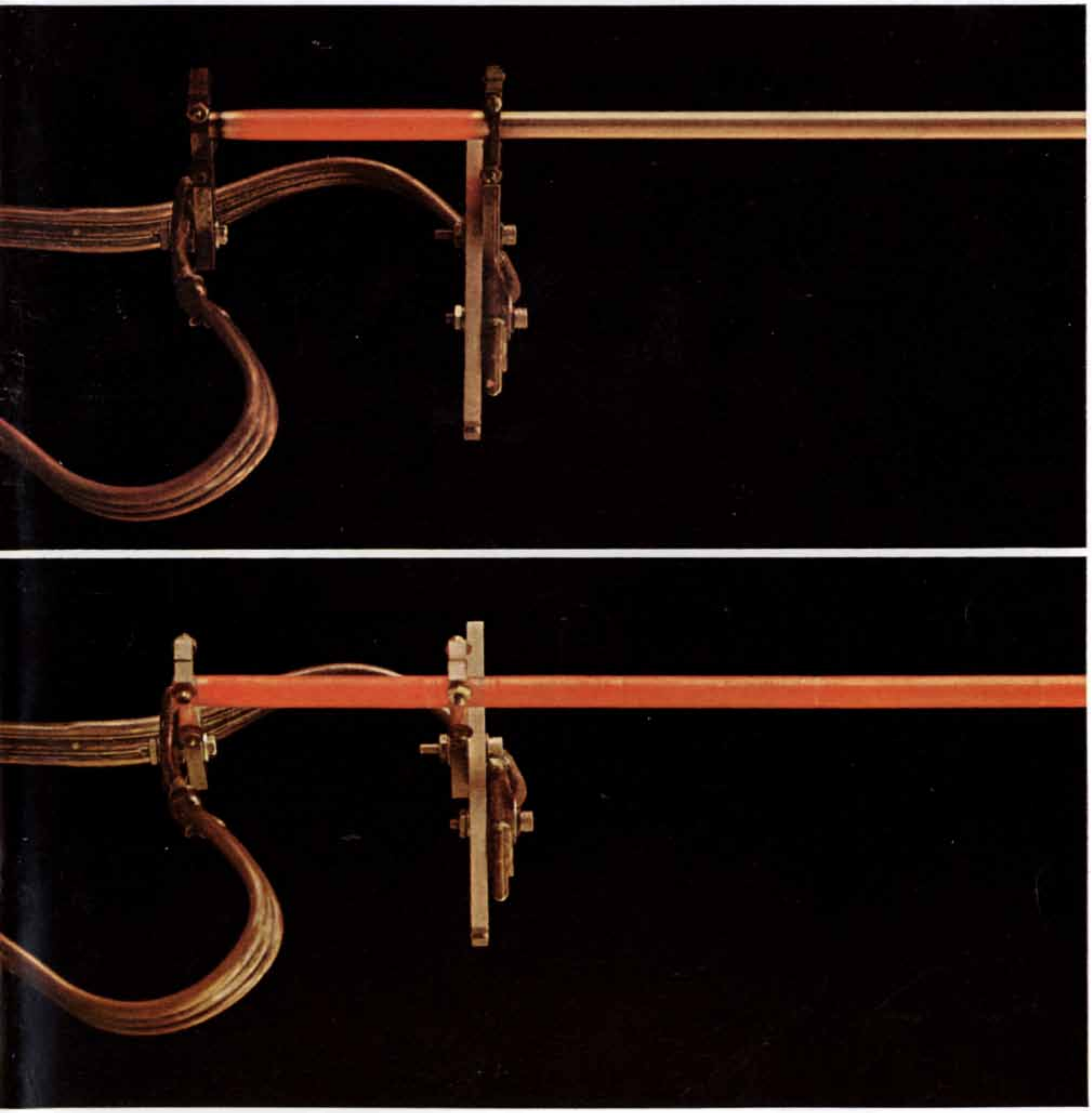
SCIENTIFIC AMERICAN



THE HEAT PIPE

SEVENTY-FIVE CENTS

May 1968

The Countess of Lovelace
(1816-1851)

Woodcarving by William Ransom
Photographed by Max Yavno

"The distinctive characteristic of the Analytical Engine, and that which has rendered it possible to endow mechanism with such extensive faculties as bid fair to make this engine the executive right-hand of abstract algebra, is the introduction into it of the principle which Jacquard devised for regulating, by means of punched cards, the most complicated patterns in the fabrication of brocaded stuffs...We may say most aptly, that the Analytical Engine *weaves algebraical patterns* just as the Jacquard loom weaves flowers and leaves."[1]

[1]Augusta Ada, Countess of Lovelace, note to her translation of the original edition of *Sketch of the Analytical Engine Invented by Charles Babbage* by L. F. Menabrea (the translation published in *Scientific Memoirs*, v. III, London, 1843, pp. 666-731).

INTERACTIONS OF DIVERSE DISCIPLINES

Jacquard's new technology of the industrial revolution gave impetus to the classical mathematics of Babbage. Today's new behavioral, management, and computer-based sciences, interacting with the classical disciplines, are creating optimal solutions to the most complex problems facing government and industry.

Of thirty disciplines represented on the Planning Research professional staff, the largest number are being applied against the economic, technical, and human problems associated with computer systems. Planning Research is a unique source for the design, implementation, and installation of large computer systems, including the largest management information and on-line systems that require the attention of specialists in many fundamental fields. A Planning Research document, *Computer Systems Design and Implementation*, describes this work. For a complimentary copy, address your request to Mr. John N. Graham, Jr., Vice President and General Manager, Computer Systems Division.

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Basic Research at Honeywell
Research Center
Hopkins, Minnesota

Field Level Detection and Measurement Of Hydrocarbons As Air Pollutants

A new sensor which detects and measures the concentration in automobile exhaust of smog-forming hydrocarbons makes possible simple, continuous, inexpensive measurements in the field.

Unfortunately, progress toward control of air pollution has been handicapped by the difficulty encountered in identifying and quantitatively measuring the concentrations of the individual pollutants.

It is generally known that five major pollutants contribute 98% of the pollution in our urban centers. They are carbon monoxide, hydrocarbons, particulate matter, oxides of sulfur and oxides of nitrogen.

Each is harmful in its own way. Carbon monoxide is obviously injurious to health. Particulates cause damage and soiling and in some situations can affect health. The oxides of sulfur are known to damage vegetation and when combined with moisture in the air form sulfuric and sulfurous acids while the oxides of nitrogen in combination with moisture in the air form nitric and nitrous acids. All these acids have corrosive characteristics.

Hydrocarbons are thought to cause smog by a complicated series of photochemical reactions with normal atmospheric components. Among these are peroxyacyl nitrates, skin and eye irritants.

Each of the five pollutants can be identified and measured under laboratory conditions. Yet practical enforcement of regulatory agencies' standards for maximum permissible levels of concentrations of pollutants requires measurement at the source and in the open air by continuous, simple measurement devices. It is necessary to inexpensively and quickly measure pollutants and their concentrations at a smoke stack, from an automobile's exhaust and in the ambient air. Complicating the measurement problem is the fact that concentrations cover a wide range; for example, hydrocarbons may range from 0 parts per million in clear air to 10,000 parts per million in an automobile exhaust.

Honeywell is doing research on the sensing and measurement of these pollutants and has recently developed a particularly interesting device for detecting and measuring hydrocarbons in auto exhaust.

It is known that gases and vapors absorb electromagnetic radiation. It happens that ultraviolet radiation is strongly absorbed by most unsaturated hydrocarbons and is not absorbed to an appreciable extent by other gases or vapors normally found in air. Therefore if one starts with a known amount of ultraviolet radiation it is most likely that any decrease that is measured in an air sample will be due to absorption indicating the presence of hydrocarbons.

Ultraviolet radiation generators are not difficult to devise but simple, inexpensive ultraviolet detectors haven't been available.

Honeywell scientists believed that the Geiger counter philosophy offered real possibilities for ultraviolet detection although a Geiger counter detects photons in the high energy range while ultraviolet radiation would have to be sensed at the 6 electron volt level.

In developing a detector tube they modified the Geiger counter approach by using a configuration in which the discharge is initiated not in the volume but at a cathode made of a material that emits electrons only when ultraviolet radiation impinges on it.

Typical hydrocarbon detector unit includes ultra-violet source, detector, sample chamber, meter and recorder output terminals.

It took ten years of experimental work with different envelopes, geometries, materials, gas fills and processing techniques in order to attain the high degree of selectivity whereby the tube would not respond to anything except ultraviolet radiation. The results were so successful that the final tube is actually blind to solar energy reaching the earth. The tube, with its high internal gain, is small and inexpensive but will conduct enough current to operate an ordinary meter upon sensing 5 to 6 electron volt ultraviolet radiation.

Applied to Honeywell's hydrocarbon detector, the sensor actuates a meter which reads the percent of ultraviolet absorbed by the hydrocarbons in the air sample being tested. With a proper conversion chart the concentration of hydrocarbons in parts per million is easily obtained.

A series of instruments covering a range of sensitivities has been developed. Each includes an ultraviolet generator, sensor and meter. Each is portable, reliable and relatively inexpensive. The most sensitive instrument can detect and measure hydrocarbons in concentrations as low as two parts per million.

Honeywell scientists are deeply involved in research on the detection and measurement of the other four pollutants with some solutions in view. Hopefully, further work will lead to additional portable measuring devices to provide needed field measurements for pollution detection and control.

If you are interested in learning more about Honeywell's research work in the detection and measurement of air pollutants or about its new hydrocarbon detector, you are invited to correspond with Dr. Frank Hughes, Honeywell Research Center, Hopkins, Minnesota. If you have an advanced degree and are interested in a career in research at Honeywell, please write to Dr. John Dempsey, Vice President Science and Engineering, Honeywell, 2701 Fourth Avenue South, Minneapolis, Minnesota 55408.

Honeywell
AUTOMATION

Established 1845 **SCIENTIFIC AMERICAN** May 1968 Volume 218 Number 5

ARTICLES

DEPARTMENTS

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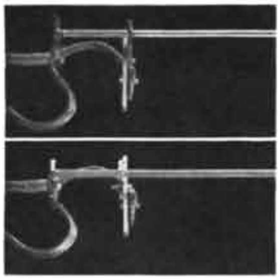

THE COVER

The two photographs on the cover demonstrate the extraordinary heat-transfer capacity of the heat pipe, a new device that shows promise of immediate application in many areas of technology (see "The Heat Pipe," page 38). The photograph at top shows a hollow stainless-steel pipe being heated on one end by passing an electric current through the section of pipe between the two electrodes at left and center. Resistance heating causes this section of the pipe to glow bright orange. Practically no heat is conducted to the part of the pipe that extends beyond the second electrode to the right, however, as is indicated by the fact that this part of the pipe does not glow. The photograph at bottom shows the same pipe, but this time with a wick, or capillary structure, lining the inside surface of the pipe. The wick is saturated with a volatile fluid that evaporates at the heat-input end and condenses at the heat-output end. The resulting circulatory system is the basis of the heat pipe's effectiveness. Although the heat pipe in the bottom photograph is heated in the same way as the hollow pipe in the top photograph, the heat pipe glows uniformly along its entire length.

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Cover photographs by Sol Mednick

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LETTERS

Sirs:

As one who has been intimately associated with the U.S. Anti-Ballistic-Missile (ABM) Defense System Program for the past five years and who has participated in many constructive dialogues on the program with Drs. Garwin and Bethe, I should like to offer some comments regarding their article "Anti-Ballistic-Missile Systems" [SCIENTIFIC AMERICAN, March].

As a general comment, let me note that neither the authors nor myself are arguing about technical facts, since in this complex area we are dealing at most with technical judgments, and more often with political opinion. Further, there are limits placed on our discussion by the necessary security classification that exists regarding the details of the program. Drs. Garwin and Bethe make three primary points, and I should like to comment on each of these in turn.

1. An ABM system designed to counter a potential Chinese ICBM threat is unnecessary because our overwhelming nuclear offensive power "should restrain China indefinitely from an attack on the U.S."

An opposing political judgment to that presented by the authors would state that deterrent power only has meaning if the potential enemy believes it will be used. I believe it is well within the realm of possibility that some future Chinese leaders might not believe we would use our nuclear power in a crisis, when we would know that we could be destroyed with certainty by a much less potent force. I readily admit that this is only opinion, but I believe it to be no more or no less credible than that expressed by the authors. The fact is that neither they nor I nor our present government leadership will be making the decisions on either side at the time of some future crisis. I believe the main purpose of our light anti-China defense system should be to give our future leadership more options in order to lend credibility to our deterrent.

2. The Sentinel system will "nourish the illusion that an effective defense against ballistic missiles is possible and will lead almost inevitably to demands that the light system...be expanded into a heavy system."

This argument has been repeated time and again, and I believe it is a toothless old saw. This country has resisted the expansion of weapon systems, both offensive and defensive, time and again by sound arguments against the necessity of such expansion. There is no reason why this pressure, if it exists at all, cannot be countered by effective leadership. The point is further clouded by the lack of precise definition of the word "effective." Somehow we only pay attention to the extremes; either the system is so "ineffective" that it does not work at all or it is so "effective" that there must be an insatiable demand for more of this good thing. Let me first state unequivocally that I agree with the authors that I cannot foresee a system so effective that by expanding the system we would have any real chance of negating the deterrent power of a sophisticated enemy such as the U.S.S.R. To attempt such an objective would truly be a waste of resources; but I should like to define an effective system as one that is able to successfully counter light attacks, and I would contend that this is a very useful military objective and a very necessary one in the situation when the U.S.S.R. has some ballistic-missile defense. I do not believe it is adequate for us to only have the power to use our force en masse to overwhelm the defense and produce "assured destruction." Suppose, for example, for any reason a potential enemy sent over a couple of missiles, perhaps to take out a military target with very few civilian casualties. Would we respond by an overwhelming attack against their cities, knowing full well that the counterresponse would lead to our destruction? The light defense goes a long way toward removing the military credibility of any light attacks and thus introduces a firebreak that makes the ballistic missile useful solely as a deterrent, which is a situation we have grown to accept.

3. Our Sentinel Chinese-oriented system is, or will be, penetrable by the Chinese.

No discussion of this subject is possible in any depth without getting into classified material. Certainly there are possible penetration aids, as the authors have pointed out, that could be attempted to defeat the Sentinel system, but the uncertainties are not all on the side of the defense. The decision to deploy the Sentinel system was a very conscious one, with a great deal of analysis done to provide reasonable assurance that the system could evolve to handle future penetration aids that could be adopted by the Chinese. This does not mean an expansion of the system to the $40-billion variety but a continued technical upgrading as necessary to include and counter advances in technology. Certainly there is no guarantee that this is possible, but there were adequate possibilities to warrant the deployment decision.

While the subject of ballistic-missile defense may be an unusual one for your journal, it is appropriate since it is primarily the technical community that has expressed opinions on the subject. I would only hope that future treatment of ABM would present both sides of this very complicated and important issue.

DANIEL J. FINK

General Manager
Space Systems
Valley Forge Space Technology Center
Missile and Space Division
General Electric Company
Philadelphia, Pa.

Sirs:

It is always helpful to know what is being said by eminent scientists about our major weapons system developments. I deeply regret that military classification prevents the scientists and engineers who know most about ballistic-missile defense capabilities from publication of a better-informed treatment of this whole subject.

What concerns me about the Garwin-Bethe approach to ballistic-missile de-

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fense is to read again about all those clever tricks that a theoretical physicist can invent on paper for an enemy use to defeat a defensive system—ideas that have been around for 10 years to my knowledge and possibly longer. The inference is that these clever tricks are easy to do with high confidence of real-world effectiveness, and that defense is helpless to react. Nothing could be further from the truth. The U.S. Air Force and the U.S. Navy are able to draw on 20 years of ballistic-missile technology and 10 years of space technology, and they still find that achievement of effective penetration aids takes years and hundreds of millions of dollars of development and testing to have *high confidence* in penetration aids. Surely no nation, not even the Chinese, would be so foolish as to plan to produce and deploy a weapons system as expensive as the ICBM without the years of painstaking and costly testing effort needed to give them high confidence that their systems would work if called on.

The fact of the matter is that the Army-proposed level of defense and our estimates of its probable effectiveness in the 1975-to-1980 time frame were carefully reviewed by technically competent and well-informed groups outside of the Army before the Secretary of Defense recommended approval of production and deployment of the Nike Sentinel system. There is nothing in the Garwin-Bethe analysis that was not known and adequately considered at that time.

A. W. Betts

Lieutenant General, GS
Chief of Research and Development
Department of the Army
Washington, D.C.

Sirs:

We agree with Dr. Fink that competent proponents and opponents of ABM systems differ primarily not on technical facts but in technical judgments and political opinions.

Dr. Fink's Point 2 is the crux of the matter. Within a few weeks after the decision to deploy Sentinel, demands were made by influential persons to expand the system as soon as possible to the $40-billion variety. Certainly effective leadership has in the past sometimes successfully resisted the expansion of weapons systems or of other programs, but the effectiveness of governments varies, and a moment of weakness or of political horse trading could saddle us with a costly, useless and dangerous system.

We think the existence of a light ABM will make it more difficult to resist pressure for its expansion.

General Betts and Dr. Fink note that successful penetration aids require more than invention, and take a lot of effort on development and testing. They also point out that a defense can be modified technically to deal with any of them. Security classification precludes meaningful technical discussion here of these moves and countermoves, but it is our experience, based on more than 10 years of involvement in these and similar military-technical problems, that in general the required reaction by the defense is slower, much more costly and less certain than the action of the offense. We do not agree that a system on the scale of Sentinel can long stay ahead of Chinese penetration aids.

The elements of the Sentinel system and the production capacity we build to produce it, together with the avowed possibility of technical upgrading of the system, may lead the U.S.S.R. to consider it as directed against themselves. Whether warranted or not, such a conclusion on their part would lead to a revived and intensified arms race. In the words of former Secretary McNamara, "the Soviets and ourselves would be forced to continue on a foolish and feckless course."

The other half of the arms race deserves mention as well. Should the U.S. become convinced, rightly or wrongly, of an expansion and increased capability of the Soviet ABM system around Moscow, our present deterrent policy would require high assurance as to the adequacy of our penetration aids and perhaps even an increase in numbers of missiles as well. As a consequence of our maintaining a high-confidence assured-destruction capability, if war actually comes, the U.S.S.R. would very likely suffer even more complete destruction than if they had not built an ABM system. Like the U.S., the U.S.S.R. would be well advised not to build an ABM system that could present even the appearance of effectiveness against a deterrent force.

RICHARD L. GARWIN

IBM-Watson Laboratory
at Columbia University
New York, N.Y.

HANS A. BETHE

Laboratory of Nuclear Studies
Cornell University
Ithaca, N.Y.

Dorothy might never have visited Oz if weather radar had been around.

Remember *The Wonderful Wizard of Oz*? And how Dorothy was carried over the rainbow by a tornado?

Nowadays she might never have made that visit. With weather radar, the Weather Bureau would very likely have detected the tornado conditions in time to warn her.

Weather radar is one of the Bureau's most useful weapons against rampaging weather. The trouble is, a complex weather radar installation at each of the Bureau's hundreds of offices would be much too expensive.

Up until now, that is.

At the Weather Bureau's request, ITT Industrial Laboratories has developed a low-cost system to transmit up-to-the-moment radar weather pictures to almost any place in the U.S.

This unique system transmits the radar pictures, displayed on the master radarscope, over ordinary telephone lines to simple receivers at neighboring stations.

The local weathermen see weather conditions firsthand. They don't have to rely completely on reports relayed via teleprinter or telephone.

This means that local forecasts and warnings are more accurate. And the better they are, the better off everyone will be—fisherman and farmer, picnicker and pilot.

Everyone, that is, except maybe Dorothy.

International Telephone and Telegraph Corporation, New York, New York 10022.

ITT

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MAY, 1918: "A recent paper by Dr. Shapley of the Mount Wilson Observatory, extending his studies of the globular clusters to a noteworthy degree, brings out new facts of a character surprising even to astronomers themselves. It has long been known that globular clusters are not uniformly distributed over the sky, nor do they, like most other celestial objects, congregate toward the plane of the Milky Way. Instead they are almost confined to one-half of the celestial sphere, which contains more than 60 such clusters, whereas in the opposite half of the heavens there are fewer than half a dozen. This shows, of course, that our solar system is nowhere near the center of the region of space within which these clusters are situated but must be nearly at its edge. Calculating the actual positions in space of the 69 clusters definitely recognized as globular, Dr. Shapley finds that they themselves form a huge flattened cluster, probably 300,000 light-years in diameter and about 100,000 light-years in thickness (omitting a few scattered clusters). The diametral plane of this great system coincides with the plane of the Milky Way—very few of the clusters being more than 50,000 light-years from this plane. The center of the system is apparently about 70,000 light-years from the sun in the direction of the great star clouds in Sagittarius. These very remarkable facts indicate strongly that the globular clusters after all are really members of the same enormous system as the stars of the Milky Way."

"'At a certain stage of social evolution,' says Sir James Frazer in his article entitled 'The Killing of the Khazar Kings' in a recent issue of *Folklore,* 'not a few races appear to have been in the habit of putting their kings to death, either at the end of a fixed term, or on the failure of the king's health and strength, or simply whenever a great public calamity, such as drought or famine, had befallen the country.' Among tribes which have practised this remarkable form of limited monarchy must now be included the Khazars, or Khozars. For some 900 years this now almost forgotten tribe from their home in the spurs of the Caucasus and along the western shore of the Caspian—called after them the Sea of the Khazars—played a great part in history on the European-Asian borderland. It is certainly remarkable that a people which had reached such a high level of civilization and culture should have practised legalized regicide. But the evidence collected by Sir James Frazer from a very wide survey of medieval literature leaves no doubt on the matter. This survey of an almost unknown tribe is a contribution to anthropology of permanent value."

SCIENTIFIC AMERICAN

MAY, 1868: "At the close of 1867 there were 650 of the 1,800 miles between Omaha and San Francisco spanned by the iron rail. By the close of 1868 we are promised 500 miles more, and by the first of July, 1870, the locomotive will make the entire distance between New York and the Golden City of the Pacific in about six days' time. No railroad enterprise was ever carried out with such dispatch before. When we consider that the two back-bone ranges of mountains are being crossed at elevations of 7,000 feet above sea-level, the magnitude and energy of the undertaking become more vivid. Both the powerful companies, who are building the line from opposite ends, are making commendable headway—the Central Pacific on the western half having 10,000 men at work, and the Union Pacific at this end having a force of 5,000."

"Faraday has shown that if a small cubical space be inclosed by arranging square bar magnets with their like poles in apposition so as to form a chamber, within that space all local magnetism inferior in power to the magnets employed will be neutralized. The same effect can be obtained with electro-magnets as with permanent magnets, and it is proposed in the *Mechanics' Magazine* thus to inclose the compass of an iron ship, as a remedy for the deviation by local attraction."

"The primitive atmosphere of the earth was greatly richer in carbonic acid than the present, and therefore unfit for the respiration of the warm-blooded animals. The agency of plants in purifying this atmosphere was long ago pointed out, and the great deposits of fossil fuel have been derived from the decomposition of this excess of carbonic acid by the ancient vegetation. In this connection the vegetation of former periods presents the phenomenon of tropical plants growing within the Polar Circle. Prof. T. Sterry Hunt considers as unsatisfactory the ingenious hypotheses proposed to account for the warmer climate of ancient times and thinks that the true solution to the problem is to be found in the constitution of the early atmosphere, when considered in the light of Dr. John Tyndall's researches on radiant heat. He has found that the presence of a few hundredths of carbonic acid gas in the atmosphere, while offering almost no obstacle to the passage of the solar rays, would suffice to prevent almost entirely the loss by radiation of obscure heat, so that the surface of the land, beneath such an atmosphere, would become like a vast orchard house, in which the conditions of climate necessary to a luxuriant vegetation would be extended even to the polar regions."

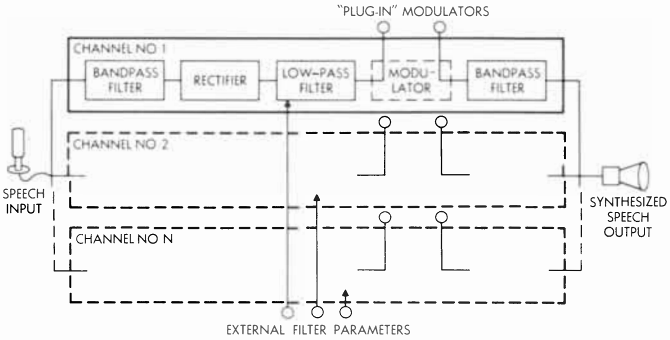
"The comparatively new metal aluminum and its alloys, which have lately attracted considerable attention and awakened some curiosity, seem to afford a promising field for the investigations and experiments of scientific men and inventors. It is singular that since its discovery as a metallic oxide existing in aluminous earths, no cheap and rapid method of extracting it has been discovered. All clays contain it, some in a less pure state than others but all in large proportions; in fact it forms the basis of clay. It might be supposed that chemical science, aided by mechanical ingenuity, might before this have found a means of producing this metal in unlimited quantities and at a low cost. The process of its extraction, however, is somewhat complicated and quite expensive. Its cost at present confines its use to small articles and the purposes of ornamentation. Yet it would seem that so valuable a metal as aluminum, distributed (in the form of an oxide) more generally and plentifully over the globe than iron is, might be procured with no greater expenditure of labor, time and money than iron. To be sure, we cannot apply the same crude means to the reduction of aluminum from its base, mother clay that we can use in the reduction of iron, and this is just where scientific knowledge and practical talent are needed. We want the metal; the exigencies of the times demand its general use. What we need now is its production in sufficient quantities and cheap enough to be employed in the arts."

Report from

BELL LABORATORIES

Breadboarding the modern way

Scientist Barry J. Karafin of Bell Laboratories checks chart recorder waveforms from a BLODIB simulation. Karafin uses the computer console at his right to interact with the simulation program. This feature was developed for the BLODIB program to give users the flexibility of making changes in such things as component values without having to re-program an entire system.



A hypothetical voice-analyzing/synthesizing system (resembling Bell Laboratories' "vocoder") . . . and how it might be simulated with BLODIB. The system would have a number of band-limited channels, each consisting of such blocks as BANDPASS FILTER, RECTIFIER, and LOW-PASS FILTER. Once the experimenter specifies one channel, he can call upon it, complete, as many times as necessary. Such a system analyzes a voice input into "channels" (narrow frequency bands). It then synthesizes (recombines the channels) so that the speech output can be heard on earphones or over a loudspeaker. It might be used to test relationships between channel width and intelligibility. To experiment with various MODULATORS, the user can leave "open terminals" (blank sections) in the program and "plug in" (supply sub-programs for) simulated modulators. The LOW-PASS FILTERS have externally variable parameters, such as cutoff frequencies; these parameters may be supplied by a user during simulation or by another computer program.

More and more, engineers use digital computers to simulate new electronic systems. It's often faster and cheaper than breadboarding . . . building an experimental system.

But simulation is most useful if the experimenter can "talk" to the computer in his own language . . . a block diagram symbolizing an electronic process. To translate such a diagram into a computer simulation program, scientists at Bell Telephone Laboratories designed an intermediate program or "compiler." The latest version is called BLODIB for BLOck DIagram compiler B (pronounced "Bloody Bee"). BLODIB's output is a simulation program—in machine language.

The BLODIB user needs little programming experience. He writes a description of a block diagram and its connections in terms from the BLODIB dictionary . . . which contains abbreviated names for most blocks, such as AMP for amplifier. The description need not follow signal flow; BLODIB arranges it properly.

The BLODIB dictionary cannot contain a block for every possible electronic function. But many new blocks can be built up from those available. And, if one combination will be used many times in a design, it can be named and used as often as necessary.

To test prototype systems, the experimenter can leave parameters variable, or he can even arrange for their values to be supplied by another computer program for automatic simulation throughout a range of settings. Also, if he is doubtful about, say, a filter, he can simulate his system without the filter and "plug in" simulation programs for various experimental filter designs. In this way, several designs can be tested before investing in a laboratory model.

The BLODIB program has been used to simulate acoustical and visual systems and was recently used to study automatic equalization techniques for Bell System data sets.

The first block-diagram compiler, BLODI, was conceived and developed at Bell Laboratories by V. A. Vyssotsky, John Kelly, and Carol Lochbaum. B. J. Karafin recently formulated the BLODIB program which extends the original BLODI program so it can interact with non-BLODI programs and provide the flexibility described above. This makes it an even more powerful tool for probing potential systems over a broad range of operating conditions.

Bell Telephone Laboratories
Research and Development Unit of the Bell System

THE AUTHORS

VICTOR F. WEISSKOPF ("The Three Spectroscopies") is professor of physics at the Massachusetts Institute of Technology. Born in Vienna, he received a Ph.D. in physics from the University of Göttingen in 1931. He was a research associate at the University of Copenhagen from 1932 to 1933 and at the Swiss Federal Institute of Technology in Zurich from 1933 to 1936. In 1937 he moved to the U.S., where for six years he was on the faculty of the University of Rochester. During World War II he was a group leader in the Manhattan project, working at the Los Alamos Scientific Laboratory. He has been at M.I.T. since 1945, except for the period from 1961 to 1965, when he was director general of CERN, the European Organization for Nuclear Research. Weisskopf holds honorary doctorates from 12 American and European universities.

M. S. F. HOOD ("The Tartaria Tablets") is a British archaeologist who since 1947 has worked mostly in Greece, specializing in the Bronze Age of Crete. He is a graduate of the University of Oxford, where he was awarded a degree in modern history. After World War II he studied prehistoric European archaeology at the University of London. He has participated in numerous archaeological excavations in Greece and Turkey. From 1954 to 1962 he was director of the British School of Archaeology in Athens. He directed excavations for the school at Emporio in Chios from 1952 to 1955 and at Knossos in Crete from 1957 to 1961. He writes that he is currently preparing reports of these excavations and writing archaeological books.

G. YALE EASTMAN ("The Heat Pipe") is with the Radio Corporation of America as manager of heat-transfer-device engineering in the plant at Lancaster, Pa. His group is charged with responsibility for the development of heat pipes, thermionic energy converters, alkali vapor arc lamps, vacuum components and gas lasers. Eastman has headed the group since 1966. Before that he was for seven years leader of an engineering group concerned with the development of new processes for making transmitting tubes and the materials that go into them. Eastman was graduated from Amherst College in 1950 with a degree in mathematics; he joined RCA immediately and was involved among other things in the development of picture tubes for color television.

ELLIS LEVIN, DONALD D. VIELE and LOWELL B. ELDRENKAMP ("The Lunar Orbiter Missions to the Moon") are members of engineering management in the Space Division of the Boeing Company. They were associated closely in the design of the Lunar Orbiter missions: Levin as system engineering manager and as the project engineer for mission design and flight data; Viele as a supervisor in system engineering and as manager of mission design and analysis, and Eldrenkamp as supervisor of trajectory and guidance analysis. Levin was graduated from Tulane University in 1942 with a bachelor's degree in electrical engineering. Viele received a similar degree from the University of Colorado in 1950. Eldrenkamp was graduated from the University of Illinois in 1953 with bachelor's and master's degrees in aeronautical engineering. Each of them has been with Boeing since soon after graduation.

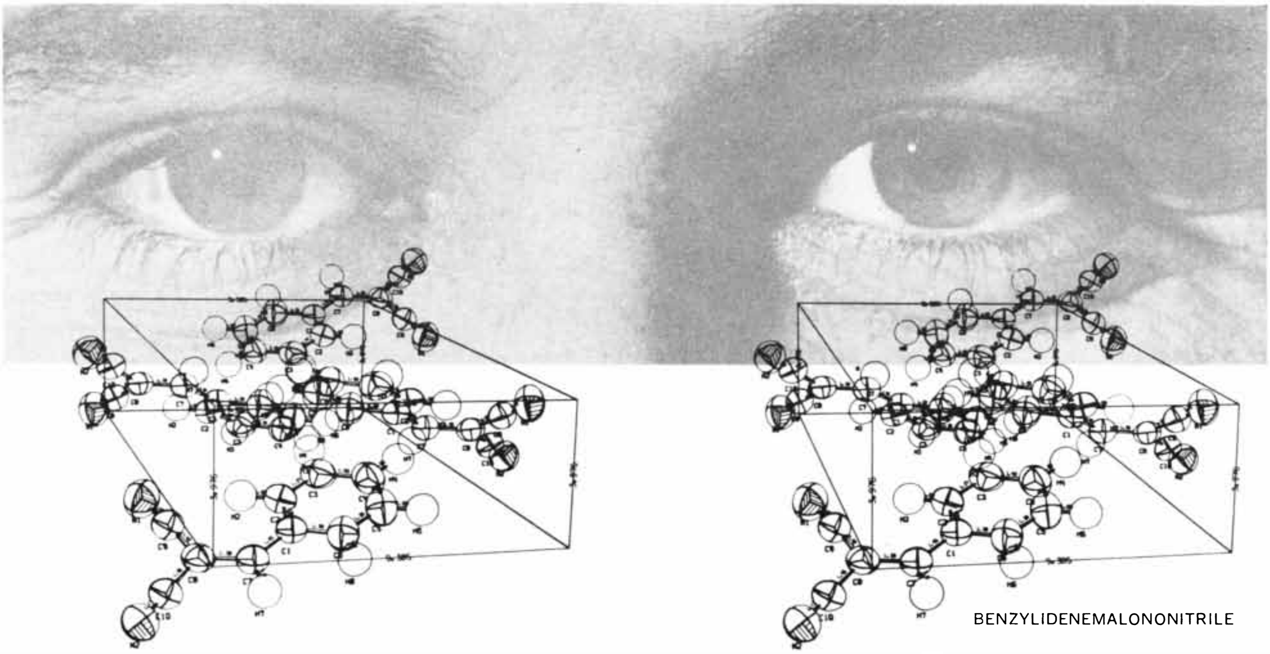
DONALD M. WILSON ("The Flight-Control System of the Locust") is professor of biology at Stanford University. He did his undergraduate work at the University of Southern California and obtained a doctorate in zoology from the University of California at Los Angeles in 1959. Thereafter he held postdoctoral research positions at the zoophysiological laboratory of the University of Copenhagen and in the department of molecular biology at the University of California at Berkeley. Wilson taught at Yale University and at Berkeley before going to Stanford last year. He writes: "My first training in biology was in marine zoology. Later, under the guidance of T. H. Bullock, I became interested in animal behavior mechanisms and neurophysiology. Currently I am especially interested in problems of genetic control and evolution of behavior mechanisms."

FREDERICK C. KREILING ("Leibniz") is professor of the history of science at the Polytechnic Institute of Brooklyn, where his interests are chiefly in the scientific revolution of the 17th century and in the history of ecological theory. Kreiling was trained as a historian, receiving a Ph.D. in modern European history from New York University in 1959. At Brooklyn Polytech he has developed a graduate program in the history of science. "I feel it is imperative," he writes, "that the history of science be cultivated as a means of combating the intellectual isolation in which modern specialists tend to find themselves." Kreiling is planning a full-scale biography of Leibniz; he notes that "the last one appeared in the 1840's." He writes that aside from his work he is "an ardent musician and once was a professional bass player."

EARL FRIEDEN ("The Biochemistry of Copper") is professor of chemistry and chairman of the department of chemistry at Florida State University, where he has been a member of the faculty since 1949. He was graduated from the University of California at Los Angeles in 1943 with a bachelor's degree in chemistry; six years later he obtained a Ph.D. in biochemistry from the University of Southern California. His article, which describes work that has engaged his interest for 15 years, is his third in SCIENTIFIC AMERICAN; the others were "The Enzyme-Substrate Complex" in August, 1959, and "The Chemistry of Amphibian Metamorphosis" in November, 1963.

ROMAN MYKYTOWYCZ ("Territorial Marking by Rabbits") is principal research scientist with the Division of Wildlife Research of the Commonwealth Scientific and Industrial Research Organization of Australia. Born in the Ukraine, he studied veterinary science at the Zootechnical and Veterinary Institute of Lvov and obtained a doctorate in veterinary medicine from the University of Munich in 1948. He writes: "I then went to Australia, and after joining the CSIRO in 1950 I became engaged in investigations of the epidemiology of diseases of wildlife species, including the rabbit, the kangaroo and the Tasmanian shearwater or muttonbird. I was associated with experiments to control plague populations of rabbits by biological means, using the virus disease myxomatosis. While studying the fluctuations of numbers of animals in free-living populations, particularly of rabbits, I came to recognize the importance of social and territorial behavior of the animal as a population-regulating factor and became interested in ethology."

R. M. FANO, who in this issue reviews *Privacy and Freedom*, by Alan F. Westin, is Ford Professor of Engineering and professor of electrical communications at the Massachusetts Institute of Technology and director of Project MAC, an M.I.T. venture involved in research on advanced computer systems.



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> *"The three crystal structures plotted in 3-dimension diagrams are (1) Hydrogen Bond (2) Titanium Tetramethoxide, and (3) Benzylidenemalononitrile.*
>
> *"They will be used as illustrations to papers in Acta Crystallographica to be published shortly.*
>
> *"All the plots look superb when viewed through prisms."*

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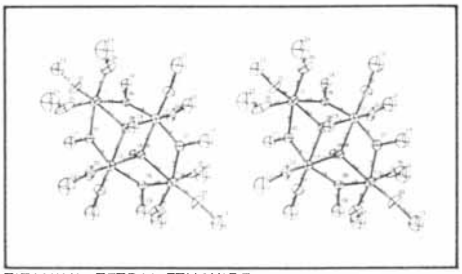
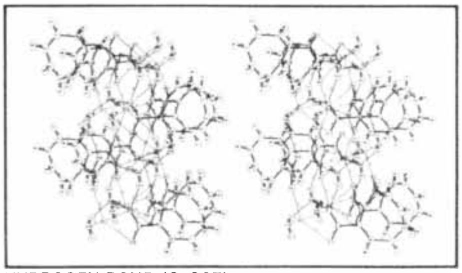


TITANIUM TETRAMETHOXIDE



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The Three Spectroscopies

The exotic particles produced by the great accelerators can be regarded as a spectrum of excited states that decay to a few ground states. Similar states exist in two older spectroscopies

by Victor F. Weisskopf

In this century the effort of physicists to comprehend the fundamental building blocks of nature has been a story of bafflement followed by clarification followed by bafflement. In the process physicists have learned to design machines for hurling particles at other particles with ever increasing energy. The simple cathode-ray tubes used to accelerate electrons at the turn of the century were succeeded by Cockcroft-Walton and Van de Graaff machines, and these were soon followed by cyclotrons, betatrons and proton synchrotrons of steadily mounting size and cost. The latest in the series is the huge machine to be constructed at Weston, Ill., which will accelerate protons to an energy of 200 billion electron volts (BeV, also abbreviated GeV, where *G* stands for "giga-," the international prefix for 10^9).

Where has all this research taken us? Is it possible to sum up the results of two-thirds of a century of analyzing the structure of matter? This article will attempt a synopsis of what has been learned.

It is now clear that the constituents of matter—atoms and molecules—accept and release energy in the form of quanta, or packets of energy. The most familiar quanta are photons, those packets of radiation we perceive as visible light but that are known as X rays or gamma rays when they are highly energetic and as radio waves when they carry very little energy. Atoms or molecules that have been raised in some fashion to an excited state fall to a lower energy state and in so doing emit one or more quanta. The study by spectroscopists of such emissions in the first quarter of the century led to a complete understanding of the atom *outside* the nucleus. The excited states of atoms and the quanta emitted by them constitute the first of what I shall call the three spectroscopies.

When it became technically possible to excite the atomic nucleus, using the neutron as well as particle accelerators, it was found that the nucleus too emits quanta in reverting to a lower energy state. These quanta include not only photons of very high energy (gamma rays) but also a new kind of quantum: the lepton pair, which consists of an electron and a chargeless particle of vanishingly small mass, the neutrino. The excited states and the quantum emissions of the atomic nucleus constitute the second of the three spectroscopies.

The third spectroscopy was for a long time not recognized as such. Instead physicists who were using the powerful accelerators built following World War II assumed that when highly energetic protons struck other protons or neutrons, they were producing a shower of new elementary particles that decayed almost instantaneously into more stable forms. By 1958 one spoke with some misgivings of 30 or so "elementary" particles, and within a few years the number of particles had increased to more than 100. It gradually dawned on physicists that it would be more reasonable to conclude that what the new accelerators had uncovered was still another spectroscopy, and that instead of calling the transitory forms new particles they should be regarded as a new set of excited states. When these states decay into less energetic states, they emit not only quanta such as photons and lepton pairs but also new kinds of quanta with substantial mass: mesons. Thus the third spectroscopy embraces the quanta of the earlier two spectroscopies and contributes its own distinctive quanta.

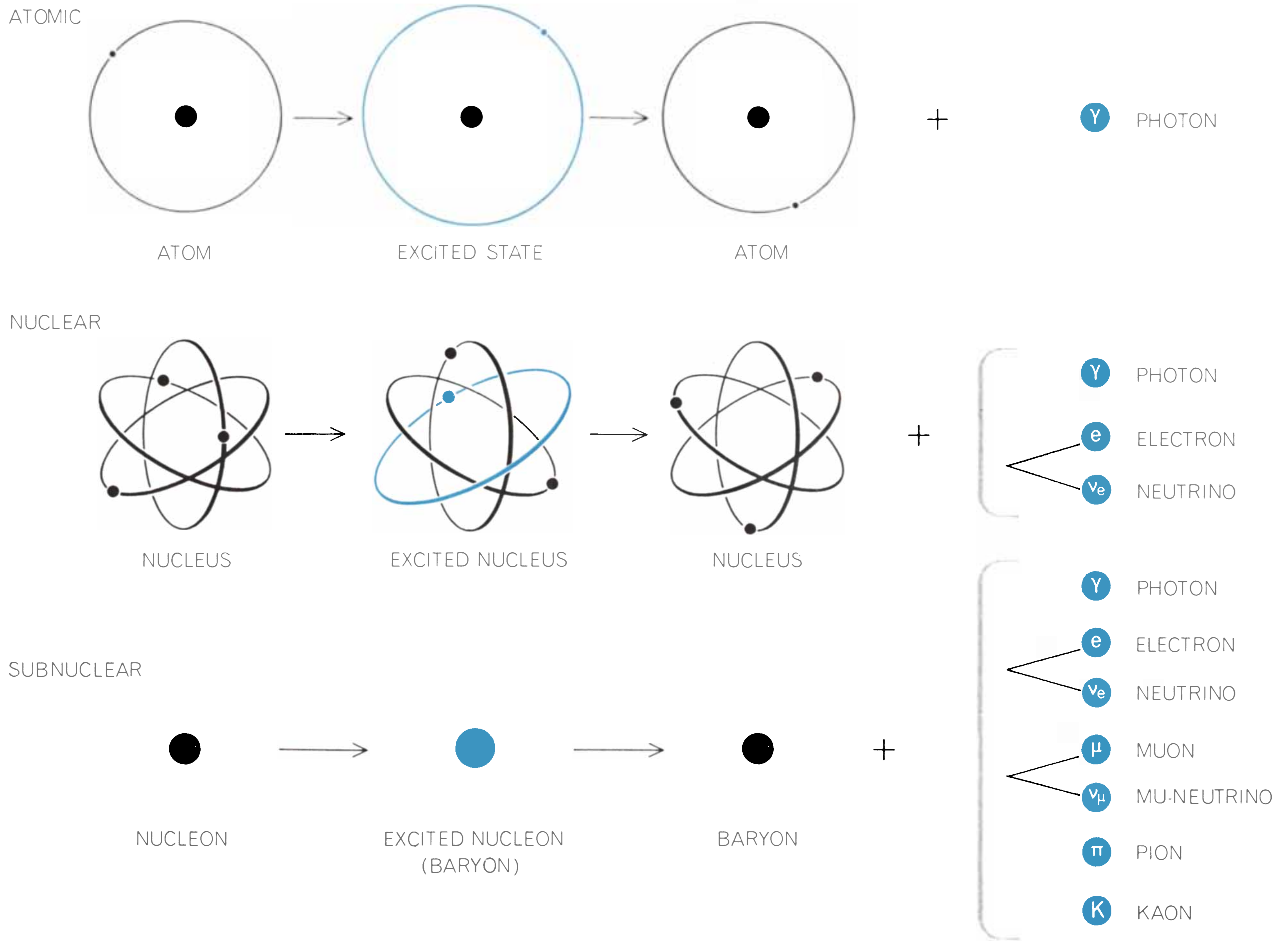
Let us now retrace the steps that led physicists to interpret the behavior of excited matter in terms of quantum emissions. The concept of the light quantum originated with Max Planck in 1900. He recognized that, if one is to account for the way matter emits radiation, atoms must emit energy in multiples of a certain irreducible value (Planck's constant, *h*). These packets of energy, later called photons, acquired a deeper reality when in 1905 Albert Einstein showed that electrons emitted by a metal in response to bombardment by light have an energy that is proportional to the frequency of the incident light. This implied that light of a given frequency is packaged in quanta whose energy is proportional to that frequency. Moreover, the constant of proportionality is Planck's constant. Thus E equals $h\nu$, where E is the energy of the photon and ν is the frequency of the light. This does not restrict the possible energy of light quanta, because light (from one source or another) is available in all frequencies.

The situation is different when one considers specific mechanical systems such as atoms or molecules. One finds that the energy of such systems can assume only certain specific and well-defined values. The series of these values is characteristic of each kind of atom or molecule; it is called the spectrum of the atom or molecule [*see illustrations on page 18*]. Historically speaking the spectrum was meant to be the totality of the spectral lines that an atom emits and absorbs. It was soon recognized, however, that the frequencies of spectral lines are always equal to the difference between two of a series of "term values." The term values, then, are what determine the line spectrum. Today we know that each of the term values corresponds to a specific energy state of the atom. When an atom undergoes a transition from one energy state to another, the energy balance is emitted in the form of a light quantum whose frequency is proportional to the energy difference of the two states divided by Planck's constant.

The spectrum of energy states is an important source of information about the internal dynamics of the atom. In the simplest of all atoms, the hydrogen atom, the energy values are given by a simple formula (often called the Balmer formula): $E_n = -R/n^2$. Here R is a constant equal to 13.6 electron volts and n is any whole number. The values of E_n are negative because they refer to the energy of a bound electron; it is the energy needed to free the electron from the state in question.

Quantum mechanics gives us the means to understand the spectra not only of hydrogen atoms but also of all other atoms and molecules. The basis of our understanding is this: Each quantum state corresponds to a certain vibrational pattern of electron waves, confined to the immediate neighborhood of the nucleus by the attractive coulomb force, or electric force, between the nucleus and the electrons. The frequencies of vibration of these wave patterns determine the energies of the quantum states by Planck's relation between energy and frequency: $E = h\nu$.

In 1926 Erwin Schrödinger calculated for the first time the patterns of a single electron wave confined by the attraction of a nucleus carrying a single unit of



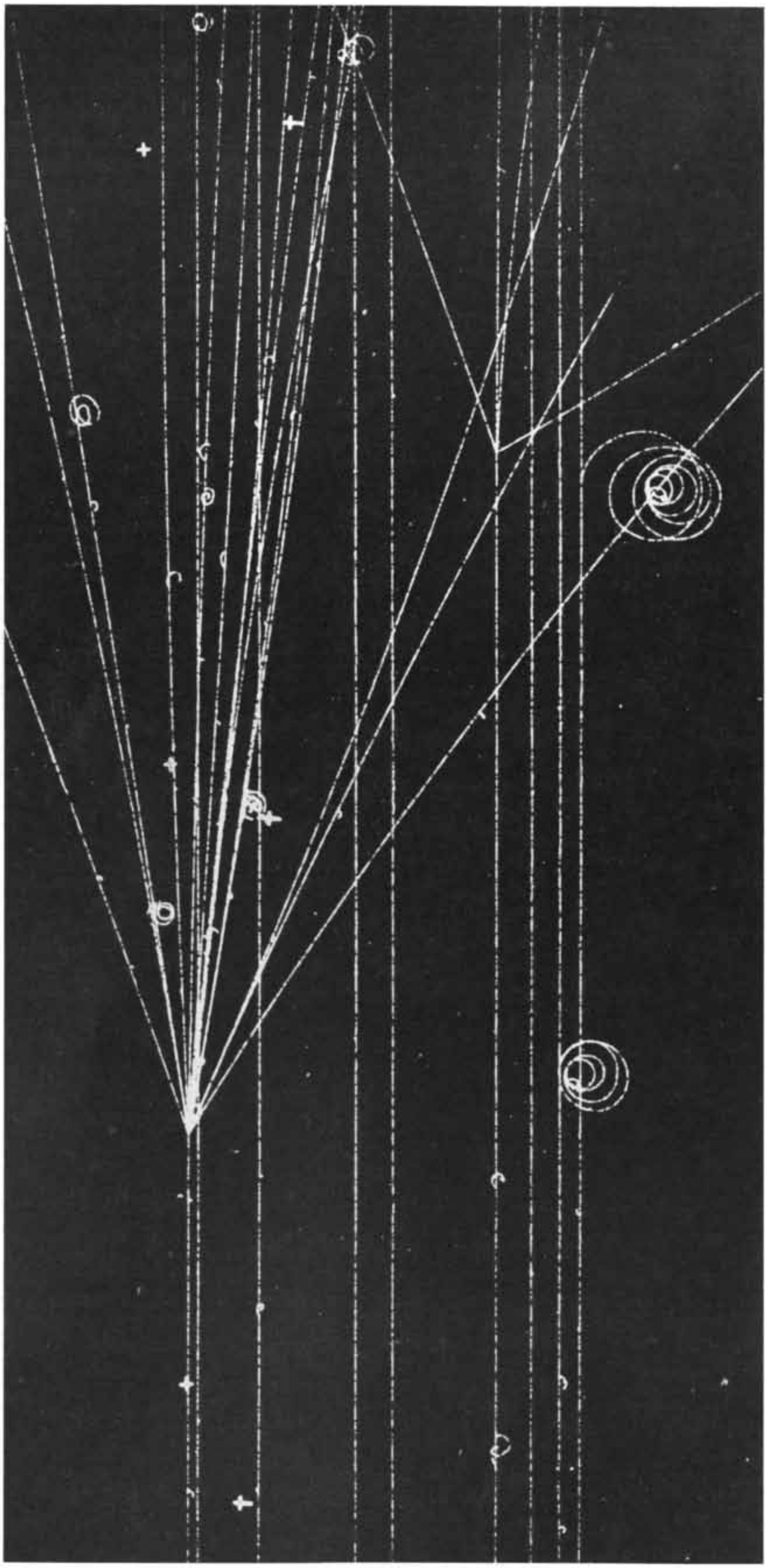
THREE SPECTROSCOPIES discussed in this article are the atomic, the nuclear and the subnuclear. In each case a particle of matter that has been raised to an excited state returns to a less energetic state by emitting a packet of energy, a quantum. Excited atoms emit photons, which are quanta of electromagnetic energy. Excited nuclei of atoms emit not only photons but also "lepton pairs," each consisting of an electron and a neutrino. Subnuclear particles such as protons and neutrons (nucleons) are raised to an excited state when exposed to energetic beams of protons or electrons in a particle accelerator. The term "baryon" designates the nucleon in all its different states of excitation. Baryons are known by many special names depending on their particular mass energy (*see illustration on pages 24 and 25*): The excited states live briefly, emit one or more quanta of energy and fall to a lower state. These quanta include unusual entities: lepton pairs of muons and mu-neutrinos and also the mesons, the most familiar being the pions and kaons.

charge. When he multiplied the frequencies of the resulting wave patterns by Planck's constant, he obtained a very simple result: the Balmer formula for the term values of hydrogen. In the years following this discovery physicists applied the Schrödinger equation with great success to more complicated atoms and also to molecules.

A few fundamental symmetries stand out and make it possible to systematize the atomic energy states. One is the spherical symmetry of the confining electric field of the nucleus. This imposes some definite patterns on the electronic vibrations, not unlike the vibrational patterns of a metal disk. Each of these patterns corresponds to a certain value of the angular momentum, which always must be an integer multiple of $h/2\pi$. This important fraction has its own symbol: $\hbar$ (spoken "h bar"). The higher the momentum, the more intricate the pattern. The higher momenta give rise to shorter wavelengths, with the result that there are more ups and downs in the wave pattern. Most important, for each angular momentum value $l\hbar$ there are $2l + 1$ different states, all of which have the same energy. They form all kinds of multiplets: singlets for $l = 0$, triplets for $l = 1$, and so on. The states of a multiplet have the same energy and correspond in some way to different directions in space of the angular momentum.

There is a second important symmetry in atoms with more than one electron. Although the symmetry is a formalized mathematical one, it can be expressed in terms of the Pauli exclusion principle, which simply states that each electron in an atom must have a different wave pattern. If all the electrons in an atom were able to occupy the same quantum state, they would all settle in the lowest state, the one in which the electron finds itself in hydrogen. All atoms would then be very similar to hydrogen. The rich variety of chemical elements flows from the fact that each additional electron must have a new quantum state. The atoms of the noble gases (helium, neon and so on) are atoms in which the number of electrons exactly fills a "closed shell": a series of patterns that combine to form a spherically symmetrical shape.

The electron patterns of several atoms are able to interlace and hold the atoms together, thereby forming a molecule. The simplest examples are molecules in which the total number of electrons is equal to the number of electrons in a noble gas. Take the molecule of methane (CH_4), which has the same number of



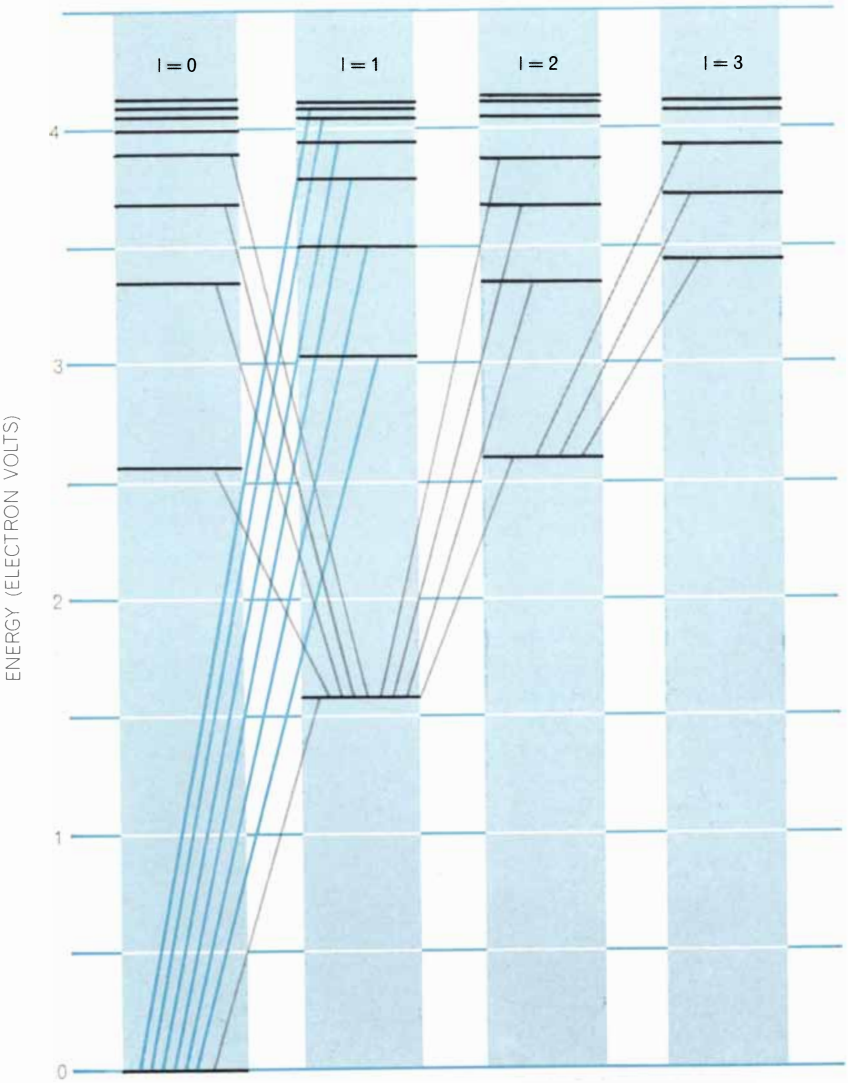
SPRAY OF MESONS is produced when a 20-billion-electron-volt (GeV) beam of protons from the accelerator at the European Organization for Nuclear Research (CERN) enters a hydrogen-filled bubble chamber. The mesons appear when energetic protons strike stationary protons. These stationary targets are provided by nuclei of hydrogen atoms in chamber.

electrons as the noble gas neon (10). The six electrons of the carbon atoms interlace with the four electrons from the four hydrogen atoms to form a closed shell [*see top illustration on opposite page*]. The carbon nucleus and the four hydrogen nuclei form a symmetrical arrangement within the spherical electron shell; they are prevented from collecting at the center by the electric repulsion of the nuclei. If some power could push the five nuclei close enough together against their mutual repulsion to bring into play the attractive nuclear forces between them, they would merge into one large nucleus, thereby making neon out of methane. Such power is available in the interior of stars, where indeed this reaction occurs.

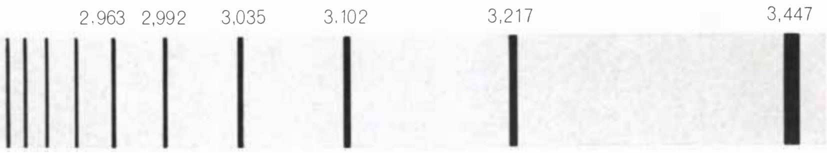
The structure of atoms and molecules is based on the electron-wave patterns formed in the attractive electric field of the atomic nuclei. Molecules are nothing more than atoms with more than one nucleus. Hence the atomic and molecular properties are all determined by the nuclear charge and mass: the charge determines the number of electrons to be assembled and the shape of their wave patterns. Because the nuclear mass is so much larger than the electron mass, the nuclei are the massive centers of atoms and molecules; the positions of the nuclei are well defined and are little affected by the motions of the electrons.

The nuclei are so small that they act on the electrons essentially as point charges. There are certain slight but significant effects that are due to the magnetism of some nuclei. Apart from such effects, however, the internal structure of nuclei is irrelevant for the atomic and molecular world. In this respect nuclei act like elementary particles with a fixed mass, charge, spin and magnetic moment. Thus all the phenomena we normally encounter on the earth—all the different forces such as chemical forces, elastic forces, cohesive forces, capillary forces—are the consequence of electric attraction between nuclei and electrons. The variety of manifestations comes from the richness of the wave patterns and their interlacing behavior. When I speak here of atomic spectroscopy, I include the spectroscopies of all the systems that are built up of atoms: gases, liquids, molecular solids and the giant molecules of living matter.

It is not difficult to show how the size and energy of atoms follow directly from the interplay between electric attraction and quantum mechanics. Consider the hydrogen atom. Here we find two countervailing tendencies. The confining tendency of the attractive coulomb force favors a small radius (r); the smaller the radius, the lower the potential $-e^2/r$ of the attractive force. This tendency is opposed by the spreading tendency of kinetic energy, which favors a large r because a larger pattern corresponds to longer wavelength and therefore smaller velocity. The two tendencies must be balanced. The lowest equilibrium is reached when the radius r assumes the value $\hbar^2/me^2$. This is the Bohr radius, which works out to .53 $\times 10^{-8}$ centimeter. The corresponding binding energy of the electron, called the Rydberg energy, is given by the ex-



SPECTRUM OF POTASSIUM consists of many quantum states (*horizontal black lines*), each at a different energy level above the ground state. Each column contains states of the same angular momentum, *l*. The line structure caused by electron spin has been omitted. The connecting lines identify some of the most frequent transitions from higher to lower states. The transition lines in color represent spectral lines depicted in the illustration below.



ABSORPTION SPECTRUM OF POTASSIUM VAPOR shows spectral lines in the region between 2,900 and 3,500 angstrom units in the ultraviolet part of the spectrum. The six strong lines of identified wavelength represent the transitions in color in the illustration at top. The line at 2,963 angstroms is the transition marked by the longest colored line. The illustration is a drawing based on a spectrogram published by Max Born some 30 years ago.

pression $R = me^4/2\hbar^2$. It is 13.6 electron volts.

The situation for other atoms is more complex but the results are not very different. The last electron in each atom is confined by a structure consisting of the nucleus and all electrons but one. This structure has a positive charge of one unit and must act on the last electron not unlike a proton. That is why the sizes of the patterns of the outer electrons in all atoms are roughly the same as the size of the hydrogen atom and why their energies are of the same order of magnitude.

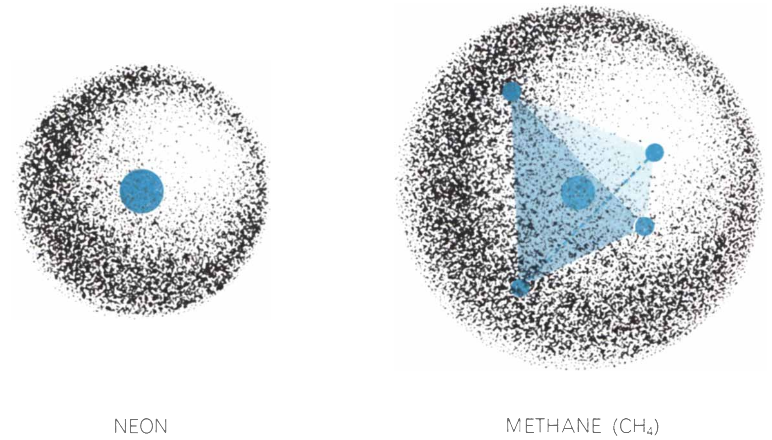
The electromagnetic nature of the electron-nucleus bond thus defines the size and binding energy of atoms. It also determines the dimensions of molecular structures. The distance between atoms in a molecule will be roughly equal to the size of the outer-electron patterns because their interlacing gives rise to the molecular structure. The energy necessary to dissociate an atom from a molecule will be of the order of the energy difference between the electron pattern in the molecular bond and in the isolated atom, that is about one or a few electron volts. Hence the Bohr radius (or the angstrom unit, 10^{-8} centimeter) is the natural unit of atomic and molecular sizes; the Rydberg energy (or the somewhat smaller electron volt) is the natural unit for atomic and molecular energies.

These figures explain why phenomena on the surface of the earth are dominated by atomic and molecular processes. At room temperature the heat energy of each atom is about a tenth of a volt; this energy is so low that electron patterns are not broken; atoms and most molecules remain intact. On the other hand, the radiation that reaches the earth from the sun consists chiefly of light quanta that have an energy of a few electron volts—an energy high enough to disrupt certain molecules but not so high as to destroy all atomic and molecular structure. Therefore under the influence of sunlight certain chemical reactions (notably photosynthesis) are induced that are basic to the maintenance of life.

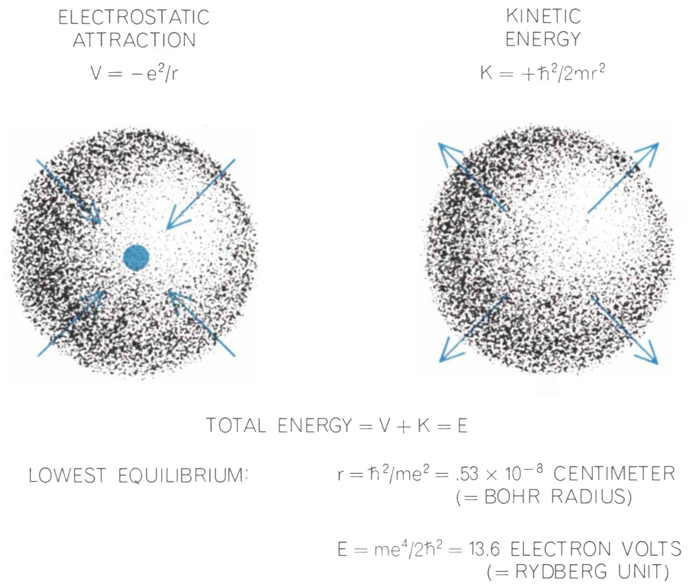
Let us now turn our attention to the constituents of the atom: the electron and the nucleus. All electrons are exactly alike; they have a small mass (about 1/1,800th the mass of the smallest atomic nucleus) and carry a unit of negative electric charge, together with spin and a magnetic moment. The spin is a quantum-mechanical type of rotation that produces the magnetic moment of the electron. All attempts so far to find a structure or some physical mechanism within the electron have been in vain. Today the electron is still considered a true elementary particle. This, however, is only a preliminary statement. We shall see later that the discovery of the heavy electron and the neutrino may be the first indication of an internal structure.

There are many different atomic nuclei, depending on which atom and which isotope one considers. Nuclei have a large mass and a positive charge concentrated in a volume whose linear dimension is a few multiples of 10^{-13} centimeter, a figure that is smaller than atomic dimensions by a factor of about 10^5. (The distance 10^{-13} centimeter is called a fermi.) Nuclei carry a different charge for each type of atom and a different mass for each isotope. This is all that counts as far as most atomic and molecular properties are concerned. For these purposes a nucleus can be regarded as a point without structure.

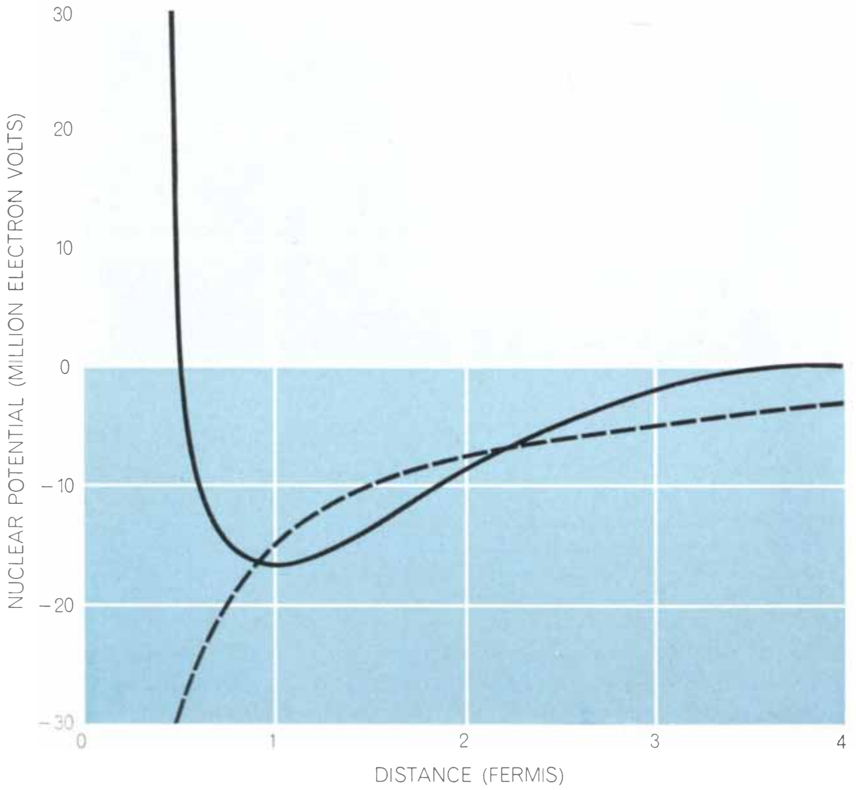
Just 50 years ago Ernest Rutherford discovered that the atomic nucleus does



CLOSED SHELLS OF 10 ELECTRONS EACH surround the nucleus of the neon atom (*left*) and the five nuclei of the methane molecule (*right*). Both neon and methane owe their stability to their having similar closed shell structures. In methane, a simple hydrocarbon gas, six of the electrons are contributed by the carbon atom and four by the hydrogen atoms. The carbon nucleus lies in the center of a tetrahedron formed by the hydrogen nuclei.



ENERGY AND SIZE OF HYDROGEN ATOM are determined by a balance between the force of electrostatic attraction, *V*, which pulls the atom's single electron toward the positively charged nucleus, and the electron's kinetic energy, *K*, which tends to enlarge the radius of the electron's orbit. The countervailing forces are in equilibrium when the radius is $.53 \times 10^{-8}$ centimeter, called the Bohr radius, and when the binding energy is 13.6 electron volts. The binding energy is commonly referred to as the Rydberg energy. In the equations $\hbar$ is Planck's constant *h* divided by 2π; *m* and *e* are the mass and charge of the electron.



STRENGTH OF NUCLEAR FORCE (*solid curve*) **varies with the distance between two nucleons. A fermi is 10^{-13} centimeter. The nuclear force is attractive where the curve lies below the zero line, repulsive above the line. Thus the force is repulsive at distances of less than half a fermi. The curve shown here is approximate. The exact value depends on the relative spin direction of the nucleons and on other factors, such as the symmetry of their wave patterns. The broken line indicates what the potential would be between two hypothetical particles that carried opposite charges equal to 3.3 times the charge of the electron.**

have a structure. Only seven years after he had determined the planetary structure of the atom he was able to show that there are protons in the nitrogen nucleus. By 1932 it was established that all nuclei heavier than the nucleus of ordinary hydrogen consist of neutrons as well as protons. Neutrons carry no electric charge, so that it cannot be an electric force that binds protons and neutrons together within the nucleus. A new force of nature—the nuclear force—must do the binding.

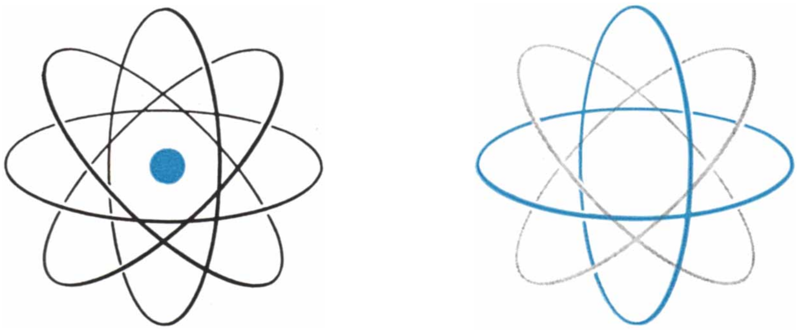
If the same laws of quantum mechanics are valid within the nucleus as within the atom, the nuclear force must bind neutrons and protons inside the nucleus in much the same way that the electric force binds electrons and nuclei inside the atom. One should expect the confined waves of protons and neutrons to produce vibrational patterns similar to the electron-wave patterns of the atom, with each pattern giving rise to a definite quantum state of the nucleus. Hence each nucleus ought to exhibit a characteristic array of energy states, giving rise to a nuclear spectrum. It was a great triumph of quantum mechanics when experiments demonstrated that such spectra indeed exist. Thus was discovered the second kind of spectroscopy, nuclear spectroscopy.

The energy differences between nuclear states are vastly larger than those found in atomic spectra: they are of the order of hundreds of thousands of electron volts [*see illustrations on opposite page*]. That is why nuclei are inert and act as unchanging particles with fixed properties—as elementary particles—as long as the energies to which they are exposed are much smaller than the step from the nuclear ground state to the first excited state. This is the case in all ordinary processes in our terrestrial environment.

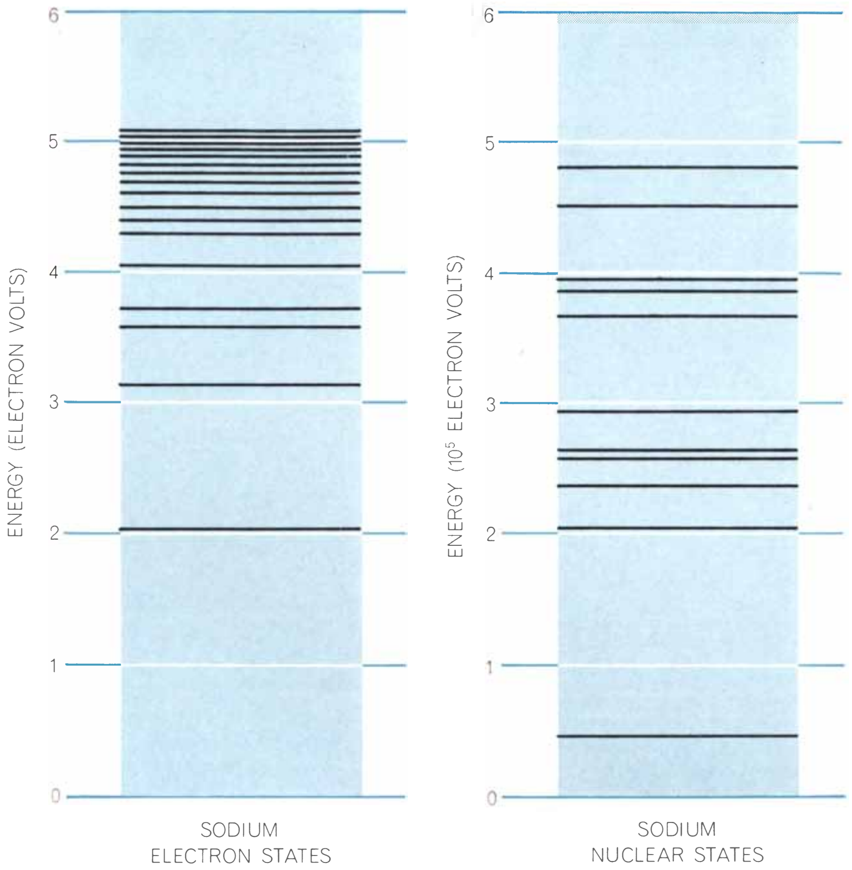
The pleasant conditions we enjoy on the earth are exceptional in the universe. We are now, however, able to create extraterrestrial conditions artificially with accelerators in which matter is exposed to beams of high-energy particles. The nuclear spectra can be studied in detail by exciting atomic nuclei with beams of protons or electrons that have energies of several million electron volts.

The nuclear force can be studied directly by observing what happens when nucleons (protons or neutrons) are brought close together. This is done by scattering experiments. For example, much can be learned about the nuclear force by studying how a beam of protons or neutrons of known energy is scattered by relatively stationary protons (for example the protons of liquid hydrogen). These studies have shown that the force between nuclear particles is very strong but that its range of action is rather short. It ceases to act at distances larger than a few fermis. Within that range the nuclear force is mostly attractive, but at very small distances (a fraction of a fermi) it becomes repulsive [*see top illustration on this page*]. The strength of the force also depends on the relative spin directions of the two particles and on other special features, such as the symmetry of their wave patterns. The force is not so simple in character as the electrostatic force between two charges. Nonetheless, one feature stands out: the nuclear force is the same between all nucleon pairs—proton-proton, proton-neutron and neutron-neutron.

How does the nuclear force compare with the electric force in strength and



AUTHORITARIAN AND DEMOCRATIC REGIMES are symbolized respectively by the relation of electrons to nucleus in an atom (*left*) **and by the relation of protons and neutrons to one another in an atomic nucleus** (*right*)**. In the atom the nucleus is the massive, fixed center around which the electrons revolve. In the nucleus, however, protons** (*color*) **and neutrons** (*gray*) **are held in similar orbits by their combined mutually attractive field.**

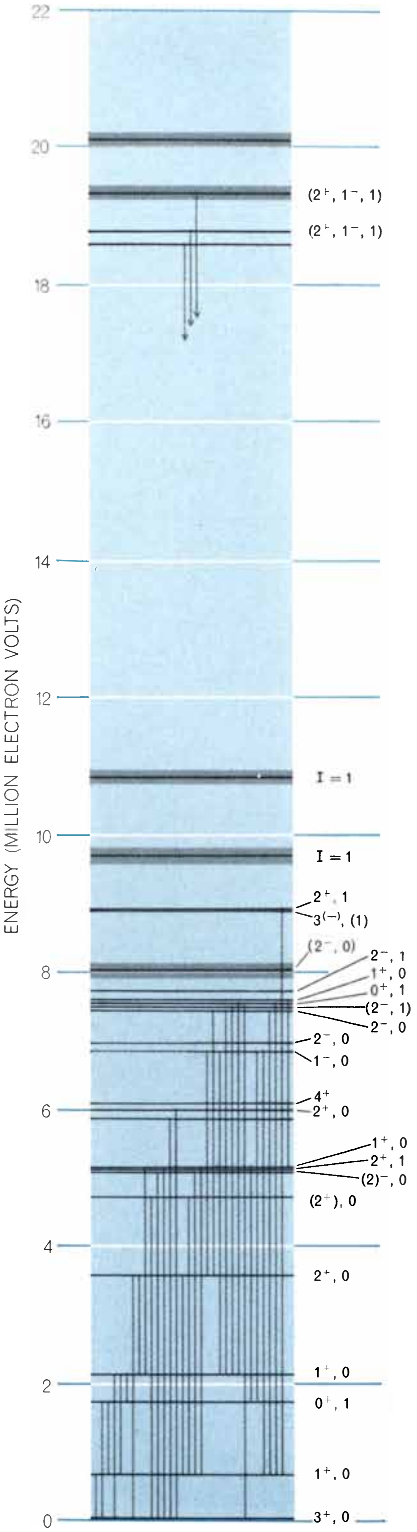


ATOMIC AND NUCLEAR SPECTRA OF SODIUM are similar in character. But the atomic spectrum (*left*) can be plotted on a scale whose units are electron volts, whereas the spectrum of nuclear states (*right*) requires a scale whose units are larger by a factor of 100,000.

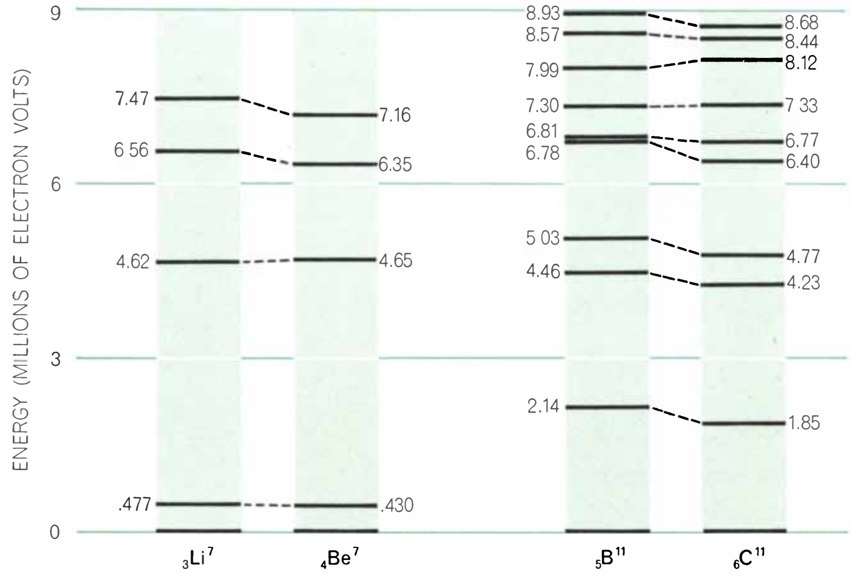
in the dimensions of its confining effect? Earlier we determined the size and energy of the hydrogen atom by calculating the balance between the attractive tendency of the electric force and the spreading tendency of the electron's kinetic energy. We can try to make the same approach to nuclei. Although the nuclear force is more complicated than the electric force, one can get an approximate idea of size and energy by stating that the attraction at distances smaller than two fermis and greater than half a fermi is about as large as an electric attraction would be at the same distance between opposite charges if each were 3.3 times larger than the electron charge. We can therefore compare the two forces by saying that there is a nuclear charge (called g) that is 3.3 times larger than the electric charge. This value, however, is a quite rough one. In reality the nuclear force is quite different from the electric one because of its short range, its dependence on spin and the fact that it is always attractive at larger distances but becomes repulsive at very small distances.

Nevertheless, we can get an approximate idea of the dimension of nuclear systems if we apply the same rules that gave us the atomic values but replace the electric charge by g and the mass of the electron by the mass (M) of the nucleon (N). (The proton and neutron have almost exactly the same mass.) We then get a nuclear Bohr radius $a_N = \hbar^2/Mg^2$ and a nuclear Rydberg energy $R_N = Mg^4/2\hbar^2$. We find that a_N is 2.5×10^{-13} centimeter and R_N is about three million electron volts (MeV). These two values provide an indication of the sizes and binding energies in nuclei. Indeed, the simplest nucleus containing a neutron as well as a proton—the deuteron—has a diameter of 2.3×10^{-13} centimeter and a binding energy of 2.1 MeV. In general the nuclear radii fall between two and 10 fermis and the energy binding a nucleon to a nucleus usually lies between 5 and 10 MeV.

There is one obvious difference between nuclear and atomic dynamics. In the atom the nucleus provides a massive center with an electric charge ranging from one to more than 100 units in the heaviest man-made elements. Furthermore, the electric force is not limited in range. Hence the attractive force of the nucleus is the overriding force acting on



NUCLEAR SPECTRUM of boron 10 shows the principal transitions (*vertical lines*) in which high-energy photons are emitted. The first digit at the right of each quantum state is the spin angular momentum, the next symbol (+ or −) is the parity, the second digit is the isotopic spin, *I*. Values in parentheses are uncertain. Gray bands indicate levels that are particularly broad. The figure follows one published by Thomas Lauritsen of the California Institute of Technology and Fay Ajzenberg-Selove of Haverford College.



SPECTRA OF "MIRROR" NUCLEI are very similar because the nuclear force does not distinguish neutrons from protons. Two nuclei form a mirror pair if they contain the same total number of protons and neutrons and if the number of protons in one nucleus equals the number of neutrons in the other. Thus $_3Li^7$ (lithium) and $_4Be^7$ (beryllium) form one mirror pair and $_5B^{11}$ (boron) and $_6C^{11}$ (carbon) form another. The subscript indicates the number of protons in the nucleus, the superscript the total number of protons and neutrons.

each electron. The dynamics within the nucleus is more "democratic": there is no central particle with an overriding attraction. All constituents have nearly the same mass and the same nuclear charge. Each particle moves and produces its vibrational pattern in the combined field of force of all the particles [*see bottom illustration on page 20*].

Nevertheless, there are many similarities between atomic and nuclear spectra. Again we find the same typical vibrational patterns, giving rise to the angular-momentum values $l\hbar$, with $2l + 1$ multiplet states of equal energy. Because the Pauli exclusion principle also applies inside the nucleus, no two equal particles can be in the same state.

Another striking similarity is found in the shell structure of both atoms and nuclei. Whenever the number of constituents—electrons in the first case, protons or neutrons in the second—reaches certain values, closed shells of increased stability are formed. Accordingly there is a periodic table not only of elements but also of nuclei.

A new symmetry appears in nuclear spectra that does not exist in atomic spectra. Since the nuclear force does not distinguish a proton from a neutron, the nuclear states that differ only in the replacement of a neutron by a proton must have the same structure and therefore the same energy [*see illustration above*]. This symmetry is not quite exact because the replacement changes the number of units of electric energy. The electric energies, however, are smaller than the nuclear energies, and besides they can be easily calculated and subtracted. This symmetry is called isospin symmetry for reasons that need not concern us here. It gives rise to groups of states called isospin multiplets.

When a nucleus is raised to an excited state and falls back to a lower energy state, it can get rid of its energy not only by emitting a light quantum, as an excited atom would do, but also—when the excitation is high enough—by emitting a lepton pair: the simultaneous emission of an electron (either a negative electron or a positron) and a neutrino. Both particles are created at the moment of transition from the higher to the lower nuclear state, just as the light quantum is born when a similar transition occurs. This new emission is called the beta decay of the nucleus. Because nature always creates particles and antiparticles in pairs, the companion particle created with the electron is understood to be an antineutrino and the one created with the positron to be a neutrino.

This emission has several unusual features. One is that electric charge is emitted; hence the nucleus must change its overall charge in the opposite direction when the emission takes place, thereby ensuring the conservation of charge. What happens is that one of the nuclear protons changes into a neutron if a positron-neutrino pair is emitted, and one of the neutrons changes into a proton when an electron-antineutrino pair is emitted. Accordingly the charge of the nucleus is no longer an absolutely fixed quantity; it can be changed by beta decay [*see illustration on opposite page*].

What cannot change in any transition is the total number of protons and neutrons, which is called the nucleon number. Nuclei that have the same number of nucleons cannot really be considered as different systems even if they have a different number of protons. They are nothing but different quantum states of the same nucleus. The energy difference between the two states must nonetheless be sufficient to produce an electron and a neutrino. Since the mass of the neutrino is zero, the minimum energy difference between two states for beta decay is simply the electron mass energy: .51 MeV. Any surplus over that minimum goes into the kinetic energy of the two emitted particles. The size of the minimum energy requirement makes it obvious why lepton-pair transitions do not occur in atomic spectra: energy differences of that scale cannot exist in atoms without destroying them.

In 1957 the surprising discovery was made that lepton-pair emission violates what had been considered a basic rule of nature. Until then it had been thought that nature did not distinguish between left and right. An ingenious experiment showed, however, that the neutrino is always emitted in a state of left-handed rotation with respect to its line of flight; the antineutrino is always in a right-handed rotational state.

The most fascinating part of atomic dynamics is the chemical bond that enables atoms to associate and form molecules in a nearly infinite variety of ways. Is there anything similar to be found in nuclear dynamics? Nuclear chemistry does exist but only to a limited degree. Two nuclei can react with each other and form an association, but the association is identical with a heavier nucleus. This is a consequence of the democratic regime in the nucleus. All constituents are similar and attract one another, whereas in the atom there are two distinctly different constituents: the nucleus and the electrons. The nuclei stay apart from one another when atoms form a molecule.

The process of combustion, however, is found in both worlds. Whenever two units merge and form a larger one, there is a release of energy because the bound system has less energy than the separated units. (This should be evident when one considers that energy must be delivered to carry out the opposite process, that is, to split a bound system into its parts.) When carbon and oxygen combine to form carbon dioxide, .7 electron volt of heat energy is released per molecule formed. When a helium nucleus and a carbon nucleus unite to form an oxygen nucleus, 20 MeV are released. Here again we see the different scale of energies in the two realms.

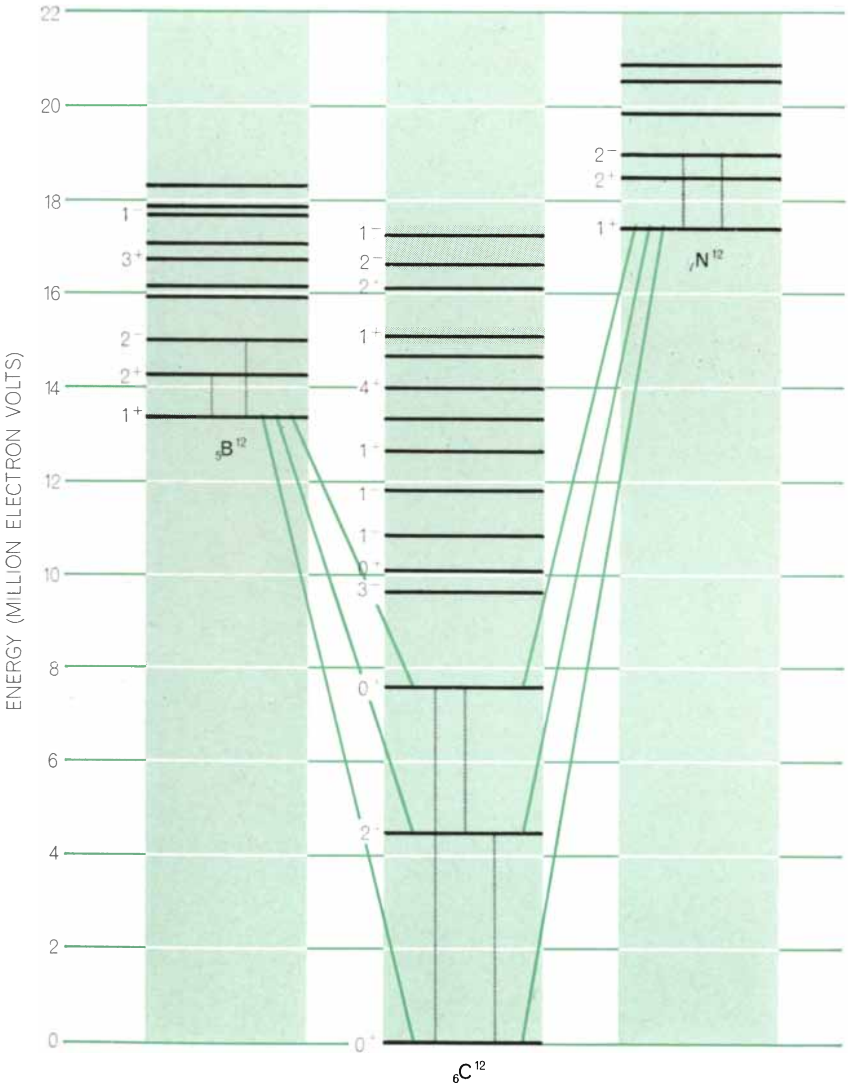
Nuclear combustion is much harder to ignite, of course, than atomic and molecular combustion. Considerable energy is required to bring the nuclei close enough so that the nuclear force will dominate the force of electric repulsion. This can be done with particle accelerators by aiming a beam of high-energy particles at a target. Nature does it in the interior of stars, where the temperature is so high that heat can provide the necessary ignition energy. In the center of the sun hydrogen burns to form helium. In older stars (red giants) helium burns to carbon and oxygen; various other nuclear reactions can take place to form still other elements. By such processes the nuclei of all the known elements have been formed. For some of these reactions the ignition temperature is so high that they can take place only in the explosion of a supernova.

Although nucleons remain stable even at the highest stellar temperatures, their stability is not infinite. This was demonstrated about 25 years ago in cosmic ray experiments. Within a few years a whole world of new phenomena was discovered with the help of large accelerators, which today produce proton beams with energies up to 70 GeV. When such beams were made to impinge on material targets, strange and unexpected things were observed. It took some time before one was able to describe what was going on in a more or less systematic way, and one is still far from a reasonable understanding of subnuclear phenomena.

What has been discovered can best be explained in the following terms. When a nucleon is hit by a particle of very high energy, it seems to behave somewhat as an atom or a nucleus does at considerably lower energy. The nucleon can be excited to a number of higher quantum states. After being excited it sometimes falls back to its original state with the emission of light quanta or lepton pairs, but in most cases, when the excitation is high enough, the emission consists of energy quanta of an unusual type: the mesons, a name that signifies particles of medium mass.

High-energy physicists often refer to these excited states as "new elementary particles." I have felt for some time that it is more logical to consider them as higher quantum states of the nucleon, since they are very short-lived and revert to an ordinary proton or neutron. The energy difference between the excited state and the ground state is emitted in the form of various quanta, in complete analogy with the excited states of the atom and the nucleus. This array of quantum states of the nucleon can be considered a new type of spectrum, the spectrum of the nucleon. It is the third of the spectroscopies revealed by physical investigation. Here I shall introduce the term "baryon," which will be used to designate the nucleon in all its different states of excitation. I shall reserve the term "nucleon" for its manifestation in the ground state in the form of a proton or a neutron.

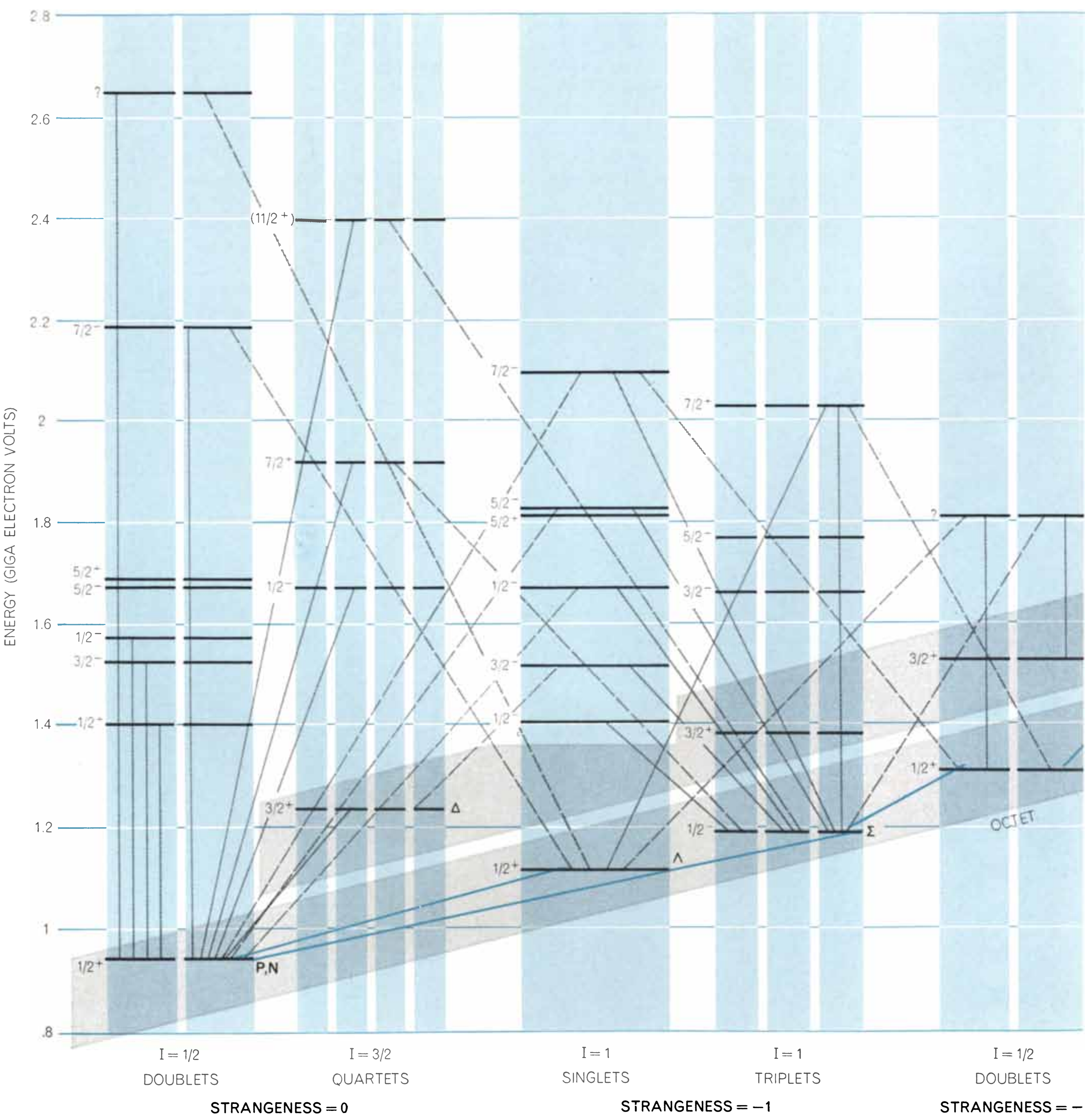
Let us now have a look at the spectrum of the baryon, that is, at its excited states as they are known today. The illustration on the next two pages shows in the form of horizontal bars the most important states discovered so far. The height of the bar on the vertical scale



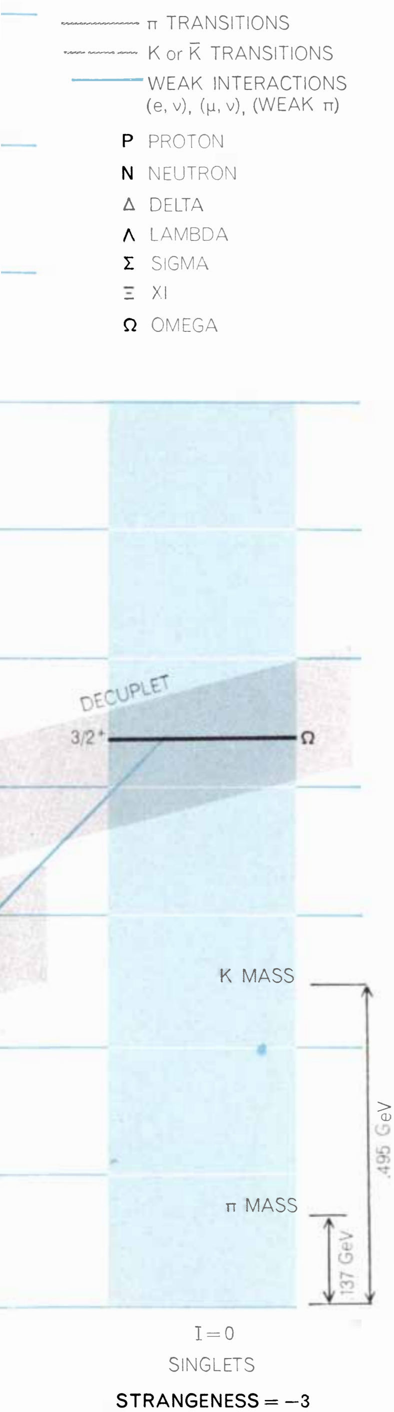
MEMBERS OF SINGLE QUANTUM SYSTEM can have different numbers of protons in their nuclei provided that the total number of nucleons (protons and neutrons) is the same. Thus boron 12, carbon 12 and nitrogen 12 form a single quantum system in which transitions are possible between members. The vertical lines indicate some of the transitions mediated by light quanta. The slanting lines identify transitions accompanied by the emission of lepton pairs. When the line descends from left to right, the pair is an electron and an antineutrino. A line of opposite slant marks the emission of a positron and a neutrino.

indicates the energy of each state. It will be seen that the energy differences are of the order of several hundred MeV, which is about 1,000 times greater than the energy differences in nuclear spectra. The ground state is actually a doublet; it represents the proton and the neutron, whose energy difference of 1.2 MeV is undetectable on the GeV scale of these figures.

The most striking feature of the baryon spectrum is the way transitions occur between states. Most of the transitions occur by the emission or absorption of mesons. Mesons are the commonest energy currency in the subnuclear world. They play the same role with respect to the nuclear force that light quanta play with respect to the electric force. For example, if a source of electric force—an electron—collides with something else (as



BARYON SPECTRUM is composed of the nucleon (*P*, *N*) and its various excited states. The states are arranged in columns according to their multiplicity and strangeness. The letter *I* denotes isotopic spin; the multiplicity is given by $2I + 1$. Strangeness is an intrinsic quantum property. In the subnuclear spectrum of the baryon the ground state is taken to be the mass energy of the proton, .938 GeV. The number to the left of each state indicates spin angular momentum and parity (+ or −). The symbol to the right is the name of the state. The quanta emitted in certain transitions are shown in the key. Photon emissions are omitted; they generally link the same states linked by pions if there is no change in charge. Colored lines indicate transitions that are mediated by weak interactions: lepton pairs or weak pion emissions. Transitions go from every member of a multiplet to every member of another, but for an electron does in striking the metal target in an X-ray tube), it radiates light quanta. If a source of nuclear force—a nucleon—violently collides with something else (as an energetic proton does in striking an accelerator target), it radiates mesons [*see illustration on page 17*].



simplicity only one such transition is shown for each pair of states. The masses of pions and kaons appear at the right. The states in the octet and decuplet exhibit certain internal symmetries. Each baryon state shown here also exists in an antimatter state, so that there is a similar spectrum of antibaryons.

The nuclear force, however, is much more complicated than the electric force, hence mesons are more complicated than photons. For one thing, mesons cannot move with the velocity of light because they have a rest mass. Moreover, there is a large variety of mesons with different masses, and some are charged and some uncharged. The most important group of mesons are the pi mesons, or pions, which have the smallest mass. There are three of them: one positive, one negative and one uncharged. The next most important group of mesons are the *K* mesons, or kaons, of which there are four. Their mass is higher than the mass of the pion and they exist in both charged and uncharged forms.

The baryon spectrum exhibits certain notable regularities. One is the existence of multiplets, or groups of states of almost the same energy differing only in their charge. They are identical in all other respects, such as lifetime, angular momentum and meson emission and absorption. The simplest and most familiar example is the ground state itself: the doublet consisting of the proton and the neutron. There are a few singlets among the excited states; the rest are multiplets—doublets, triplets and quartets. They are called isospin multiplets, and one formally ascribes to them an isospin quantum number I such that the multiplicity is $2I + 1$. Thus the proton-neutron pair has a quantum number I of 1/2. (The reason for expressing I in multiples of 1/2 is based on an analogy between these multiplets and the ones that occur for states with a certain value, J, of the angular momentum, also expressed in multiples of 1/2.)

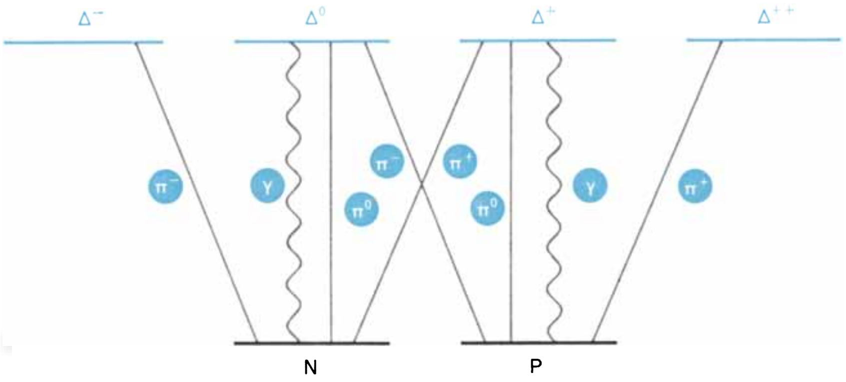
The next regularity in the baryon spectrum is associated with *K*-meson emission and absorption. Certain transitions are implemented by pion absorption or emission and not by kaons; other transitions are implemented only by kaons and not by pions. One can divide the states into groups within which only pion transitions occur and ascribe to each of these groups a new quantum number, S, with the values 0, −1, −2 and −3. (The negative values of S have historical reasons.) Then the rule is that pion transitions occur only between states of the same quantum number. Kaon transitions change S by one unit. For this to be possible the kaons must carry a unit (positive or negative) of S with them. The symbol S stands for the "strangeness" quantum number, a somewhat misleading term surviving from a time when such exotic designations seemed appropriate.

A paradoxical situation seems to arise for the baryons of lowest energy in which S is different from zero. Consider the lowest state of the $S = -1$ group, the lambda particle (Λ). It should drop to the nucleon ground state ($S = 0$) only with the emission of a kaon. The energy difference between this state and the ground state, however, is 176 MeV, which is only about a third of the mass energy needed to create a kaon. Thus a kaon cannot be emitted. But since nature requires a route to the ground state some other form of emission must exist. Experience has shown that light-quantum emission never occurs between states of different S. All that remains are the weak interactions that give rise to lepton-pair emissions and also to weak pion emissions. These transitions, however, are very slow, which is why the lambda state has the relatively long lifetime of 2.5×10^{-10} second, whereas normal meson-emitting states exist as briefly as 10^{-22} second.

The lambda state was therefore regarded as a separate particle. The situation is reminiscent of the days when atomic spectra were badly understood. Spectroscopists had found two helium spectra, "parahelium" and "orthohelium," representing states that seemed to have no transitions between them. They believed they were dealing with two different atoms until Werner Heisenberg pointed out that both spectra can arise from the same helium atom. In one case the atom's two electrons have their spins parallel; in the other case the spins are antiparallel. Only rarely will one of the electrons "flip over" with the emission of a photon, thereby providing a transition between the two states.

So far I have mentioned only two kinds of meson, pions and kaons, but there are many others. There is, in fact, a spectrum of mesons [*see illustration on page 27*]. As in the baryon spectrum, the meson states can be grouped according to multiplicity and strangeness. There are also transitions between meson states. When one meson changes into another, the energy difference is emitted in the form of pions, kaons, lepton pairs and light quanta, precisely as in the baryon spectrum.

There is one significant difference between the two spectra: in the meson spectrum the ground state, the pion, is not stable. It is therefore not a particle in the same sense as the nucleon; it is a quantum of energy that can transform itself into other energy quanta such as light or lepton pairs. The uncharged pion decays after 10^{-16} second into light;



DECAY OF DELTA STATE of the baryon is accompanied by emission of photons or pions. The emitted quanta carry off nearly 300 MeV of energy, allowing the delta baryon to fall to the nucleon ground state. The delta state is an isotopic quartet with four substates: one negative, one neutral, one singly positive and one doubly positive. In falling to the ground state the first and fourth substates must change by one unit of charge, which is accomplished by the emission of a charged pion. The second and third substates need not change sign.

the charged pions decay after 10^{-8} second into lepton pairs.

How can one explain these excited baryon or meson states? The atomic and nuclear quantum states could be interpreted as different dynamical forms of a system of constituents held together by a binding force: nuclei and electrons in the first case, protons and neutrons in the second. The baryon and meson spectra are not yet understood. No Rutherford has so far succeeded in breaking the nucleon into its constituent parts. Indeed, we do not know if such constituents exist at all. All we know is that the nucleon can exist in many quantum states when enough energy is delivered to it. We also know the various ways in which these states can exchange their energy.

Although nothing definite has yet been found to indicate that baryons and mesons have an internal structure, there are certain indications to suggest that the baryon may be made up of three constituents and the meson of two. The hypothesis, briefly, is as follows. The baryon is supposed to consist of three hypothetical subparticles called quarks. There are three types of quark: *p*, *n* and λ (lambda). The first two quarks are so designated because they form a doublet just as the proton and the neutron do. All three quarks have a spin of 1/2 unit and are very much alike except for their electric charge. Here a curious assumption is introduced: the *p* quark is assigned a charge that is +2/3 times the unit charge; the *n* quark is assigned a charge of −1/3 unit. Such fractional charge units have never been observed in nature. The λ quark is different: it is assumed to have a strangeness quantum number S of −1, whereas the *n* and *p* quarks have S equal to 0. The charge of the λ quark is −1/3 unit. This set of three quarks is provided with a set of antiparticle quarks: $\bar{n}$, $\bar{p}$ and $\bar{\lambda}$ [*see top illustration on page 28*].

According to the quark model, baryon states with S equal to 0 are composed of three quarks of the *p* or *n* type. Three *p*-type quarks would give a charge of three times +2/3, which is +2. Three *n*-type quarks would give a charge of −1. With such combinations we can obtain charges −1, 0, +1, +2, which satisfy all the charges of baryons with S equal to 0. The proton, for example, would consist of one *n* quark and two *p* quarks, the neutron of two *n*'s and one *p*. The states with S equal to −1 consist of one λ quark and two quarks of the *p* or *n* type. This gives rise to charges of −1, 0, +1. The states with S equal to −2 and S equal to −3 respectively have two or three λ quarks, which results in charges of −1 or 0 for S equal to −2, and a charge of −1 for S equal to −3. These are just the charges found among baryon states with a strangeness of −1, −2 and −3.

It can also be shown that a number of other properties of these states are well reproduced by the quark model, for example the appearance of isotopic doublets and quartets for S equals 0, isotopic singlets and triplets for S equals −1, doublets for S equals −2, and no isotopic multiplets for S equals −3. In this tentative picture the quantum states of the baryon are different dynamical forms of a three-quark system, with the combination that makes up the proton having the lowest energy.

The quark model also provides a scheme for building mesons. There is an important difference, however: mesons are energy quanta that can be emitted and absorbed freely. This means that quarks could enter into their structure only as particle-antiparticle pairs. Such pairs can be considered a form of exchangeable energy currency because the members of a pair can annihilate each other and thus change into other forms of energy, or they can be made from other forms of energy by the process of particle-antiparticle creation. For this reason the quark model assumes that mesons consist of a quark and an antiquark bound together. The emission of a meson would be equivalent to the creation of a quark-antiquark pair. It would be in some ways similar to lepton-pair emission, which is also the simultaneous creation of a particle and an antiparticle. The different combinations of the three types of quark and antiquark give rise to most of the observed meson types [*see illustration on page 29*].

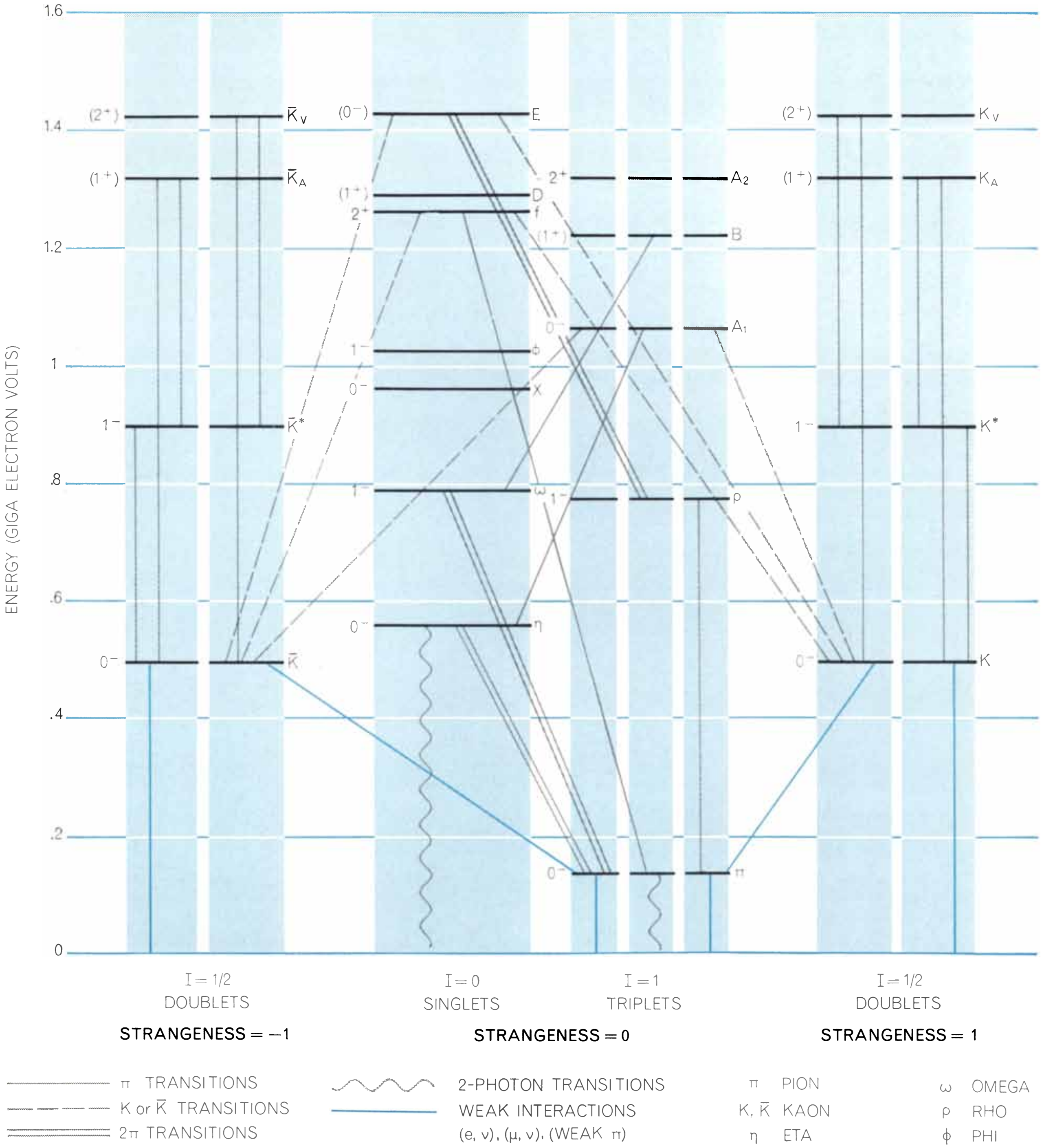
The quark picture enables us to classify quantum states in the baryon and meson spectra into groups of states that differ only by exchanging one quark type for another. It can also be shown that these groups consist of eight or 10 states, thus forming octets or decuplets. The lowest-lying octet consists of the nucleon doublet, the lambda singlet, the sigma (Σ) triplet and the xi (Ξ) doublet. The states within these groups differ somewhat in energy but their properties are rather similar in other respects.

Apparently a new symmetry is at work here; it has been given the abstract name of SU_3 symmetry. If the quark picture were right, it would mean that the internal forces are not much dependent on the quark type. Therefore states differing only by the types of quark should be similar. Whenever one finds a spectroscopy of higher order, a new symmetry seems to appear. Atomic spectra exhibited rotational symmetry; nuclear spectra introduced isotopic symmetry, and subnuclear spectra now may add SU_3 symmetry.

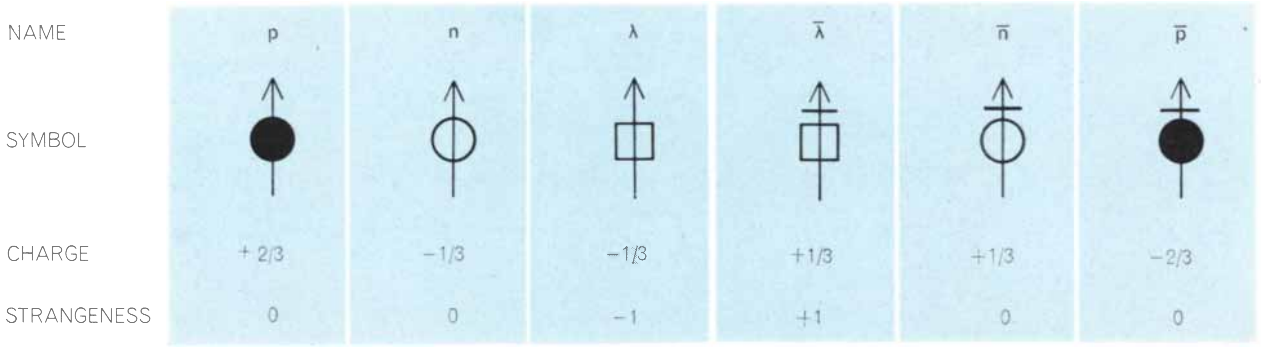
Altogether the quark model of baryons and mesons has been surprisingly successful in describing the properties of quantum states and the transitions between them. For example, let us consider the transitions that take place between the first excited state of the baryon, the delta (Δ) state, and the ground state [*see illustration on this page*]. In the quark model the two middle states of the delta quartet (Δ^0 and Δ^+) differ from the proton and neutron ground states only by virtue of the fact that in the deltas the three quarks have parallel spin, giving a total spin of 3/2 (1/2 for each quark), whereas in the proton one of the quarks has its spin opposed to the other two, so that the net spin is only 1/2. Hence a transition from Δ^0 and Δ^+ to the ground state corresponds to the spin flip of one quark. It is relatively easy to calculate the radiation emitted by such a flip if one knows the magnetic moment of the flipping quark, which can be figured out by assuming that the moments of the three quarks together should add up to the known magnetic moment of the proton. Such calculations have indeed given the observed electromagnetic radiation for the transition between delta and the proton.

Let me emphasize, however, that quarks have never been observed, even in nucleon collisions of the highest available energy. It may be that the binding force that holds quarks together is so high that much larger energies are needed to tear them apart. It may also be that we are still far from understanding the structure of baryons and mesons and that we have found only a certain similarity between the properties of baryons and the behavior of a hypothetical three-quark system and between the properties of mesons and the behavior of quark-antiquark systems.

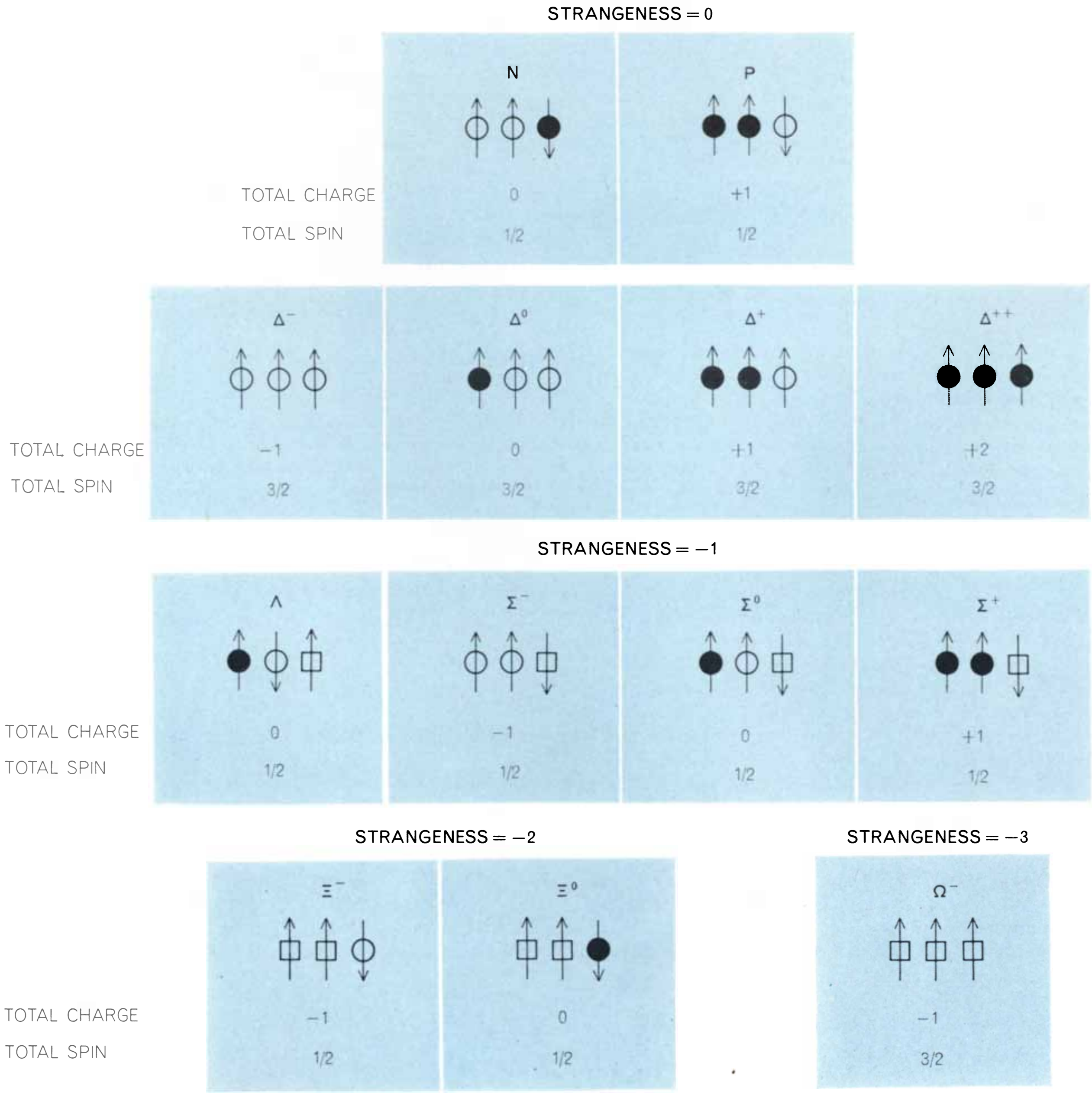
If the quark model were correct, we



MESON SPECTRUM, like the baryon spectrum, can be arranged so that the various states fall in columns according to their multiplicity and strangeness. In contrast with the baryon spectrum, the ground state (pion) of the meson spectrum is unstable. It decays by weak interaction either into lepton pairs or into photons. Kaons and the eta meson can vanish similarly without generating pions.



THREE QUARKS, and their antiparticles (*right*), have been proposed as the hypothetical building blocks of baryons and mesons. Unlike all particles discovered so far, quarks would carry less than a whole unit of the charge of the electron. The lambda (λ) quark is provided with a negative unit of strangeness. Each quark and antiquark carries half a unit of spin, the direction of which is shown by an arrow. As in the world of known particles, the hypothetical antiquarks mirror the properties of the quarks.



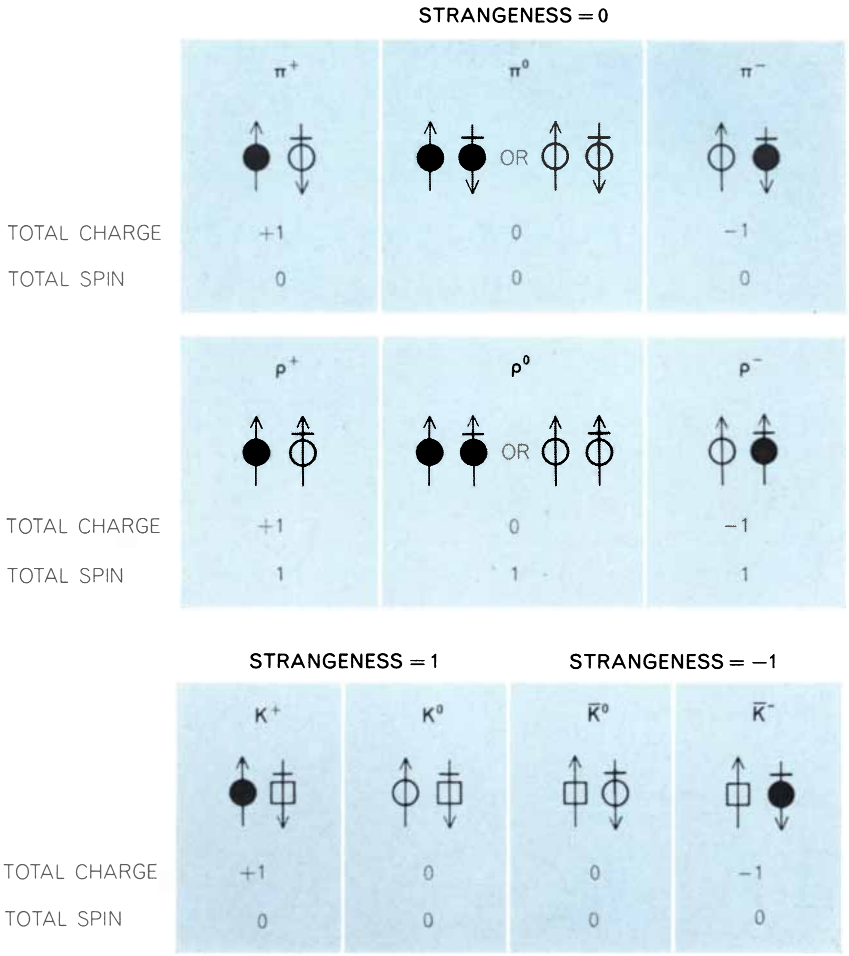
SETS OF THREE QUARKS in various combinations provide the known properties of baryons. When two spin arrows point in opposite directions, they cancel, thus the net spin of most of the baryons is 1/2. When all three arrows point the same way, the spin is 3/2.

would have to assume the existence of a new and extremely strong force between quarks. The nucleons would be "molecules" made up of quarks, and the force between nucleons—the nuclear force—would be analogous to the chemical force between molecules. Whatever the true nucleon structure may be, it is probable that the forces between nucleons are determined by the structure of the nucleons in some way. The complicated aspect of the nuclear force suggests to many physicists that it is an involved manifestation of something deeper that is actually simpler and more basic in character. One hopes that the nuclear force will one day be explained by some fundamental phenomenon in the internal dynamics of the nucleon, just as the complicated chemical forces today can be traced back to the simple electric attraction between nuclei and electrons.

The lepton emissions exhibit another series of puzzles in the world of subnuclear phenomena. The amounts of energy available for emission are much larger here than in nuclear transitions. Sometimes, if enough energy is available for a lepton emission, the "electron" of the emitted lepton pair has a mass that is 200 times heavier than that of an ordinary electron. This heavy electron, called the muon, differs from the ordinary electron only in its larger mass. The neutrino accompanying the muon has also shown an unexpected feature: it is not the same kind of neutrino that accompanies the lightweight electron. Although it too has a vanishingly small rest mass, it can be clearly distinguished from the ordinary neutrino.

The heavy electron is not a stable particle. It is observed to transform itself in a millionth of a second into a neutrino of the new kind, with the emission of an ordinary lepton pair. It therefore decays into an ordinary electron and two neutrinos, one of which is the special neutrino associated with the muon and the other the ordinary neutrino of the lepton pair.

It is tempting to conclude that the two electrons and the two neutrinos are all quantum states of one particle, inasmuch as transitions can occur among them. We may have found here the beginning of a fourth spectroscopy, the lepton spectrum, which may be an indication that electrons and neutrinos have an internal structure. In any case it is certain that the problem of electronic structure is a fundamental one, since it must be intimately connected with the question of the nature of electric charge and with the significance of the unit of charge that plays such a fundamental role in nature.



A QUARK AND AN ANTIQUARK account for the observed properties of the principal mesons. Pi (π) and rho (ρ) mesons have strangeness equal to zero, hence do not include a lambda quark. In the kaon sets, normal lambda quarks produce a strangeness of —1 for the $\bar{K}^0$ and K^- pair and antilambda quarks produce a strangeness of +1 for K^0 and K^+.

In this article we have seen that each of the three spectroscopies represents the relevant quantum states of a different realm of phenomena. The first is the world of atoms and molecules that embodies our immediate environment on the surface of the earth. It is a subtle and vulnerable environment, involving as it does small energy exchanges among its constituents, the atoms and molecules.

The second is the world of nuclear phenomena. Its constituents are the nuclei, and its elementary particles are neutrons and protons, electrons and neutrinos. The nuclei interact in nuclear processes with energy exchanges of many hundreds of thousands of electron volts. In nature such interactions occur on a grand scale only within stars.

In the third realm, the world of subnuclear phenomena, the constituents are nucleons and mesons. We do not yet know if there are elementary particles making up these constituents. The energy exchanges in subnuclear processes are hundreds of millions or billions of electron volts. These are energies that would tear nuclei apart, just as nuclear energies would tear atoms apart. The subnuclear world is not known well enough for us to assign it a place in the universe. Its ultrahigh energy processes occur in a very small and insignificant way whenever cosmic rays impinge on matter. Perhaps the place to look for such processes is in the newly discovered cataclysmic events associated with quasars and exploding galaxies. The enormous amounts of energy released in these phenomena may be an indication that subnuclear processes play a significant role. It is certain that the processes observed when matter is exposed to the beams of our multibillion-volt accelerators belong to a new and partly undiscovered realm of natural phenomena buried deep in the interior of matter, where nature behaves in a manner totally different frcm anything previously known.

THE TARTARIA TABLETS

Three inscribed tablets found in Romania may be 1,000 years older than the oldest examples of writing from Mesopotamia. They are probably not that old, but they do illuminate the contacts between ancient cultures

by M. S. F. Hood

The earliest known writing appears on clay tablets uncovered at Uruk, a Sumerian city that flourished in Mesopotamia during that region's early Bronze Age. The tablets are known to be a little more than 5,000 years old. Prehistorians were surprised, therefore, when what appears to be much earlier writing was found a few years ago in the ruins of a Neolithic village in the Balkans. The Neolithic find, consisting of three small clay tablets, was made at Tartaria in the Transylvanian region of Romania. On the widely accepted basis of carbon-14 dating, the Tartaria tablets could be more than 1,000 years older than the oldest Sumerian ones. This was not the only surprise at Tartaria. Some of the signs incised on the Tartaria tablets proved to be almost identical with Sumerian ones of the period around 3000 B.C. The Tartaria tablets also looked much like the written records produced in Crete around 2000 B.C., when the earliest archives uncovered at Knossos were established. The Tartaria discovery obviously raises a number of puzzling questions.

The least troublesome questions concern the distance between the Balkans on the one hand and Crete and Mesopotamia on the other. It is now established beyond doubt that in Neolithic times the Near East and other areas around the Mediterranean were crisscrossed by trade routes over which the volcanic glass obsidian, for example, was carried hundreds of miles from mine to toolmaker [see "Obsidian and the Origins of Trade," by J. E. Dixon, J. R. Cann and Colin Renfrew; SCIENTIFIC AMERICAN, March]. Other materials may have moved over these routes, and written records could easily have been among them.

The questions that arise because of the differences in age between Neolithic Tartaria, early Bronze Age Sumer and late Bronze Age Crete are much more troublesome. Are the Tartaria tablets in fact older than the earliest writing at Uruk? Could writing have first been invented in Neolithic Europe? Was this key element in civilization disseminated from Europe to the Near East, in contradistinction to the usually accepted view that the movement was in the opposite direction? Assuming that such was the case, how can one account for the arrival of writing in distant Mesopotamia perhaps 1,000 years before archives first appear in comparatively nearby Crete? These are only a few of the questions one might ask.

I hope to show that reasonably satisfactory answers can be given to most of such questions, if not all of them. First, however, the reader will need to be acquainted with the Tartaria site and its

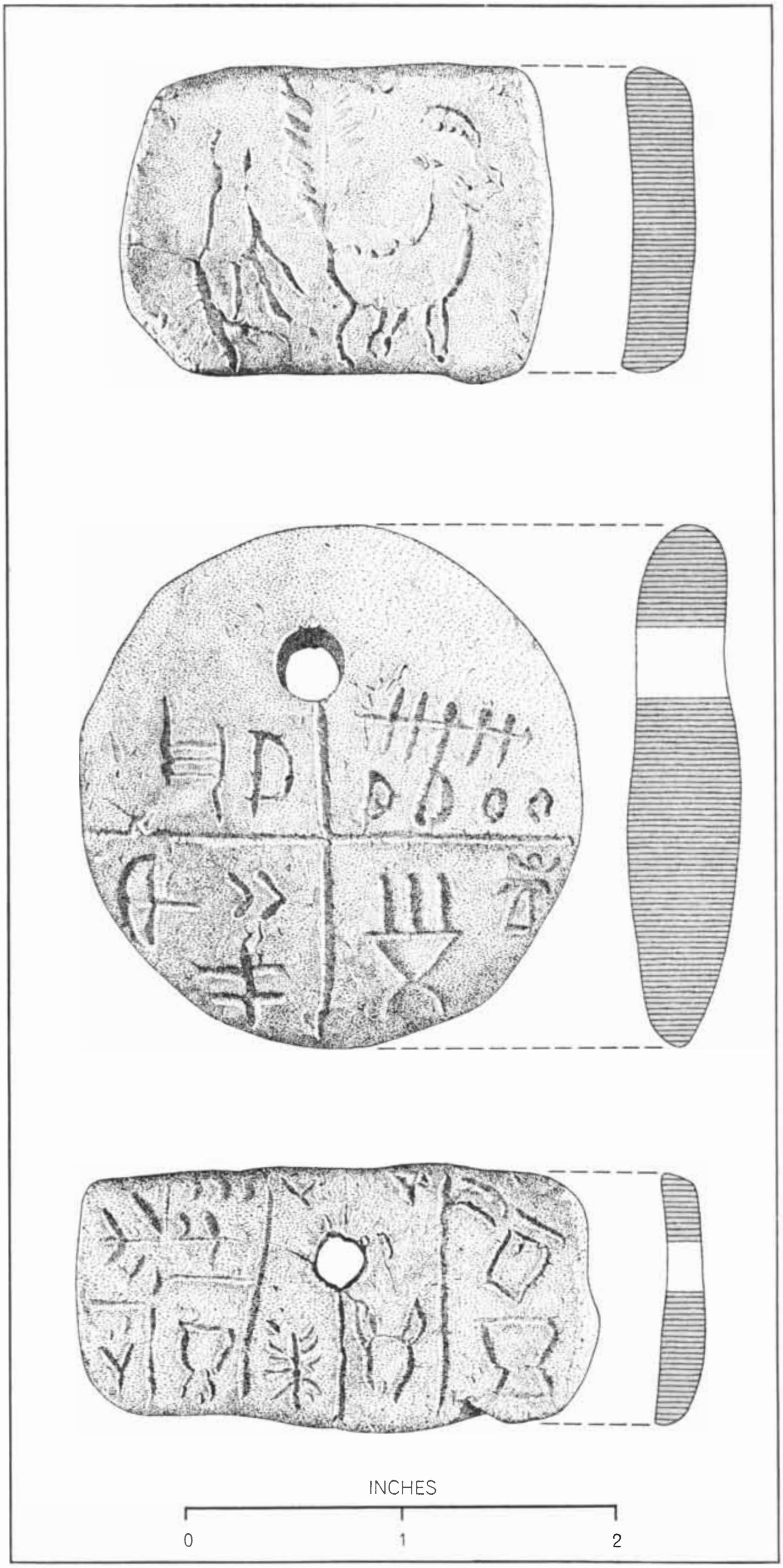
SUMERIAN WRITING of the period around 3000 B.C. covers a clay tablet found at Jemdet Nasr in Mesopotamia. Several parallels exist between Sumerian writing and the inscriptions on tablets found at Tartaria in Romania (*see illustration on opposite page*). The Tartaria site belongs to the Neolithic period and thus the tablets have been thought to be older than the earliest Sumerian writing. The Jemdet Nasr tablet is reproduced by permission of the Keeper of the Department of Antiquities, Ashmolean Museum, University of Oxford.

contents, and with some facts about Balkan archaeology and about early writing in general. Tartaria is a town some 70 miles south of the city of Cluj; it lies on the Maros River near a part of Transylvania that was famous in classical times for its rich gold deposits. The Tartaria site is a mound some 250 yards long and 100 yards wide. It was first excavated in 1942 and 1943 but the war forced a halt; digging began again, under the direction of N. Vlassa of the Cluj Institute of History and Archaeology, only in 1961.

The main reason for excavating the Tartaria mound was that it was an undisturbed site and might provide a much-needed key to a more famous Neolithic site nearby: the mound at Tordos. This was one of the first Neolithic sites to be studied in Europe; excavations had been made there off and on since 1874. The most recent excavation had been undertaken in 1910. Soon afterward a nearby stream shifted its course and washed away most of the mound. Not all the digging had been up to modern standards, and it was hoped that a clear stratigraphic record from Tartaria would enable prehistorians to put the large number of artifacts from Tordos in their proper chronological sequence.

The culture represented at both Tordos and Tartaria is called Vinca after a major Neolithic village site in Yugoslavia, 120 miles southwest of the two mounds in Romania. The Vinca people were farmers who built simple huts with a framework of wooden posts and walls woven from thin branches and daubed with clay. When such a dwelling fell into disrepair or was destroyed, the villagers built a new hut on top of the leveled wreckage of the old one. Settlement mounds thus rose in the Balkans in the same way as did the *hüyüks* of Asia Minor and the *tepes* and *tells* of the Near East. The mound at Vinca is more than 30 feet high and has many successive building levels. The Tartaria mound is only six feet high but four periods of occupation can be distinguished.

The Vinca culture evidently lasted a long time, perhaps for 1,000 years or more. It is traditionally classified as a Neolithic culture, that is to say, a culture in which metal and its uses were unknown. In actuality two main phases of the culture can be distinguished, and throughout the later phase the Vinca farmers possessed axes and other tools made of copper, as well as axes and adzes made of polished stone and knives and arrowheads made of chipped flint and obsidian. Traces of copper have also been found in strata belonging to the



THREE INSCRIBED TABLETS, found at the bottom of an ash-filled pit at Tartaria, are reproduced slightly larger than actual size. The tablets are marked on one face only. Many of the marks resemble the signs used for numerals and for syllables in Sumerian writing.

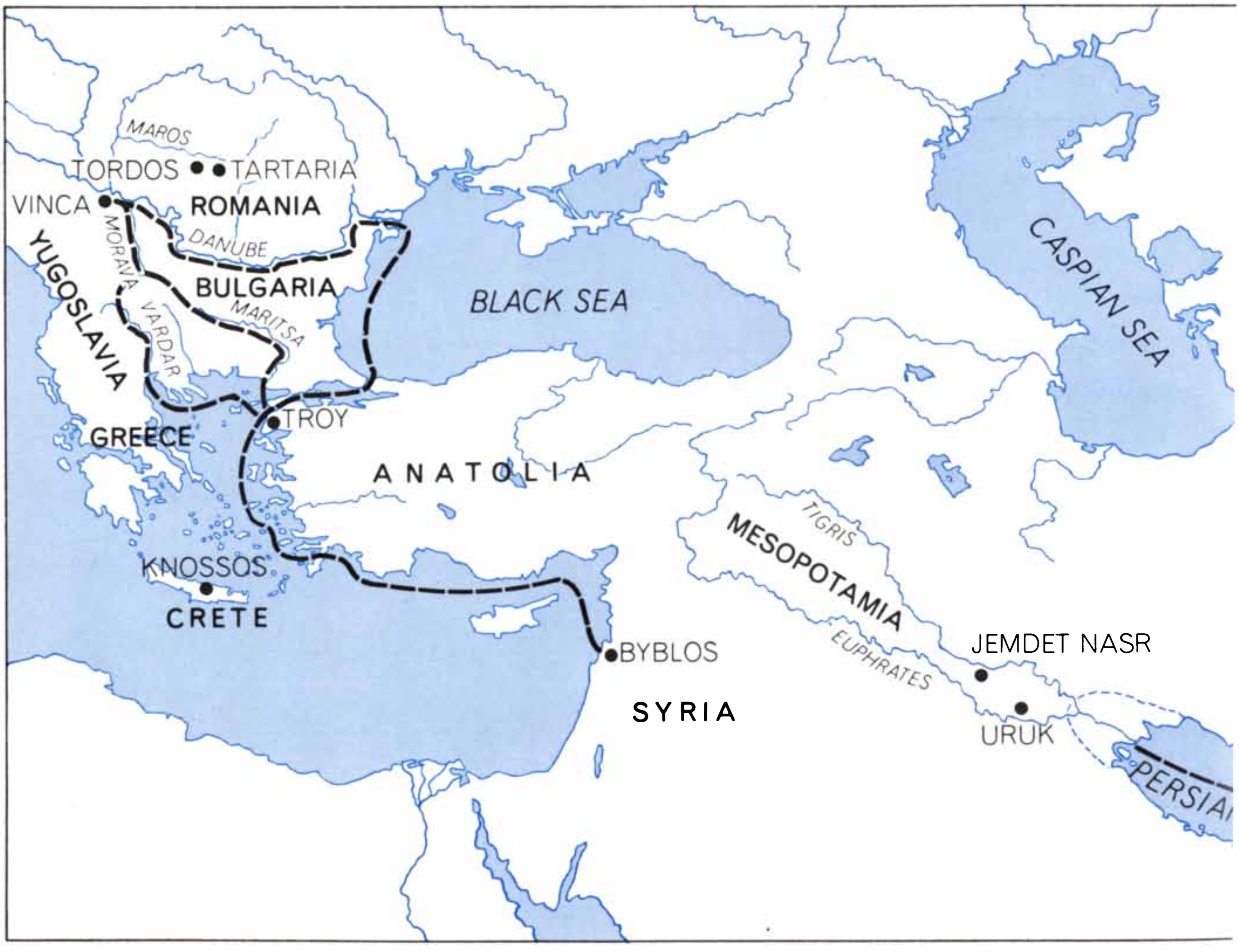
earlier phase of the Vinca culture; these traces are thought to be the remains of imported metal ornaments rather than objects made locally.

Of the upper three occupation levels at Tartaria, the lower two belong to the later phase of the Vinca culture and the uppermost to a still later period. The lowest level at the site belongs to the earlier Vinca phase. Vlassa and his coworkers discovered that a pit had been dug down below the lowest level, apparently during the time when that level was occupied. The pit was filled with ashes. In a small heap at its bottom the diggers found 26 clay figurines, two stone figurines, a seashell bracelet and the three inscribed tablets. Nearby were the disjointed and scorched bones of an adult human. The pit had evidently been used for a ritual, perhaps a sacrifice involving some form of cannibalism, and the tablets may owe their preservation to their having been baked in the same fire that scorched the bones and filled the pit with ashes.

The Tartaria tablets are small. Two of them are rectangular; they are respectively two inches and two and a half inches across, an inch high and a quarter of an inch thick. The third tablet is a roundel, or disk; it is two and a quarter inches in diameter and is thicker than the other tablets [*see illustration on preceding page*]. The tablets are inscribed on only one face. The roundel and the larger of the rectangles have a hole in them through which a string may have been passed; they are also incised with signs that appear to be more than simple pictographs. The third tablet seems to be exclusively pictographic; at its right side is the figure of a goat, in the middle what may be the branch of a tree or an ear of grain, and at the left another animal, perhaps a second goat.

Most of the signs on the roundel resemble symbols the early Sumerians incised in clay to record numerals or syllables. Their closest Sumerian counterparts are signs written during a period around 3000 B.C. This fact was noted by Vlassa at the time the tablets were discovered and was subsequently confirmed by the late Adam Falkenstein of the University of Heidelberg, the principal student of the written records of Uruk. Tablets that bear writing of this period, known as the Jemdet Nasr phase, have been unearthed both at the city of Uruk and at the lesser site of Jemdet Nasr itself. Among the more striking resemblances are the following.

To write the number 10 the Sumerians at that time held a round stick upright and pressed its end straight into the clay, making a circular mark. They represented two other numbers by pressing the end of the stick into the clay at an angle, making a semicircular mark: a small semicircle represented the number one, a large semicircle the number 60.



ANCIENT WORLD, from the Indus to the Danube, may have been familiar to the merchant voyagers of the Near East. In the latter half of the third millennium B.C. the Mesopotamian monarch Sargon of Akkad conquered Syria and also raided into eastern Anatolia. In

The Tartaria roundel is incised with similar circles and semicircles in two sizes, rendered in outline rather than punched into the clay.

To denote the syllables *En-Gi*, the name of a god, the Sumerians linked one sign, a long line crossed by a number of short dashes, with another, a grid with several parallel bars. A sign resembling each of the Sumerian ones appears on the Tartaria roundel, although they are incised separately rather than together. Perhaps the most striking resemblance is a candelabrum-shaped sign in the lower right quadrant of the roundel. A sign just like it is very common on the tablets from Jemdet Nasr. A number of other parallels between the Jemdet Nasr and the Tartaria signs can be noted [*see bottom illustration on page 35*].

The parallels are not limited to signs alone. For example, the Sumerians incised their tablets with horizontal and vertical lines to separate one group of signs from another. There are similar dividing lines on the Tartaria roundel and the larger rectangle. In addition, on the Sumerian tablets a single word sign or a pair of signs is regularly found within a marked-off space along with signs that represent numbers. Two of the four divisions of the Tartaria roundel contain similar combinations. Finally, the Sumerians usually wrote on rectangular tablets.

There are differences as well as parallels. Rectangular Sumerian tablets with holes in them have been found, but they are extremely rare. Moreover, although most of the Tartaria signs are comparable to Sumerian signs, and some are strikingly comparable, they are by no means always identical with them.

Some of the differences between the Tartaria tablets and early Sumerian writing are points of resemblance with respect to the early written records of Crete. The earliest known Cretan tablets, including rectangles and roundels, often have string holes [*see top illustration on page 35*]. At least four signs on the Tartaria tablets resemble signs on the tablets found in the 1900's by Sir Arthur Evans in the part of the palace at Knossos that he named the Hieroglyphic Deposit. Since then similar tablets have been found in the ruins of the palace at Phaistos in southern Crete and at Mallia, east of Knossos.

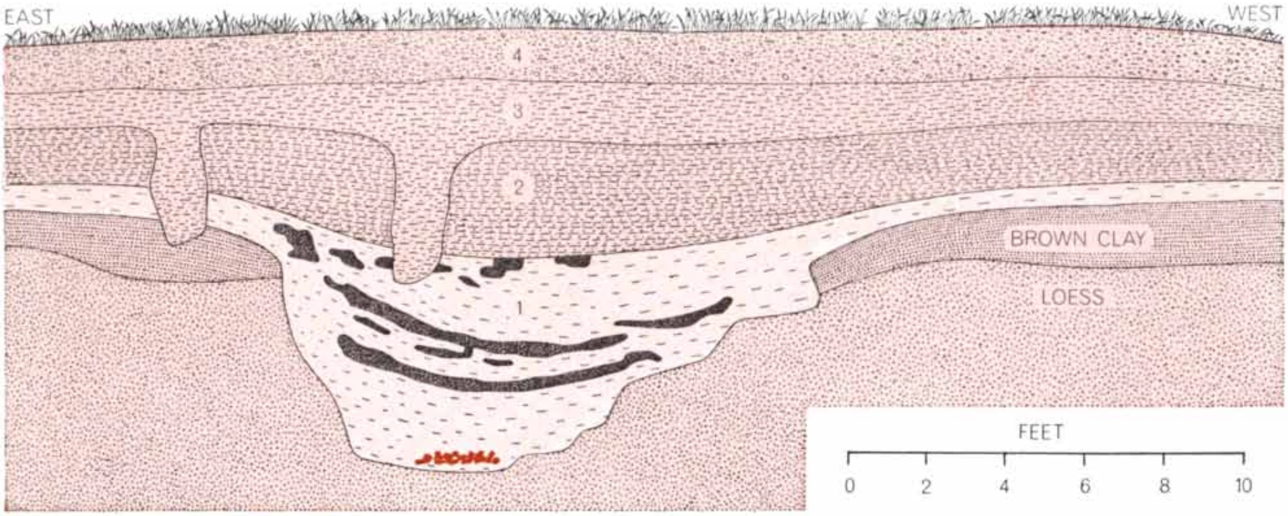
There are also differences between the Tartaria tablets and those of Crete. A few of the earliest Cretan tablets, for instance, have lines that mark off groups of signs, but the practice was evidently becoming obsolete and most tablets have no lines. Every Tartaria sign that has a Cretan equivalent also has a Sumerian one, but some signs with Sumerian equivalents have no Cretan counterparts.

his successors' day traders visited the Indus delta (*right*). The author suggests that Syrian traders may have traveled beyond Troy to the middle Danube (*left*) in even earlier times.

The Jemdet Nasr phase of Sumerian history is dated around 3000 B.C. In Crete, where the earliest evidence of writing is in the form of stone seals engraved with signs and of clay impressions made with seals, no sign-bearing seal is yet known that can be dated more than a century or so before 2000 B.C. The oldest written tablets discovered so far do not appear until later; the tablets in the Hieroglyphic Deposit at Knossos, for example, may not have been made until 1700 B.C. The early forms of Sumerian and Cretan writing may therefore have been separated in time by as much as 1,300 years. They have a minimum separation of some 900 years.

A number of carbon-14 dates from Neolithic sites in the Balkans indicate that the Vinca culture rose well before 4000 B.C. and perhaps even before 5000. This means that the Tartaria tablets could be a good deal more than 1,000 years older than their Sumerian counterparts and more than 2,000 years older than the Cretan ones. Is it possible somehow to bring these dates into line?

One way to do so is to deny that the Tartaria tablets are from the earlier phase of the Vinca culture. One might suggest that the pit where they were found had been dug down not from the lowest level of the Tartaria mound but from somewhere higher up. The pit's contents could then be given a considerably later date. But the excavation was a careful one, and Vlassa certainly got the impression that the pit had been dug down from the mound's lowest level. Vlassa's position is independently supported by the opinion of most experts that the figurines found in the pit are characteristic of the earlier phase of the



TARTARIA MOUND is seen in cross section. The three upper strata represent the later phase of the Vinca culture and a period thereafter. Two small pits had been dug down from the surface of the third level. The lowest stratum belongs to the earlier Vinca phase; here a large pit had been dug down into the underlying loess. It contained the tablets, human bones and other remains.

Vinca culture and not of the later phase, although this view is not held unanimously.

If we accept the Tartaria tablets as being from an authentically early period, what other ways are there to explain the puzzle? One would be to deny that the tablets had any real connection with early Sumerian writing, but the resemblances are so strong that such an argument is difficult to accept. Another way would be to challenge the validity of the carbon-14 dates obtained from Neolithic sites in the Balkans. This does not, of course, mean doubting the scientific principles of carbon-14 dating. The many carbon-14 dates for Neolithic cultures in central and eastern Europe are reasonably consistent and also in good agreement with the sequence of relative chronology suggested independently by archaeological correlations. There may nonetheless be room for thinking that the entire sequence of carbon-14 dates obtained for Neolithic Europe north of the Mediterranean is both too early and too long.

It has been suggested that carbon-14 dates may vary slightly in relation to latitude. Perhaps the variations due to latitude were greater in the Neolithic period than is now supposed. Perhaps factors of climate, or other factors that are not yet understood, have drastically influenced the carbon-14 dates for certain areas during early periods. Whatever the truth of the matter, once it is agreed that the Tartaria tablets' connection with Sumerian writing is authentic, and that they were written during the earlier phase of the Vinca culture, I find one conclusion inescapable. This is that the Vinca culture must have arisen some 1,500 years later than its carbon-14 dates suggest, that is, later than 3000 B.C.

One way to escape even this conclusion is to propose that the art of writing originated in the Balkans. But the origin of writing in Sumer can be traced with considerable precision from pictographic beginnings just before the Jemdet Nasr phase through the comparatively advanced writing of Jemdet Nasr—part ideographic and part phonetic—to the cuneiform of later Sumerian times. In contrast, the Tartaria tablets are a unique phenomenon in Balkan prehistory. They appear for an instant in time, boldly outlined against a barbaric background, and are succeeded by long ages of continuing barbarism that harbor no further suggestion of an acquaintance with writing. It seems impossible that the Balkan Neolithic was the milieu in which man first achieved literacy.

Let us assume, then, that the carbon-14 record is sufficiently wrong to allow setting the date of the Tartaria tablets at some time after 3000 B.C. It still remains to be shown how Sumerian writing of that period could have reached the wilds of eastern Europe. To consider the journey one step at a time, one can start by seeking an explanation for the similarity between Sumerian writing and the early archival writing of Crete.

Syria and Lebanon are clearly potential intermediaries between Sumer and Crete. At Byblos, Lebanon's ancient seaport, the large clay jars that were used for burials in the period that precedes the Jemdet Nasr phase in Sumer are stamped with groups of signs. The signs have been interpreted as a rudimentary form of writing at the pictographic stage, the same stage that had then been reached by the Sumerians. If the signs stamped on the Byblos jars represent writing, it is plausible to suppose that the idea had come from Mesopotamia.

No formal writing of the kind indicated by collections of tablets is known in Syria before about 2000 B.C. Long before that, however, Syrians scratched marks on their pottery, apparently so that the owners could tell which pots were theirs. The practice is first evident in Syria at the time of the Jemdet Nasr phase in Sumer, when writing had become comparatively advanced. The Syrian owners' marks are not true writing, but they may reflect some acquaintance with the art. Certainly Syria and Mesopotamia had close relations during this period: cylinder seals of the Jemdet Nasr type, as well as the impressions made by them, are found in Syrian sites. It is conceivable that, in addition to owners' marks, Syrians at this time had a system of writing inspired by the Sumerian example and using many of the same signs.

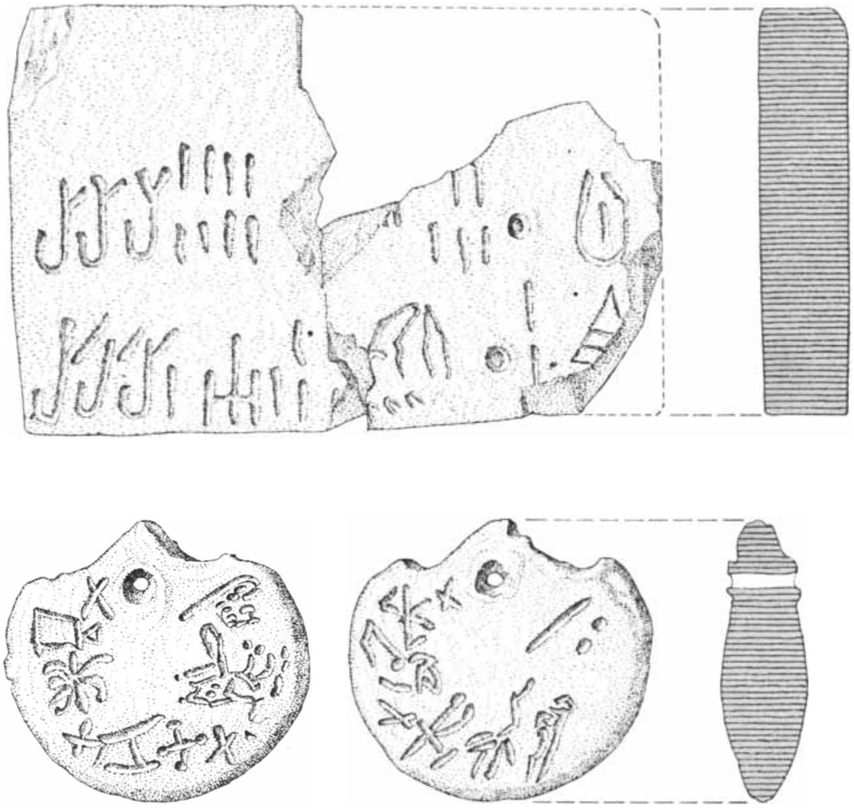
The Jemdet Nasr phase was the last in which the Sumerians wrote on their tablets by scratching signs in the soft clay. In the Early Dynastic period that followed all tablets are written in cuneiform, a system that uses a special, wedge-shaped implement to mark the clay. If, as I suggest, a system of writing in the Jemdet Nasr style was then known in Syria, it could have continued in use there for some time after cuneiform was adopted in Mesopotamia. Such a development could have enabled Syria to transmit a system of writing with incised signs to Crete even a long time after incised writing had vanished from its original home. Such a hypothesis helps to solve one of our dating difficulties; it means that neither the early writing of Crete nor the Tartaria tablets need to be contemporaneous with the Jemdet Nasr phase in Mesopotamia.

Looking at the other end of the line for connections that would tie the Balkans to the Mediterranean, we readily find a geographic one. Only a short distance from Vinca down the Danube the main stream is joined by the north-flowing Morava River. Traveling southward along the valley of the Morava one crosses easily into the valley of the south-flowing Vardar River and can follow that route to the shores of the Aegean Sea. Exotic elements in the Vinca culture reflect this propinquity. It has even been suggested that the Vinca people, or at least some of them, came to the Danube from Macedonia and before that from Asia Minor beyond the Dardanelles. This is open to question, but in some respects the Vinca culture certainly resembles a simplified and barbarized form of Macedonian culture, which in turn is a simplified version of the early cultures of Troy in Asia Minor.

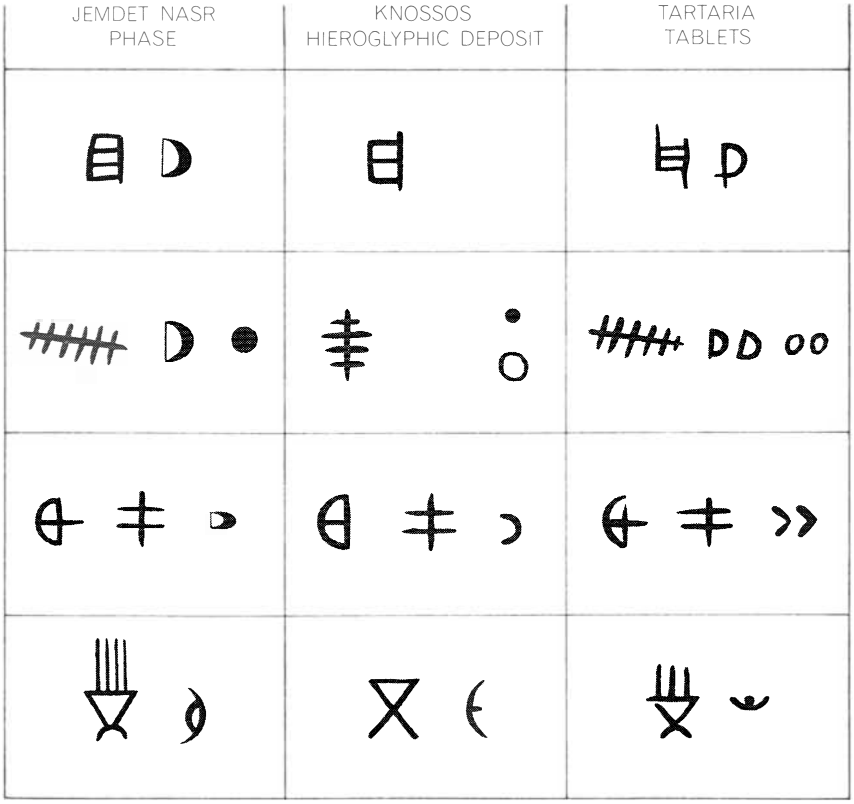
Many of the vases made by Vinca potters have shapes that are basically akin to Trojan ones. Pots with dark, polished surfaces, often decorated with incisions filled with a white paste, are common both in the first settlement at Troy and in the earlier phase of the Vinca culture. Vinca wares also show affinities with later pottery at Troy. In particular, pot lids strikingly decorated with representations of the human face are found in the lowest level and above at Vinca. They are not unlike the face-decorated pot lids found at Troy in the second settlement (Troy II) and later.

Even more compelling evidence of influences from Asia Minor in the Vinca culture is found in the numerous signs the Vinca people scratched on their pots, presumably as owners' marks. There are comparable marks—in many cases identical ones—on Trojan pots and spindle whorls dating from the period of Troy II and later. During this period similar marks appear in other parts of western Asia Minor, scratched or painted on pots. Within the area of the Vinca culture, owners' marks are particularly abundant at Tordos; the signs were usually incised on the bottom of a pot or low on the side before firing. Most Tordos pots that carry such marks have only one, but some have two or more.

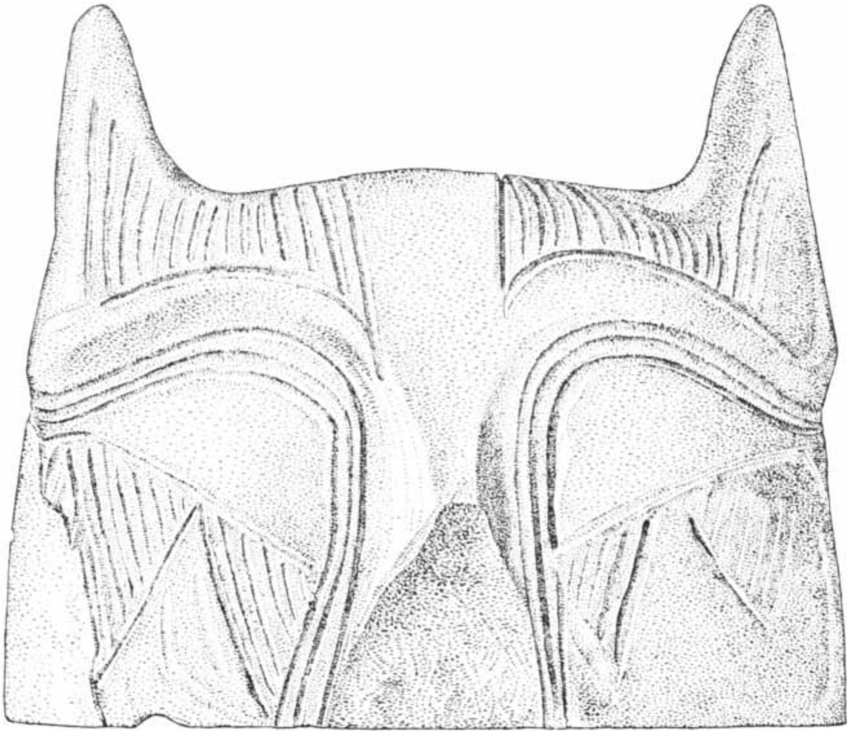
Several of the marks used by both Trojan and Vinca potters are identical with signs that appear in the earliest Sumerian writing. Because the signs are



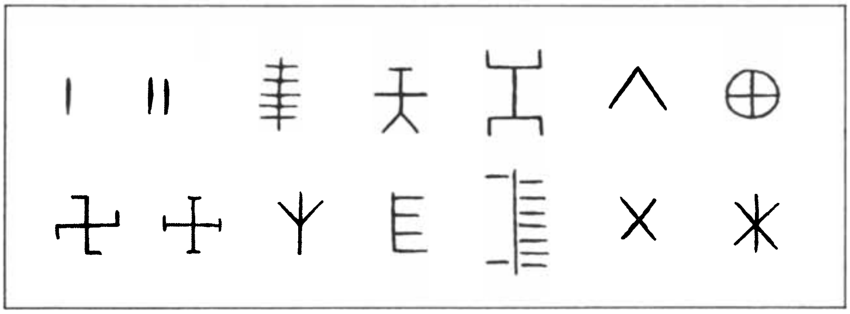
CRETAN WRITING that appears on the tablets found in the ruins at Knossos includes a few signs that resemble inscriptions on the Tartaria tablets. Other points of resemblance include tablets rectangular in shape (*top*), circular in shape (*bottom*) and with string holes.



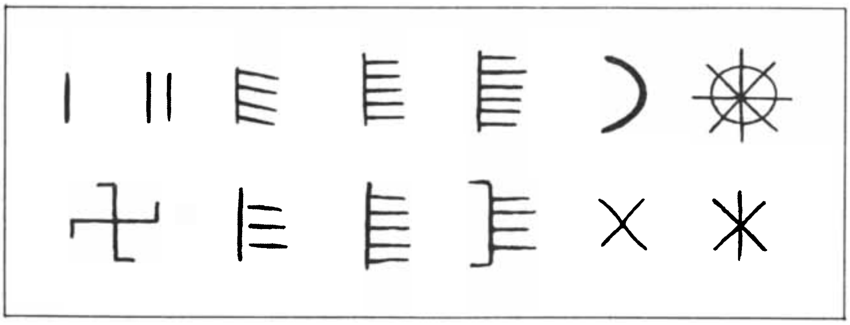
PARALLELS are apparent between the signs used in Sumerian writing of about 3000 B.C. (*left*), those of Cretan writing 1,000 years later (*center*) and the marks incised on the Tartaria tablets (*right*). Here only the Tartaria inscriptions are shown at a common scale.



DECORATED POT LID from the lower levels of the Vinca mound, a Neolithic village site in Yugoslavia, shows a representation of a human face, a motif evidently derived from Asia.



OWNERS' MARKS were placed on the sides or bottoms of pots by the potters of the Vinca culture. Pottery marked in this fashion is particularly abundant in the Tordos mound, a Neolithic site in the Transylvanian region of Romania only a few miles from Tartaria.



SIMILAR MARKS appear on the pottery and the spindle whorls unearthed from the second settlement and later levels at Troy, as well as elsewhere in western Asia Minor. The ones illustrated here are all from Troy II finds. Some are identical both with owners' marks of the Vinca culture and with signs that appear in early Sumerian writing. The author suggests that Trojan and Vincan marks, like the Tartaria ones, were brought from the Near East. This would mean that the Vinca culture is much younger than has generally been supposed.

simple ones, this coincidence has usually been explained away as an example of independent invention. In the light of the Tartaria discovery another interpretation suggests itself. Might not some of the signs, if not most of them, have been copied from the early writing of the Near East?

The traits that Troy and Vinca have in common imply that the Vinca culture could not have arisen much before the time of Troy II. Carbon-14 analysis of material from sites in western Asia Minor places Troy II some centuries after 2600 B.C., but the carbon-14 dates are not for Troy itself or for sites in the city's immediate neighborhood. On the basis of other criteria dates have been proposed for Troy II that range from 2600 to 2100 B.C. If one accepts a date of 2300 to 2200 B.C. for the start of Troy II, the Tartaria tablets need not have been made until as late as the turn of the second millennium B.C. Such a date would make the tablets not much older than the comparable tablets in Crete.

It is not hard to imagine how Trojan owners' marks could have reached the potters of Tordos. But how were the Trojan potters able to borrow the signs from Mesopotamia in the first place? Again Syria seems a probable intermediary. The people of Troy II evidently had many contacts with Cilicia, the southeastern coastal region of Asia Minor that borders Syria on the west. Cilician vase shapes were copied at Troy, and the "fast" potter's wheel, which was first used at Troy early in the Troy II period, may have been an import from Cilicia. The arrival of Mesopotamian influences in the Balkans by way of Syria, Cilicia and Troy is therefore far from impossible. Syrian and Cilician merchants may actually have had direct commercial contacts with the Balkans as early as the time of Troy II. When copper and bronze tools, weapons and ornaments came into general use in the Balkans, they were largely Syrian (ultimately Mesopotamian) types. The reader will recall that copper tools were present during the later phase of the Vinca culture and that traces of imported copper also appear in earlier Vinca strata.

What could have drawn Near Eastern goods, and perhaps Near Eastern traders as well, to the Balkans? It may have been mineral riches. The treasures of gold and silver unearthed from the ruins of Troy II attest to the city's wealth. Much of the Trojan jewelry is comparable in design and craftsmanship to Syrian and Mesopotamian work; some of it resembles the jewelry found in the royal tombs of Ur in Mesopotamia. Whence came the gold for these Trojan treasures? Perhaps from western Asia Minor, where the "golden Pactolus" runs to the sea. Some, however, may have reached Troy from gold-rich Transylvania.

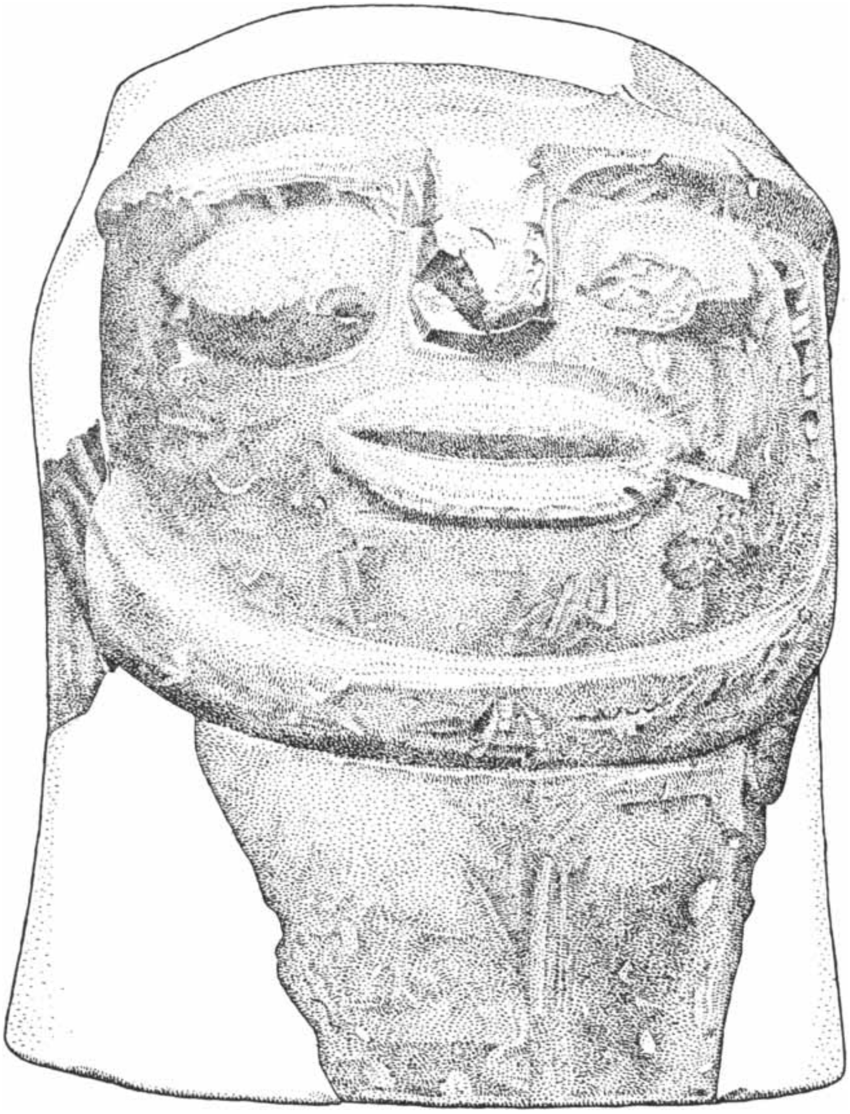
Gold is not the only metal that could have enticed merchants to the middle Danube and beyond. Deposits of cinnabar, the ore that yields mercury, are found near Vinca. Tin, important in bronze metallurgy, can be had in the Erz Mountains to the northwest in what is now Czechoslovakia. The journey from the Aegean to Vinca by way of the Vardar valley is not a difficult one. Traders from the south could also have sailed through the Dardanelles into the Black Sea and entered the Danube at its mouth. Still a third route is along the valley of the Maritsa River, through present-day Bulgaria.

Near Eastern merchants traveled great distances in those days, as is shown by the records of the dynasty founded by Sargon of Akkad soon after 2400 B.C. Sargon himself conquered Syria and appears to have campaigned far into eastern Asia Minor. In the opposite direction Akkadian merchants sailed the length of the Persian Gulf and beyond to trade with the remote civilization of the Indus valley. Romania is no farther, as the crow flies, from Mesopotamia than the Indus is. Even the distances of the two voyages—to Vinca from some port in Syria by way of the Danube, and to the Indus from the head of the Persian Gulf—are roughly comparable. In my opinion it is within the context of some such trade contact that the Tartaria tablets and their analogies with the early writing of Sumer and Crete can best be explained.

The ritual setting in which the Tartaria tablets were found provides a second possible context. It is just barely conceivable that magicians or priests of the Vinca culture were familiar with the art of writing, but even such familiarity is not necessary to the hypothesis. The culture's relatively elaborate ritual equipment seems to be of Near Eastern derivation. The furnishings include little three- and four-footed clay altars and an abundance of figurines such as the ones found at Tartaria. Both the altars and the figurines have analogies in the Aegean world to the south. A large ritual jar from an early level at Vinca is incised with a design that seems to represent the façade of a shrine; it is comparable to the shrine façades depicted on Sumerian seals of the Jemdet Nasr period and later. One can imagine archaic Sumerian writing as a part of some religious complex that eventually reached the Balkans from the Near East.

There is even a kind of backward precedent for such an event. Twice in later history systems of writing reached this part of Europe in the train of an imported religion. The first time, in the fourth century A.D., a Gothic bishop, Ulfilas, invented an alphabet so that his barbarous tribesmen could read the Bible in their own language. The second time, in the ninth century A.D., two Greek missionaries, Cyril and Methodius, invented the alphabet that won the Slavs of Moravia and Bohemia to Christianity. It is not impossible that missionaries of an even older religion carried the first example of writing to the Balkans thousands of years earlier.

But do the Tartaria tablets actually bear writing? Probably not. The tablets appear to be of local clay, which favors their having been made on the spot and not imported. The close resemblance of their signs to Sumerian ones, however, favors their having been copied from some other document available to the copyist on the spot. It seems quite possible that they are merely an uncomprehending imitation of more civilized peoples' written records. Certainly the language in which they are written, if it is one, is unknown. Perhaps the Tartaria tablets are nothing more than a pretense by some unlettered barbarian to command the magic embodied in an art he had witnessed but did not understand.



HUMAN FACE decorates a pot lid unearthed from the stratum at Troy that holds the remains of the city's second settlement. Other affinities between the pottery of the Vinca culture and of Troy include pots with similar shapes, polished surfaces and incised decorations.

THE HEAT PIPE

This new device can be several thousand times as effective in transporting heat as the best metals. It shows promise of being immediately useful in many areas of technology

by G. Yale Eastman

The transportation of heat plays an increasingly important role in many areas of modern technology. For example, a nuclear power station produces energy in the form of heat, which must be brought out of the core of the reactor before it can be converted into useful electric power. Similarly, almost all electrical devices, including solid-state electronic components, generate heat as a useless by-product, which must be removed from the immediate environment and disposed of in some suitable heat "sink."

It is hardly surprising, therefore, that a major research effort has been mounted to find more efficient means of moving heat from one place to another. The trouble is that metals, even though they conduct heat much better than other substances, are poor conductors of heat. Copper, for instance, is usually regarded as one of the best conductors of heat. Yet if a thermal power of 10,000 watts were applied to one end of a solid copper bar one inch in diameter and one foot long, the temperature difference along the bar could theoretically exceed 30,000 degrees Fahrenheit. That is, one end could become a vapor hotter than the sun's surface, while the other end remained at room temperature! Thus it is quite remarkable that a device just emerging from the laboratory can transfer this amount of heat with a temperature difference of only a few degrees. This new device, called the "heat pipe," can be several thousand times more effective in transporting heat than the best metallic conductors.

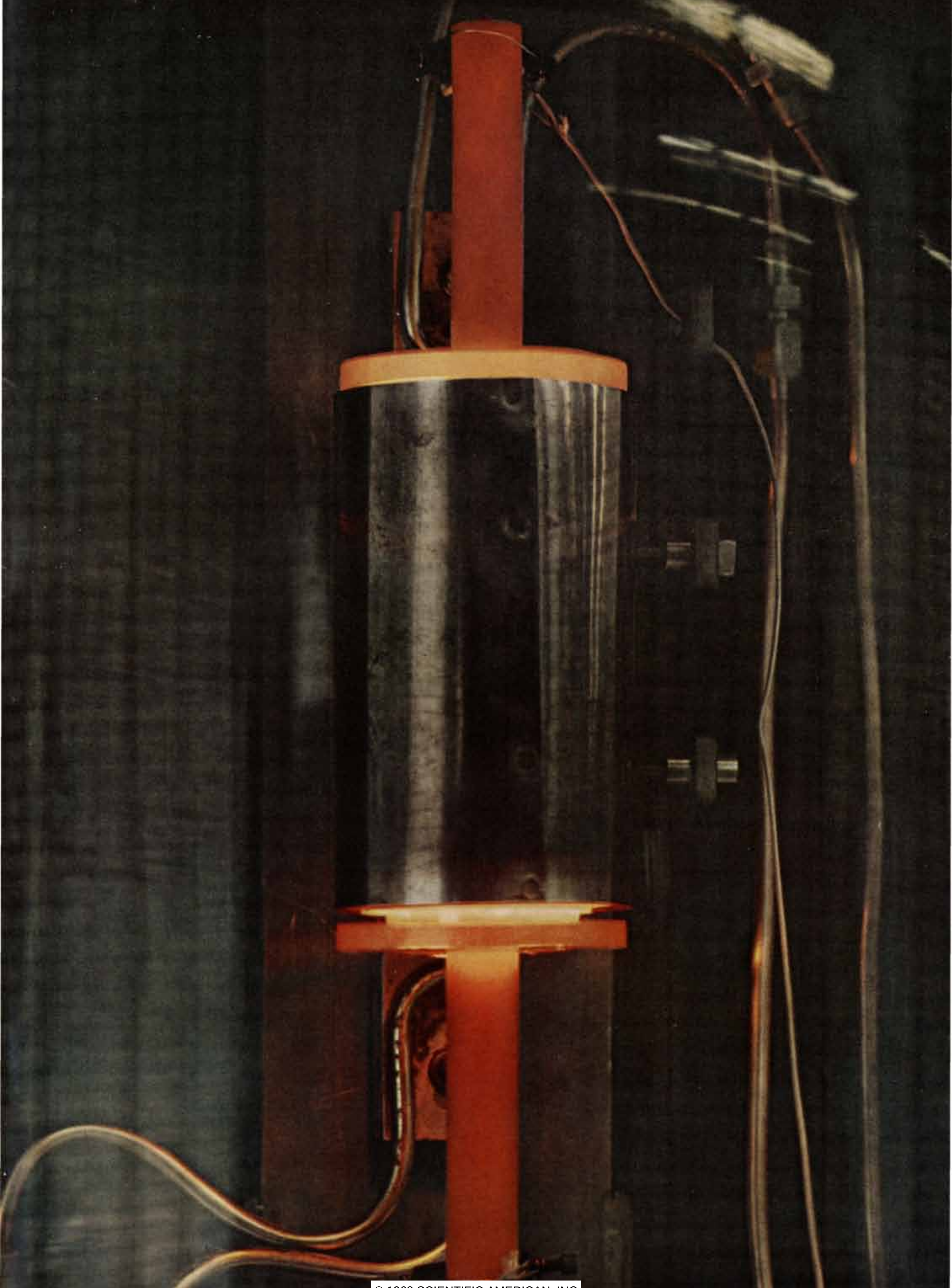
The principle of the heat pipe was first put forward in 1942 by Richard S. Gaugler of the General Motors Corporation. Gaugler's device was not effectively put into use, however, and as a result his proposal was not widely known in 1963, when George M. Grover of the Los Alamos Scientific Laboratory independently hit on a similar device and coined the name "heat pipe" to describe it. Grover and his colleagues originally developed the heat pipe for use in highly specialized power-generating systems for spacecraft. The heat pipe is one of the first such space components to show promise of immediate application in other areas. Since 1963 the development of the heat pipe for a wide range of industrial applications has been taken up by a number of research groups, including our own at the Radio Corporation of America.

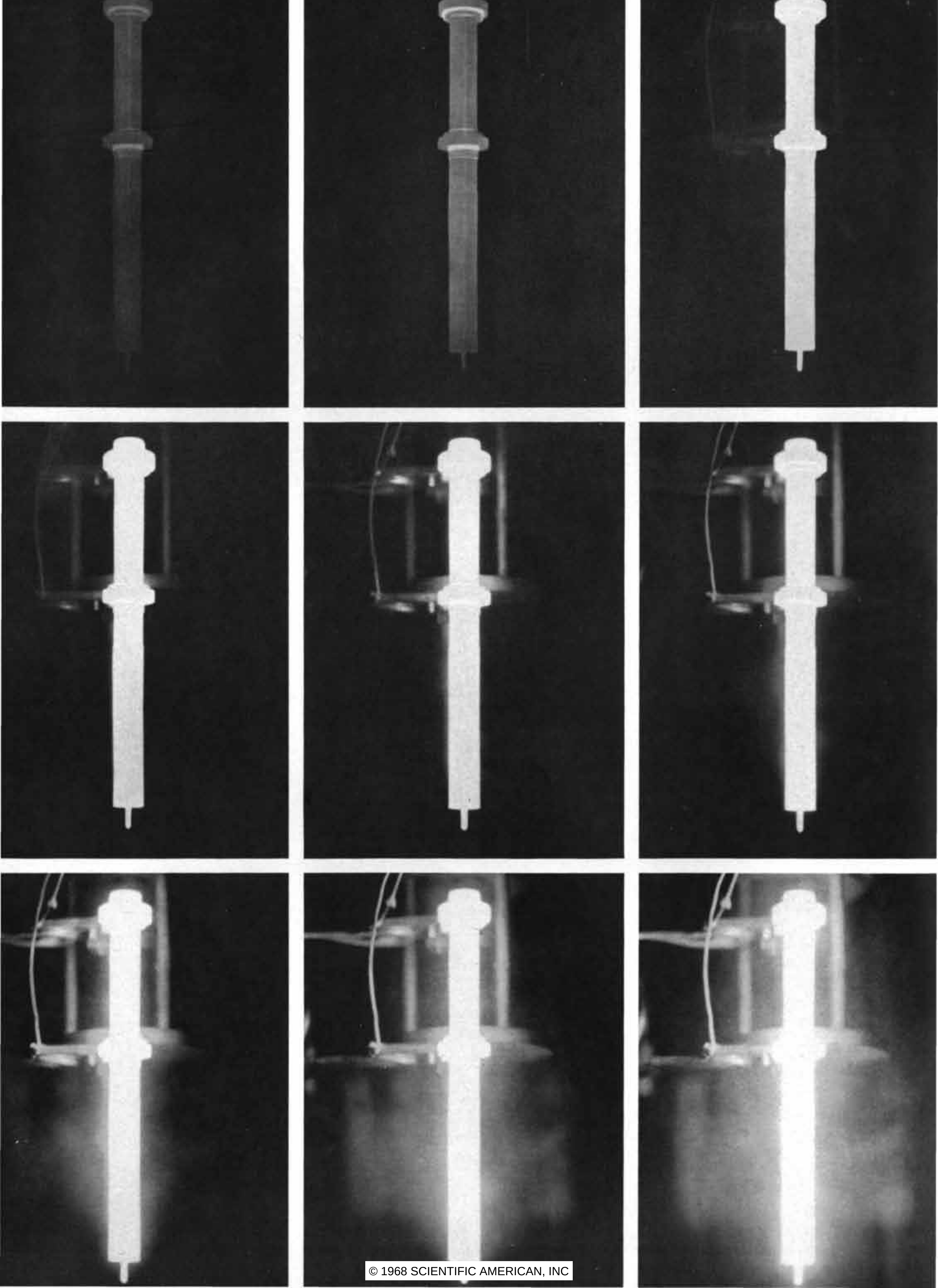
The heat pipe is essentially a closed, evacuated chamber whose inside walls are lined with a capillary structure, or wick, that is saturated with a volatile fluid [*see top illustration on page 42*]. The operation of a heat pipe combines two familiar principles of physics: vapor heat transfer and capillary action. Vapor heat transfer is responsible for transporting the heat energy from the evaporator section at one end of the pipe to the condenser section at the other end. This principle is of course the same as that used in conventional steam-heating systems. What distinguishes the heat pipe from such systems is that in the heat pipe capillary action is responsible for returning the condensed working fluid back to the evaporator section to complete the cycle. (Capillary action is the process by which moisture rises in a bath towel when one end is dipped in water.)

The function of the working fluid within the heat pipe is to absorb the heat energy received at the evaporator section, transport it through the pipe and release this energy at the condenser end. It is this process that is called vapor heat transfer. When a liquid vaporizes, two things happen. First, a large quantity of heat is absorbed from the heated area. This change takes place because energy is needed to separate molecules that are in contact in the liquid state. The quantity of energy required to evaporate a unit mass of liquid at a given temperature is called the latent heat of vaporization.

Second, as the working fluid vaporizes, the pressure at the evaporator end of the pipe increases. The pressure is caused by the thermal excitation of the molecules comprising the newly created vapor. The vapor pressure sets up a pressure difference between the ends of the pipe, and this pressure difference causes the vapor, and thus the heat energy, to move toward the condenser section. When the vapor arrives at the condenser section, it encounters a temperature lower than that of the evaporator. As a consequence the vapor turns back to a liquid and thereby releases the thermal energy stored in its heat of vaporization.

EFFECT OF GRAVITY on the operation of a heat pipe is shown to be negligible in this demonstration in which the heat pipe is being heated in its middle by an electric coil inside the metal sleeve at center. The uniform orange color of the heat pipe indicates that heat is being transferred equally upward and downward by the flow of vapor through the core of the pipe. Heat is being removed by radiation from the surface of the pipe, accompanied by condensation of the vapor inside the pipe. The cycle is completed by the return flow of liquid through the capillary structure, or wick, that lines the inside surface of the pipe. The heat pipe here was developed for the Air Force by the Radio Corporation of America.





In addition, as the fluid condenses, the vapor pressure created by the molecules decreases, so that the necessary pressure difference for continual vapor heat flow is maintained.

It is important to note that the vaporized fluid stores heat energy at the temperature at which the vapor was created, and that it will retain the energy at that temperature until it meets a colder surface. The result is that the temperature along the entire length of the heat pipe tends to remain constant. It is this tendency to resist any difference in temperature within the heat pipe that is responsible for the device's high thermal conductance.

One of the requirements of any self-contained vapor heat-transfer system is a means of returning the condensed liquid to the evaporator to replenish the supply. In older systems this return was accomplished either by gravity or by a pump. Each of these methods has disadvantages. The use of gravity requires that the boiler always be located below the condenser, and this arrangement is not always convenient. A separate pump eliminates the gravity restriction, but it requires outside energy for its operation. Such a system depends on a second source of energy, with the attendant complexity of control and reduced reliability.

The heat pipe, on the other hand, can operate against gravity and without a second external energy source. Movement of the working fluid is accomplished by capillary action within the wick that connects the condenser to the evaporator. The driving force that causes the liquid to move through a capillary is the surface tension of the liquid. Surface tension results from the forces of attraction between the molecules of the liquid. In any liquid each molecule is surrounded by other molecules, so that the pull between adjacent molecules in one direction is balanced by an equal pull of the molecules in the other direction. The net result is that no motion occurs. At the surface, however, there is no pull from outside to balance the pull from inside the liquid. Accordingly there is a net force that tends to pull the surface molecules inward and create a shape with a minimum surface area. This tendency explains why droplets and bubbles tend to be spherical.

When a fluid is placed in a vessel composed of a material that the fluid "wets" well, there is an attractive force between the fluid and the wall of the vessel. The force combines with the surface tension in such a way as to move the liquid surface toward the unfilled portion of the vessel [*see bottom illustration on page 43*]. If the vessel is a capillary of small diameter (or any wick material with small continuous pores), this force, called capillary attraction, can be large compared with the mass of fluid in the capillary. Rapid motion of the fluid then results.

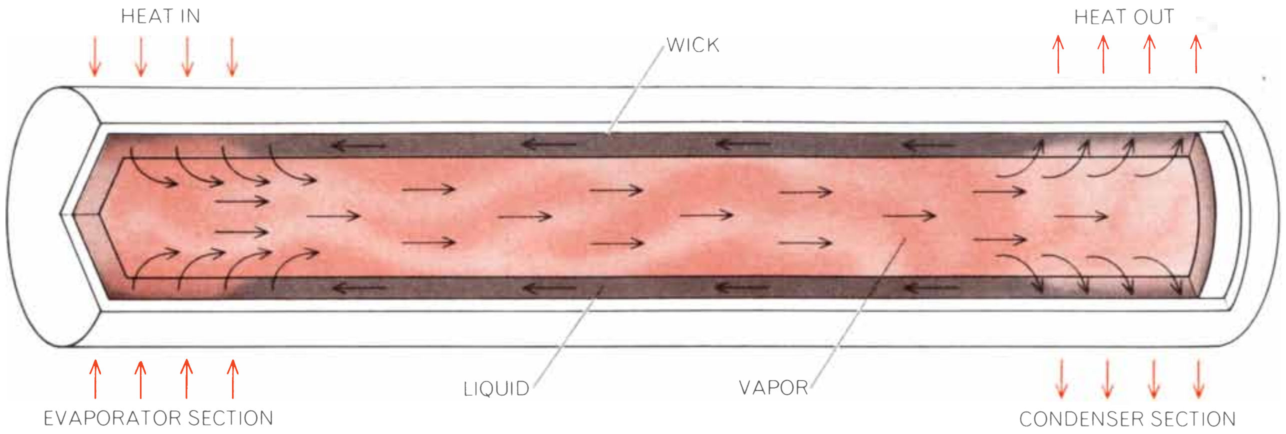
Thus the capillary provides a structure in which the liquid pumps itself along. This process will continue indefinitely in the absence of other forces, as in gravity-free space. If the motion is upward against a force such as gravity, a limit will be reached when the weight of the fluid column being lifted is equal to the lifting force. A high-performance heat-pipe fluid has a high latent heat of vaporization, a high surface tension and a low density. Low viscosity is also a desirable property to minimize "drag" as the liquid moves along through the wick. The heat pipe derives its unique properties, therefore, from the combination of vapor heat transfer and capillary pumping.

There are five properties of the heat pipe that deserve special mention because they serve to define the areas in which practical applications are to be found for the device. First, devices that operate on the principle of vapor heat transfer can have several thousand times the heat-transfer capacity of the best metallic conductors, such as silver and copper. In one case a thermal power of 11,000 watts has been carried 27 inches by a one-inch heat pipe with a temperature loss so small that it was difficult to measure accurately. By way of comparison, a copper block nine feet in diameter and weighing about 40 tons would be required to produce the same result.

A second property of the heat pipe is called "temperature flattening." There are many heat-transfer applications in which a uniform temperature over a large surface area is required. Without the heat pipe special care must be taken to ensure a uniform temperature of the heat source. A heat pipe, however, can be coupled to a nonuniform heat source to produce a uniform temperature at the output, regardless of the point-to-point variations of the heat source. This statement is true because evaporation and condensation of the working fluid take place at essentially the same temperature. Variations in source temperature affect only the rate of evaporation; an increase in the temperature of the heat source at a given point on the surface of the evaporator causes an increase in the rate of evaporation at that point without affecting the temperature of evaporation. Condensation of the working fluid at the heat-delivery zone takes place at the temperature at which the fluid was evaporated, regardless of the pattern of the heat input. In fact, the entire surface of the heat pipe is held constant within very narrow limits. The heat pipe is therefore an isothermal device for most practical engineering purposes. A demonstration of this property in conjunction with a nonuniform heat source is given when a flame is used to supply thermal power to a heat pipe. Although a flame is one of the most nonuniform of all heat sources, the heat pipe still delivers thermal power with a high degree of uniformity.

Third, the evaporation and condensation functions of a heat pipe are essentially independent operations connected only by the streams of vapor and liquid in the pipe. The patterns and area of evaporation and condensation are independent. Thus the process occurring at one end of the pipe can take place uniformly or nonuniformly, over a large or a small surface area, without significantly influencing what is going on at the other end. This separation of functions leads to one of the most valuable properties of the heat pipe: its ability to concentrate or disperse heat. This property has been called "heat-flux transformation." If thermal power is introduced to the heat pipe at a slow rate over a large surface area, the same total amount of working fluid can be evaporated as when the power is introduced at a high rate over a small surface area. Similarly, vapor can be condensed rapidly over a small area or slowly over a large area. It is the ratio of the surface area of the evaporator to the area of the condenser that determines whether heat energy is concentrated or dispersed at a constant temperature. In that way the thermal power available per unit of heat-transfer

TEMPERATURE UNIFORMITY is maintained over the entire surface of a heat pipe for a wide range of temperatures. In this demonstration a heat pipe is shown being heated through a range of temperatures from 1,700 degrees Fahrenheit (*top left*) to 2,800 degrees F. (*bottom right*) by means of a pair of electrodes fastened to the top and middle of the pipe. The uniform intensity of the light emitted from the incandescent surface of the pipe at each stage indicates the underlying uniformity of temperature. The containment vessel of this Air Force heat pipe was made of a molybdenum alloy; the working fluid was lithium.

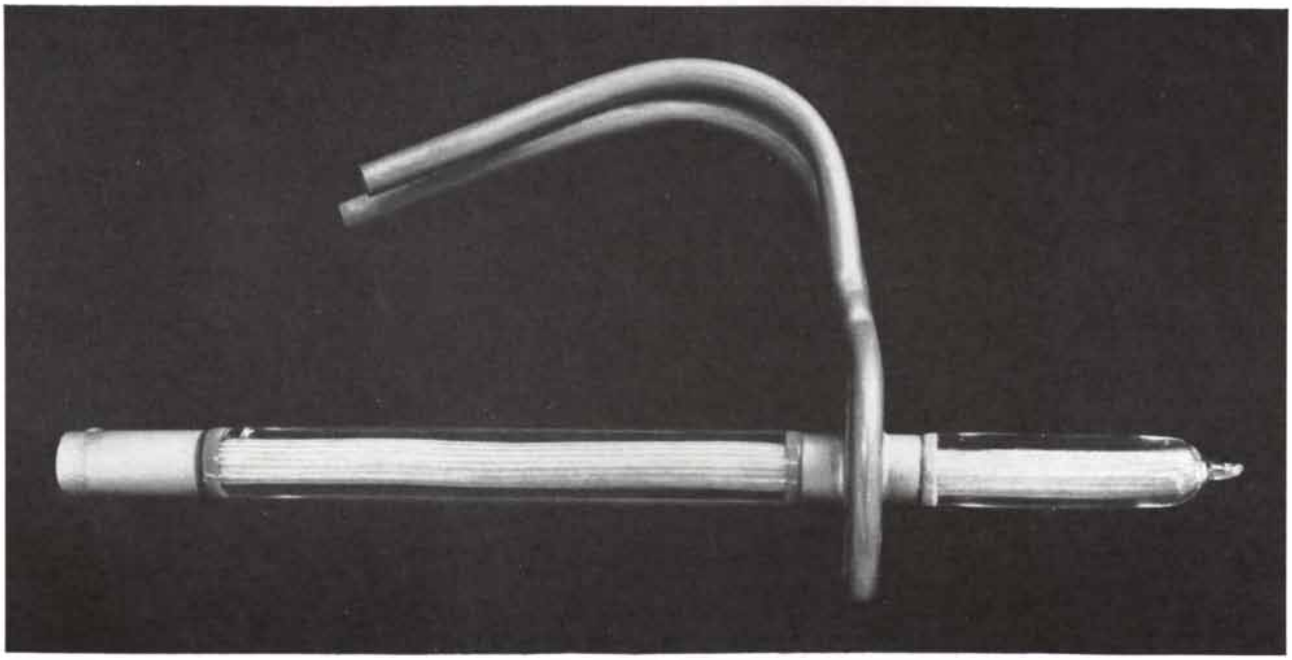


CUTAWAY DRAWING of a typical cylindrical heat pipe shows the circulatory system on which the operation of the device is based. The input of heat to one end of the pipe causes the working fluid to evaporate from the wick and also increases the vapor pressure at that end. As a result the vapor moves down the core of the pipe, carrying heat energy toward the output end. When heat is removed from the pipe, the vapor condenses and goes back into the wick. The condensate returns to the input end by capillary action. Because the fluid boils and condenses at roughly the same temperature, the temperature along the pipe tends to be uniform.

area can be either increased or decreased. This property of the heat pipe makes it possible to match sources and users of heat that were formerly incompatible because of their differing natural heat-transfer rates.

Two examples from the space-power field illustrate the use of this heat-flux-transformation property. Radioactive isotopes that could not be used previously because of their low power output are now being considered as heat sources for space-power systems. Concentration of the heat by means of the heat pipe will make their use possible. As an example of the reverse process, electronic devices such as transmitting tubes and transistors generate heat at a high power density. In space, where all heat must be dissipated by radiation, this high power density far exceeds the capability of the best radiators. The concentrated heat can be effectively radiated only when spread over a large area. In order to accomplish such radiation by conventional means heat must be conducted over considerable distances with attendant temperature losses. The lower temperature requires a correspondingly larger radiator. The result can be a bulky and heavy structure. The heat pipe, however, can spread this high thermal power density, transforming it to a lower power density with a negligible temperature drop, and subsequently deliver the thermal power uniformly over the radiating surface. The fact that the heat pipe is hollow also makes it light in weight [*see illustration on page 44*].

The heat pipe can also be used to overcome present industrial problems.



ELECTRICALLY INSULATING MATERIALS were used exclusively in the construction of this heat pipe, designed to remove large quantities of heat from high-voltage electrical circuits. The containment vessel is made of glass, the wick of fiber glass, and the working fluid is a fluoridated hydrocarbon. The two tubes extending from the pipe are employed to measure thermal conductance.

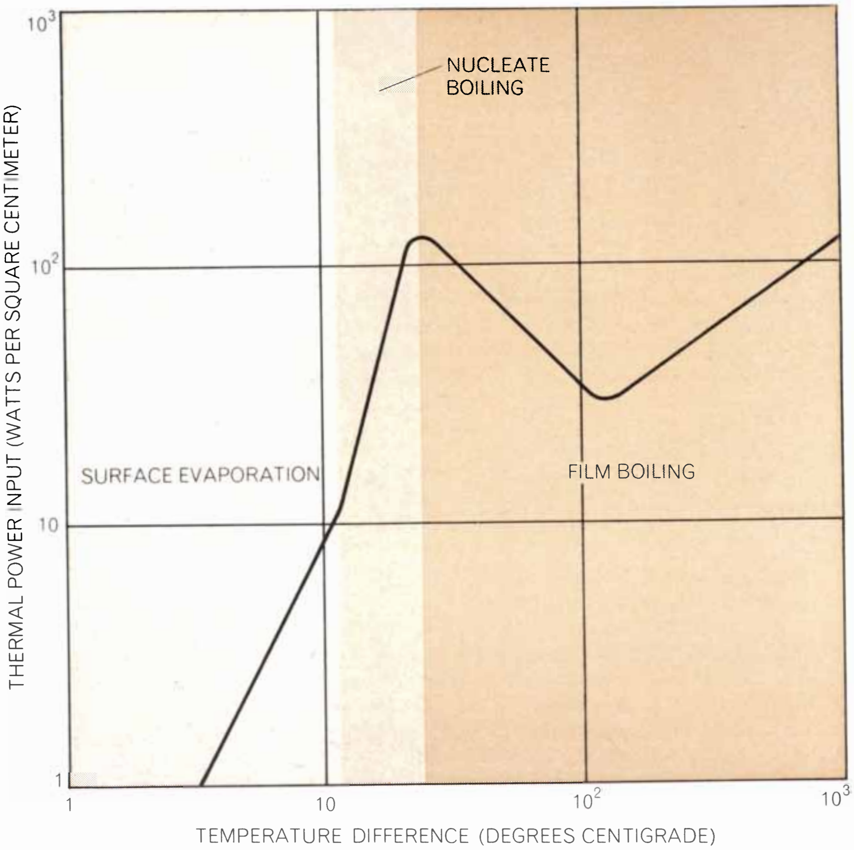
The heat developed at the anode of a radio transmitter tube, for example, is too concentrated to be dissipated readily by the use of conventional air-cooling fans. Cooling usually requires a high-pressure, high-power blower that becomes excessively noisy. A heat pipe can accept the high power from the tube, move it a considerable distance with a negligible temperature drop and spread it over a larger area, where it can be removed quietly by a low-pressure, low-power blower.

A fourth property of the heat pipe is that it makes it possible to separate the heat source from the heat sink. It is often inconvenient or undesirable to have the heat source and the consumer of heat in close contact. In the example given above, it is generally inconvenient to locate all the electronic components of a spacecraft at the radiator in order to maximize temperature loss. In another instance it may be desired to transport heat from a nuclear reactor some distance through a radiation shield, without a drop in temperature, to the point of use, where the nuclear effects of the reactor environment can be made less troublesome. The heat pipe can carry out this function.

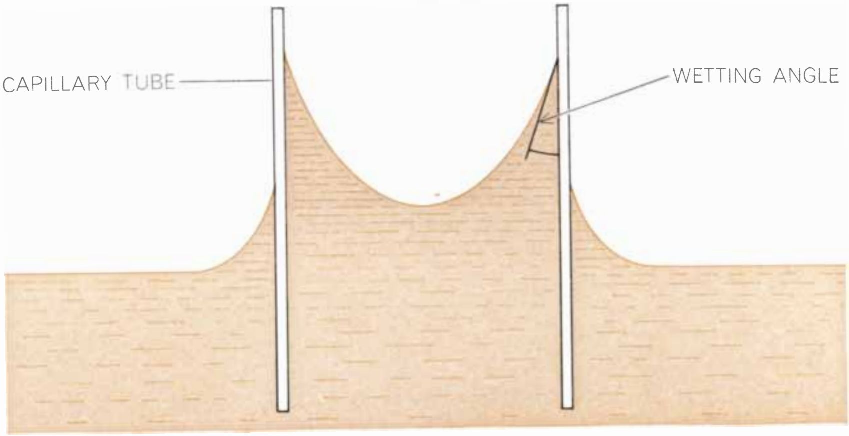
Fifth, the heat pipe can also be operated so that the thermal power and/or the temperature at which the power is delivered to the intended heat sink can be held constant in spite of large variations in the power input to the heat pipe. The surplus power beyond the needs of the heat sink is dissipated by means of an excess-power radiator. Temperature variations of less than 1 percent have been achieved with changes in input power of a factor of 10.

A notable feature of the heat pipe related to this last property is that once the heat pipe has been set for operation at a particular operating temperature no further external control is required. As a result there are no control mechanisms to fail or drift off calibration. The combination of temperature stability and self-containment can be used in conjunction with a nonuniform heat source for accurate control of the temperature of a chemical solution, a piezoelectric crystal, a heat-treating furnace or a radioactive isotope.

Although the heat pipe is a remarkably versatile device, it must operate within certain design limitations. Operation of the heat pipe is governed by four limiting factors: (1) the maximum total power that can be transferred in a device of a given size, (2) the maximum



THREE STAGES OF VAPORIZATION are apparent on this graph, which shows the temperature difference between the outside surface of a container and the surface of a pool of liquid boiling inside the container as a function of the input power density. In the first stage (surface evaporation) the input heat is just enough to cause evaporation of the liquid at its surface. In the second stage (nucleate boiling) vapor bubbles form within the body of the fluid and rise to the surface. (There is strong evidence that nucleate boiling does not take place in a heat pipe.) In the third stage (film boiling) the individual bubbles tend to form a film that covers all or large portions of the surface. (The initial downward part of the curve corresponds to partial film boiling.) The onset of the film-boiling stage represents a critical input power density that cannot be exceeded without damaging the container.



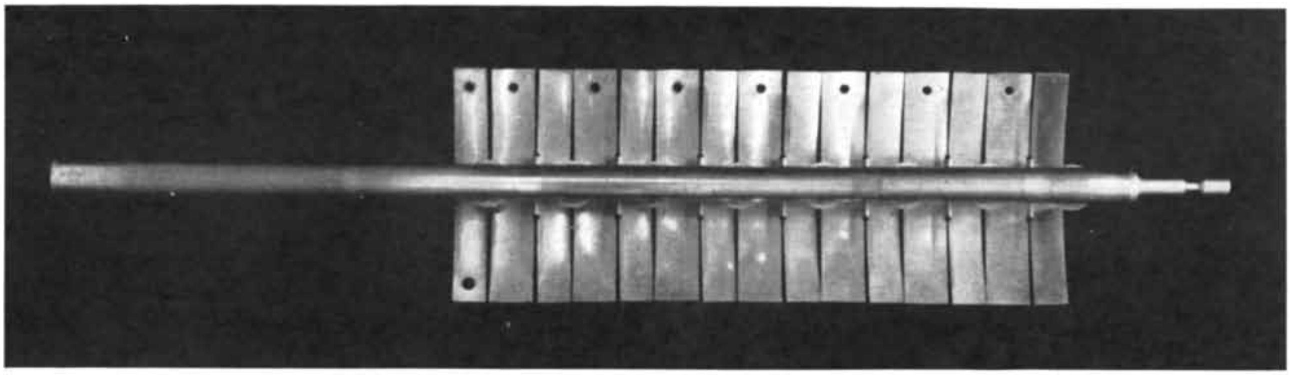
CAPILLARY ACTION within the wick that lines the inside surface of a heat pipe provides the means for returning the condensed liquid to the evaporator section in order to replenish the supply of vapor. An attractive force between the liquid and the wall of the capillary tube combines with the surface tension of the liquid to move the liquid surface toward the unfilled portion of the tube. The driving force is determined by the "wetting angle" of the liquid and the pore size of the capillary. In the absence of other forces the liquid will pump itself along indefinitely. In the presence of a force such as gravity a limit will be reached when the weight of the fluid column being lifted is equal to the lifting force.

HEAT RADIATOR FOR SPACECRAFT incorporates 100 stainless-steel heat pipes (*horizontal tubes*) in which the working fluid is sodium. The heat pipes are designed to remove heat from the condenser section of a potassium-filled "loop" (*flattened vertical tube*), which in turn passes through the nuclear reactor and turbine used to power the spacecraft. The advantages of using heat pipes to dissipate unwanted heat in space include light weight, gravity-free operation and efficient dispersion of heat over a large radiating surface. This particular radiator is designed to dissipate 50,000 watts of heat energy at an operating temperature of 1,420 degrees F. The entire assembly measures 23 inches by 43 inches and weighs only 17 pounds. The device was developed for the Air Force by RCA; one of the horizontal heat pipes was used for the demonstration shown in the color photograph on page 39.

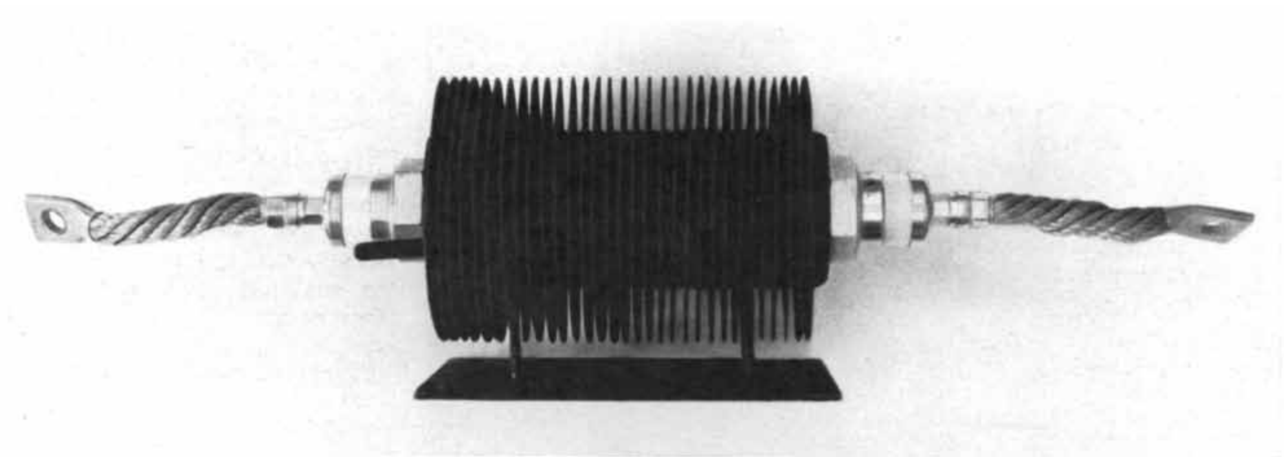
power per unit of evaporator area that can be handled safely, (3) the maximum and minimum useful temperature for a given working fluid, (4) the extent of operation in a gravitational field or other acceleration. Let us consider these four limiting factors separately.

The upper limit to the power-handling capacity of a given heat pipe is determined by the ultimate pumping capacity of the wick. If the heat pipe is operated above this limit, the evaporator does not receive enough working fluid to absorb the incoming heat energy from the source. Consequently the temperature of the evaporator section rises rapidly and undesirably. The ultimate pumping capacity of the wick is determined by the size and geometry of the wick, as well as by the properties of the fluid, for example its heat of vaporization, surface tension, liquid density and viscosity. This limiting value, however, is usually quite high.

In ordinary "pool" boiling, such as takes place in a kettle of water heated on a stove, the process of vaporization proceeds through three definable stages as the power input is increased, eventually reaching a critical limit [*see top illustration on preceding page*]. In the first stage of evaporation the input heat is just enough to cause evaporation of the liquid at the surface without disturbing the body of the fluid. The second stage involves what is called nucleate boiling, during which vapor bubbles form within the body of the fluid and rise to the surface. As the thermal power is increased and the bubbling becomes more vigorous the individual bubbles tend to form a film that covers the entire surface or large portions of it. This condition, called film boiling, is the third stage of vaporization. The effect of film boiling is that the vapor blanket sharply reduces the heat transfer from the input surface, with a resulting rise in the temperature of the surface. The onset of film boiling then represents a critical input power density that cannot be exceeded without risking damage to the container material of the vessel. Growing evidence indicates that the high purity of the fluid, the presence of the wick and the motion of the fluid through the wick and across the heat-input surface tend to prevent the formation of bubbles and thus reduce the blanketing effect. Nevertheless, there is still a maximum input power density that cannot be exceeded, often called the critical heat-flux density. This limiting value is very high, on the order of 320,000 B.T.U.'s per hour per square foot of evaporator surface for water at 212 degrees F., or 1,600,000 B.T.U.'s



POWER DISTRIBUTOR FOR SPACECRAFT is the function of this heat pipe, which also uses sodium as its working fluid. Attached to the heat pipe are eight silicon-germanium thermoelectric conversion modules, which convert a fraction of the heat delivered by the heat pipe into electric power. The excess heat is radiated into space by means of the rectangular metal plates behind the converters.



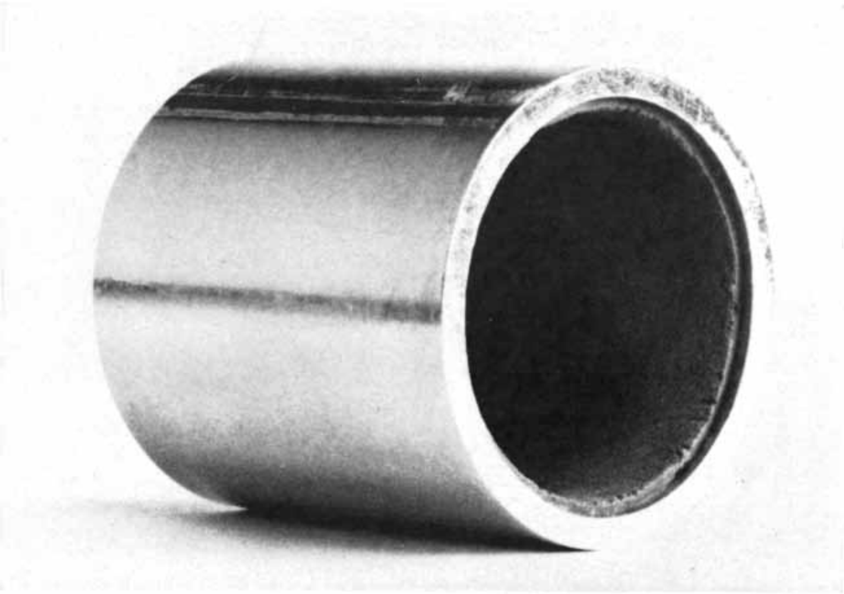
COOLING DEVICE for use with semiconducting electronic components consists of a heat pipe that passes through the center of a series of hollow copper convective fins (*black disks*). The heat pipe shown here is simultaneously cooling two 250-ampere silicon rectifiers, which are located at the two ends of the heat pipe. The device is designed to dissipate 100 watts of heat at 100 degrees centigrade with natural convection or 600 watts at the same temperature with forced convection (that is, with the aid of a blower).

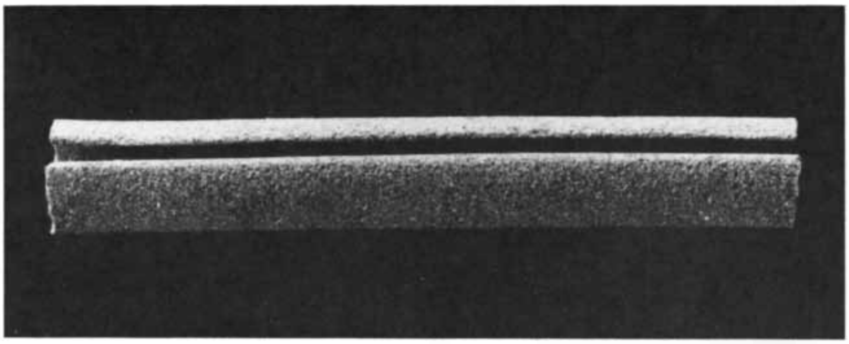
per hour per square foot for lithium at 2,700 degrees F.

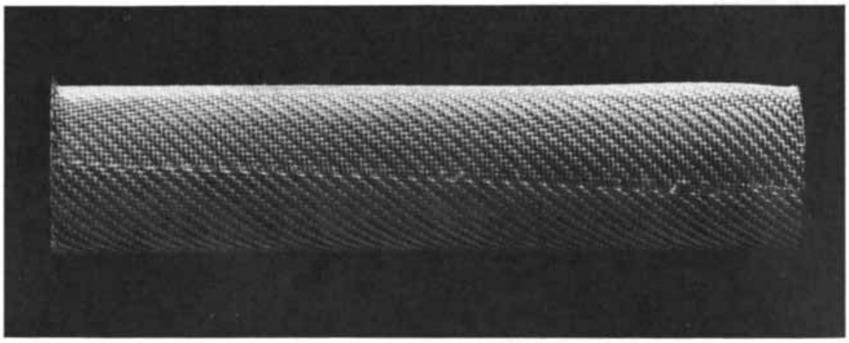
As the temperature of the heat pipe is increased, the rate of evaporation, and consequently the vapor pressure of the working fluid, increases rapidly. The power-handling capacity of the heat pipe also increases, since it is the vaporization of the working fluid that is responsible for heat transfer. For a particular working fluid there is a minimum temperature below which the rate of evaporation becomes insufficient to effect a smooth transfer of thermal power. There is also a maximum operating temperature of the working fluid that is based on the maximum safe vapor pressure allowed within the heat pipe. As the rate of evaporation increases with temperature, the vapor pressure within the container also increases, stressing the container walls. The maximum operating temperature, therefore, is determined by the "creep" strength of the containment material of the heat pipe. Typically the pressure in a heat pipe at the operating temperature is between .03 atmosphere and 10 atmospheres (between .4 pound and 150 pounds per square inch).

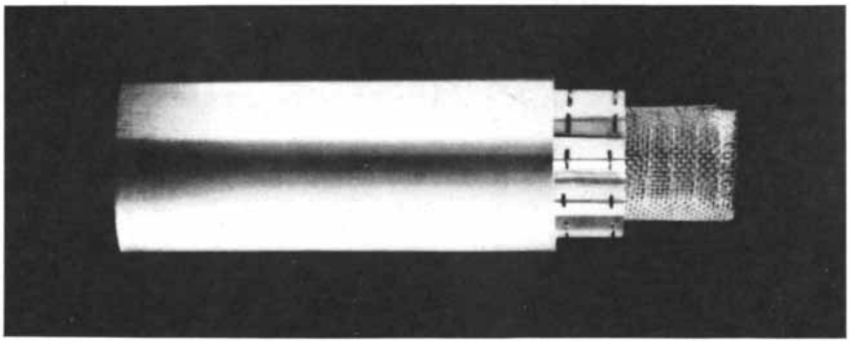
To repeat, the driving force that moves the condensate through the wick to the evaporator is the surface tension of the fluid. The extent to which this force can be brought to bear on the fluid is determined by the "wetting angle" and the pore size of the capillaries. If a heat pipe is subjected to a force that is so directed as to oppose the return of the condensate (such as the acceleration of gravity or of a rocket engine), less fluid can be moved because the surface tension must divert some of its force to overcome the new opposing force. This effect reduces the total power-handling capacity of the heat pipe. In this situation the latent heat of vaporization, the liquid density and the viscosity of the fluid act to determine the extent to which proper heat-pipe operation can be sustained. The heat of vaporization determines the quantity of fluid that must be evaporated to carry the required thermal power and therefore the quantity of condensate that must be returned. The liquid density controls the mass that must be transported by the surface tension. The viscosity determines the amount of frictional drag that opposes fluid flow through the wick. Within limits the effects of such outside forces can be reduced by decreasing the size of the capillary pores in order to increase the surface area of the capillary structure and consequently its lifting ability. A reduction in pore size, however, also increases the viscous drag because of the increased surface area.

Since the pertinent physical properties vary widely from fluid to fluid, the effects of outside forces also vary widely. For example, operating a heat pipe against gravity (that is, in the vertical direction with the evaporator at the top) decreases the total power capability of a









WICKS FOR HEAT PIPES can come in a variety of materials and structures. At top is a copper heat pipe with a wick of porous copper powder deposited on the inside surface. Second from top is wick consisting of a feltlike matting of nickel fibers. Third from top is a wick made of four layers of molybdenum mesh. At bottom is a heat pipe with a combination wick consisting of a molybdenum mesh layer inside a corrugated molybdenum layer.

lithium heat pipe only about 10 percent compared with horizontal operation. On the other hand, the corresponding difference in the operation of a mercury heat pipe can be several orders of magnitude.

Heat pipes have been made to operate at various temperatures spanning the range from below freezing to over 3,600 degrees F. The power transferred ranges from a few watts to more than 17,000 watts. Working fluids have included methanol, acetone, water, fluoridated hydrocarbons, mercury, indium, cesium, potassium, sodium, lithium, lead, bismuth and a range of inorganic salts. The containment vessels have been made of glass, ceramic, copper, stainless steel, nickel, tungsten, molybdenum, tantalum and various alloys. The wicks or capillary structures have included sintered porous matrixes, woven mesh, fiber glass, longitudinal slots and combinations of these structures in various geometries. In physical size heat pipes have ranged from a quarter of an inch to more than six inches in diameter and up to several feet in length. Moreover, heat pipes can be designed in almost any configuration.

An operating life in excess of 10,000 hours without failure or detectable degradation has been achieved with a range of fluid-container systems. The longest of these tests has currently passed 16,000 hours at 1,100 degrees F., using potassium as the working fluid in a nickel containment vessel.

One interesting combination of materials involves the use of electrical insulating materials throughout the heat pipe: vessel, wick and fluid [*see bottom illustration on page 42*]. Such a device can move large quantities of heat from locations at high voltage. Tests to date have exceeded 5,000 volts. This unusual combination of high thermal conductance and high electrical resistance seems destined to find application in a number of electronic and electrical circuits.

In short, the heat pipe is a unique and versatile heat-transfer device. Its special properties are high thermal conductance, temperature flattening, heat-flux transformation and separation of heat source from heat sink. These properties are responsible for stimulating new developments in such varied areas as thermal-to-electrical energy conversion devices for space-power systems, heat sinks for electronic components and devices, special medical uses, coolers for electric motors and thermal-control systems for spacecraft.

In hope of doing each other some good

Sharing the brains

All ten men in this picture hold down jobs in the manufacture of Kodak cameras and projectors. One of them is an assistant vice-president of Eastman Kodak Company, and two of them happen to be mentally retarded. The latter two are here representing all the young adults working in the plant of a subcontractor of ours, the local chapter of the New York State Association for Retarded Children. With them are Kodak men who have used their brains to perfect procedures whereby the subassemblies produced at the Association's Work Training Center pass the same rigid reliability standards that have for generations maintained Kodak's position and reputation.

Hold back the medals. This has been going on for years, and with the physically handicapped as well. We have sacrificed nothing. The cost is the same as if the work were done in-plant. For many of the retardees the work experience has ultimately led to job placement in the community at large.

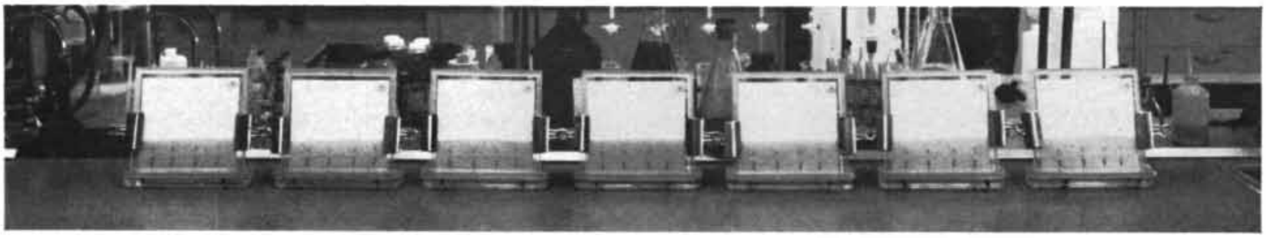
Ten good, sensible guys, all in all.

While cleaning coal, watch the quotations

Start looking at 2-Ethylisohexanol if your prosperity depends on clean coal. For a sample write Eastman Chemical Products, Inc., Kingsport, Tenn. 37662 (Subsidiary of Eastman Kodak Company).

Even if your prosperity *does* depend on clean coal, you are certainly not ready yet to order a tank of 2-Ethylisohexanol. First you need to see how it performs in coal flotation in comparison to what you are now using. You have to decide whether you are going to use it straight or in a combination with ingredient X and maybe also Y to float off your coal dust on your air bubbles while dropping off whatever is to be dropped off. You have to have it all worked out in advance how much you can afford to pay for 2-Ethylisohexanol in comparison with methylisobutylcarbinol and/or how much better will be your recovery of carbon. You have to figure what equipment or labor the changeover would require, if any. Then you will know what to do when the time comes. Or has it come already?

Like coal, sausage too is an everyday necessity. It is said now to be manufactured by computer. Proportions set by the day's price quotations on beef, pork, veal. All good.



Seven sheets

CHROMAGRAM, our trademark for scissorable polyester sheets that become chromatograms, has been successful after its fashion. As measured by published papers and procedures in which these sheets figure, the acceptance has met our fondest hopes. Happy the manufacturer whose product is widely recognized to perform as advertised! He must never allow his happiness to be marred on learning that the customers are accomplishing too much with too little product. Yet there must be some wholesome way to push those consumption figures higher faster. Let us inspire more workers to swell further the output of procedures employing CHROMAGRAM Sheet. Let us sing them no jingles but spell out the useful facts:

Silica gel-coated EASTMAN CHROMAGRAM Sheet is used for polar compounds as it comes from the box. For relatively non-polar neutral or acidic organic compounds one activates first at 100C for 15 to 30 minutes. One can also pretreat with buffers, salts, oil phases. pH is near neutral.

Alumina-coated CHROMAGRAM Sheet is on the basic side but can be switched to neutral or acidic by following directions. Use it for relatively non-polar basic organic compounds. If they are highly non-polar, activate.

Since purity of the coating is all-important in cellulose-coated CHROMAGRAM Sheet, binder is omitted and yet the coating stays tight. Polar compounds of all types are cleaner resolved with shorter migration than in the old paper chromatography. Do electrophoresis at right angles to the partition chromatography.

EASTMAN CHROMAGRAM Sheet 6066, also without binder, also for electrophoresis-crossed partition TLC, differs from the polyamide class of TLC coatings in at least one respect: exposure to alcohol vapor after development makes the coating separable as a transparent pellicle for direct uv spectrophotometry.

The silica gel and alumina coatings are 100μ, the cellulose 160μ, and the polyamide type 60μ. All but the last are available with an incorporated inorganic fluorescent indicator.

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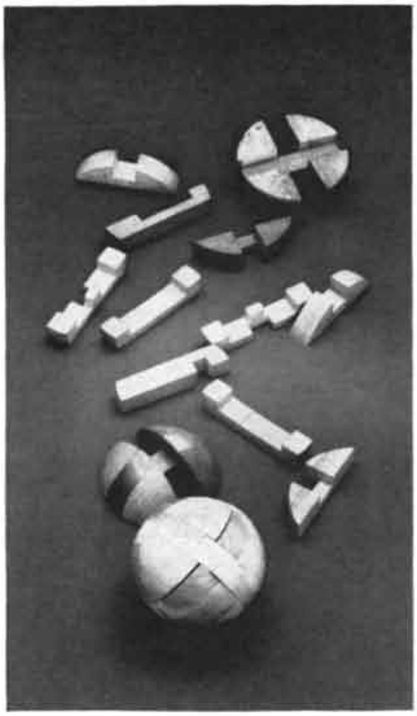

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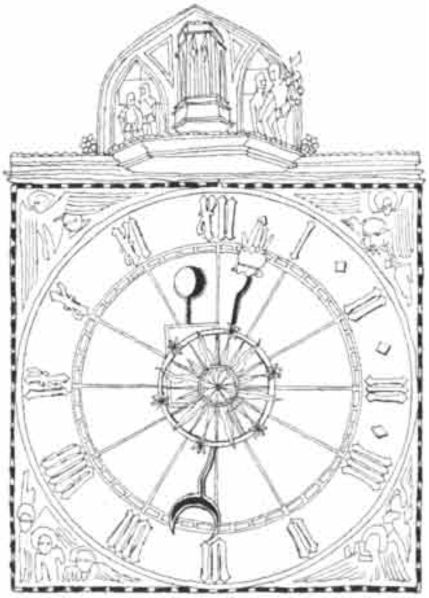

Nonproliferation

The past two months have seen some further progress toward the control of nuclear weapons. In Geneva the text of a nonproliferation treaty was agreed to by the U.S. and the U.S.S.R. and was generally approved by most of the other members of the 17-nation disarmament committee; it was scheduled for debate in the United Nations General Assembly late in April. In Mexico City the U.S. followed Britain in signing a protocol in which these two nuclear powers agreed to respect the 1967 Treaty of Platelolco, which made Latin America a nuclear-free zone.

A nonproliferation-treaty draft was first proposed jointly by the U.S. and the U.S.S.R. last August. In it the two nations agreed not to transfer nuclear weapons or explosives to other nations or help them to manufacture or acquire such weapons or explosives. That draft was unsatisfactory to many of the nonnuclear countries. The latest draft was an effort to meet their objections. It includes a legal commitment by the nuclear powers to facilitate the development of peaceful uses of nuclear energy, particularly in the developing nations, and to carry out peaceful nuclear-explosive projects for nonnuclear countries at cost. It also—for the first time—legally commits the nuclear powers to work for nuclear disarmament. In addition, Great Britain joined the U.S. and the U.S.S.R. in proposing a Security Council resolution binding the three powers to come to the assistance of a nonnuclear country that is threatened with nuclear attack.

The Treaty of Platelolco (named for the section of Mexico City in which it was negotiated) was adopted in February, 1967, and has been signed by all Latin-American countries except Cuba. It forbids the acquisition of nuclear weapons by any of the signatories or the "stationing" or "presence" of such weapons on their soil. Now that Britain and the U.S. have pledged to respect the treaty, the Latin-American countries are expected to press for similar recognition of its provisions by the U.S.S.R., which has been reluctant to sign the protocol because of Cuban objections.

Disaffiliation

The growing concern among members of the academic community over the moral and political implications of applied research on military projects has manifested itself recently in the form of a resolution, currently being considered by the 12 member universities of the Institute for Defense Analyses (IDA), that calls for a modification of the "corporate structure and responsibility" of the board of trustees and the management of IDA. The resolution, drafted by the institute's member trustees at a meeting in March, would eliminate institutional membership in IDA. Instead, each member university would designate annually a senior officer to serve in an individual capacity as a trustee of IDA. The designated trustees could in turn elect public trustees to the board.

The drafting of the resolution followed soon after faculty meetings at two of the member institutions, Princeton University and the University of Chicago, voted overwhelmingly to approve committee reports that called for changes in their relationship with IDA. The Princeton faculty committee recommended joint action with the other 11 members "to change the structure of IDA to one in which universities are not responsible for its management and activities." The report pointed out that this course of action "would permit an orderly transition from IDA's present form of organization to a new one." The Chicago faculty report, approved a week later, called for prompt and unilateral withdrawal from IDA. On both campuses the issue of the university's relationship with IDA was raised by student and faculty protests against the role of IDA in providing secret research related to the war in Vietnam.

So far the governing board of only one member, Columbia University, has approved the resolution. Still not heard from are the 11 other members (Princeton, Chicago, the University of California, the California Institute of Technology, Case Western Reserve Institute of Technology, the University of Illinois, the Massachusetts Institute of Technology, the University of Michigan, Pennsylvania State University, Stanford University and Tulane University).

Turned off on Science

In the past few years many educators and others active in science and engineering have noted with concern an apparent drift of young people, in the U.S. and in other industrialized countries, away from scientific studies and careers. In Britain three years ago a committee headed by F. S. Dainton of the University of Nottingham was appointed to look into the situation and to examine specifically the flow of students from secondary schools into scientific courses at the university level. The committee's recent report documents the "swing away from science" and suggests some remedies.

In 1962, according to the Dainton Report, 42 percent of British secondary school students were headed for the universities in the "science stream." In 1967 science's share was 31 percent, and it looks as though it will be 25 percent in 1971. University admissions reflect the trend: there was a decline from 45.9 percent in 1962 to 40.6 percent in 1967 in admissions to studies under science and technology faculties. It has actually become difficult to find enough qualified students to fill some university science departments. The Dainton Report blames to a large extent the intense specialization that is characteristic of British secondary schools. Universities in England and Wales generally require that students take the equivalent of the bachelor's degree in only three years. In science particularly this calls for high entrance requirements, and secondary schooling must be correspondingly specialized and advanced. A student aiming at a university course in science, engineering or medicine usually needs to make his decision and begin intensive work in his specialty at the age of 13. The report recommends a broader span of studies in the final years of secondary school so that "irreversible decisions for or against science, engineering and technology" can be postponed as long as possible. To keep the path to science open, for example, it urges that nearly all students should keep studying mathematics throughout their school years. And the report recommends a corresponding flexibility in university admission requirements.

Oldest Amino Acids?

What may be the oldest amino acids on earth have recently been extracted from crystalline rock that is at least 3.1 billion years old. The rock, an early Precambrian chert, comes from the Fig Tree formation near Barberton in South Africa; it contains fossils resembling bacteria and algae that are recognized as the earth's oldest known organisms. Writing in *Proceedings of the National Academy of Sciences,* J. William Schopf and Elso S. Barghoorn of Harvard University and Keith A. Kvenvolden of the National Aeronautics and Space Administration report that chromatographic analyses reveal the presence in the chert of two free amino acids and 17 combined ones. The most abundant of the amino acids in the rock is glycine; the investigators attribute this both to glycine's chemical stability and to the fact that it is a product of the degradation of less stable amino acids. Several of the other amino acids present in the chert are also degradation products.

The investigators note that amino acids are readily formed by nonbiological processes, but they nonetheless favor a biological origin for the ones from the Fig Tree chert. They point out that not only does the rock contain fossils but also every amino acid present can be found in living organisms today or can be derived from them by degradation. No technique exists for directly dating organic materials recovered from ancient rocks, so that the Fig Tree amino acids may be as old as the chert or may be of much later origin. Evidence favoring their having the same age as the chert was obtained when the investigators compared the amount of amino acid per gram of rock in the Fig Tree samples with both the amount in the Gunflint chert, a 1.9-billion-year-old formation in Canada, and the amount in the Bitter Springs chert, a billion-year-old formation in Australia. Although the three samples contained roughly the same amount of organic material, the amount of amino acid was largest in the Bitter Springs sample, second largest in the Gunflint sample and smallest in the Fig Tree sample. The differences, which agree with the differences in the age of the cherts, suggest that the amino acids were present in all three at the time of their formation.

Hot Spots

Four radio telescopes located as far apart as California and Sweden have been used cooperatively to measure with unprecedented accuracy the diameter of two types of intense radio source: quasars, which may be the most distant objects known, and regions within our own galaxy where new stars may be forming. By comparing the signals received at two widely separated antennas it is possible to acquire information equivalent to that obtainable from a single telescope whose diameter equals the base-line distance between the two antennas. The signals are recorded on magnetic tape at the two sites and correlated with the help of precise timing signals provided by atomic clocks.

The first results of the new measurements were reported at a recent meeting of the American Astronomical Society, held at the University of Virginia. A study of 3*C* 273, the brightest of all the quasars, has revealed that its structure is more complicated than had been thought. It was known to consist of two major components, *A* and *B,* the latter of which was also known to be double. The *B* component coincides in position with a starlike object. One of its components had previously been shown to have a diameter of about .02 second of arc. The other component has now been found to consist of two or more emitting regions, one of which has a diameter of .002 arc second and the other of less than .0006 arc second.

The last value is the limit of resolution of the new experimental technique at the wavelength used (six centimeters); it is equivalent to the angle subtended by a disk four feet in diameter at the distance of the moon. There are theoretical reasons for believing this component is smaller by a factor of six than the limiting resolution. This would correspond to a diameter of less than one light-year, assuming that 3*C* 273 is several billion light-years away.

The second series of results concerns the diameter of regions within our own galaxy that emit radio waves at the 18-centimeter wavelength of the hydroxyl


Sometimes one head is better than two.
If you don't give lettuce seeds enough space, you wind up with two scrawny, stunted lettuces that nobody wants, instead of one big fat one. And the seeds are too small to space out well with mechanical planters. They come up in clumps, which you have to thin out by hand.
Now Union Carbide has developed a way to space the seeds out on tape and plant the tape. We make the tape of a plastic that dissolves in water. You plant it and water it and the seeds start to grow. Just the right distance apart.
Planting lettuce this way gives farmers big savings on thinning costs. And you can plant all the seeds at the same depth, so they come up all together. Which means harvesting costs less and yields are bigger.
Seed tape also works with tomatoes, celery, asparagus, sugar beets and other crops with small, light seeds. So we expect to be making a lot of it, along with all the other things we make to help people grow more food. Now if we could add something to it that speeds up germination....
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radical (OH). These regions, suspected of being protostars, present a paradox. Although the emitting OH radical cannot be more than a few degrees above absolute zero, the intensity of the emission is such that the gas appears to be at trillions of degrees centigrade. This has led theorists to conclude that the emitting mechanism is similar to the one exploited in masers and lasers, devices in which populations of atoms are raised to an excited state and emit their energy in unison when suitably stimulated. Seven of the emitting regions seem to be embedded in a large mass of glowing hydrogen gas 6,000 light-years away in the constellation Cassiopeia.

The new experiments show that one of the OH regions has a diameter of only .004 arc second, indicating that the source has a diameter of about 600 million miles, or hardly more than the distance from the sun to Jupiter. When the observed intensity of emission is computed for a disk of this small diameter, the apparent emission temperature is 10^{15} degrees. There is as yet no satisfactory theory of how a mechanism of the maser type could operate in interstellar space to mimic such temperatures in a cold gas. The experiments represent a collaboration among workers at the National Radio Astronomy Observatory in Green Bank, W.Va., the University of California Observatory at Hat Creek, the Lincoln Laboratory of the Massachusetts Institute of Technology and the Chalmers University of Technology at Onsala in Sweden.

Elastomers and Vibration

The piercing squeal the wheels of a train sometimes make as the train rounds a curve can be considerably reduced by a recently developed technique called constrained-layer damping. Other structural noises, such as those resulting from the vibrations of an airplane fuselage or the drumming of water on the tub of an automatic dishwasher, have been similarly reduced in experiments with the technique by T. P. Yin and his colleagues in the Elastomer Chemicals Department of E. I. du Pont de Nemours & Co. The technique involves sandwiching a layer of elastomer, or viscous and elastic synthetic polymer, between the vibrating member and a thin layer of constraining material such as steel or aluminum. Applied to portions of the vibrating body, the material damps the vibrations and reduces the noise. Before the development of the technique, which required the availability of elastomers designed specifically to absorb vibrational energy, damping of this magnitude could not be achieved even by applying relatively thick layers of viscoelastic materials such as felt and tar to the vibrating body.

In experiments with railroad wheels Yin's group found that constrained-layer damping reduced noise from 110 decibels to 80 decibels, which means from a level that is acutely painful to most people to a level that is still loud but not painful. Studies in other laboratories showed that putting patches of the material on the inside of airplane fuselages reduced not only noise but also (by a factor of 100) the tendency of the fuselage metal to crack as a result of fatigue from vibrations. Yin's group is also experimenting with constrained-layer damping of certain household appliances in which noise is a problem.

Vanishing Detergents

Studies conducted in Illinois and Wisconsin indicate that the pollution of water by detergents not only has been arrested but also has declined since detergents that decompose readily were put on the market starting in 1965. William T. Sullivan and Ralph L. Evans of the Water Quality Section of the Illinois State Water Survey report in *Environmental Science and Technology* that the concentration of the surfactant compounds in the Illinois River has dropped 61 percent since the change, even though the use of synthetic detergents has increased markedly during the same period. Gerald W. Lawton, chief of the environmental health section of the State Laboratory of Hygiene in Wisconsin, has reported that the waters at 37 monitoring sites in that state have shown sharply reduced contents of detergent.

The original "hard" detergents, which often created foam on the bodies of water into which they were drained after use, are known chemically as sodium alkyl benzene sulfonates. They are not readily decomposed by natural biological processes. The "soft" substitutes, which are now the only ones made in the U.S., are known as linear alkylate sulfonates. They are decomposed biologically both in sewage-treatment plants and in natural bodies of water.

The Illinois River receives most of the waste waters from many communities and industries. Sullivan and Evans report that the detergent load at Peoria dropped from a mean of 20.6 tons per day in 1961–1962 to nine tons per day in 1965–1966. In the same period of time the total sales of synthetic detergents in the U.S. rose from 3.6 billion pounds to

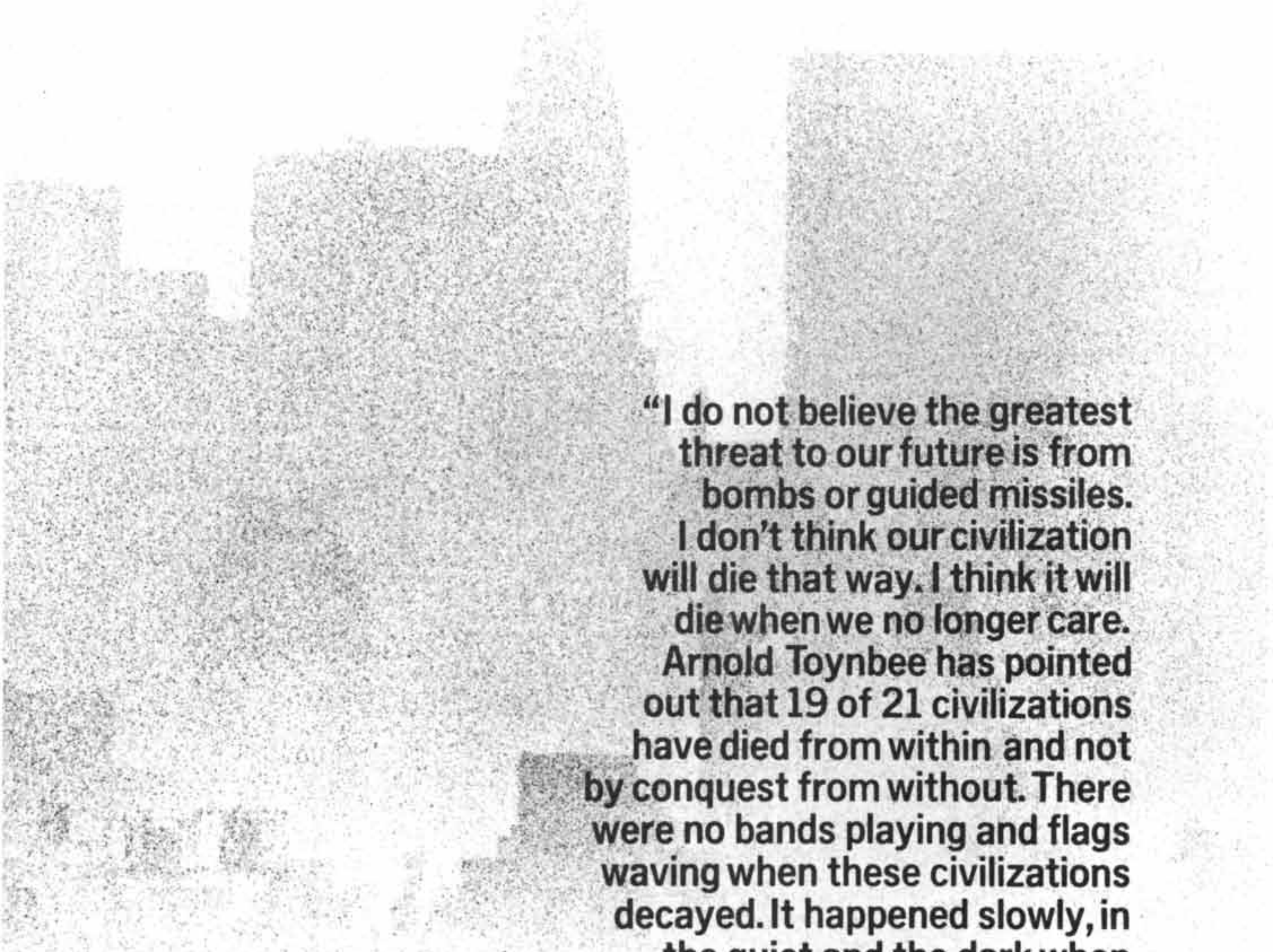
4.2 billion pounds. The significant difference was that in 1961–1962 all the detergents made in the U.S. were of the "hard" type, whereas after June 30, 1965, all were of the "soft" type.

Contagious Sterility

A synthetic insect hormone has been shown in recent experiments to be so potent that it not only sterilizes insects but also can pass from insect to insect in sterilizing doses. The hormone is a powerful chemical relative of the "paper factor" juvenile hormone discovered in 1965 and identified as a terpene of the balsam fir by Carroll M. Williams of Harvard University and Karel Sláma of the Czechoslovak Academy of Sciences. Sláma announced the successful laboratory test of the hormone during a recent conference on pest control sponsored by the International Biological Program.

Juvenile hormones, substances secreted by insect larvae, must be absent if successful metamorphosis from the larva to the adult insect is to take place. The first of the substances to become known, secreted by larvae of the *Cecropia* silkworm moth and discovered in 1956 by Williams, will disrupt metamorphosis on contact with the larvae of almost all insect species. The paper-factor hormone, which was first detected in paper made from the balsam fir, affects only one family of insects: the Pyrrhocoridae, a group of true bugs that includes some of the most destructive pests of the cotton plant. Its sharply delimited effect ranks it with X-ray sterilization (the method that has eliminated the screwworm fly, a cattle pest) as a control that selectively strikes one of the .1 percent of insects that are pests but leaves untouched the 99.9 percent that are innocuous or helpful (see "Third-Generation Pesticides," by Carroll M. Williams; SCIENTIFIC AMERICAN, July, 1967).

The insect Sláma and his associates used in their tests is the linden bug, the male of which may mate twice daily. The Czech workers applied one milligram of the synthetic hormone to each male. When the males mated, the females were contaminated and made sterile by the hormone. More remarkable, the contamination of the females was sufficient to contaminate all the normal males with which the females subsequently mated, and these contaminated males in turn rendered other normal females sterile before the hormone became too dilute to be effective. As a result the sterility of the laboratory linden bug population soon reached epidemic proportions.


"I do not believe the greatest threat to our future is from bombs or guided missiles. I don't think our civilization will die that way. I think it will die when we no longer care. Arnold Toynbee has pointed out that 19 of 21 civilizations have died from within and not by conquest from without. There were no bands playing and flags waving when these civilizations decayed. It happened slowly, in the quiet and the dark when no one was aware."

Could this happen to us? To our families? To our way of life? Could this happen to America the beautiful?

Well, look around. You can see signs of it this very moment in every major city in this country. You can see it in the slums, in the jobless, in the crime rate. In our polluted air, in our foul rivers and harbors and lakes. You can see it in our roads strangled with traffic.

You know the problems confronting our cities. Now we must all do something about it. While there is still time. Before our cities become unfit places in which to live.

Why are the life insurance companies so concerned?

Our business involves people. Our service is security for their future. Unless the problems of our cities can be solved, we are dismayed at the prospect of greater personal tragedy and at the economic consequences.

The alarm has already been sounded. By the President of the United States. By concerned people all over America. America's life insurance companies—so long a part of the American scene and quite probably of your own life—are adding their voices to a call for action. We hope that call can help persuade men of good will, as businessmen and as private individuals, to act and act now.

Concerted action *now* can be effective. For the very cities that are suffering most have at their command human and economic resources unmatched anywhere else in this world. Now it is up to all of us to see to it that these resources are put to constructive use.

What can business and industry do?

The job of rehabilitating our cities, of making them fit for all to live in, must rest primarily with government. But it's a job too big for government alone.

It's everybody's problem. Business, labor, private citizens. Negro and white alike.

So everyone is needed to solve it. Help is needed in building and improving housing, creating job-training centers, re-evaluating hiring practices, participating in community programs of health and education.

Here are some efforts already under way:

As a start, Detroit auto companies have hired some 30,000 ghetto residents.

As a start, Aerojet-General Corporation bought an abandoned plant in Watts, staffed it with 430 unskilled employees and secured a 2.5 million-dollar Defense Department contract.

As a start, United States Gypsum Company has rehabilitated 12 slum tenements (250 units) in Harlem and is now engaged in other projects in Chicago and Cleveland.

The Avco Economic Systems Corporation recently opened a printing plant in Roxbury, Massachusetts, with 69 employees. The operation marks the beginning of a training and permanent-employment program for an eventual 232 hard-core unemployed.

The Fairchild Hiller Corporation, working with the Model Inner City Community Organization, is establishing a wood products plant in Washington D.C. that will eventually be community-owned, with newly employed slum residents sharing in profits.

A group of life insurance companies has made a commitment to invest 1 billion dollars for housing and jobs in slum areas. More than one-third of this has already been earmarked for specific projects.

Many other businesses throughout the country are taking up this call to action. But it's only a beginning. To make a truly effective beginning all businesses and industries must help. For the cost will be huge.

What can the individual citizen do?

First, the private citizen must educate himself to the dimensions of the problem. By reading. By listening to what his own civic leaders have to say. By pondering what responsible broadcast and newspaper leadership recommends.

He can take a further step in joining citizens' organizations, working with local educational and planning boards, and lending his support to community efforts to lick the problem.

And there are things he can do personally.

As a start, interested groups are working in cooperation with local labor unions in helping young ghetto residents of Newark, Cleveland, Buffalo and Brooklyn to enter the building and construction trades. By recruiting, screening, counseling and tutoring, they have already helped 250 men from the Brooklyn area alone to gain union membership.

As a start, a former auto worker has formed a committee which will soon have Watts citizens farming some 30 acres for themselves for profit.

As a start, individuals, local businessmen, and corporations in St. Louis have contributed over $150,000 to a neighborhood organization to rehabilitate slum dwellings and make possible resident ownership.

It's up to all of us.

Our cities have now become one of the greatest challenges facing this country. We feel America has the means to face this challenge and win.

What about you? Whether you are moved to act out of compassion or self-interest, do act. For whoever you are, whatever you do, you, in your own way, can help. And you can begin today.

For suggestions about kinds of constructive action you, your business, religious, social, or civic organization can take, send for the free booklet, "Whose Crisis? . . . Yours."

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277 Park Avenue
New York, N.Y. 10017
On behalf of the Life Insurance Companies in America

The Lunar Orbiter Missions to the Moon

Five spacecraft in lunar orbit photographed in detail the entire side of the moon facing the earth and almost all of the opposite side

by Ellis Levin, Donald D. Viele and Lowell B. Eldrenkamp

In a corridor of the Boeing Space Center near Seattle there is a little sign that reads "5 for 5." The sign briefly summarizes the fact that all five Lunar Orbiter missions, which were primarily designed to make photographs of the moon from spacecraft in lunar orbit, were successful. The results included complete photographic coverage of the side of the moon that is visible from the earth and coverage of more than 99.5 percent of the side that cannot be seen from the earth. Most of the near side is now depicted in Lunar Orbiter photographs that provide resolution at least 10 times better than it is possible to obtain with the best earth-based telescopes. Although the photographs of the far side were made at higher altitudes than most of the photographs of the near side, the far side is now depicted in greater detail than was previously obtainable of the near side from earth-based observations.

The Lunar Orbiter series was one of three programs organized by the National Aeronautics and Space Administration in preparation for the Apollo missions in which men will land on the moon. The first of the other programs was the Ranger series, which provided experience in reaching the moon with spacecraft and also yielded the first closeup pictures of the lunar surface. The second of the other programs was the Surveyor series, in which spacecraft made "soft" landings in prospective Apollo landing areas, tested the mechanical and chemical properties of the lunar surface and made pictures of the immediate surroundings. Ranger and Surveyor spacecraft provided detailed information about small areas of the moon; the purpose of the Lunar Orbiter missions was to obtain good photographic coverage of large areas.

As defined in a contract between the Langley Research Center of NASA and the Boeing Company, which was the prime contractor for the Lunar Orbiter project, the main objective of the series was to obtain detailed photographic coverage of a number of areas along the equator on the near side of the moon that were regarded as potential landing sites for Apollo spacecraft. The project was designed to be flexible, however, and as a result it was possible to expand the objectives as the series progressed. For example, the coverage of potential Apollo sites from the near-equatorial orbits of the first three missions was good enough to warrant putting the last two spacecraft into near-polar orbits, thereby providing for virtually complete photographic coverage of the moon.

The five Lunar Orbiter spacecraft made a total of 1,950 photographs. Already the photographs have been put to several uses. NASA has used them to select five potential Apollo landing sites from some 40 candidates that had been identified from earth-based observations [*see illustration on page 71*]. The photo-

FAR SIDE of the moon appears in a photograph made through the wide-angle lens of *Lunar Orbiter III*. The spacecraft was about 900 miles above the moon and 250 miles south of the lunar equator. At the top, which is north, the photograph spans about 700 miles; the curved southern horizon stretches to within 400 miles of the moon's south pole. The conspicuous crater filled with dark material is called Tsiolkovsky.

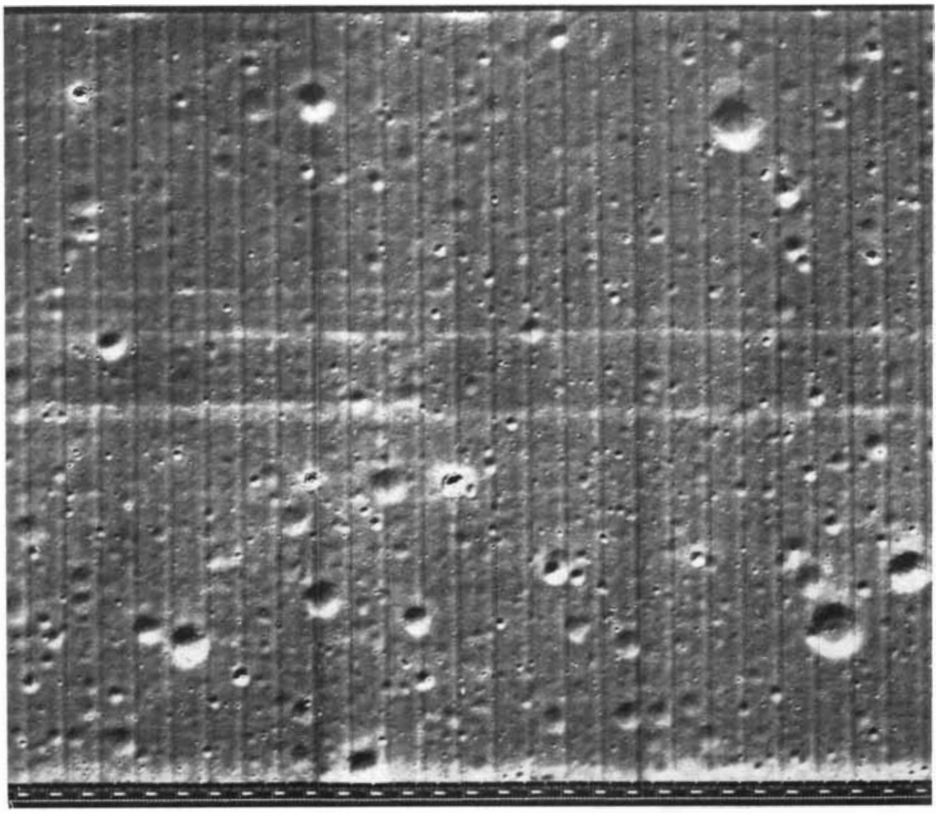
graphs have been used to choose landing sites for several of the Surveyor spacecraft and to help interpret results from the Surveyor missions. The photographs have been used as a basis for detailed maps of the lunar surface, including far-side maps that could not have been made previously. From Orbiter photographs NASA has made models of the lunar surface for study and practice landings by astronauts. The photographs are also providing valuable information for investigators studying the processes that have shaped the surface of the moon.

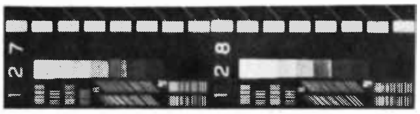
In addition to the photographs, the Lunar Orbiter missions have secured several other kinds of information. Each spacecraft carried devices for detecting radiation and the impact of micrometeoroids. Observations of the orbits of the spacecraft, as they were tracked by stations of the Deep Space Network in California, Spain and Australia, yielded improved data on the moon's overall shape and gravitational field. Separate tracking by the Manned Spaceflight Network gave the Apollo tracking teams valuable training for the manned missions of the future. In another experiment *Lunar Orbiter V* was carefully maneuvered in lunar orbit to reflect sunlight from its solar panels and its underside mirrors, and the reflection was photographed with a telescope on the earth.

Design of the Missions

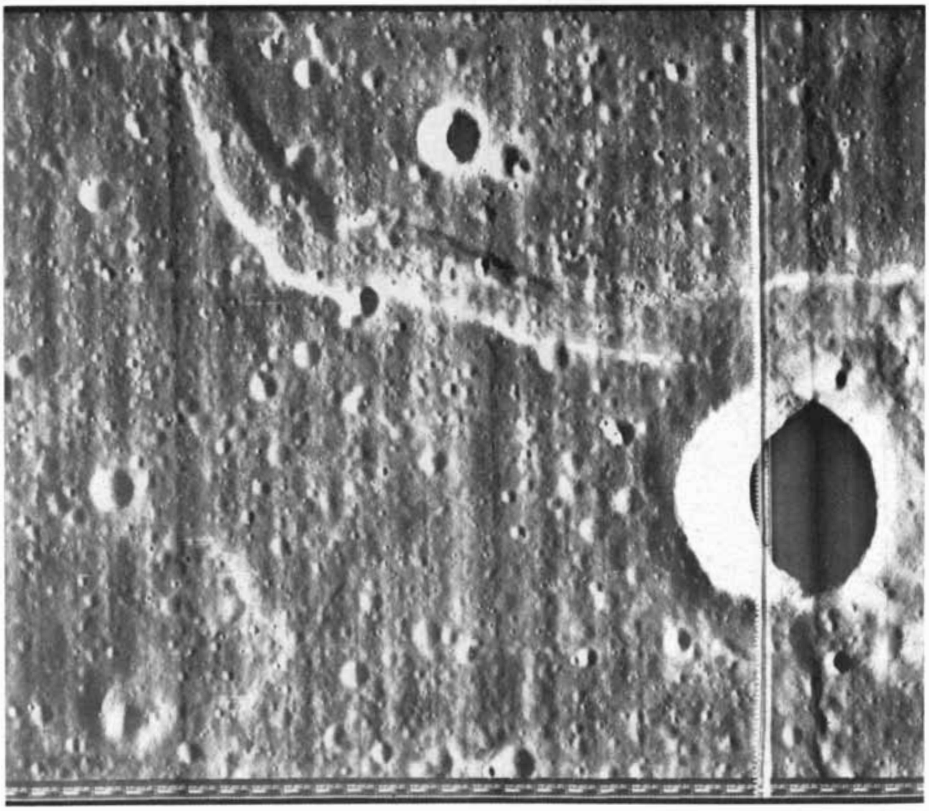
In planning the Lunar Orbiter missions a considerable number of objectives and constraints had to be identified and taken into account. Each spacecraft had to be launched from the Kennedy Space Center by an Atlas-Agena rocket on a course that would bring it to a predetermined point in the vicinity of the moon four days later. There its velocity would be reduced and redirected by the firing of its rocket engine so that the spacecraft would be captured by the moon's gravitational field and would achieve a suitable initial orbit of the moon. After being tracked for several days the spacecraft would be further slowed so that its perilune, or closest approach, would be reduced to about 28 miles above the lunar surface, which would be the primary altitude for photography.

Originally the plan was to make the initial orbit circular at about 575 miles above the lunar surface; the slowing maneuver would put the spacecraft into an elliptical orbit with a perilune of 28 miles and an apolune, or maximum altitude, of 575 miles. During the design

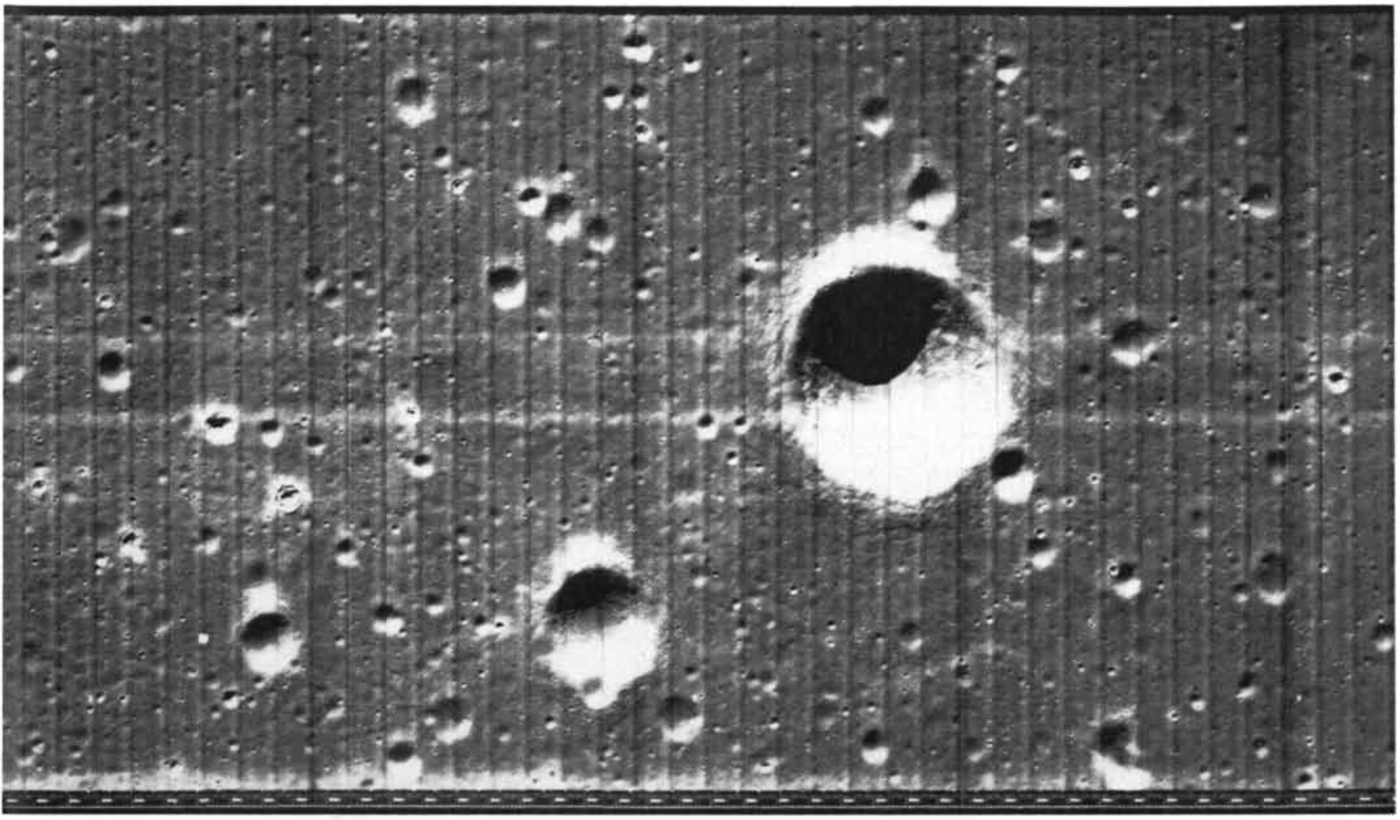




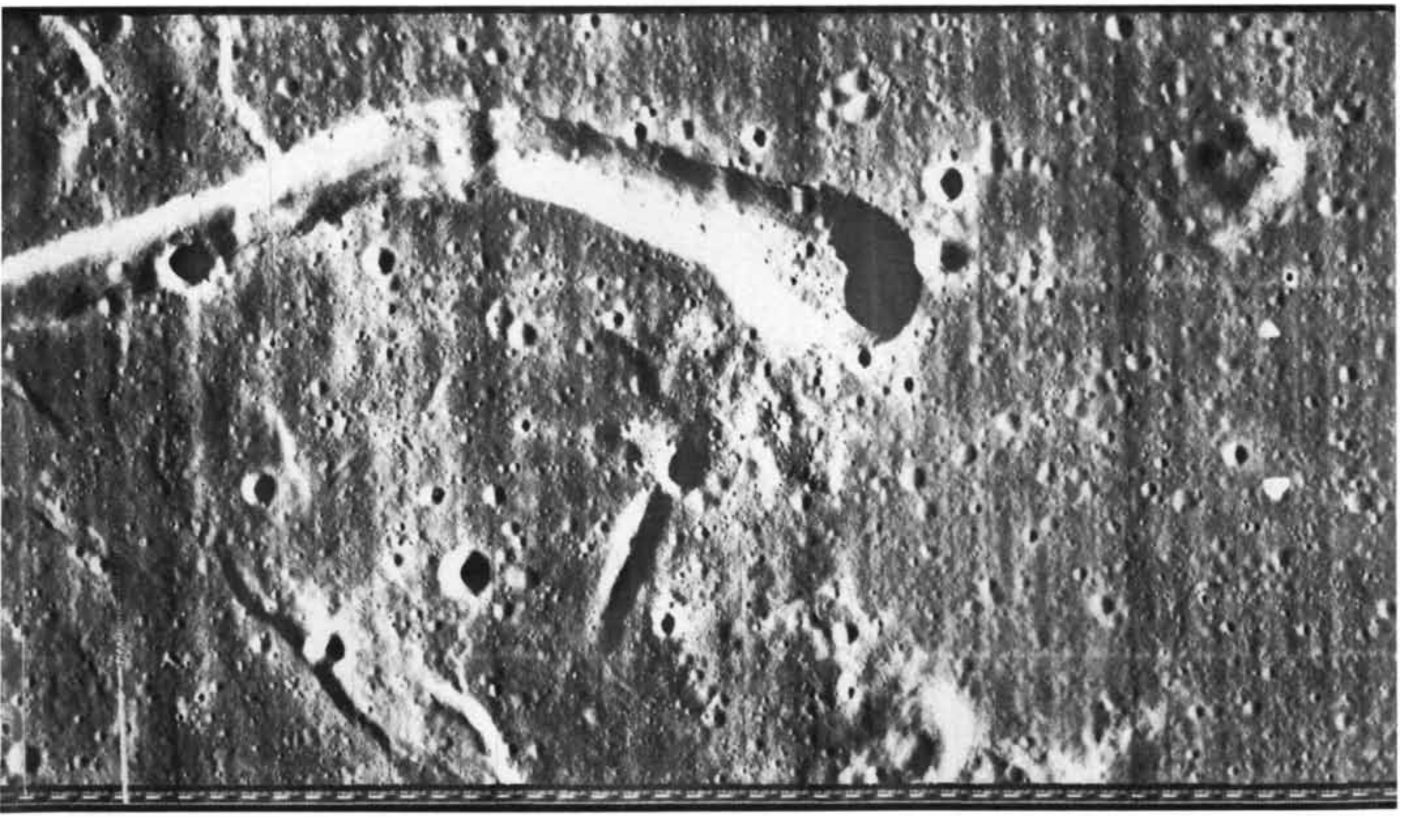
LANDING AREA of the U.S. spacecraft *Surveyor I* is included in a view obtained by the telephoto lens of *Lunar Orbiter III*. The scale is about .6 mile per inch. Vertical



RILLE STRUCTURE in the Marius Hills region was photographed with the telephoto lens of *Lunar Orbiter V*. The scale is about 1.2 miles per inch. The spoonlike rille, or valley, that



bands result from the scanning process by which the spacecraft transmitted its photographs to the earth; light horizontal bands were made in the spacecraft's photographic subsystem. A few craters appear by their distinctness to be of more recent origin than the others. At left below the photograph is an enlargement of the edge data preexposed on the film. The data include framelet numbers, gray scale and resolution bars to aid in the calibration of photographs and the control of the readout of photographs.

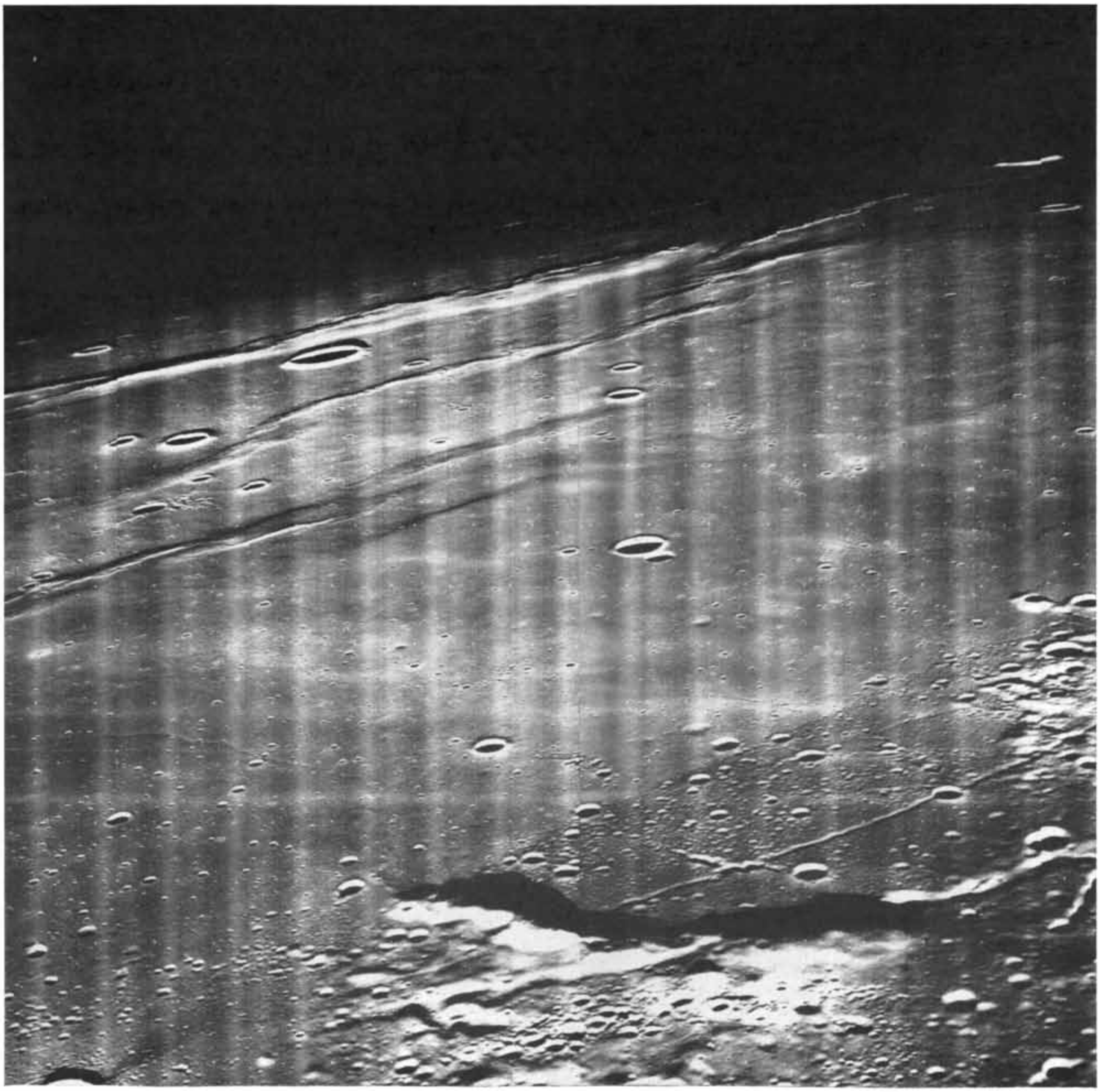


winds through most of the photograph is one of a number of unusual features in the area; among the others are the domes shown in the illustration on page 63. Region was one of several included in the mission of *Lunar Orbiter V* as being of special interest.

phase the plan was changed to make the initial orbit elliptical with a perilune of 120 miles and an apolune of 1,150 miles. This change avoided the impractical alternative of increasing the weight of the spacecraft by adding batteries; in an elliptical orbit the spacecraft would spend more time in the sun and so could make more use of solar power. The change also reduced the amount by which the velocity of the spacecraft would have to be modified in the maneuvers near the moon. Another significant change was to provide for four days for the spacecraft to travel from the earth to the moon instead of the three days taken by the Ranger and Surveyor vehicles; in this way the velocity-change requirement for the Orbiters was further reduced and there was more time to track an Orbiter and analyze its trajectory as it traveled to the moon.

The greater part of the photography would be done near perilune. The perilune altitude was chosen to achieve a balance between good photographic resolution and coverage of sufficiently large areas. Beyond that the shapes of the orbits had to be established in such a way that the location of perilune would coincide with the time when the illumination of the area being photographed was suitable for photography. On the moon the illumination would be suitable when the sun was between 10 and 30 degrees above the local horizon, so that it would be possible to detect small slopes, depressions and protuberances.

In principle the times of suitable illumination could be either shortly after sunrise or just before sunset. In actuality, since the spacecraft would be traveling from west to east across the visible face of the moon, at least on the initial missions, the time of the most suitable illu-

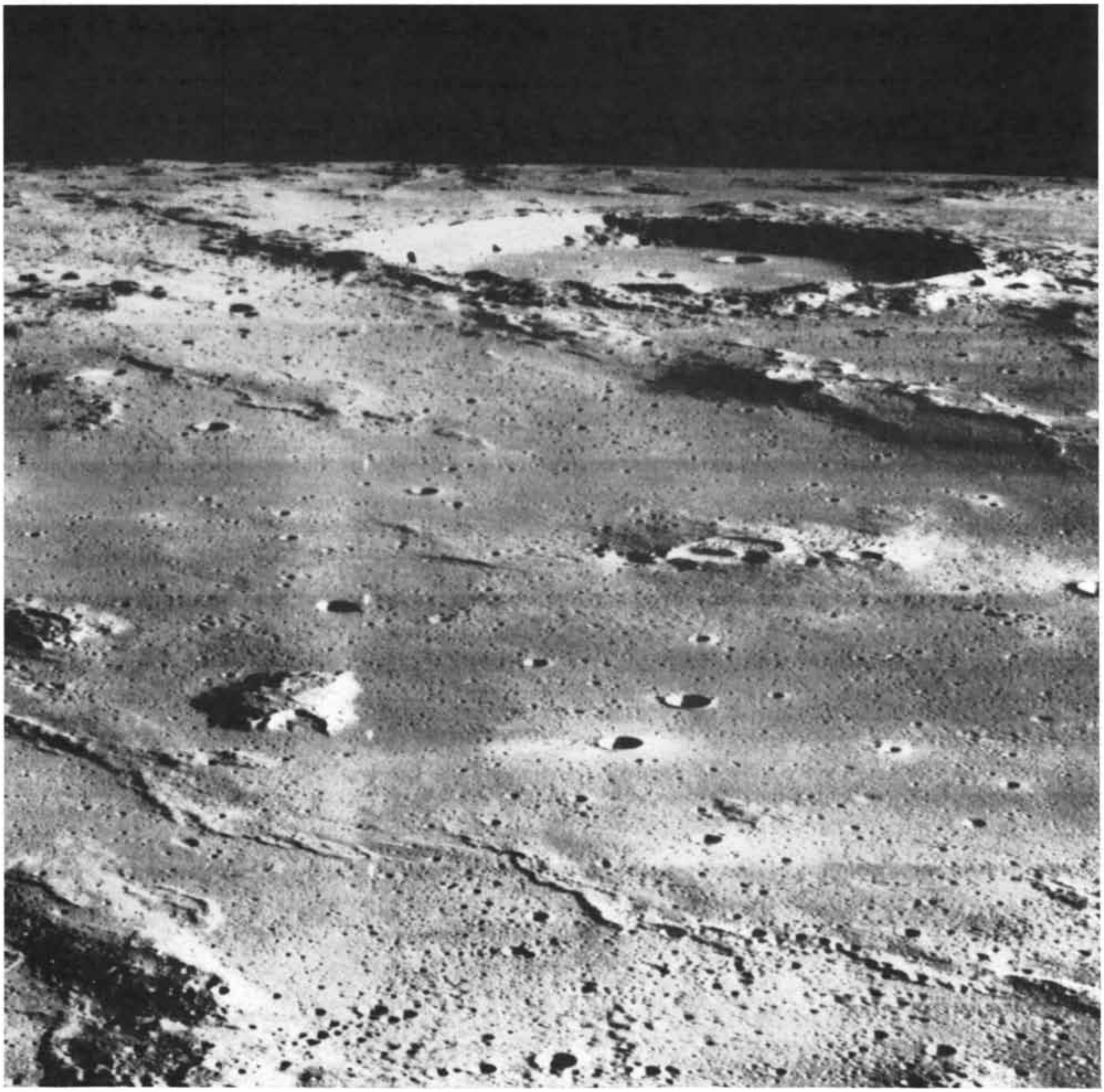


POTENTIAL LANDING SITE for manned Apollo spacecraft was photographed by *Lunar Orbiter III* in an oblique view that resembles what the astronauts would see as they approached the lunar surface. The chief mission of the Orbiter project was to obtain photographs of a number of potential landing sites for Apollo vehicles. This one is near the western edge of the Apollo zone.

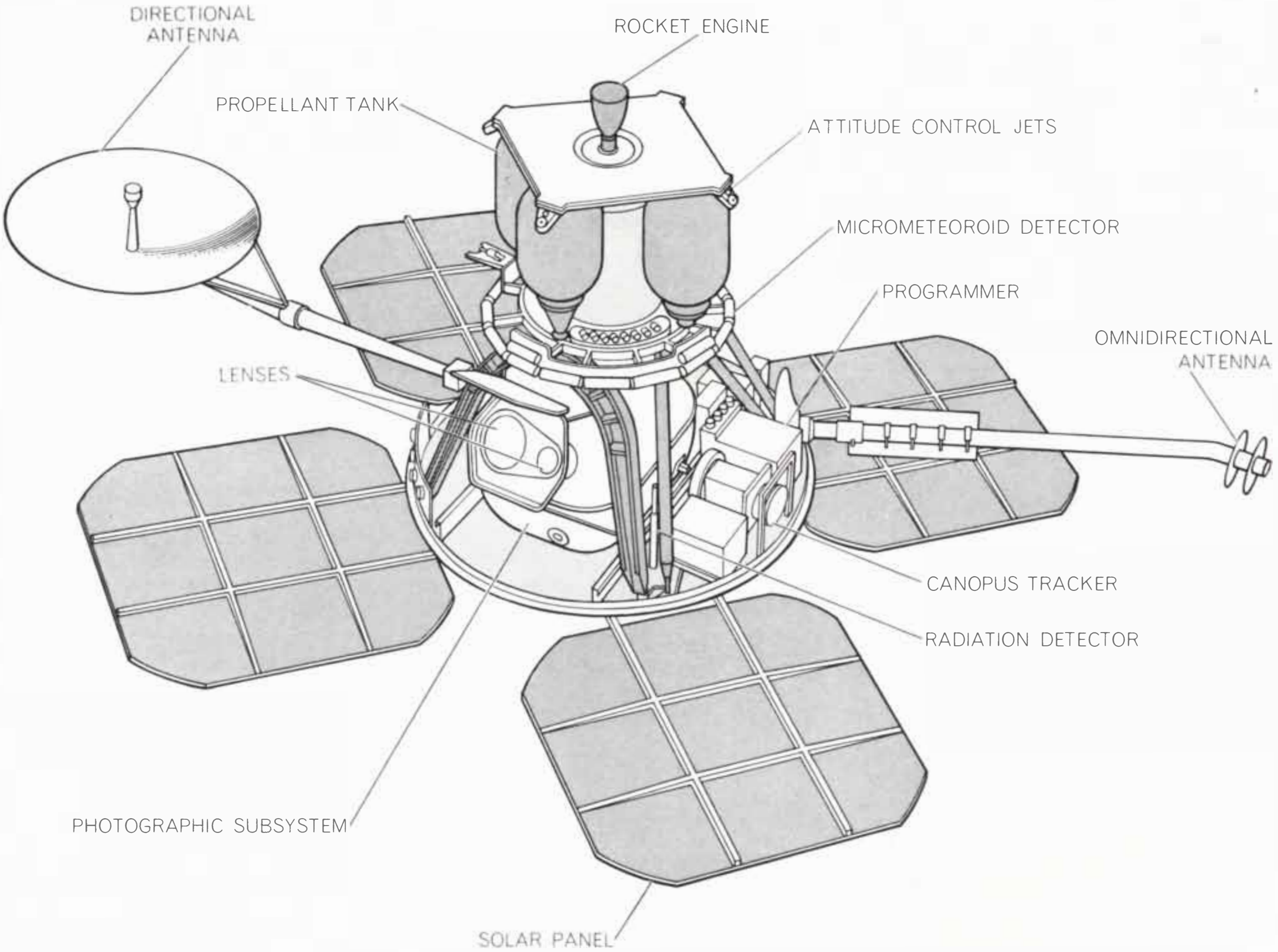
mination was sunrise. Then the spacecraft would be moving into the sun after photography and so could draw for extended periods the solar power needed to process the photographs of the near side—the side of primary concern.

In order to plan for thorough photographic coverage of the equatorial band containing the potential landing sites for Apollo spacecraft, we had to give special consideration to the inclination of the orbit, that is, the angle between the plane of the orbit and the plane of the lunar equator. The inclination had to be low enough to obtain suitable overlapping of photographs from adjacent orbits and yet high enough to provide photographic coverage in good lighting over an acceptably wide range of latitudes. In the end an inclination of 12 degrees was chosen for the first two missions; for the third it was 21 degrees.

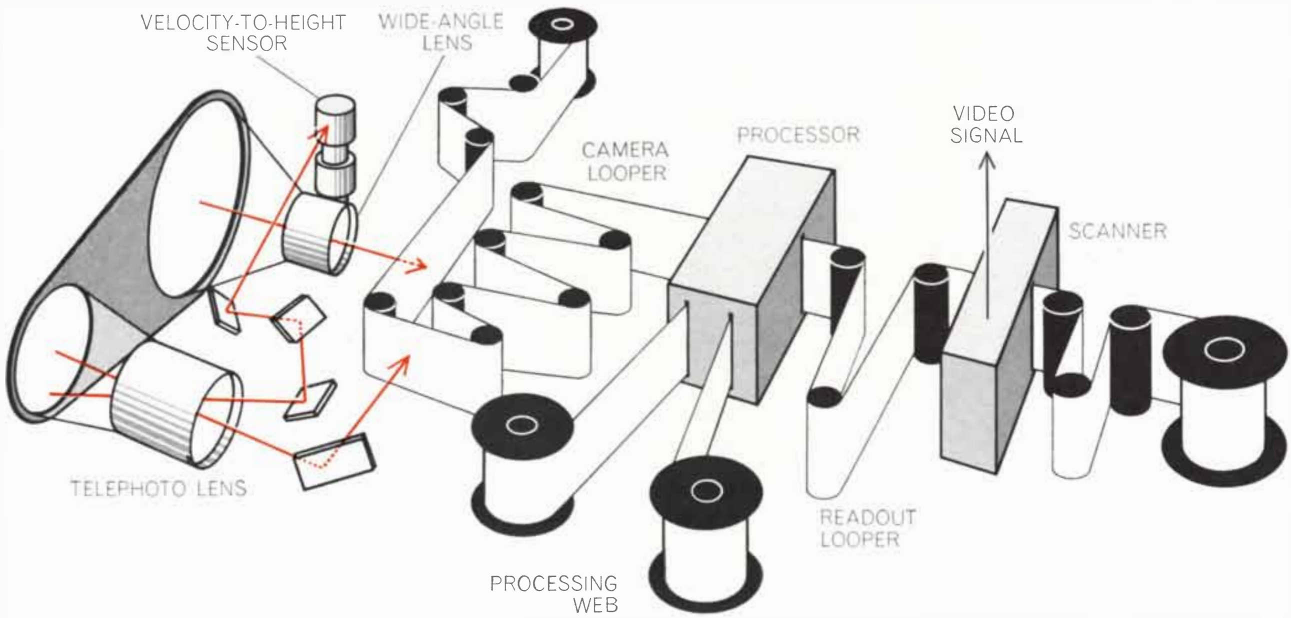
Another consideration was to achieve orbits that were sufficiently stable with respect to the moon to permit control of the spacecraft's perilune altitude for photography and to avoid having the spacecraft crash onto the moon before the transmission of its photographs to the earth could be completed. Instabilities arise not only from variations in the moon's gravitational field but also from the gravitational attraction of the earth and the sun on the spacecraft. The gravitational variations of the moon are due to the distribution of the lunar mass and to the moon's departures from a spherical shape. The variations could not be predicted accurately before the first Orbiter flight. As a result we had to make allowances for the extremes in the best available theoretical model based on observations from the earth [*see bottom illustration on page 65*]. We charted a course between the extremes and made



LUNAR DOMES near the crater Marius, which is near the horizon, were seen in detail for the first time in this oblique photograph made with the wide-angle lens of *Lunar Orbiter II*. The domes, which are from two to 10 miles in diameter and 1,000 to 1,500 feet high, are of special interest because they resemble volcanic features found on earth. Marius is about 25 miles wide and one mile deep.



LUNAR ORBITER SPACECRAFT is depicted as it appeared while it was in operation, except that an aluminized Mylar wrapping used as a thermal barrier is not shown. Antennas and solar panels were folded close to the body of the spacecraft during launching.



PHOTOGRAPHIC SUBSYSTEM of the Orbiter spacecraft had 260 feet of 70-millimeter film. Simultaneous exposures were made through the two lenses. Film was stored on loopers until it could be put through the processor, where it was developed. In scanning the direction of movement was reversed, so that a full readout could not be done until photography was complete and the processing web had been cut. Readout loopers made it possible to read out selected portions of film before photography was completed.

provision for changing the course of the spacecraft after it had been in orbit long enough for us to determine the combined effects on the spacecraft of the earth, the moon and the sun.

Several other matters had to be taken into account; here we can only mention them. One was the effect of radiation on the film. Another was the choice of exposure settings. Another was wisely budgeting the spacecraft's film and fuel, which entailed choosing the optimum sequence of activities for the missions. It was also necessary to observe a limitation that the capacity of the launch vehicle put on the weight of the spacecraft and to make sure that adequate tracking facilities were available.

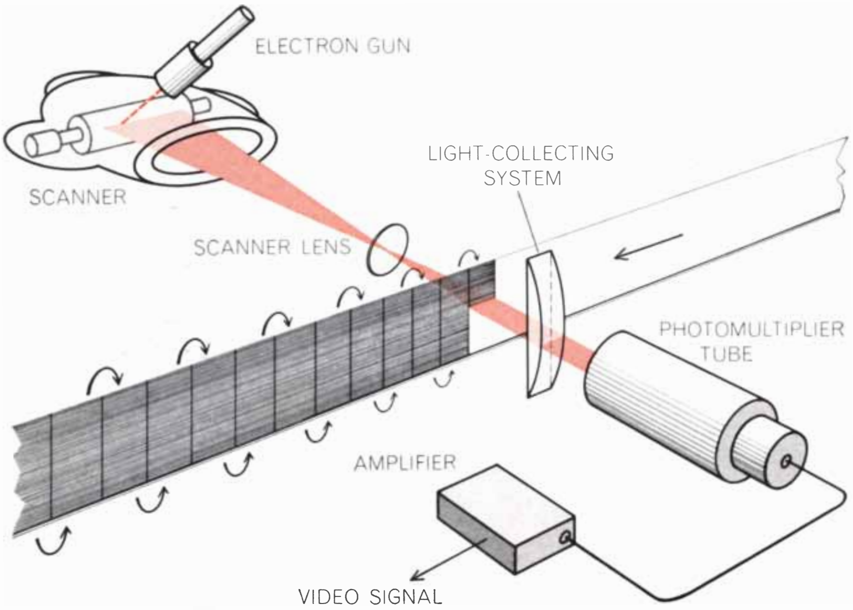
The Spacecraft

On the launching pad a Lunar Orbiter spacecraft was a compact package five and a half feet high and five feet wide. Once in space it unfolded two antennas and four solar cells [*see top illustration on opposite page*]. The high-gain antenna was highly directional, the low-gain one nearly omnidirectional. When they were deployed, on booms that extended from opposite sides of the spacecraft, they spanned 18½ feet from tip to tip. The solar panels, spanning a little more than 12 feet when they were extended, provided the electrical energy for the operation of the spacecraft and for recharging the battery used when the spacecraft was not in the sun. Power for changes of velocity was provided by a rocket engine; changes of attitude were achieved with nitrogen-gas jets. At launch the craft weighed close to 850 pounds, including about 150 pounds for the photographic subsystem and 262 pounds of propellant for the engine.

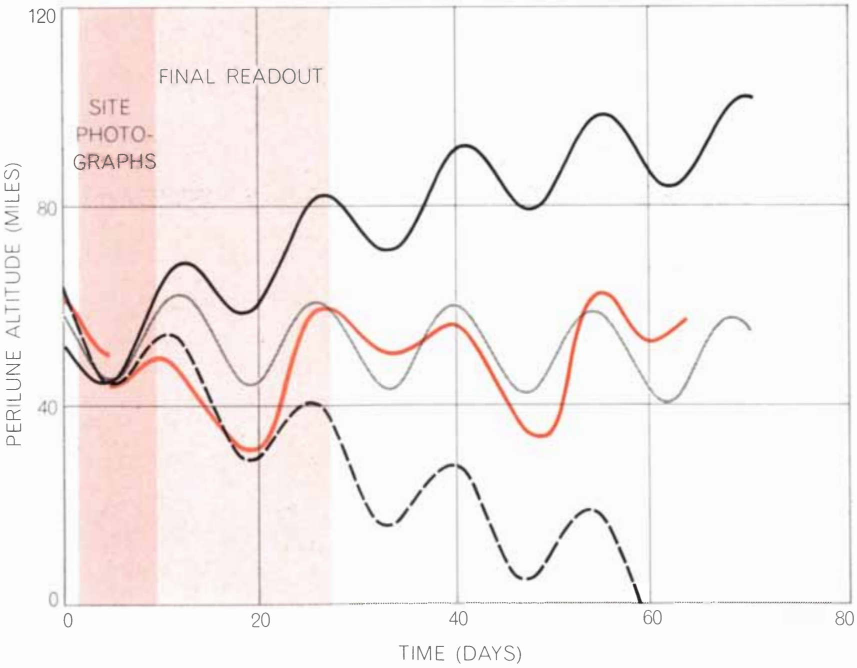
In space an Orbiter was stabilized on three axes: pitch, yaw and roll. A sun-sensor provided the angular reference needed to control pitch and yaw; roll was controlled by a sensor that locked on the bright star Canopus. When these celestial references were not visible to the sensors, stabilization was provided by three gyroscopes.

The photographic subsystem, which was built by the Eastman Kodak Company, contained elements for making photographs, processing the film and converting the image on the developed film into electrical analogue signals that were communicated to the earth. Although the system carried a single 260-foot roll of 70-millimeter film, the handling of the film was arranged—by means of storage loopers—to provide flexibility in moving the film through the camera, the processor and the readout apparatus at different rates and at appropriate times [*see bottom illustration on opposite page*].

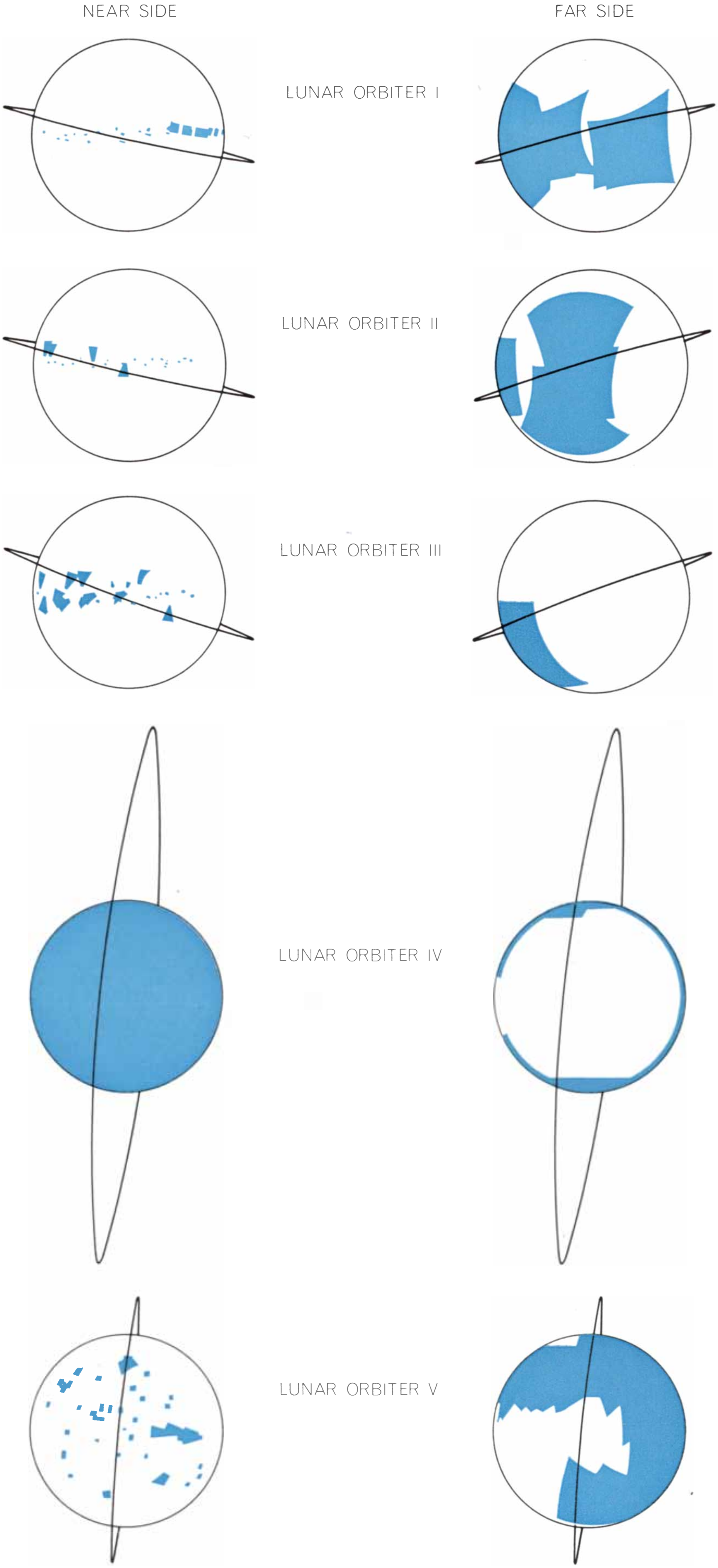
The camera had a wide-angle lens with a focal length of 80 millimeters and a telephoto lens with a focal length of 610 millimeters. Each had its own shutter. The shutters operated simultaneously, so that each exposure produced two photographs. At any given altitude the telephoto lens viewed about 5 percent of the terrain covered by the wide-angle lens but gave a resolution about eight times better than that provided by the wide-angle lens. For example, in vertical



SCANNING PROCESS moved a microscopic spot of light, generated by a beam of electrons aimed at a drum coated with a phosphor, along a portion of the film. The density of the image on the film governed the strength of the light reaching the photomultiplier tube, which generated electronic signals for transmission to the earth. One complete scan read out the information on a band of film that took up .1 inch along the length of the film and 60 millimeters of its width. These are the bands one sees in photographs from the Orbiters.



ACTUAL ALTITUDE of first Orbiter at perilune (*color*) is compared with three preflight calculations using different lunar-gravity assumptions. Earth's gravity causes 14-day variation. Perilune had to be chosen to avoid crashing prematurely or impairing photography.



photography at an altitude of 28.5 miles the telephoto lens covered an area 2.6 by 10.2 miles at a resolution of three feet; the wide-angle lens covered an area 19.6 by 23.2 miles at a resolution of 24 feet. Coverage of large areas was obtained by overlapping photographs made successively in the direction of flight or made on succeeding orbits.

Because the spacecraft moved at a speed of about 4,300 miles per hour while making photographs near perilune and the film exposures were rather long (1/25, 1/50 or 1/100 second) the photographs would have been blurred if the camera had not had a mechanism that compensated for the motion of the image at the plane of the film. This compensation was achieved by means of a device that sensed the velocity-to-height ratio of the spacecraft and drove the film platen to follow the image along the direction of flight. The sensor determined the velocity-to-height ratio by measuring the apparent motion of a small portion of the lunar surface as viewed through the telephoto lens.

The exposed film was developed in a processor using the Bimat technique devised by Eastman. In the Bimat method the exposed film is pressed against a special processing web, or rolled strip, with a gelatin layer that has been soaked in a solution that develops and fixes the film in one step. The film was then separated from the processing web and was dried by being passed over an electrically heated drum.

The developed film was read out by an electronic scanner that worked with a rapidly moving spot of light. One transverse band of film, called a framelet, was scanned at a time. A framelet occupied .1 inch of the length of the film and 2¼ inches of the film's width [*see top illustration on preceding page*]. One band can be regarded as analogous to a page in a book; reading it required 17,000 horizontal movements by the spot of light and took 22 seconds. At the end of a scan the film was advanced .1 inch and the next band was scanned in the same way, although in the opposite vertical

SUMMARY OF MISSIONS by the five Lunar Orbiter spacecraft shows the orbit of each one and, in color, the areas each one covered photographically. The primary mission of the Orbiters was to photograph potential Apollo sites on the near side of the moon along the equator. That work was essentially completed after the first three missions, so that the last two spacecraft were put into near-polar orbits to photograph other sites and most of the moon.

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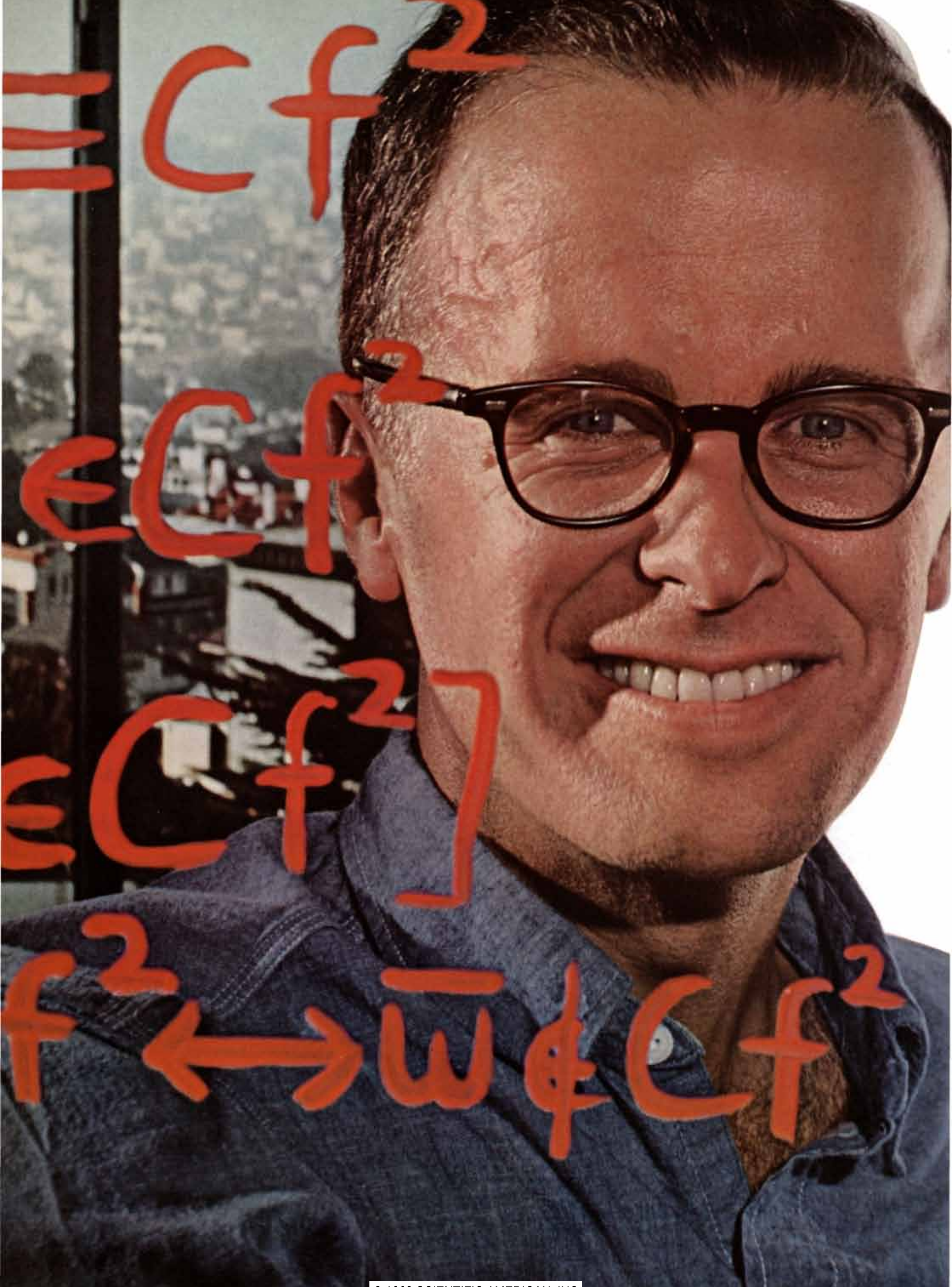

Meet an elder statesman in the computer business.

IBM's John Backus is 43, pretty young for an elder statesman in most industries. But then, the computer business is less than 20 years old. And mathematician Backus has been in it since the beginning.

He started working with computers in the early 1950's. It was about the time a leading business magazine estimated that no more than 50 companies would ever have use for a computer.

Today, it is estimated that there are well over 50,000 computer installations in the United States alone. Part of the reason for this astonishing growth: the progress made in programming. In this field, John Backus was a pioneer.

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With a small group of associates, John Backus tackled the problem and stayed with it for three years. The result was the simplified programming system called FORTRAN (FORmula TRANslator) which made programming considerably less expensive than before. Today, FORTRAN is probably the most widely used programming system in the world.

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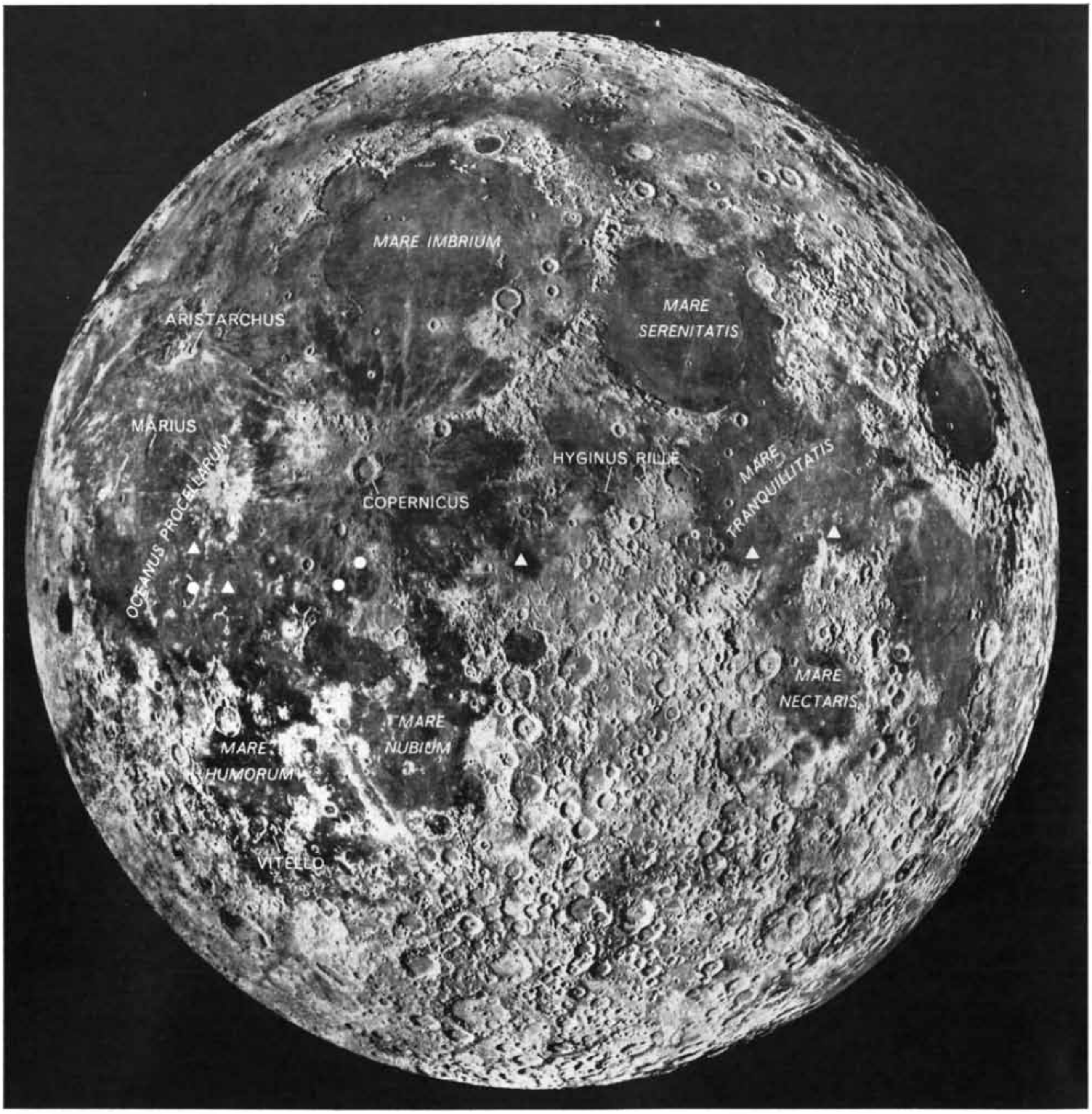
direction. It took about 43 minutes to scan the 11.6 inches of film taken up by one wide-angle and one telephoto exposure.

As the spot of light passed through the image on the negative it was modulated by the density of the image: the darker areas of the film transmitted less light than the lighter areas. The intensity of the light passing through the film at any moment was sensed by a photomultiplier tube, which generated an electrical signal proportional in strength to the intensity of the light. This signal, amplified and transmitted to the earth by means of the spacecraft's high-gain directional antenna, could be used to reproduce the images that had been obtained by the camera in the spacecraft.

The communications subsystem, provided by the Radio Corporation of America, used a technique called vestigial side-band amplitude modulation in conjunction with a 10-watt amplifier and the directional antenna to pack the wide-band video information and the accompanying telemetry into the band of frequencies allotted to the Deep Space Network. When the spacecraft was not transmitting photographs, telemetry from the spacecraft and commands to it were communicated through the low-gain omnidirectional antenna.

Reconstruction of the photographs on the earth involved recording each scanned band on 35-millimeter film. When the appropriate strips of 35-millimeter film are placed side by side, a duplicate of a photograph made by the spacecraft is produced (at an enlargement of about 7.5 diameters). The strips of 35-millimeter film, each representing

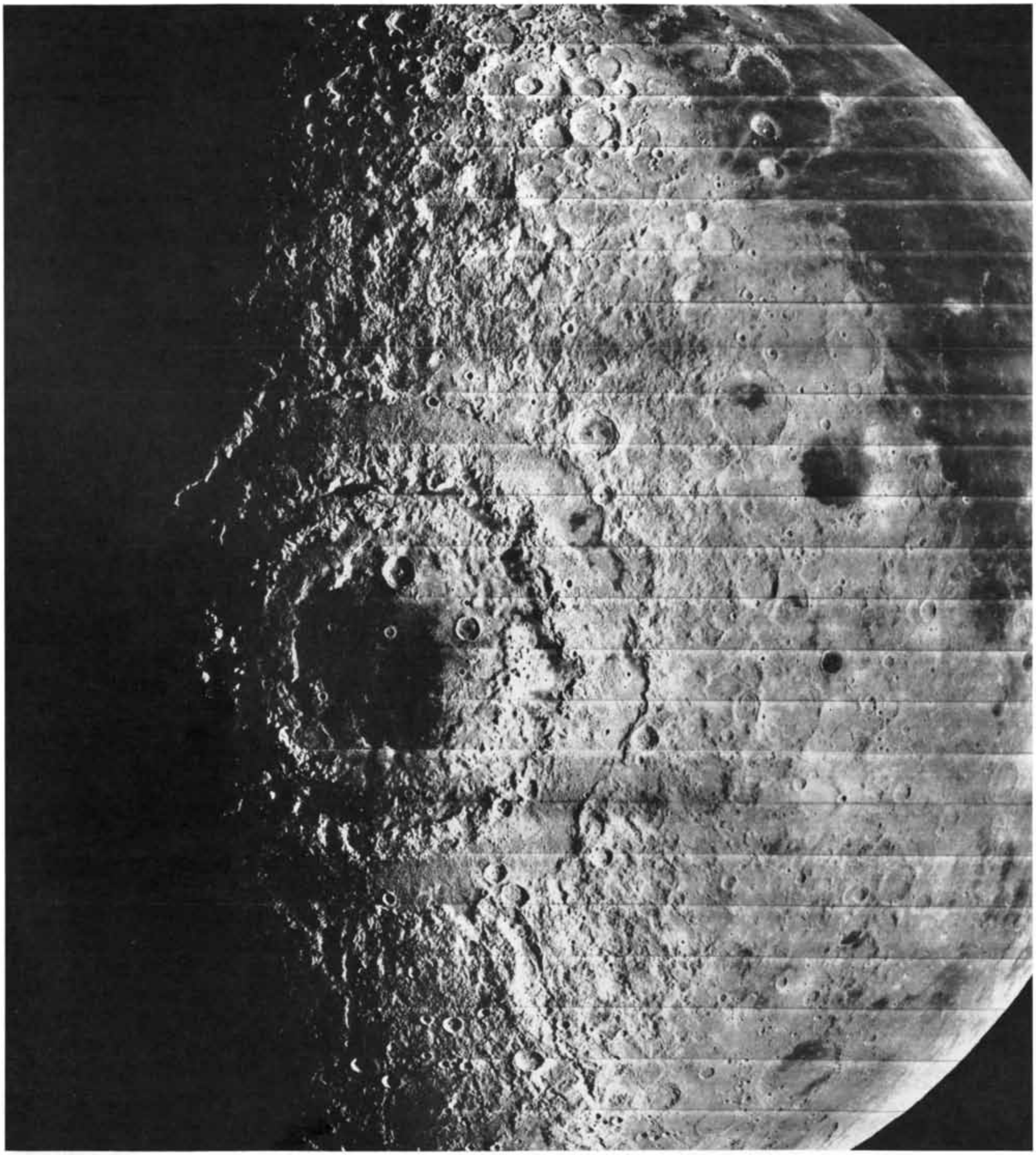


APOLLO SITES chosen by the National Aeronautics and Space Administration on the basis of photographs from Orbiter and Surveyor spacecraft are shown on a photograph made with an earth-based telescope. NASA first chose eight sites and then reduced the number to five, which are represented by triangles; circles indicate eliminated sites. Eventually the five sites will be reduced to three.

one scanned band of spacecraft film, give the Lunar Orbiter photographs their characteristic striped appearance.

A complete readout could not be started until all the film had been exposed. The direction of film movement during readout had to be the reverse of the direction in which the film moved as the photographs were being made. It was not possible to run film backward through the processor while the Bimat system was still functioning, because the dried negative might have stuck to the processing film. When all the film had been exposed, however, the Bimat web could be cut on command from the earth, and then the film could be pulled backward for readout.

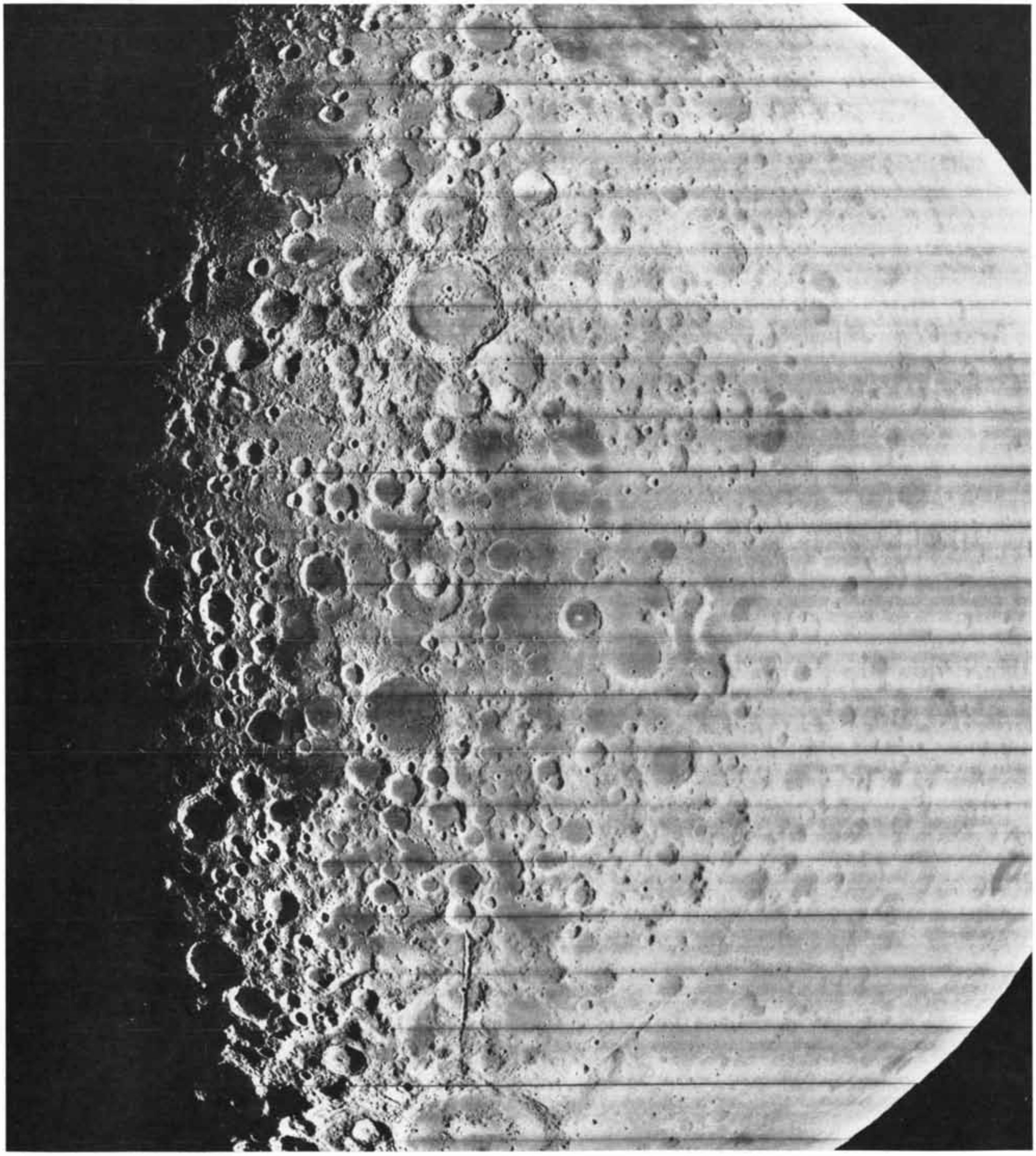
It seemed evident during the planning of the missions that some provision should be made for partial readout be-



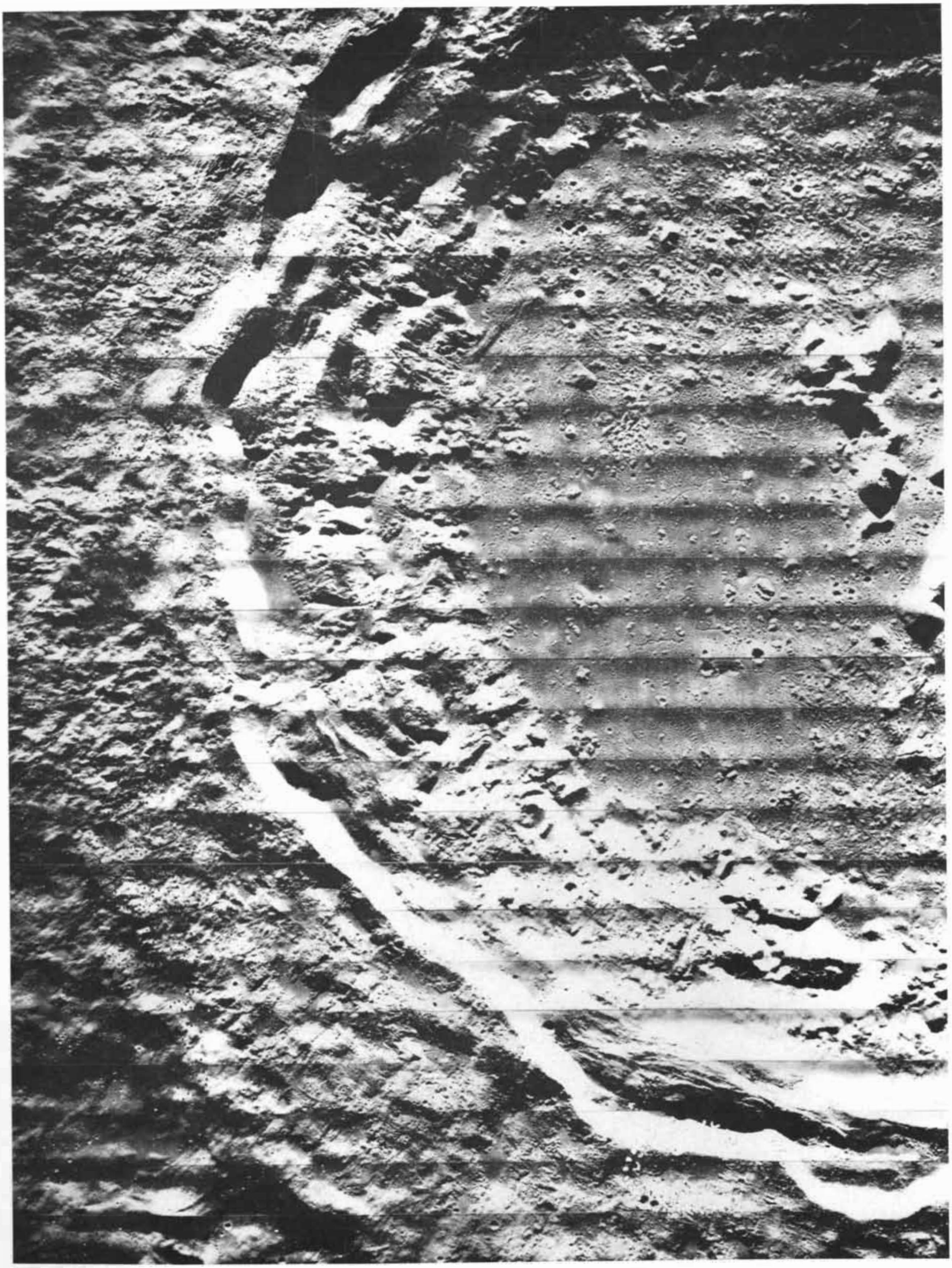
ORIENTALE BASIN is an enormous lunar feature that had not been viewed from above until *Lunar Orbiter IV* made this photograph from an altitude of 1,690 miles. The view is what one would see if it were possible to look around the lower left edge of the moon as it is seen from the earth. The Cordillera Mountains, which rim the basin on the right, can be seen from the earth, but only in profile. Across the outer ring the feature is about 600 miles in diameter. Orientale may be the most recent of the large circular lunar basins. The large dark area in the upper right part of the photograph is Oceanus Procellarum, which is visible from earth.

fore the photography was completed, not only because of the need to check on the quality of the photographs but also because there would be intense interest in what kind of scenes the cameras were recording. Accordingly a looper was built into the photographic subsystem between the processor and the scanner. A small amount of film could be read out and temporarily stored on the looper without going back into the processor. Many of the photographs that were published in newspapers and magazines during Lunar Orbiter missions were obtained with this system. Early readouts were also used for planning subsequent Surveyor and Orbiter missions.

The first of the Lunar Orbiter spacecraft was launched from Cape Kennedy on August 10, 1966. Succeeding ones were launched at intervals of approxi-



SOUTH-POLAR REGION of the moon was photographed through the wide-angle lens of *Lunar Orbiter IV* from an altitude of 1,856 miles. The view is what one would see if it were possible to look around the lower right edge of the moon as it is seen from the earth. The conspicuous trough near the bottom of the photograph is about 150 miles long. In places it is nearly five miles wide. It is also fairly young, as indicated by the fact that it cuts through several features. A still younger crater can be seen near the middle of the trough. It has been speculated that one way a trough could be made is by a rigid body that strikes the surface at a low angle.



CRATER COPERNICUS was photographed vertically through the wide-angle lens of *Lunar Orbiter V.* The crater is likely to be explored by a party from one of the Apollo missions because the slumping walls of the crater may expose a sequence of geological events. North is at left; the rim there is the one that appeared in widely reproduced oblique photographs of Copernicus from *Lunar Orbiter II.* The small dots in that area are marks resulting from the developing process in the spacecraft's photographic subsystem.

mately three months, so that the last of the Orbiters began its mission a little less than a year after the first one—on August 1, 1967. On many occasions the flexibility built into the system proved invaluable.

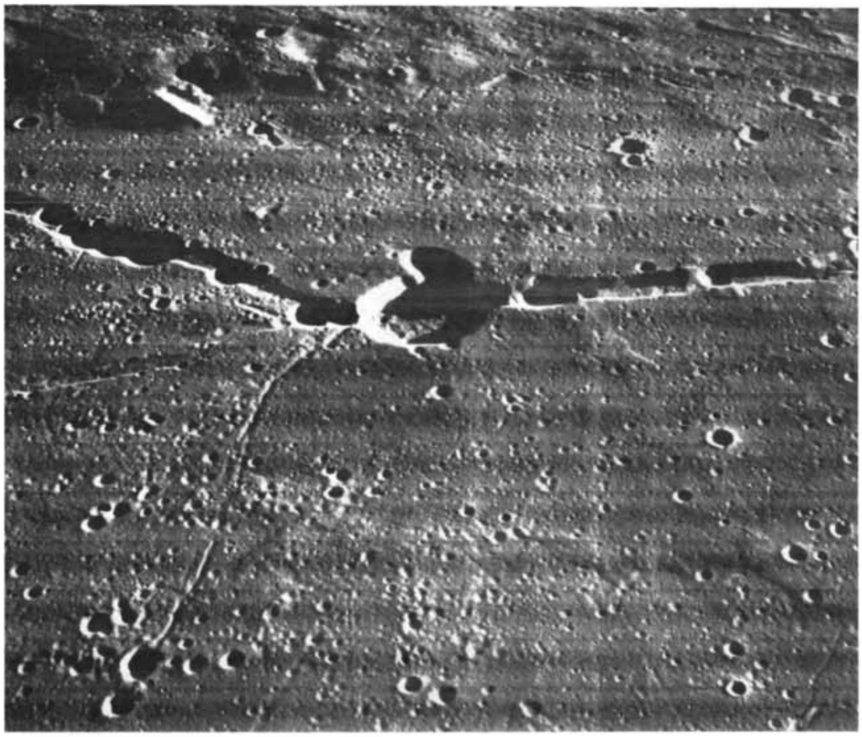
For example, the mission of *Lunar Orbiter I* had no advance plan for using certain frames of film involved in dealing with what was called the film-set problem: the fact that the film had to be moved after a certain amount of time, even if no photography was in progress, so that it would not be deformed by remaining too long on any of the sharp bends in the winding mechanism. As the mission proceeded it was decided to use these frames to obtain previews of sites for later missions, photographs of the far side and a picture showing the earth as it is seen from just beyond the limb of the moon.

The instrument for such flexibility was the digital programmer carried by each Lunar Orbiter. The programmer controlled more than 70 functions of the spacecraft. It could store a large program of instructions, which could be changed by command from the earth whenever the spacecraft was within reach of communications. With each successive mission more use was made of the programmer's capabilities.

The Missions

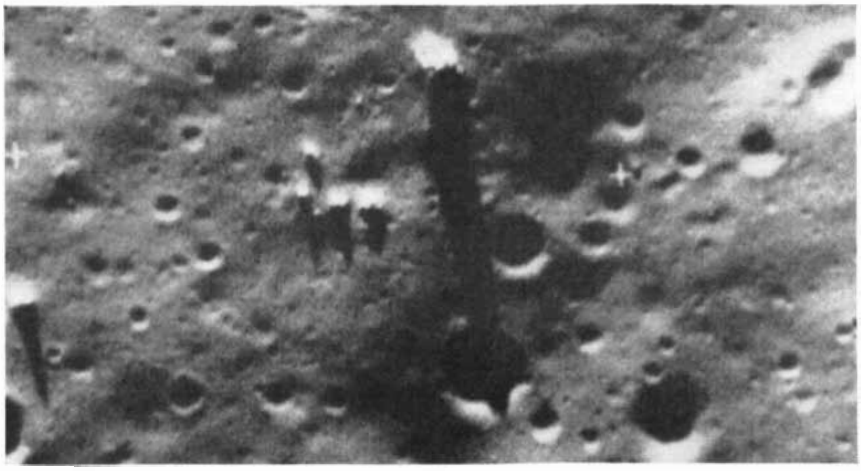
Lunar Orbiter I primarily accomplished an examination of nine potential Apollo sites in the southern portion of the equatorial band in which all such sites are located. *Lunar Orbiter II* made a similar examination of sites in the northern portion of the band. In addition *Lunar Orbiter II* undertook an experiment in converging stereoscopic photography, which entails making overlapping photographs of a given site from two different orbits. The technique is particularly valuable for photographic analysis of the topography of an area. The results were so good that it was decided to add such coverage to the photography planned for the Apollo sites. *Lunar Orbiter II* also made oblique photographs of many areas of scientific interest. One such picture, widely published at the time, showed the inside of the crater Copernicus from a perspective that could not have been obtained from the earth.

The third Orbiter made a detailed examination of 10 promising Apollo sites selected from the photographs secured during the first two missions. After the third mission NASA made its selection of eight sites as being the most promising

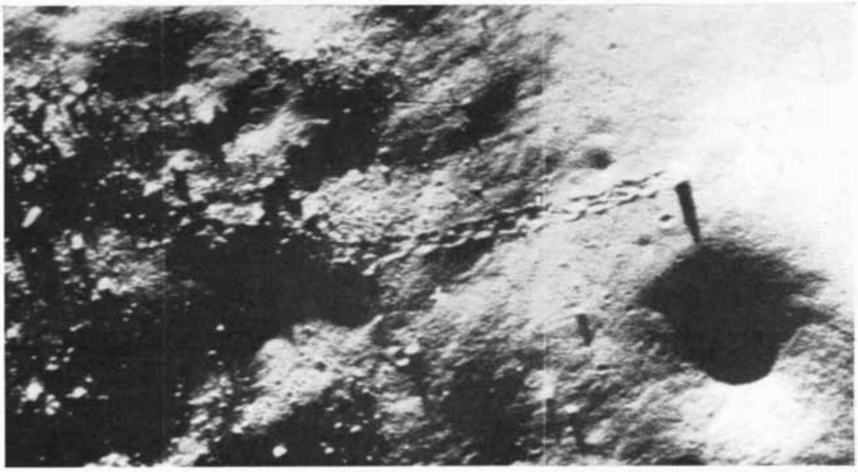


HYGINUS RILLES extend to the northwest and the east of the crater Hyginus, which is about 6½ miles in diameter and 2,600 feet deep. The oblique photograph was made by *Lunar Orbiter III*. The two large rilles appear to be associated with Hyginus and a smaller rille extending to the southwest appears to be associated with a smaller crater near Hyginus.

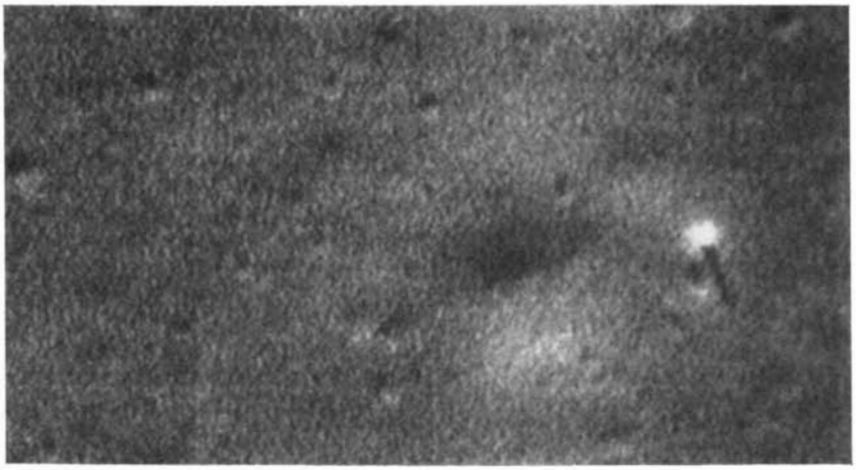
FINE DETAIL of a terrace, a steep slope and a mare area in Oceanus Procellarum was obtained through the telephoto lens of *Lunar Orbiter III* at an altitude of about 32 miles.



LARGE OBJECTS, probably boulders, cast long shadows in an enlargement of a photograph made with the telephoto lens of *Lunar Orbiter II.* The object casting the longest shadow is about 50 feet wide at its base and stands as much as 75 feet high. The white cross is a reference mark preexposed on the film; width of cross represents about 25 feet of lunar surface.



DISLODGED ROCK in the crater Vitello has left a 250-yard trail on the lunar surface after rolling down a slope into a depression and up the other side. The rock is about 19 yards in diameter. The view is an enlargement of a photograph made with the telephoto lens of *Lunar Orbiter V.* Many rocks, including several that had rolled, were observed in Vitello.



SURVEYOR I SPACECRAFT is identifiable by the shadow it casts. Its landing place was photographed with the telephoto lens of *Lunar Orbiter III* and its location was established by means of triangulation from objects that appear in photographs made by *Surveyor I.*

for the Apollo missions. Since then NASA has reduced the number of sites to five; eventually it plans to focus on three sites for planning Apollo missions.

The primary task of the Lunar Orbiter program was essentially completed during the first three missions. Accordingly NASA used the last two Orbiters to photograph areas of scientific interest. *Lunar Orbiter IV* was assigned the task of photographing the entire front face of the moon, which it did at resolutions of 150 to 300 feet. It also made excellent vertical photographs of the lunar limbs.

Lunar Orbiter V photographed 51 selected areas on the near side at resolutions of six to 16 feet, virtually completed the coverage of the far side and added a photograph of what an observer on the moon would call a nearly full earth. The mission also secured stereoscopic photographs of Apollo areas not previously covered by that technique and obtained oblique photographs simulating what Apollo astronauts might see as they approach the moon.

Among the sites of particular scientific interest was the crater Aristarchus, where some earth-based observers had detected signs of what they thought might be current volcanic activity. Similarly, *Lunar Orbiter V* obtained photographs of the Marius Hills region, which has a number of domelike structures that might be indicative of past volcanic activity. Another area of interest is Copernicus, where the slumping of walls might be expected to have exposed a sequence of geological events on the moon. Such a site would be a prime target of exploration during one of the Apollo missions. *Lunar Orbiter V* made vertical photographs of Copernicus to complement the oblique photographs obtained by the second Orbiter.

All the Lunar Orbiters remained in orbit for a time after completing their photographic mission. During that period they continued gathering data from their nonphotographic experiments on radiation, micrometeoroids and lunar gravitation. They also were used for other special tests. Eventually each Orbiter except the fourth was deliberately crashed onto the lunar surface. The reason was to make sure that they would not become sources of interference with communication between the earth and other spacecraft that are sent to the moon or elsewhere in the future. Communication between the earth and *Lunar Orbiter IV* was lost in July, 1967, but computations of its orbit indicate that it crashed on the moon in October.

We are not in a position to interpret in detail the photographs from the Orbiter missions. Analysis of the lunar surface by means of the photographs is being done by NASA, other Government agencies and independent investigators. We think the photographs accompanying this article, which provide examples of both the wide-angle and the telephoto coverage obtained by the Orbiter cameras, speak for themselves in terms of photographic quality and the detail they show.

A Sampling of Photographs

It is possible to point out here several of the interesting lunar features in the photographs that either cannot be seen from the earth or are viewed from perspectives not available to earth-based observers. In a wide-angle photograph of the far side of the moon [*pages 58 and 59*] the most conspicuous feature in the rugged terrain is the crater called Tsiolkovsky, which is largely filled with the dark material characteristic of a lunar mare, or "sea."

The Orientale Basin [*page 72*] can be partly seen from the earth, but in a perspective that gives no hint of its extraordinary bull's-eye configuration or its great size. The Cordillera Mountains, which form the eastern rim of the basin, are visible from the earth, but only in profile because they appear at the left edge of the moon's visible face.

Near one of the potential Apollo landing sites is a crater [*illustration at right*] that gives the appearance of having been formed more recently than most of the others so far studied on the moon. The crater, which is about 500 feet in diameter, is in Oceanus Procellarum about 35 miles north of the lunar equator and 800 miles west of the center of the moon's visible face. The material ejected from the crater overlies all the surrounding material and appears to be much less eroded than other features.

Evidence that objects on the moon sometimes move appears in a photograph showing part of the inside of the crater Vitello [*middle of opposite page*]. A boulder visible in the photograph has rolled into and out of a small depression, leaving a distinct trail. The boulder is about 60 feet in diameter.

The kind of terrain that NASA is considering for the landing of Apollo spacecraft can be seen in a photograph [*page 62*] made with the wide-angle lens of the camera aboard *Lunar Orbiter III*. The terrain is fairly smooth. The site is 48 degrees west of the center of the visible face of the moon.

An unusual view of the rille, or valley, associated with the crater Hyginus appears [*top of page 75*] in an enlargement of part of a wide-angle photograph secured by *Lunar Orbiter III*. The feature is visible from the earth but not in this perspective. The crater itself is about 6½ miles wide and 2,600 feet deep.

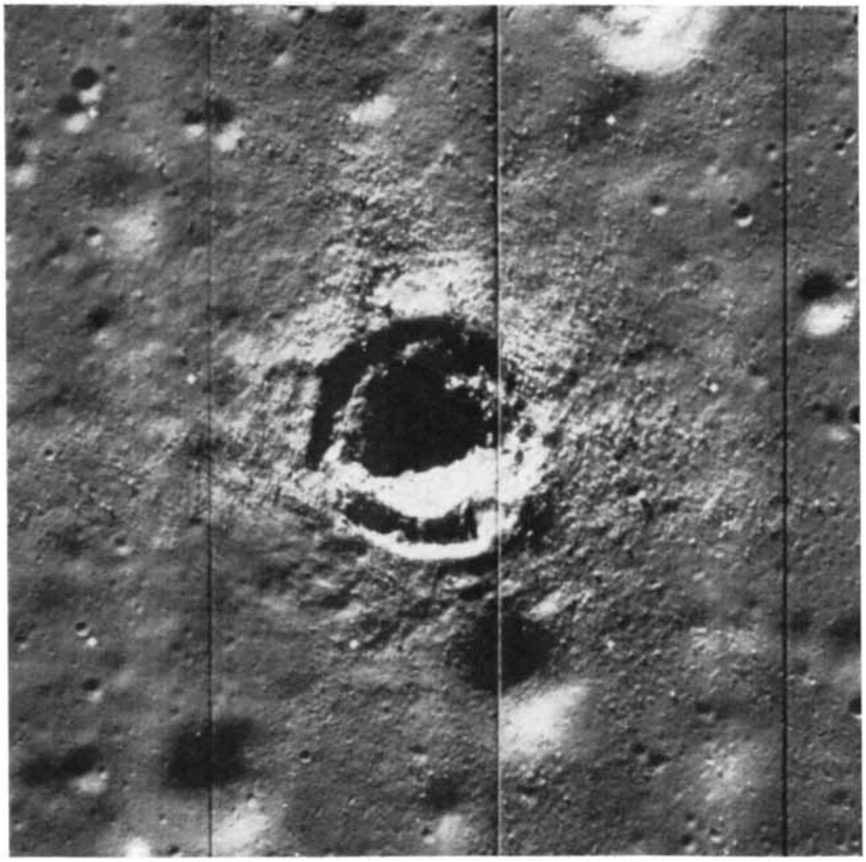
Nonphotographic Results

By means of the Lunar Orbiter spacecraft it was possible to gather a considerable amount of information about the moon's gravitational field, the intensity of solar radiation in the vicinity of the moon and the frequency of micrometeoroids. These data have been summarized for us by three investigators at NASA's Langley Research Center in Virginia. William H. Michael, Jr., is principal investigator for the experiments in selenodesy, Trutz Foelsche for the radiation measurements and Charles Gurtler for the detection of micrometeoroids.

Michael reports that the analyses of data obtained from tracking Lunar Orbiter spacecraft have provided new information on the moon's mass, its density and its radius. He writes: "The new determination of the mass of the moon has been performed by a more direct procedure than that used in previous analyses, and the result is in close agreement with the value obtained from analyses of Ranger spacecraft data. Present indications . . . are that the material in the interior of the moon is probably of more or less uniform density, that the density increases somewhat toward the center of the moon, but that a small core of higher-density material cannot yet be completely ruled out. These indications are in contrast to somewhat questionable previous results, obtained prior to the establishment of lunar satellites, which suggested that the density of the moon was greater in the outer portions of the moon.

"The radius of the moon in the equatorial region on the near side . . . is about two kilometers less than that previously obtained from analyses of earth-based photographs. This result may indicate either that the mean radius of the moon is less than was previously thought or that the center of mass of the moon is slightly displaced toward the earth relative to the center of figure."

Among the conclusions reached by



RECENT CRATER is identifiable by the freshness of the material around it. Boulders as small as one yard in diameter can be seen in the pattern of rays. Sliding of the material inside the crater has caused the double-wall appearance. The crater, which is in Oceanus Procellarum, is about 165 yards wide. The third Orbiter made photograph at 31-mile altitude.

VIEW OF THE EARTH from a distance of 224,000 miles was made through the telephoto lens of *Lunar Orbiter V* last August 8. The time was noon in Saudi Arabia, which occupies most of the Arabian Peninsula (*left center*). Spacecraft was about 3,640 miles above moon.

PRINCIPAL FEATURES of the earth that can be seen in the Lunar Orbiter photograph at the top of this page are identified. Some features were partly obscured by light clouds.

Foelsche and his colleagues are the following: (1) No trapped energetic particles are observed near the moon over long periods when the sun is quiet. Thus the intrinsic magnetic field of the moon is weaker than the one at the boundary of the earth's radiation belts; indeed, the moon may have no magnetic field. This finding leads to the conclusion that the moon, unlike the earth, does not have an extended liquid core in which slow fluid motions can occur. (2) Three events involving the emission of energetic particles by the sun were detected by the Lunar Orbiter spacecraft. All the events were of moderate scale and fairly low particle energy.

Gurtler reports that 18 punctures were recorded by the 100 micrometeoroid detectors carried by the Orbiter spacecraft. (There were 20 detectors on each spacecraft.) "These data," he writes, "indicate that the measured rate in the lunar environment is less than half the rate in the near-earth environment as measured by the same type of detectors on *Explorer XVI* and *Explorer XXIII*." According to Gurtler the punctures were distributed randomly around the Orbiter spacecraft, suggesting that the micrometeoroids did not come from any preferred direction.

The work of many agencies, companies and individuals was brought together on the Lunar Orbiter team. The efforts of all who participated in the program are acknowledged, even though it is not possible to name them here.

In the American program of lunar exploration attention is now focused on the Apollo project. When the men in an Apollo landing vehicle approach the moon, they will have the benefit of Lunar Orbiter photographs to help them identify their landing area and the landmarks around it. Later missions will use Lunar Orbiter photographs to select areas on the moon that seem particularly likely to reward the kind of close inspection that parties of astronauts will be able to conduct. The astronauts will also have the benefit of the nonphotographic findings from the Orbiter missions as a major contribution to the effort to make their mission to the moon a safe one.

Analysis of the photographs should yield knowledge about the processes that shaped the lunar surface. That knowledge could be expected to contribute to the understanding of the processes that formed the surface of the earth. Finally, the extensive knowledge and operational experience gained from the Orbiter missions will surely contribute to the exploration of the planets beyond the moon.

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Despite this scientists are optimistic. In fact, current results indicate that reliable 14-day forecasts are a distinct future possibility. Also, the observational network must be expanded to the whole of the earth.

It will take some time, therefore, before two week forecasts become standard. Scientists estimate five to ten years.

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But in the past I could never really see what I had done until I brought it back to the lab. Then I would often look at the results and wonder if I had not missed something. Perhaps a different angle, lens opening, or some little detail which could have improved the composition.

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Take this photograph, for instance. As you can see, it was taken in a wooded area near a small stream. The sun was peeking through the clouds and hitting different places with different light effects. What you can't see is the large variety of photographs that came before it. Because I began to get new ideas as I saw each new picture. In fact I became so engrossed that I hardly noticed when it became dark.

Later in looking over what I had taken I became aware that I had explored things in a new way. Some of the photographs were very uncharacteristic of me. And that's good. Because anything that starts you thinking in a fresh way is good.

I used to cultivate accidents. Now with Polaroid film, I can cultivate results. This I could never do before."

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The Flight-Control System of the Locust

Groups of nerve cells controlling such activities as locomotion are regulated not only by simple reflex mechanisms but also by behavior patterns apparently coded genetically in the central nervous system

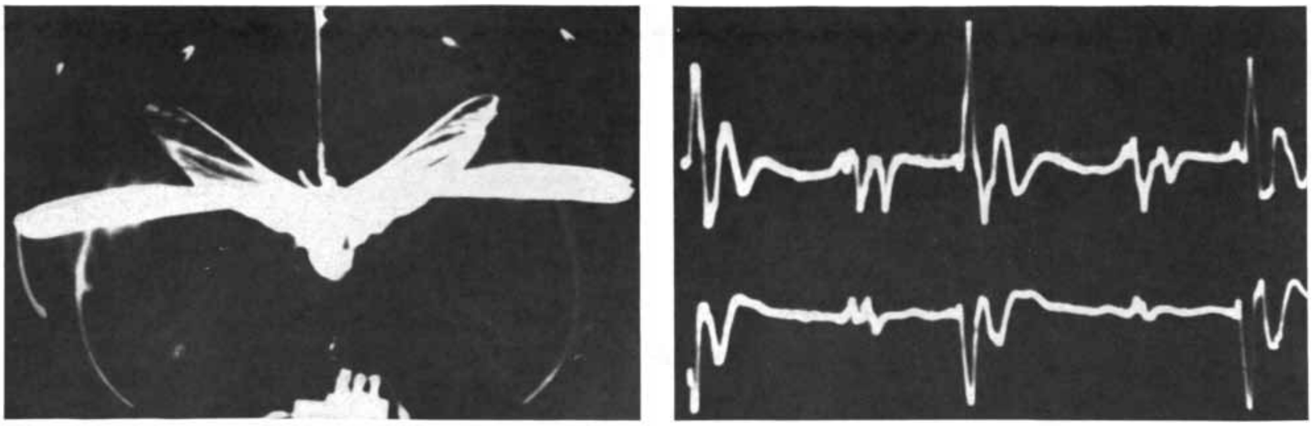
by Donald M. Wilson

Physicists can properly be concerned with atoms and subatomic particles as being important in themselves, but biologists often study simple or primitive structures with the long-range hope of understanding the workings of the most complex organisms, including man. Studies of viruses and bacteria made it possible to understand the basic molecular mechanisms that we believe control the heredity of all living things. Adopting a similar approach, investigators concerned with the mechanisms of behavior have turned their attention to the nervous systems of lower animals, and to isolated parts of such systems, in the hope of discovering the physiological mechanisms by which behavior is controlled.

One way to approach the study of behavior mechanisms is to ask: Where does the information come from that is needed to coordinate the observable activities of the nervous system? We know that certain behavior patterns are inherited. This means that some of the informational input must be directly coded in the genetic material and therefore has an origin that is remote in time. Nonetheless, probably all behavior patterns depend to some degree on information supplied directly by the environment by way of the sense organs. Behavior that is largely triggered and coordinated by the nervous input of the moment is commonly called reflex behavior. Much of neurophysiological research has been directed at the analysis of reflex behavior mechanisms. Recent work makes it clear, however, that whole programs for the control of patterns of animal activity can be stored within the central nervous system [see "Small Systems of Nerve Cells," by Donald Kennedy; SCIENTIFIC AMERICAN, May, 1967]. Apparently these inherited nervous programs do not require much special input information for their expression.

I should point out here that whereas there is now general agreement among biologists that many aspects of animal behavior are under genetic control, it is not easy to show in particular cases that a kind of behavior is inherited and not learned. I believe, however, that this is a reasonable assumption for the cases to be discussed in this article, namely flight and walking by arthropods (insects, crustaceans and other animals with an external skeleton).

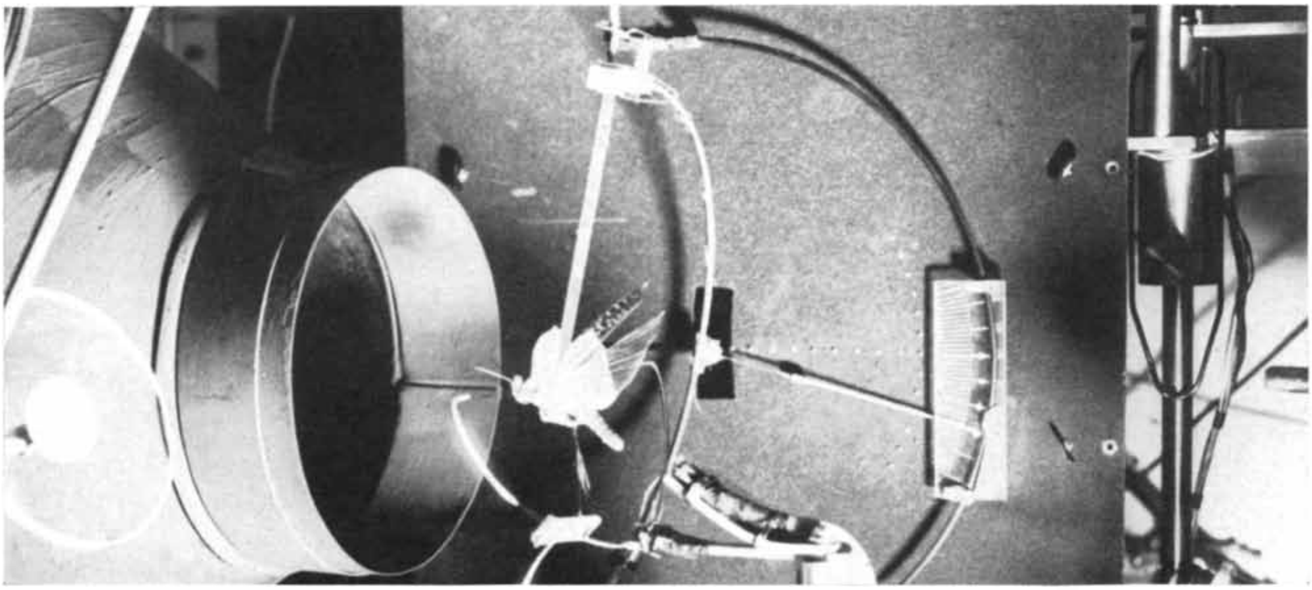
The studies I shall describe were begun as part of an effort to demonstrate how several reflexes could be coordinated into an entire behavior pattern. Until recently it was thought by most students of simple behavior such as locomotion that much of the patterning of the nervous command that sets the muscles into rhythmic movement flowed rather directly from information in the immediately preceding sensory input. Each phase of movement was assumed to be triggered by a particular pattern of input from various receptors. According to this hypothesis, known as the peripheral-



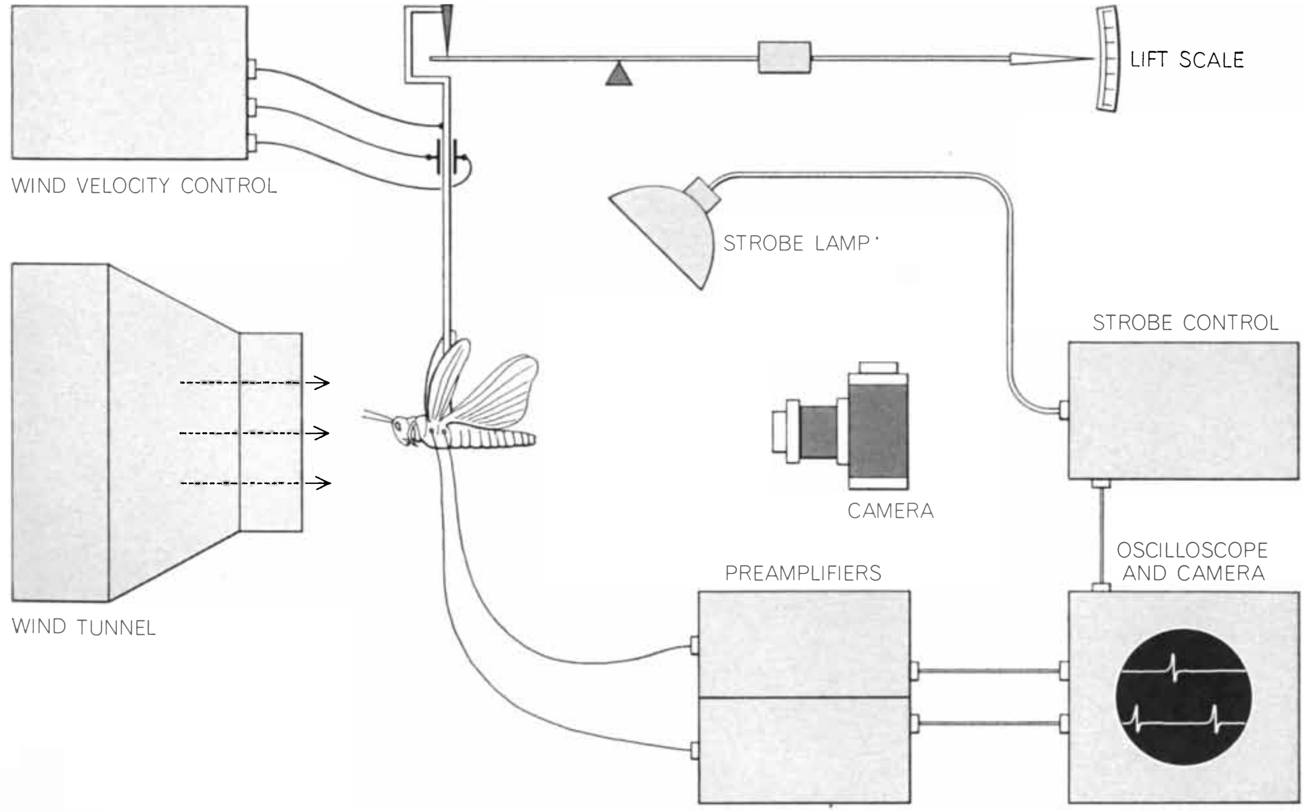
LOCUST WING position and wing-muscle action potentials were recorded in synchronous photographs. The flash that illuminates the locust (*left*) is triggered by the first muscle potential (*at left on oscilloscope trace*). The wing motion is traced by spots of white paint on each wing tip that reflect room light through the open shutter. The trace at the top shows three "doublet" firings of downstroke muscles controlling the forewing; the bottom trace shows similar firings for the hindwing. The smaller potentials visible between the large doublets are from elevator muscles more remote from the electrodes. The oscilloscope traces span 100 milliseconds.

control hypothesis, locomotion might begin because of a signal from external sense organs such as the eye or from brain centers, but thereafter a cyclic reflex process kept it properly timed.

This cyclic reflex could be imagined to operate as follows. An initiating input causes motor nerve impulses to travel to certain muscles, and the muscles cause a movement. The movement is sensed by position or movement receptors within the body (proprioceptors), which send impulses back to the central nervous system. This proprioceptive feedback initiates activity in another set of muscles, perhaps muscles that are antagonists of the first set. The sequence of motor outputs and feedbacks is connected so that it is closed on itself and cyclic activity results. Clearly such a system depends on a well-planned (probably inherited) set of connections among the many parts involved; thus both the central nervous system and its peripheral extensions (the



NERVE AND MUSCLE impulses were recorded during flight with this equipment. The locust is flying, suspended at the end of a pendulum, at the mouth of a wind tunnel. The scale at the right registers the insect's angle of pitch. The wires lead to amplifiers.



EXPERIMENTAL SETUP is diagrammed. The motion of the pendulum controls the wind-tunnel blower, so that the insect can fly at its desired wind speed. Muscle or nerve impulses are displayed on the oscilloscope, which in turn controls the stroboscopic flash lamp.

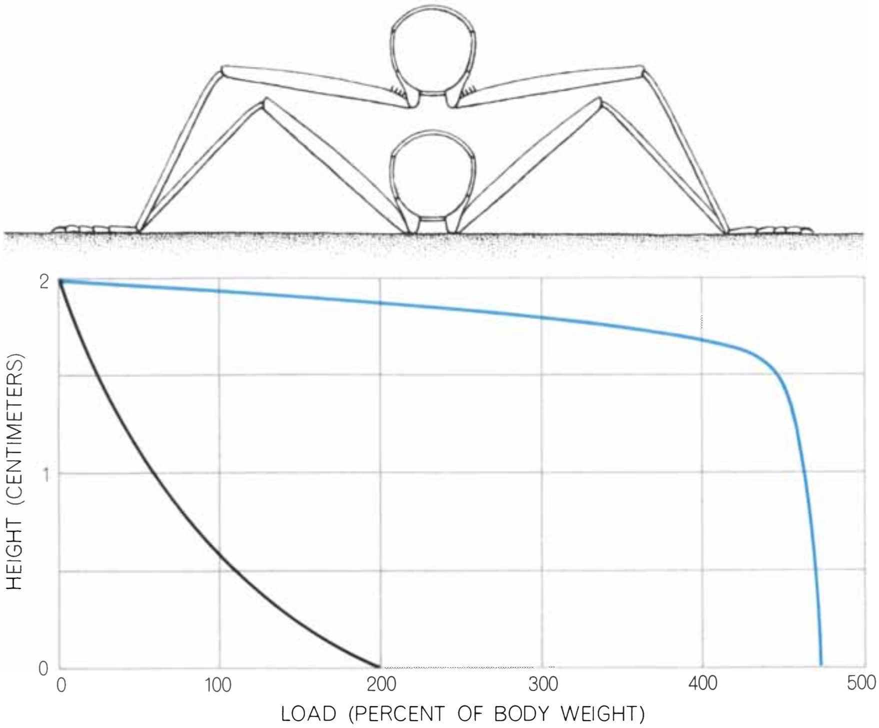
muscular and sensory structures) are crucial to the basic operation of the system.

An alternative hypothesis, known as the central-control hypothesis, suggests that the output pattern of motor nerve impulses controlling locomotion can be generated by the central nervous system alone, without proprioceptive feedback. This hypothesis has received much support from studies of embryological development. Only a few zoophysiologists have favored it, however, because the existence of proprioceptive reflexes had been clearly demonstrated. It seemed that if such reflexes exist, they must operate.

Proprioceptive reflexes certainly play an important role in the maintenance of posture. I suspect that this may be their basic and primitive function. In many animals—insects and man included—proprioceptive reflexes help to maintain a given body position against the force of gravity. A simple example was described by Gernot Wendler of the Max Planck Institute for the Physiology of Behavior in Germany. The stick insect, named for its appearance, stands so that its opposed legs form a flattened "M" [*see illustration at right*]. Sensory hairs are bent in proportion to the angle of the leg joints. The hairs send messages to the central nervous ganglia, concentrated groups of nerve cells and their fibrous branches that act as relay and coordinating centers. If too many impulses from the hairs are received, motor nerve cells are excited that cause muscles to contract, thereby moving the joint in the direction that decreases the sensory discharge. Thus the feedback is negative, and it results in the equilibration of a certain position.

If a weight is placed on the back of the insect, one would expect the greater force to bend the leg joints. Instead the proprioceptive feedback loop adjusts muscle tension to compensate for the extra load. The body position remains approximately constant, unless the weight is more than the muscles can bear. If the hair organs are destroyed, the feedback loop is opened and the body sags in relation to the weight, as one would expect in an uncontrolled system.

If the leg reflexes of arthropods are studied under dynamic rather than static conditions, one finds also that they are similar to the reflexes of vertebrates. When a leg of an animal is pushed and pulled rhythmically, the muscles respond reflexively with an output at the same frequency. At high frequencies of movement the reflex system cannot keep up and the output force developed by the muscles lags behind the input movement. The peripheral-control hypothesis postulates an interaction of similar reflexes in each of the animal's legs. If one leg is commanded to lift, the others must bear more weight and postural reflexes presumably produce the increased muscle force that is needed. If any part oscillates, other parts oscillate too, perhaps in other phase relations. Although no such total system has been analyzed, one can imagine a sequence of reflex relationships that could coordinate all the legs into a smooth gait.



STICK INSECT keeps its body height nearly constant as the load on its leg muscles changes. Hairs at the first leg joint sense the angle of the joint and a reflex loop maintains the angle until the animal is overloaded (*colored curve*). If the sensory hairs are damaged, the reflex loop is opened and the body sags quickly as more weight is added to it (*black curve*).

Against this background I shall describe the work on the nervous control of flight in locusts I began in the laboratory of Torkel Weis-Fogh at the University of Copenhagen in 1959. Weis-Fogh and his associates had already investigated many aspects of the mechanisms of insect flight, including the sense organs and their role in the initiation and maintenance of flight [see "The Flight of Locusts," by Torkel Weis-Fogh; Scientific American, March, 1956]. These studies, and the general climate of opinion among physiologists, tended to support a peripheral-control hypothesis based on reflexes. To test this hypothesis I set out to analyze the details of the reflex mechanisms.

An important consideration in the early phases of the work was how to study nervous activities in a small, rapidly moving animal. This was accomplished by having locusts fly in front of a wind tunnel while they were suspended on a pendulum that served as the arm of an extremely sensitive double-throw switch. The switch operated relays that controlled the blower of the tunnel, so that whenever the insect flew forward, the wind velocity increased and vice versa. Thus the insect chose its preferred wind speed, but it stood approximately still in space. Other devices measured aerodynamic lift and body and wing positions; wires that terminated in the muscles or on nerves conducted electrical impulses to amplifying and recording apparatus.

Early in the program of research we found that fewer than 20 motor nerve cells control the muscles of each wing, and that we could record from any of the motor units controlled by these cells during normal flight. We drew up a table showing when each motor unit was activated for various sets of aerodynamic conditions. The results of this rather tedious work were not very exciting but did provide a necessary base for further investigation. Moreover, I think we can say that these results constitute one of the first and most complete descriptions of the activity of a whole animal analyzed in terms of the activities of single motor nerve cells. In brief, we found that the output pattern consists of nearly synchronous impulses in two small populations of cooperating motor units, with activity alternating between antagonistic sets of muscles, the muscles that elevate the wings and the muscles that depress them. Each muscle unit normally receives one or two impulses per wingbeat or no impulse at all. The variation in the number of excitatory impulses sent to the different muscles serves to control flight power and direction.

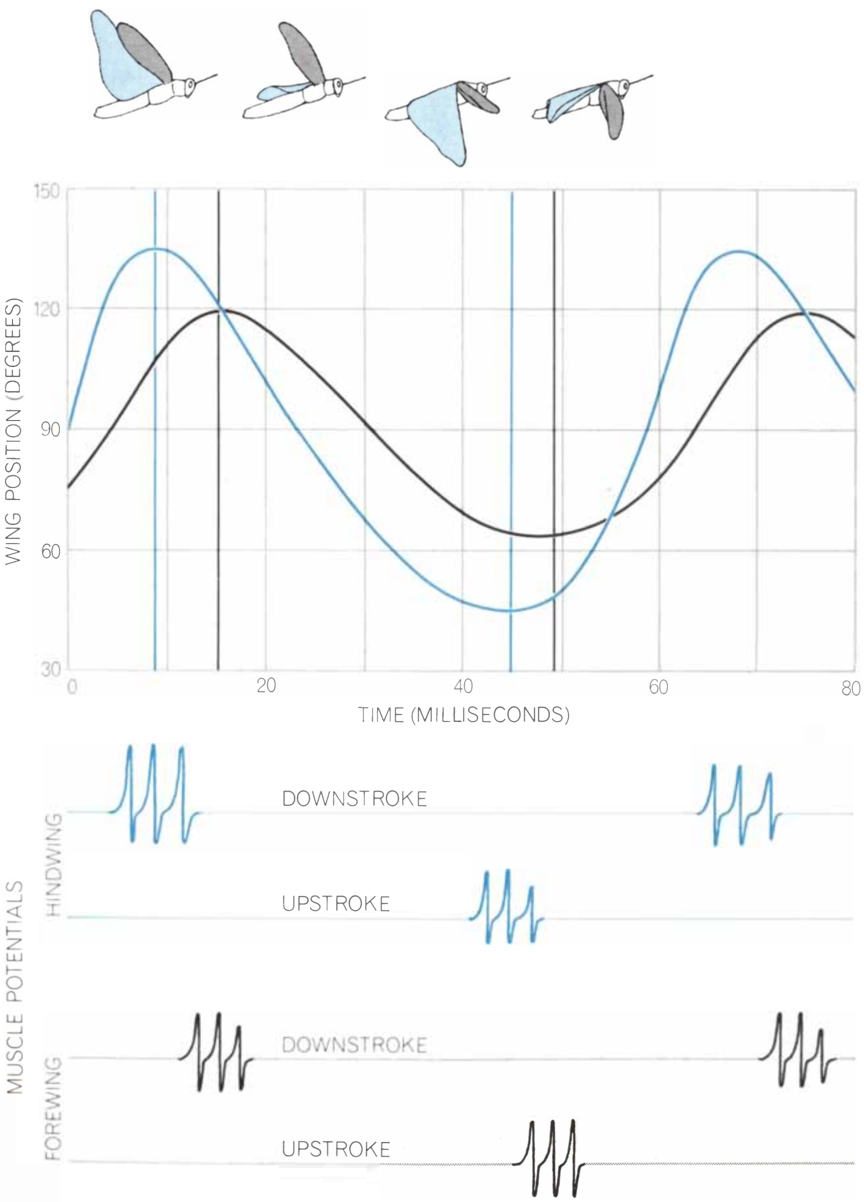
We also found it possible to record from the sensory nerves that innervate, or carry signals to, the wings. These nerves conduct proprioceptive signals from receptors in the wing veins and in the wing hinge. The receptors in the wing veins register the upward force, or lift, on the wing; the receptors in the wing hinge indicate wing position and movement in relation to the body. These sensory inputs occur at particular phases of the wing stroke. The lift receptors usually discharge during the middle of the downstroke; each wing-hinge proprioceptor is a stretch receptor that discharges one, two or several impulses toward the end of the upstroke [*see illustration on page* 88].

Everything I have described so far about the motor output and sensory input of an insect in flight is consistent with the peripheral-control hypothesis. Motor impulses cause the movements the receptors register. According to the hypothesis the sensory feedback should trigger a new round of output. Does this actually happen?

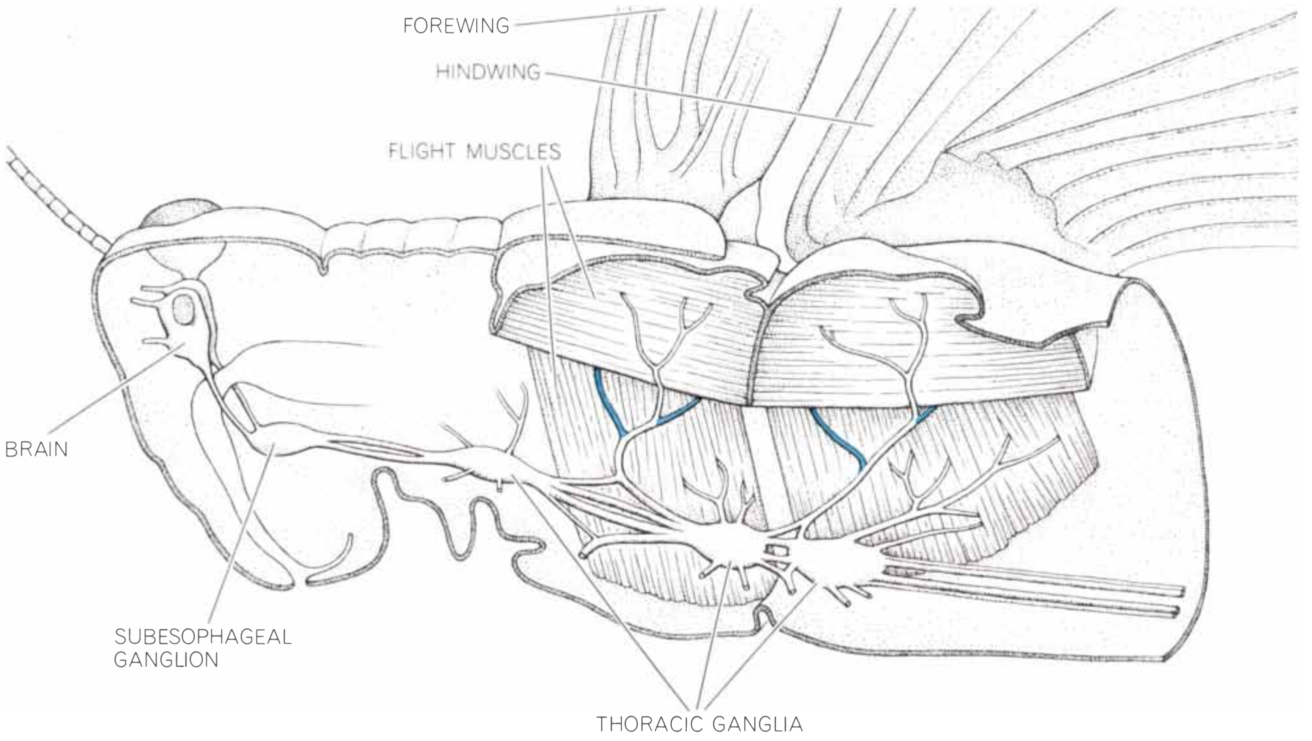
A useful test of feedback-loop function is to open the loop. This we did simply by cutting or damaging the sense organs or sensory nerves that provide the feedback. Cutting the sensory nerve carrying the information about lift forces caused little change in the basic pattern of motor output, although it did affect the insect's ability to make certain maneuvers. On the other hand, burning the stretch receptors that measure wing position and angular velocity always resulted in a drastic reduction in wingbeat frequency. These proprioceptors provide the only input we could discover that had such an effect. Most important of all, we found that, even when we eliminated all sources of sensory feedback, the wings could be kept beating in a normal phase pattern, although at a somewhat reduced frequency, simply by stimulating the central nervous system with random electrical impulses.

From these studies we must conclude that the flight-control system of the locust is not adequately explained by the peripheral-control hypothesis and patterned feedback. Instead we find that the coordinated action of locust flight muscles depends on a pattern-generating system that is built into the central nervous system and can be turned on by an unpatterned input. This is a significant finding because it suggests that the networks within the nerve ganglia are endowed through genetic and developmental processes with the information needed to produce an important pattern of behavior and that proprioceptive reflexes are not major contributors of coordinating information.

Erik Gettrup and I were particularly curious to learn how the wing-hinge proprioceptor, a stretch receptor, helped to control the frequency of wingbeat. When Gettrup analyzed the response of this receptor to various wing movements, he found that to some degree it signaled to the central nervous system information on wing position, wingbeat amplitude and wingbeat frequency. We then cut out the four stretch receptors so that the wingbeat frequency was reduced to about half the normal frequency and artificially stimulated the stumps of the stretch receptors in an attempt to restore normal function. Under these conditions we found that electrical stimulation of the stumps could raise the frequency of wingbeat no matter what input pattern we used. Although the normal input



MUSCLE-POTENTIAL RECORDS are summarized in relation to wing positions in a flying locust. The curves (*top*) show the angular position (90 degrees is horizontal) of the hindwings (*color*) and forewings (*black*). The four simulated traces at the bottom show how the downstroke and upstroke muscles respectively fire at the high and low point for each wing.



NERVES AND MUSCLES controlling flight in the locust are shown in simplified form. The central nervous system includes the brain and the various ganglia. From the thoracic ganglia, motor nerves lead to the wing's upstroke muscles (*vertical fibers*) and the downstroke muscles (*horizontal fibers*) above them. There are also sensory nerves (*color*) that sense wing position and aerodynamic forces.

from the stretch receptor arrives at a definite, regular time with respect to the wingbeat cycle, in our artificially stimulated preparations the effect was the same no matter what the phase of the input was.

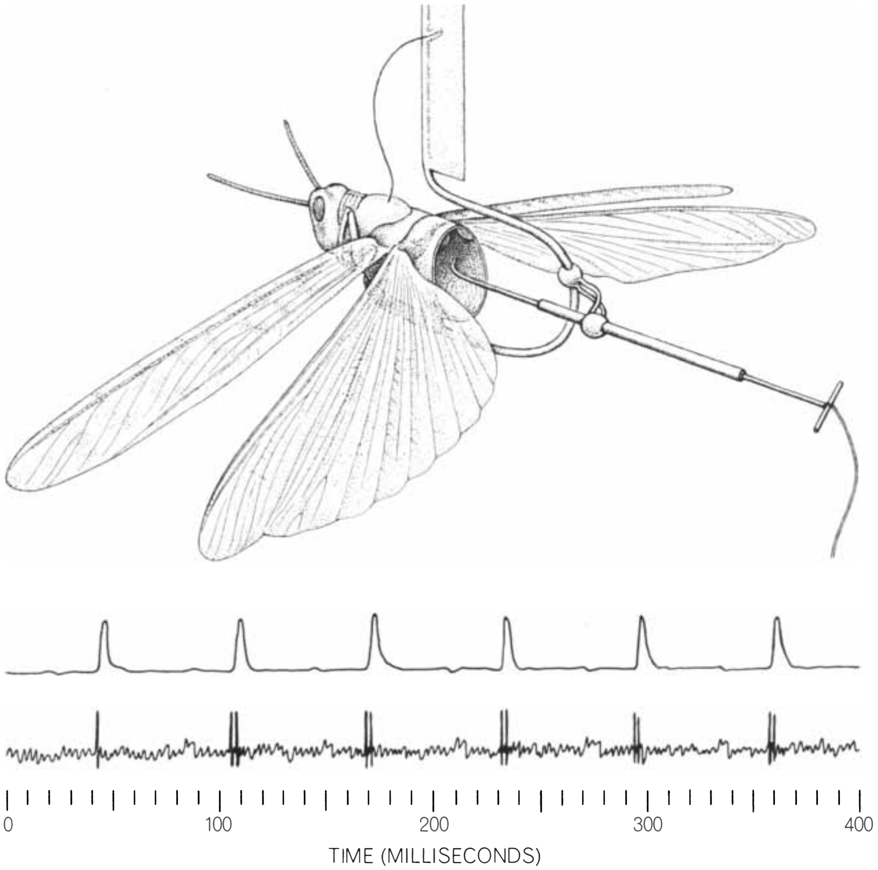
We also found that the response to the input took quite a long time to develop. When the stimulator was turned on, the motor output frequency would increase gradually over about 20 to 40 wingbeat cycles. Hence it appears that the ganglion averages the input from the four stretch receptors (and other inputs too) over a rather long time interval compared with the wingbeat period, and that this averaged level of excitation controls wingbeat frequency. In establishing this average of the input most of the detailed information about wing position, frequency and amplitude is lost or discarded, with the result that no reflection of the detailed input pattern is found in the motor output pattern. We must therefore conclude that the input turns on a central pattern generator and regulates its average level of activity, but that it does not determine the main features of the pattern it produces. These features are apparently genetically programmed into the central network.

If that is so, why does the locust even have a stretch reflex to control wingbeat frequency? If the entire ordered pattern needed to activate flight muscles can be coded within the ganglion, why not also include the code for wingbeat frequency? The answer to this dual question can probably be found in mechanical considerations. The wings, muscles and skeleton of the flight system of the locust form a mechanically resonant system—a system with a preferred frequency at which conversion of muscular work to aerodynamic power is most efficient. This frequency is a function of the insect's size. It seems likely that even insects with the same genetic makeup may reach different sizes because of different environmental conditions during egg production and development. Hence each adult insect must be able to measure its own size, as it were, to find the best wingbeat frequency. This measurement may be provided by the stretch reflex, automatically regulating the wingbeat frequency to the mechanically resonant one.

What kind of pattern-generating nerve network is contained in the ganglia? We do not know as yet. Nonetheless, a plausible model can be suggested. The arguments leading to this model are not rigorous and the evidence in its favor is not overwhelming, but it is always useful to have a working hypothesis as a guide in planning future experiments. Also, it seems worthwhile to present a hypothesis of how a simply structured network might produce a special temporally patterned output when it is excited by an unpatterned input.

When neurophysiologists find a system in which there is alternating action between two sets of antagonistic muscles, they tend to visualize a controlling nerve network in which there is reciprocal inhibition between the two sets of nerve cells [*see top illustration on page 89*]. Such a network can turn on one or both sets at first, but one soon dominates and the other is silenced. When the dominant set finally slows down from fatigue, the inhibiting signal it sends to the silent set also decreases, with the result that the silent set turns on. It then inhibits the first set. This reciprocating action is analogous to the action of an electronic flip-flop circuit; timing cues are not needed in the input. The information required for the generation of the output pattern is contained largely in the structure of the network and not in the input, which only sets the average level of activity. A nerve network that acts in this way can consist of as few as two cells or be made up of two populations of cells in which there is some mechanism to keep the cooperating units working together.

In the locust flight-control system several tens of motor nerve cells work together in each of the two main sets. The individual nerve cells within each set



SENSORY DISCHARGES in nerves from the wing and wing hinge are recorded with wires manipulated into the largely eviscerated thoracic cavity of a locust. The top record is of downstroke muscle potentials, which are repeating at the wingbeat frequency. The bottom record is of a sensory (stretch) receptor from one wing, firing one or two times per wingbeat.

seem to share some excitatory interconnections. These not only provide the coupling that keeps the set working efficiently but also have a further effect of some importance. Strong positive coupling between nerve cells can result in positive feedback "runaway"; the network, once it is activated, produces a heavy burst of near-maximum activity until it is fatigued [*see middle illustration on opposite page*] and then turns off altogether until it recovers. A network of this kind can also produce sustained oscillations consisting of successive bursts of activity alternating with periods of silence without any patterned input. Thus either reciprocal inhibition or mutual excitation can give rise to the general type of burst pattern seen in locust motor units. Both mechanisms have been demonstrated in various behavior-control systems. It is likely that both are working in the locust and that these two mechanisms, as well as others, converge to produce a pattern of greater stability than might otherwise be achieved.

In summary, the model suggests that each group of cooperating nerve cells is mutually excitatory, so that the units of each group tend to fire together and produce bursts of activity even when their input is steady. In addition the two sets are connected to each other by inhibitory linkages that set the two populations into alternation. Notice that in these hypothetical networks the temporal pattern of activity is due to the network structure, not to the pattern of the input. Even the silent network stores most of the information needed to produce the output pattern.

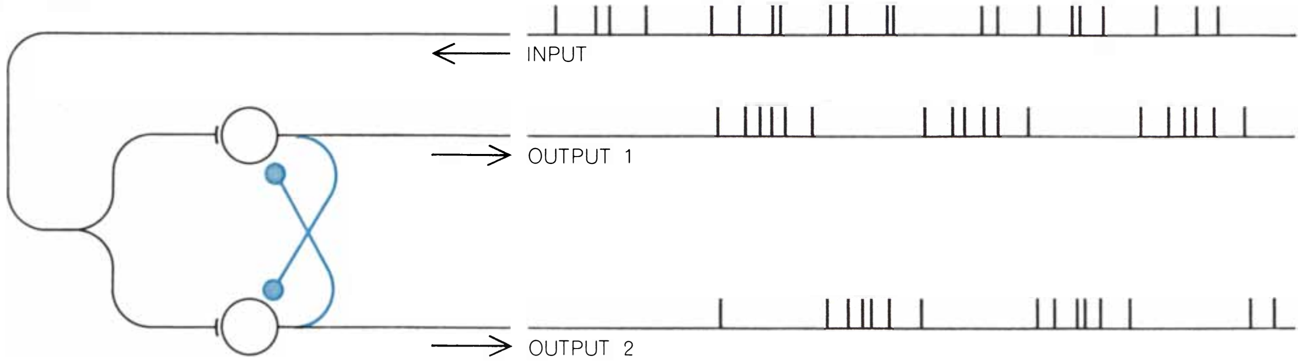
The locust flight-control system consists in large part of a particular kind of circuit built into the central ganglia. Some other locomotory systems seem much more influenced by reflex inputs. As an example of such a system I shall describe briefly the walking pattern of the tarantula spider. There is much variation in the relative timing of the eight legs of this animal, but on the average the legs exhibit what is called a diagonal rhythm. Opposite legs of one segment alternate and adjacent legs on one side alternate so that diagonal pairs of legs are in step [*see illustration on page 90*].

The tarantula can lose several of its legs and still walk. Suppose the first and third pairs of legs are amputated. If the spider's legs were coordinated by means of a simple preprogrammed circuit like the one controlling the locust's flight muscles, one would expect the spider to move the remaining two legs on one side in step with each other and out of step with the legs on the other side. A four-legged spider that did this would fall over. In actuality the spider adjusts relations between the remaining legs to achieve the diagonal rhythm. Other combinations of amputations give rise to other adaptations that also maintain the mechanically more stable diagonal rhythm.

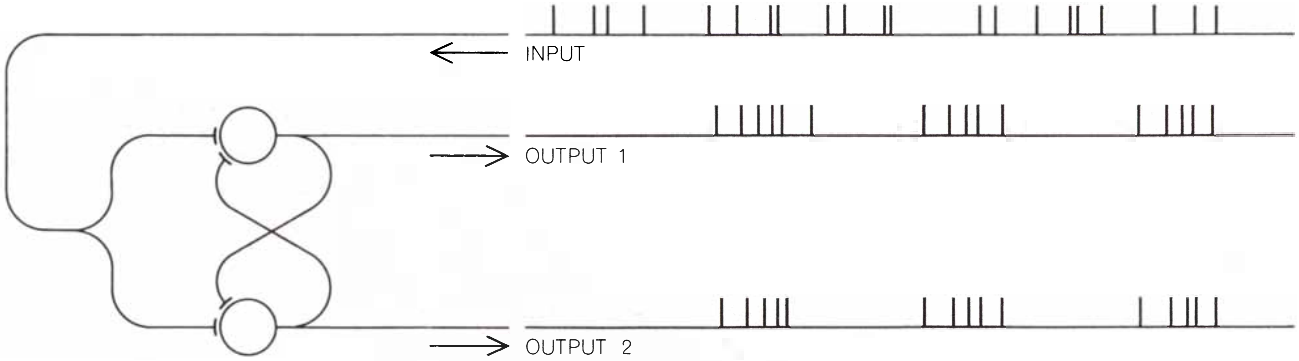
Thus it appears that the pattern of coordination does depend on input from the legs. One can advance a possible explanation. Each leg is either driven by a purely central nervous oscillator or each leg and its portion of ganglion forms an oscillating reflex feedback loop. Suppose the several oscillators are negatively coupled. A pair of matched negatively coupled oscillators will operate out of phase. If the nearest leg oscillators are negatively coupled more strongly than the ones farther apart, the normal diagonal rhythm will result. For example, if left leg 1 has a strong tendency to alternate with right leg 1 and right leg 1 alternates with right leg 2, then left leg 1 must operate synchronously with right leg 2, to which it is more weakly connected. Now if some of the oscillators are turned off by amputating legs, so that either the postulated oscillatory feedback loop is broken or the postulated central oscillator receives insufficient excitatory input, new patterns of leg movements will appear that will always exhibit a diagonal rhythm.

The real nature of the oscillators involved in the leg rhythms is not known. These results and the postulated model nonetheless illustrate how sensory feedback could be used by the nervous system in such a way that the animal could adjust to genetically unpredictable conditions of the body or environment without recourse to learning mechanisms. Could this be the role of reflexes in general? We have seen that in the locust flight system much information for pattern generation is centrally stored—presumably having been provided genetically—and that the reflexes do seem to supply only information that could not have been known genetically.

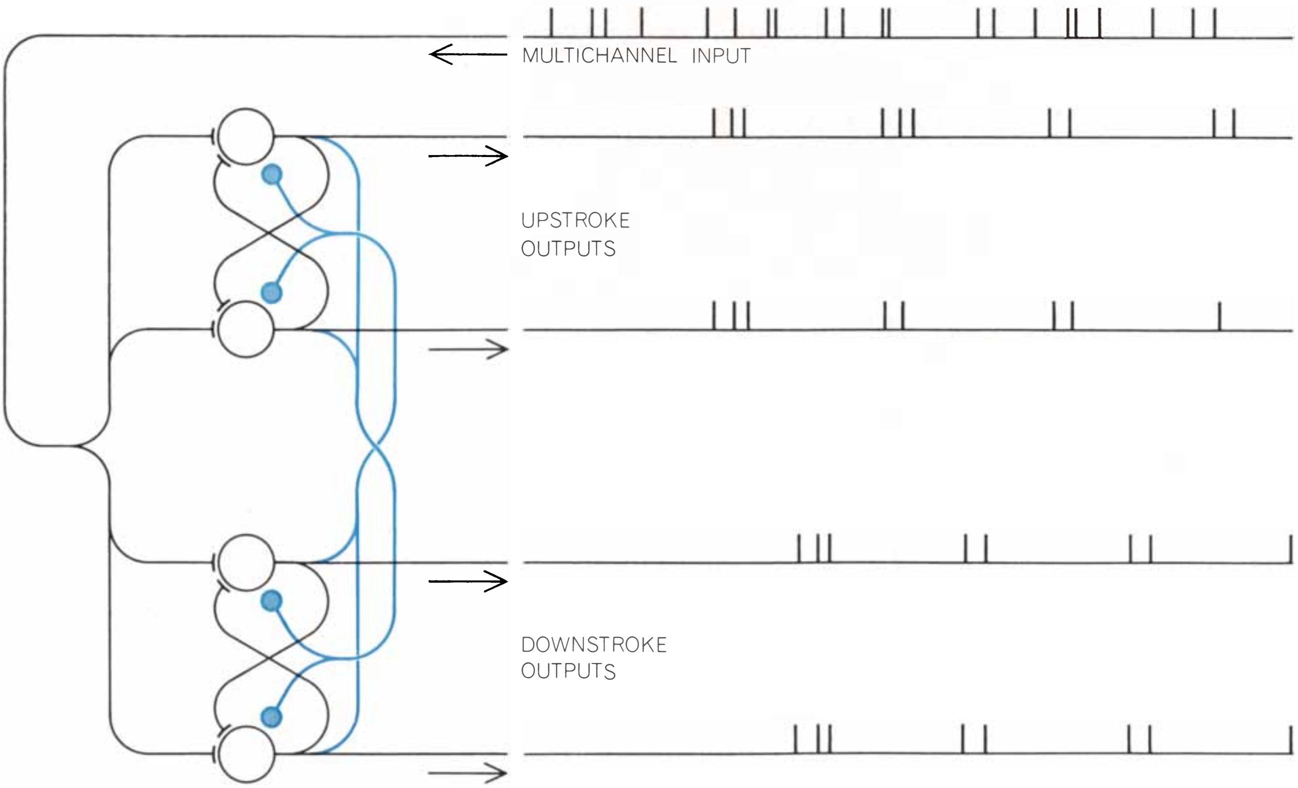
A way to describe the two general models of muscle-control systems has been suggested by Graham Hoyle of the University of Oregon. He calls the cen-



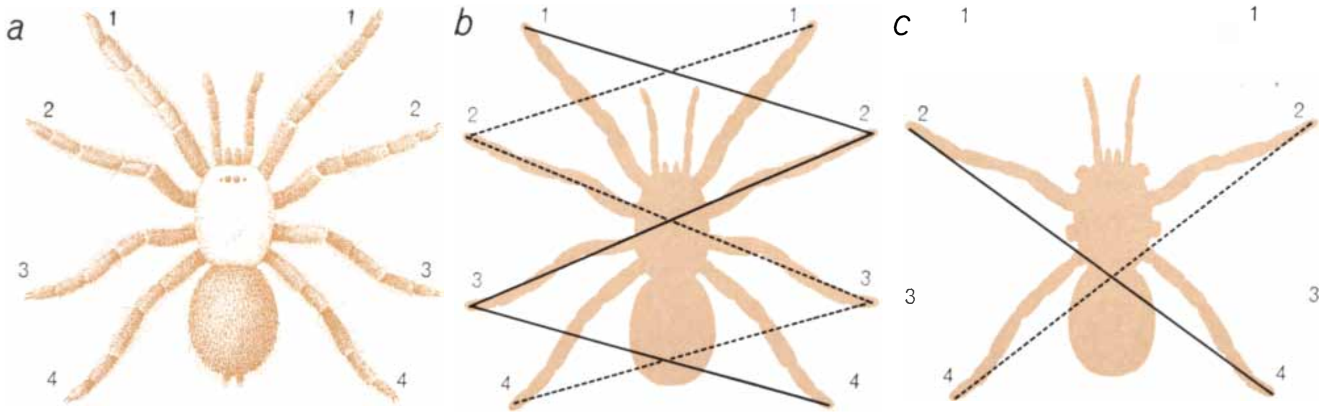
CROSS INHIBITION is one kind of interaction between nerve cells. The cells are connected in such a way that impulses from one inhibit the other (*color*). This can cause a pattern of alternating bursts, each cell firing (inhibiting the other) until fatigued. The hypothetical network shows how an unpatterned input can be transformed into a patterned output by structurally coded information.



IN CROSS EXCITATION the output from each cell excites the other. This makes for approximate synchrony. There may also be a positive feedback "runaway" until fatigue causes deceleration or a pause; once rested, the network begins another accelerating burst.



HYPOTHETICAL NETWORK of nerve cells in the locust might involve two cell populations, an upstroke group (*top*) and a downstroke group (*bottom*). Cells *within* a group excite one another but there are inhibitory connections *between* groups (*color*). The inhibition keeps the activity of one group out of phase with that of the other, so that upstroke and downstroke muscles alternate.



LEGS OF TARANTULA *(a)* move in diagonally arranged groups of four *(b)*. The diagonal pattern persists if some legs are removed *(c)*, suggesting that proprioceptive reflexes set the pattern or that changed input alters inherent central nervous system activity.

trally stored system of pattern generation a motor-tape system. In such a system a preprogrammed "motor score" plays in a stereotyped manner whenever it is excited. For a system in which reflexes significantly modify the behavioral sequences, Hoyle suggests the term "sensory tape" system. I prefer the term "sensory template." Such systems have a preprogrammed input requirement that can be achieved by various outputs. If the output at any moment results in an input that does not match the template, the mismatch results in a changed output pattern until the difference disappears. Such a goal-oriented feedback system can adapt to unexpected environments or to bodily damage. Spider and insect walking patterns show a kind of plasticity in which new movement patterns can compensate for the loss of limbs. In the past this kind of plasticity has often been interpreted as evidence for the reflex control of locomotory pattern. The locust flight-control system, on the other hand, certainly has a motor score that is not organized as a set of reflexes. Can a motor-score system show the plastic behavior usually associated with reflex, or sensory-template, systems?

For several years we thought that the locust flight-control system was relatively unplastic. We knew about the control of wingbeat frequency by the stretch reflex and about other reflexes, for example a reflex that tends to keep the body's angle of pitch constant. When I had made recordings of nerve impulses to some important control muscles before and after cutting out other muscles or whole wings, however, I had not found differences in the motor output. I therefore concluded that the flight-control system was not capable of a wide range of adaptive behavior. On this basis one would predict that a damaged locust could not fly, or could fly only in circles.

The locust has four wings. Recently I cut whole wings from several locusts, threw the locusts into the air and found to my surprise that they flew quite well. The flying locust shows just as much ability to adapt to the loss of a limb as a walking insect or spider does. For the crippled locust to fly it must significantly change its motor output pattern. Why did the locust not show this change in the experiments in which I made recordings of nerve impulses to its muscles?

In all the laboratory experiments the locust was approximately fixed in space. If the insect made a motor error, it might sense the error proprioceptively, but it could not receive a feedback signal from the environment around it indicating that it was off course. The free-flying locust has at least two extraproprioceptive sources of feedback about its locomotory progress: signals from its visual system and signals from directionally sensitive hairs on its head that respond to the flow of air. Either or both of these extraproprioceptive sources can tell the locust that it is turning in flight. In the free-flying locust the signals are involved in a negative feedback control that tends to keep the animal flying straight in spite of functional or anatomical errors in the insect's basic motor system. When animals are studied in the laboratory under conditions that do allow motor output errors or anatomical damage to produce turning motions, then compensatory changes in the motor output pattern are observed provided only that the appropriate sensory structures are intact.

The locust flight-control system consists in part of a built-in motor score, but it also shows the adaptability expected of a reflex, or sensory-template, type of control. From these observations on plasticity in the locust flight system one can see that there may be no such thing as a pure motor-tape or a pure sensory-template system. Many behavior systems probably have some features of each.

What we are striving for in studies such as the ones I have reported here is a way of understanding the functioning of networks of nerve cells that control animal behavior. Neurophysiologists have already acquired wide knowledge about single nerve cells—how their impulses code messages and how the synapses transmit and integrate the messages. Much is also known about the electrical behavior and chemistry of large masses of nerve cells in the brains of animals. The intermediate level, involving networks of tens or hundreds of nerve cells, remains little explored. This is an area in which many neurobiologists will probably be working in the next few years. I suspect that it is an area in which important problems are ripe for solution.

I shall conclude with a few remarks on the unraveling of the mechanisms of genetically coded behavior. As I see it, there are two major stages in the readout of genetically coded behavioral information. The first stage is the general process of development of bodily form, including the detailed form of the networks of the central nervous system and the form of peripheral body parts, such as muscles and sense organs that are involved in the reflexes. This stage of the genetic readout is not limited to neurobiology, of course. It is a stage that will probably be analyzed largely at the molecular level. The second stage involves a problem that is primarily neurobiological: How can information that is coded in the grosser level of nervous-system structure, in the shapes of whole nerve cells and networks of nerve cells, be translated into temporal sequences of behavior?

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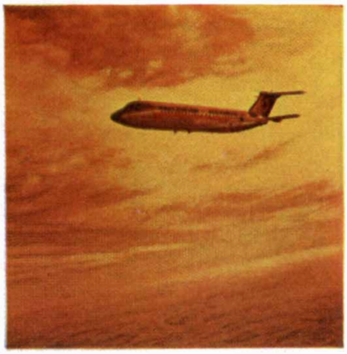

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LEIBNIZ

The theme of his career was the search for a universal language and algebra of reasoning. He perfected the calculus by establishing its fundamental notation, and he pointed the way toward symbolic logic

by Frederick C. Kreiling

...there would be no more need of dispute between two philosophers than between two accountants. It would suffice for them to take their pencils in their hands, sit down to their slates, and say to each other...: "Let us calculate."

—GOTTFRIED WILHELM LEIBNIZ

Such was Leibniz' dream: to develop a generalized symbolic language, and an algebra to go with it, so that the truth of any proposition in any field of human inquiry could be determined by simple calculation. His quest was unsuccessful, but he did invent the calculus, a mathematical way of dealing with change and motion, and he did devise and promote much of modern mathematical notation. Perhaps even more important, his vision pointed the way toward modern symbolic logic, as such 20th-century mathematicians and logicians as Bertrand Russell, Kurt Gödel and Alfred Tarski have recognized. Indeed, Norbert Wiener suggested that Leibniz might be considered the patron saint of communication theory and control theory, twin mathematical foundations of much contemporary technology, because his thought centered on "two closely related concepts, that of a universal symbolism and that of a calculus of reasoning. From these are descended the mathematical notation and the symbolic logic of the present day."

The same passion for universality that prompted Leibniz' search for a mathematical *lingua generalis* informed his entire varied career. He functioned at one time or another, and often simultaneously, as political theorist, diplomat, engineer, inventor of gadgets and house historian for German princely families. He aimed at binding into a consistent whole all the tangled threads of 17th-century thought, and in his philosophy he did manage to link mathematics, physics, metaphysics, psychology and theology. In the last analysis, however, his effort at synthesis failed. His life is interesting more for his extraordinary versatility and his sharp perceptions, many of them foreshadowing modern developments, than for a unified and systematic body of thought.

PORTRAIT OF LEIBNIZ on the opposite page was painted in about 1695, when he was head of the ducal library and an adviser to the court in Braunschweig (Brunswick). The portrait, now in the Duke Anton Ulrich Museum there, was once attributed to Andreas Scheits but is now thought to have been done by Christoph Bernhard Francke.

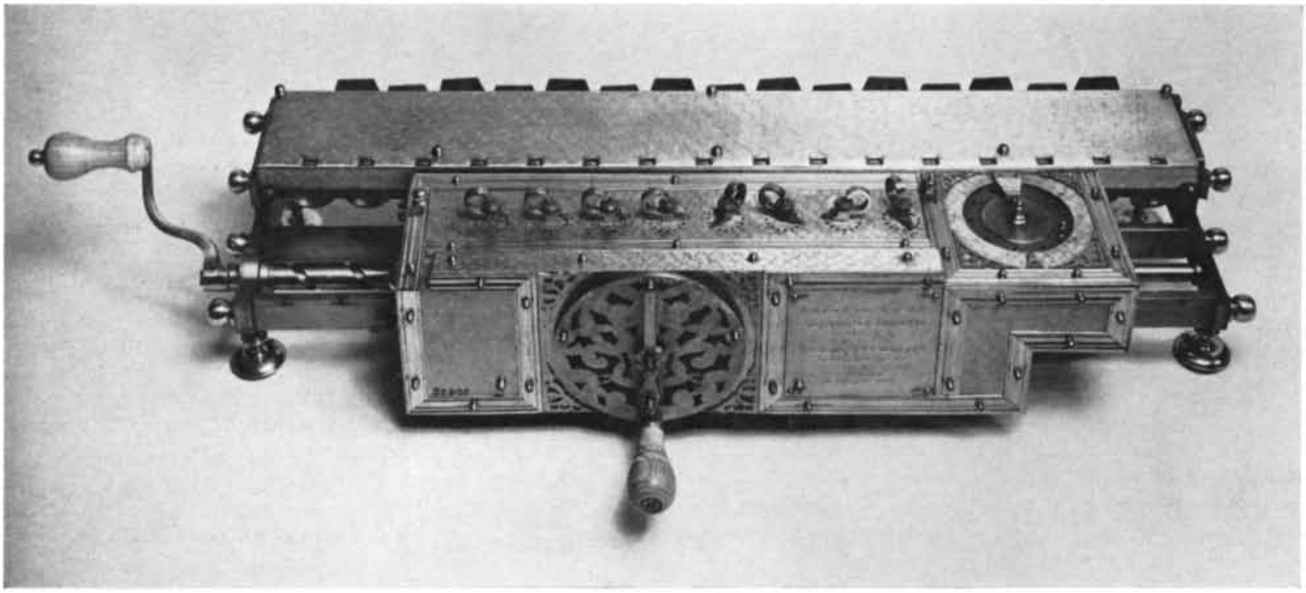
Gottfried Wilhelm Leibniz was born in Leipzig in 1646, the son of a professor of moral philosophy at the university. At eight he taught himself Latin; soon he was reading Greek and at 14 he was immersed in Aristotle. He immediately found himself questioning the master's formal system. The 10 Aristotelian "categories"—substance, quantity, quality, relation, place, time, position, possession, action, affection—had been held for centuries to be necessary elements of all thought, scientific or otherwise; for the scientific revolution of the 17th century to advance, their hold on the imagination of learned people had to be loosened. Encountering them as a boy, Leibniz wondered whether perhaps the Aristotelian categories had subsets, whether they could fit into larger categories, whether a "regular passage" might not be found among them. (Eventually just such questions were to be dealt with in the 19th century by George Boole and John Venn.)

Leibniz' philosophy of mathematics turned out to be much like Aristotle's in that its metaphysical and logical theories were closely related. Aristotle had held that in logic every proposition could be reduced to a subject-predicate form; this directly paralleled his metaphysical doctrine that the world is made up of "substances" with "attributes." Leibniz held that the predicate of every proposition is "contained in" the subject, and this paralleled his metaphysical doctrine that the world consists of self-contained points, the "monads," that operate in preestablished harmony. The metaphysics, in turn, was inextricably bound up with mathematics. "There are," he wrote in the *Monadology,* the final summary of his philosophy, "two kinds of truth, those of reasoning and those of fact. Truths of reasoning are necessary and their opposite is impossible; truths of fact are contingent [on definition or on perception, for example] and their opposite is possible." Truths of reasoning, for Leibniz, included all mathematical axioms, postulates, definitions and theorems, since their opposites involve contradiction.

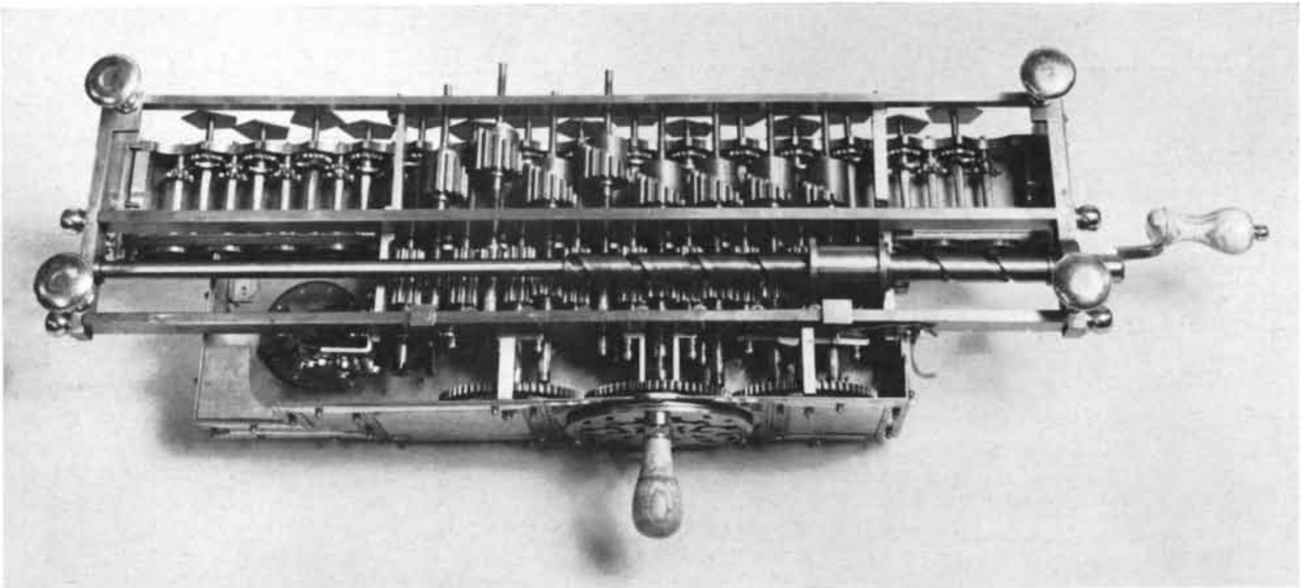
Leibniz agreed in theory with Plato that diagrams, geometric figures and means of notation in general were mere aids to mathematical thinking, but he placed great emphasis on their importance in practice. He called them the "thread of Ariadne" that could guide the mind, and he was always looking for "methods of forming and arranging characters and signs, so that they represent thoughts, that is to say, that they are related to each other as the corresponding thoughts." Unlike most mathematicians of his day, he made an extended study of notation, in the course of which he corresponded with many of the leading mathematicians he knew: the Bernoullis in Switzerland, John Wallis in England, Christiaan Huygens in Paris. He was responsible for introducing more signs and symbols than any other mathematician with the exception of Leonhard Euler, and he promoted the use of still more. He recommended the use of parentheses to set apart portions of algebraic expressions instead of the vinculum, a line above the terms, which had long been in use. He proposed the dot to indicate multiplication (because the St. Andrew's cross was too readily confused with the letter X), the decimal point, the equal sign, the colon for division and ratio. He also introduced numerical superscripts as exponents for the letter terms in algebra instead of merely repeating the letter.

The notation of the calculus as we know it today is in large part due to Leibniz. For the process of integration, which had been developing slowly ever since the time of Archimedes, he proposed the familiar symbol $\int$, an elongated *s* signifying "summation." Perhaps the best-known of his innovations is the *d* for the differential. Isaac Newton, who had invented the calculus independently, used dots and dashes above the letters to indicate what he called "fluxions" and "fluents," and they were difficult to read and to print. It is generally agreed that the development of the calculus in England was hindered until well into the 19th century because English mathematicians remained loyal to Newton's notation while their Continental colleagues moved ahead into new areas with Leibniz' more expressive system. Leibniz sought to make the form of a symbol reflect its content. "In signs," he wrote, "one sees an advantage for discovery that is greatest when they express the exact nature of a thing briefly and, as it were, picture it; then, indeed, the labor of thought is wonderfully diminished."

Leibniz had a touch of the mystic, and sometimes he saw mathematical notation as a reflection of a higher order of



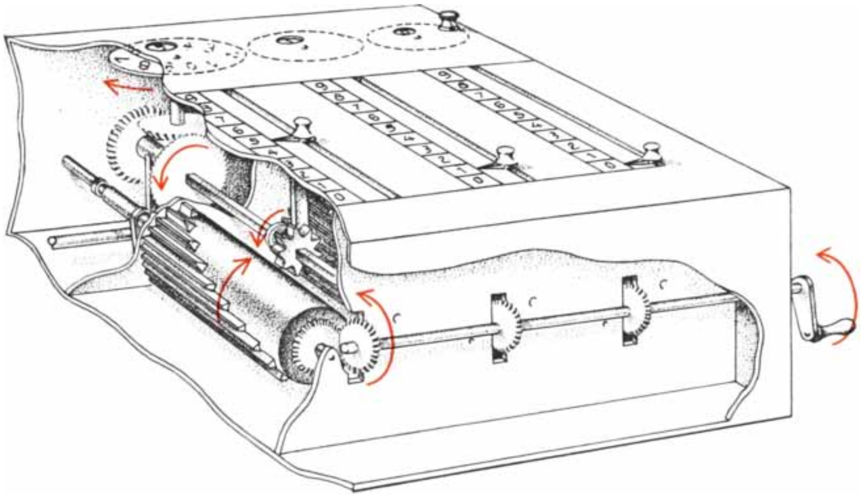
CALCULATING MACHINE, designed by Leibniz to do multiplication and division by repeated addition and subtraction, may never have been built in his day. This version was made to his specifications in 1923 and is in the Deutsches Museum in Munich.



MACHINE is seen from the bottom. The key elements are the eight "stepped cylinders" with teeth of different lengths. As each turns it advances a totalizer gear by an amount that depends on the number of teeth engaged, which in turn depends on the cylinder's position.

reality. Having devised a system of binary arithmetic, for example, he came to see its symbols as analogues of the ancient Chinese magic symbols called trigrams, the meaning of which he thereupon tried to fathom. His interest in Chinese culture had a more practical aspect, however. The fact that Chinese ideograms symbolize concepts rather than sounds, and can therefore represent the same things in different dialects, suggested to him that he might find in Chinese a means of constructing his universal symbolic language. He strove to advance cultural contact between Europe and China, with Russia serving as an intermediary. This was one of the objectives he proposed to Peter the Great when in 1711 he discussed with the czar the formation of a scientific society in Russia.

If Peter were to send a mission to China, Leibniz suggested, a suitable diplomatic present might well be Leibniz' own calculating machine [*see illustrations on opposite page*]. Blaise Pascal had earlier constructed several devices for addition and subtraction; Leibniz extended Pascal's principles to accomplish multiplication and division by repeated addition or subtraction. The key elements in Leibniz' machine were the "stepped cylinders," in effect long gears with nine teeth, each a different length. Smaller gears were set above them, each representing a digit of the multiplicand and placed so as to be engaged by that number of the long gears' teeth [*see illustration on this page*]. Each complete turn of the set of long gears therefore registered the multiplicand once; the multiplier was expressed by the number of times the long gears were turned. When the first commercial calculating machines were made in the early 19th century by Charles Xavier Thomas in Alsace, they incorporated the Leibniz stepped wheel.



PRINCIPLES of the Leibniz calculating machine are illustrated in a diagram based on one from a 19th-century book. In this version a crank (*right*) turns a set of stepped cylinders. The totalizer gears are positioned by knobs to represent the multiplicand, in this case 510; a turn of the cylinder at left, for example, therefore engages five teeth of its totalizer, turning the square shaft and, through bevel gears, advancing the counter (*top*) to 5. Thus each turn of the crank adds the multiplicand one more time. As a counter goes from 9 to 0 an arm attached to it causes the next cylinder to the left to advance one unit to effect the carrying function.

Leibniz' considerable flair for engineering was exhibited primarily in the large number of designs he left, most of them unexecuted: wagon wheels that would plow through mud, improved ship hulls and smokestacks, even a new type of nail with tiny spurs to fix it more firmly in the wood. To some extent his technological ability was put to the service of the various dukes and princes by whom he was employed as a kind of all-purpose civil servant. There was, for example, the incident of the silver mines. Leibniz' patron Duke John Frederick of Hanover owned mines in the Harz mountains; their yield was low, but they helped to maintain the duke's balance of payments. Thus it was a serious matter when a drought lowered the level of streams at the surface, rendering inoperative the waterwheels that drove pumps to clear the mine passages of seeping ground water. Leibniz was given a contract to set up a windmill-operated pump and work it for one year; if the pilot project was successful, Leibniz would receive 1,200 talers a year, a considerable income. The inevitable friction between science adviser and bureaucrat ensued: the mine directors protested that Leibniz was a theorist who lacked practical experience; he accused them of incompetence. His plan—to use windmills to pump the mine water above the surface and then let it flow down an inclined plane, turning a waterwheel that would help to pump more water—was technically valid. It ran into all kinds of trouble, however, at least partly because the directors had given him the most difficult mine to work with. Leibniz persisted, and after four years the system finally seemed to be functioning. A delegation from the duke arrived for an inspection. That day the wind failed, and Leibniz' grant was promptly terminated. He persisted for two years with his own money, but finally gave up, fearing that his reputation would be ruined.

Typically the trips to the Harz mountains developed new interests for Leibniz: geology and paleontology. In these areas his ideas were essentially those of most other 17th-century students of natural history, but he asked some interesting questions. He saw that the traditional views could not account for the age of the earth, which, it seemed to him, must be immensely old. The whole question of chronology, both evolutionary and historical, was a burning issue in those years. Newton was interested in it. Robert Boyle and the Italian scholar Lodovico Antonio Muratori spent years trying to establish precise dates for historical events, and chronology was a major concern in Leibniz' ventures into historiography.

In 1685, as the windmill project was abandoned, Duke Ernst August of Hanover commissioned Leibniz to write a full-length history of his house. The duke wanted a document that would justify his political aspirations; Leibniz looked on the project as an intellectual challenge. He grounded the history in a number of geological observations and then burrowed into old documents, copying out royal edicts and diplomatic letters. After several years he brought out one thick volume, and then two more, all stuffed with quotations from original sources. His readers had expected something a little more digestible. When some of them told him so, he replied that what he had attempted was a unique kind of work that would put the events of the past into a clear new light; among other things, he felt that an authentic history could establish a new code of international relations.

Leibniz was in some respects rather conservative. The disunity of the remains of the Holy Roman Empire pained him; unlike most political theorists of his day, he was for holding it together in the name of a united Europe rather than seeing it break up into nation states. His role as a diplomat was often that of a mediator between opposing political factions. The same was true in religion: he spent years trying to bring about unity between the Catholic and the Protestant church. In position papers and correspondence he often used the pen name "Pacidius."

If he was a peacemaker in diplomacy, Leibniz was an impassioned partisan in physics, mathematics and philosophy. Through correspondence and publication he engaged in a series of strenuous debates, largely with English scholars. It all began when he and Newton became embroiled in their bitter struggle over which of them had first devised the calculus. Neither appears to have been exactly forthright; each unnecessarily denigrated the contributions of the other. It is now fairly certain that they each discovered it independently. Newton wrote on his method of fluxions for dealing with velocities and change as early as 1665 and continued to do so for the next decade, but he did not publish on the subject until 1687, three years after Leibniz had published in the journal *Acta Eruditorum* a brief and cryptic essay: "A new method for maxima and minima, as well as tangents,...and a curious type of calculus for it."

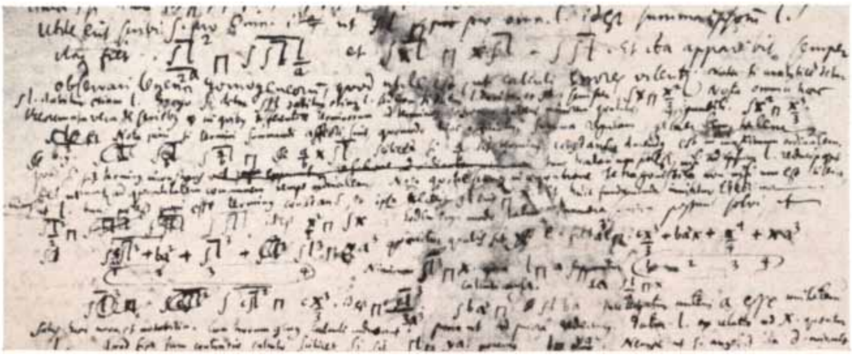
Leibniz had come to the calculus by way of combinatorial analysis. (It was in his *De arte combinatoria,* written at the age of 20, that he first proposed "a general method in which all truths of the reason would be reduced to a kind of calculation.") At first it was the logical and the occult that interested him most; he studied the number diagrams of the 13th-century Spanish mystic Ramón Lull, for example. It was only when he visited Paris and London in the 1670's that he became acquainted with leading mathematicians, including Huygens, and learned about contemporary advances in algebra and geometry. Soon he discovered the fundamental principle of the calculus: that differentiation, the means of studying limits and rates, is the inverse of integration. Neither Leibniz nor Newton was ever able to establish a rigorous basis for the calculus, but both had overcome the prime obstacle set up by the mathematics of the ancients: the belief, inspired by Plato, that scientific treatment of variability was impossible because of the unchanging nature of true reality.

Leibniz' dispute with Newton spread into other areas, notably the nature of gravitation. The controversy that surrounded Newton's ideas is easier to understand for us—who have been exposed to relativity and quantum theory and to the intellectual resistance to them—than it was for 19th-century scholars, whose belief in the absoluteness of Newton's universe had been repeatedly confirmed.

What is important to realize is that to Leibniz—and to Huygens and other leading natural philosophers—Newton's theory seemed a regression to medieval notions that had been dispelled with great effort. Natural philosophers interested in physics had gradually freed themselves from the old scholastic concepts of qualities and powers and from animistic ideas in general. They had come to see every force as the effect of the motion of material particles; they admitted of no way for bodies to affect one another except through the force of impact exerted when they came into contact. They had gone as far as to develop complex systems for explaining the motions of the planets and the behavior of heavy bodies on the earth by means of the motion of corpuscles. To accept the theory of gravitation uncritically would be to forsake these ideas for an explanation that apparently depended on a mysterious force exerted on each other by two separate bodies in empty space, without benefit of a medium between them. It meant a return to "action at a distance," which even scholastic philosophers had rejected.

In short, gravitation seemed to Leibniz to contradict the mechanistic principles to which he was fully committed. He began his critique in 1690, after reading Newton's *Principia,* and kept it up until he died. Some of his ideas on the subject, developed in correspondence with Samuel Clarke, an English philosopher and friend of Newton's, had a prophetic edge. Space and time are not independent, absolute entities as René Descartes and Newton held, he wrote, but rather systems of relations and order among things. "As for my own opinion," he wrote in his third letter to Clarke, "I have said more than once that I hold space to be something purely relative, as time is; that I hold it to be an order of coexistences, as time is an order of successions. For space denotes, in terms of possibility, an order of things which exist at the same time, considered as existing together without inquiring into their manner of existing." Again, in his fifth letter he observed that "it is sufficient to consider these...relations and the rules of their changes without needing to fancy any absolute reality out of the things whose situation we consider."

As Albert Einstein noted, Leibniz' criticisms were justified. Einstein pointed out, however, that "had they won out at that time, it hardly would have been a boon to physics, for the empirical and theoretical foundations necessary to follow up his idea were not available in the 17th century" [see "On the Generalized Theory of Gravitation," by Albert Einstein; SCIENTIFIC AMERICAN, April, 1950].



INTEGRATION SIGN, the $\int$ (for "summation"), was proposed by Leibniz in a letter to Henry Oldenburg, secretary of the Royal Society, written in 1675. "It will be useful," he suggests, "to write $\int$ for omn.," which had been used to indicate the product of integration.

Together with Huygens, Leibniz also contributed to the first clear formulation of the principle of the conservation of mechanical energy, the energy of motion and position. Here again his ideas emerged in the course of a long dispute, this time with the Cartesians. Descartes had believed the quantity of rest and motion in the universe was constant and the "efficiency" of objects was equal, in the case of colliding bodies, to the product of their mass and velocity (mv). Leibniz held that the velocity should be squared—that the measure was mv^2. It is easy to resolve the dispute in contemporary terms: what the Carte-

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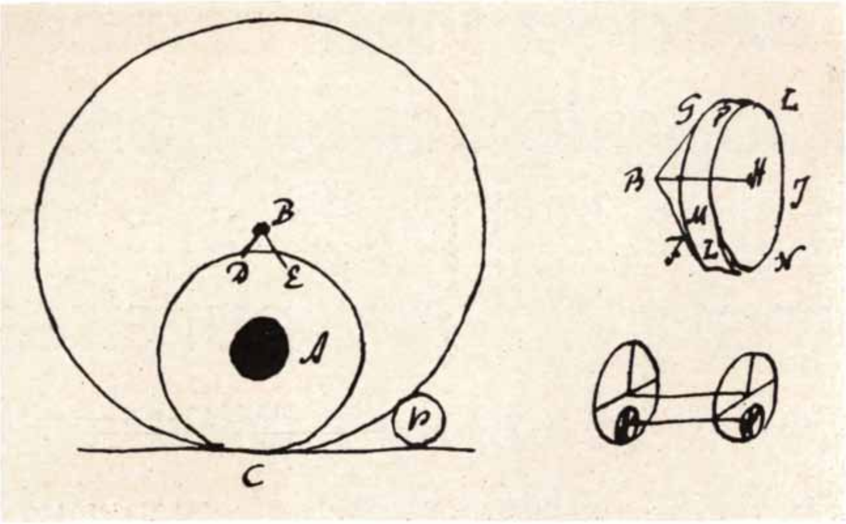

SKETCH BY LEIBNIZ illustrates his design of a wheel to move through mud or over obstacles. An eccentric flywheel (*A*) rides in the rim of a wagon wheel (*B*), storing momentum to help surmount a stone (*p*) in the road. The spokes could be bowed or the wheel made of two disks (*top right*) to accommodate the flywheel. Complete assembly is at bottom right.

sians were talking about is what we call momentum, whereas Leibniz was talking about kinetic energy.

When Leibniz spoke of energy, however, he had more in mind than physical laws. What was real for Leibniz was not "extension," as Descartes had held, but "activity" proportional to degree of "sensitivity." The fundamental unit in his metaphysics was the monad, and the simplest monad was a kind of dimensionless elementary particle of energy; then there was a series of gradually more sensitive, and consequently more active, units including the human psyche and ultimately God. At certain of the higher levels the monad was something like a point of view—a substance capable of perception. Here Leibniz distinguished between animals and men. Animals have perceptions and, through memory, a "sort of consecutiveness" that as he describes it is very like the modern concept of a conditioned reflex. Men "act in like manner as animals" most of the time but also have "the knowledge of eternal and necessary truths" that "gives us reason and the sciences, thus raising us to a knowledge of ourselves and of God."

Leibniz' psychological ideas were more fully developed in a long unpublished work he wrote to refute John Locke's *Essay concerning Human Understanding*. He respected Locke but he could not accept the English philosopher's doctrine that the mind amounts to a blank tablet on which experience writes. It was not that Leibniz believed in a concrete factual memory that was present in the brain at birth, but he did insist that experiences are registered in the mind in certain distinct patterns. Moreover, he did not agree with Locke and Descartes that conscious awareness makes up the whole of mental activity. In effect, he proposed the existence of an unconscious. He observed that dreams often awaken previous thoughts; he even conceived of a theory of psychic trauma, noting that "when we are stunned by some blow, fall, symptom, or other accident, an infinite number of minute confused sensations take form within us."

In this remarkable man's body of thought, then, one finds the seeds of symbolic logic and computer design, hints of the special theory of relativity and some anticipation of Freudian psychology. Many scholars have held that Leibniz could have been a greater mathematician if he had stuck to mathematics—but he simply did not want to stick to mathematics. Scholars deplore the fact that he wasted many years as an adviser on trivial matters to German princes—but he chose that career deliberately, in preference to what he considered a dull life in a university town, because routine made him uneasy. He enjoyed meeting people, being involved in the tumultuous public affairs of the day, feeling that he was helping to set things right. He enjoyed traveling, and as he bounced in stagecoaches from capital to capital, engaged in petty diplomatic intrigues, he filled hundreds of sheets of paper with speculations on scores of different subjects. The papers were found when he died, neglected and quite alone, in 1716. They have yet to be completely sorted and analyzed.

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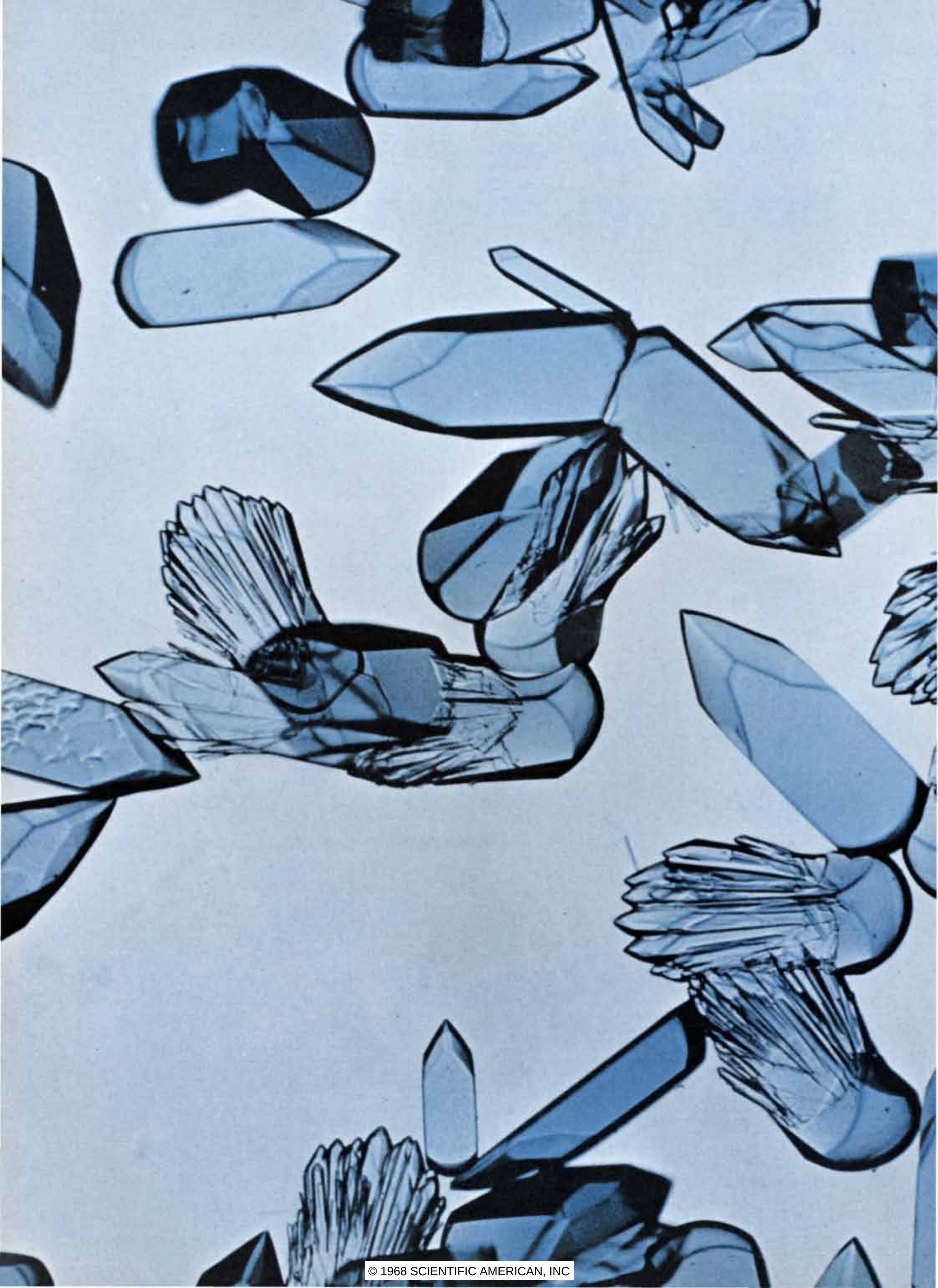


THE BIOCHEMISTRY OF COPPER

Like iron, copper is indispensable to the life processes of most animals and plants. Its chemical nature notably allows it to play a key role in the function of proteins

by Earl Frieden

The history of the highly useful metal copper is interwoven with the development of civilization. Copper has been a key element in the industrial life of man from the beginning of the Bronze Age (about 3500 B.C.) up to the present age of electricity. Not nearly as well known, however, is the fact that copper is a key element in life itself. Without copper most animals, including man, could not exist. It is equally necessary for most plants. Areas of the earth that are barren of available copper (as in certain parts of Australia) are deserts, incapable of supporting plant or animal life. Recent research has established that copper, like certain other necessary trace elements, plays an essential role in the biochemistry of living matter. Indeed, because copper is an essential constituent of many enzymes and other biological catalysts, it can be described as one of the prime movers of the biochemical machine.

Although the metal has been a familiar element for thousands of years (it was named for Cyprus, the richest known source of copper in ancient times), its presence in living matter was not discovered until about a century and a half ago. The amount required by an organism is minuscule; the adult human body, for example, contains only about 100 milligrams of copper. Yet copper has been found to be involved in life processes to a surprising extent. Organisms differ greatly in their dependence on most other elements, but they have in common a cardinal need for an indispensable quota of copper, albeit a small one. Evidently copper, along with iron and a few other trace minerals, became incorporated in living matter at an early stage in the evolution of life, and it has remained as a vital trace element ever since.

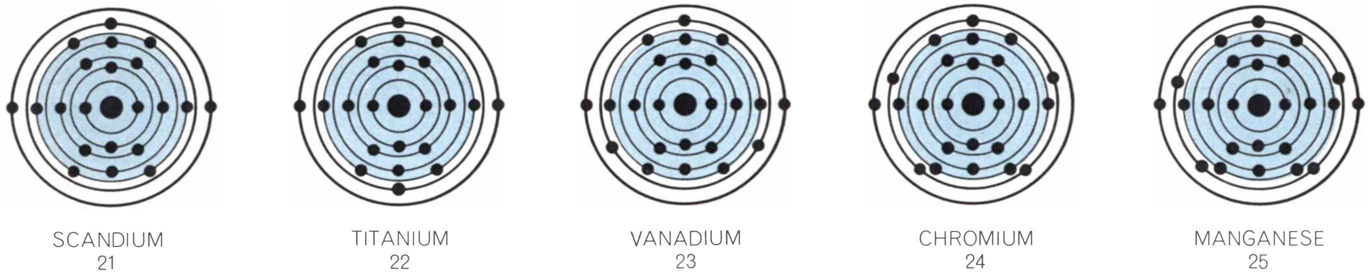
CRYSTALS OF CERULOPLASMIN, a copper protein, were obtained by fractionating blood serum. Nearly all the copper in human serum is concentrated in this protein. The photomicrograph was made by Anatol G. Morell, Irmin Sternlieb and Milton Kurtz of the Albert Einstein College of Medicine. Magnification is about 150 diameters.

Why copper? What special qualities account for its effectiveness as a biological agent? The answer is that copper, to a greater degree than any other metal, possesses three chemical properties that are extremely important for carrying out metabolic processes. In the first place, copper ions react with amino acids or proteins more strongly than other metal ions do, and consequently copper forms very stable chelates with the biologically active substances. In an enzyme containing copper, for instance, the copper ion is embedded in the molecule so firmly that no amount of dialysis (the removal of small molecules from a solution by their selective passage through semipermeable membranes) will separate the copper from the protein; the copper ion can be released only by a drastic change in the structure of the protein or by exposure to an even stronger chelating agent. In the second place, copper is an exceptionally effective catalytic agent. The copper ion itself is probably the most versatile catalyst of all the elements, and its catalytic activity may be enhanced and made more specific when the ion is incorporated in a protein to form a copper enzyme. In the third place, copper's ionization states have flexible properties that qualify it uniquely for metabolic functions. The metal usually exists in three states: as the free, neutral atom, as the cuprous ion (with one electron removed) and as the cupric ion (with two electrons removed). One ion is easily converted to the other, by the addition or the release of an electron, which thereby gives copper great versatility as an electron acceptor or an electron donor. Moreover, compounds containing singly ionized copper are easily oxidized by oxygen from the air; consequently copper enzymes that act as oxidative catalysts (donating oxygen to a substrate) are promptly reloaded by reoxidation to repeat their function.

Copper is a member of the family of elements known as the "first transition series": elements 21 to 30 in the periodic table, which comprise scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper and zinc. These elements, differing essentially only in the number of electrons in the 3*d* shell, have many physical and chemical properties in common. Several of them share the three important properties possessed by copper, and by virtue of these properties they serve as biological trace elements. In each case, however, the metal is intensely specific in its chemical functions.

The biological role of copper is complex and not easy to detect. One of the reasons its presence in the body went unsuspected until recent times is that copper deficiency is rare in animals and has never been observed in human beings. We are supplied with an abundance of copper in our water and food, including contributions from copper-containing cooking utensils. An excess of copper in the body can be toxic, perhaps because the copper ions inactivate enzymes by reacting with their sulfhydryl groups. Fortunately protective mechanisms in the body restrict the absorption of copper and other metals.

The effects of copper deficiency have been investigated in animals in which it



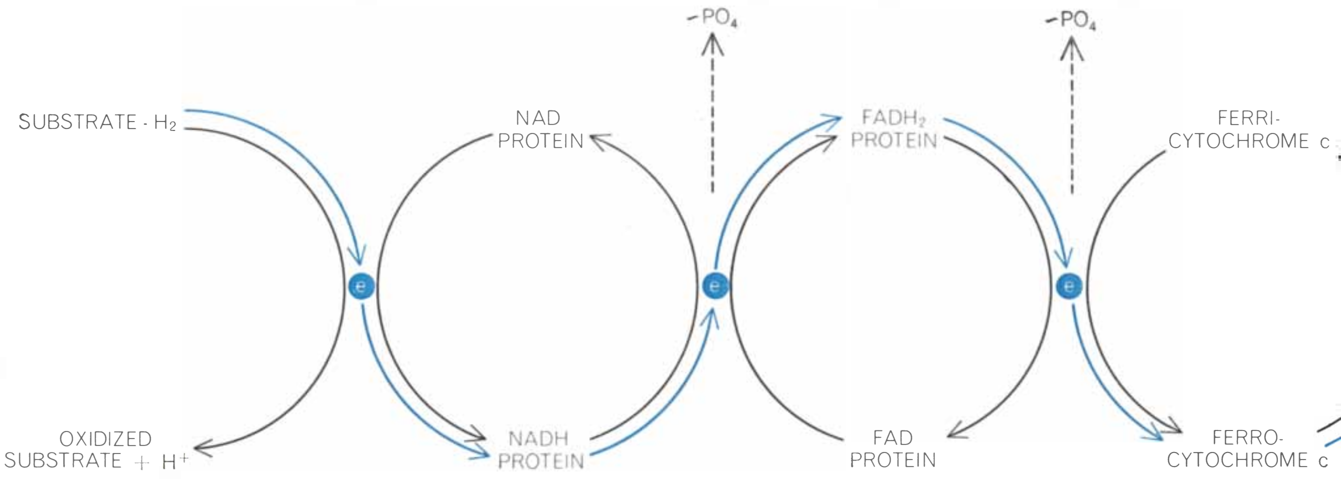
ELEMENTS IN FIRST TRANSITION SERIES, of which copper is one, essentially differ only in the number of electrons in their two outermost electron shells; consequently they share a number of physical and chemical properties. In this group are several metals

occasionally occurs naturally (dogs, lambs, pigs, chickens) and in experimental animals in the laboratory. Severe copper deficiency, it has been found, is responsible for the swayback disease in lambs, for bone defects in dogs, pigs and chickens and for decoloration of sheep wool and rat hair. The swayback disease results from degeneration of the sheath around the spinal cord; lack of copper impairs the animal's ability to synthesize the phospholipids that form the outer covering of nerves. The decoloration of wool and hair has been traced to depletion of the animals' supply of the copper enzyme tyrosinase. Further, it is known that severe copper deficiency in animals leads to a reduction in the synthesis of hemoglobin, with consequent anemia and a deficiency of proteins that require heme, the iron-containing pigment in hemoglobin. Just what specific role copper plays in the synthesis of hemoglobin remains an unsolved problem.

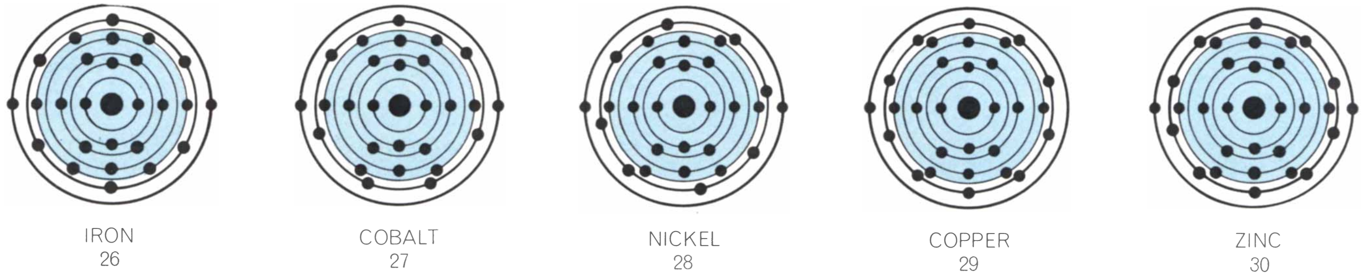
The most striking effect that has been observed in copper-starved animals is a large reduction in their supply of copper enzymes, notably cytochrome oxidase. This important enzyme is the principal "terminal" oxidase in all animals and in most plants. A terminal oxidase is the last enzyme involved in the oxidation of a substrate. When the final reaction cannot proceed, all the intermediate carriers remain in a reduced state and cannot be oxidized in the usual way. Since all energy in animals is derived from oxidative reactions, the terminal oxidases constitute a particularly crucial point of vulnerability in metabolism. This explains why many plants and animals are highly sensitive to poisoning by cyanide: that substance completely inhibits all copper and iron terminal oxidases.

It has been suggested that copper-containing terminal oxidases may also be involved in the damage to tissues produced by ionizing radiation. Jack Schubert of the University of Pittsburgh believes radiation produces organic peroxides that oxidize cuprous ions in proteins to the cupric (doubly ionized) state, which somehow becomes fixed so that the proteins can no longer react with molecular oxygen, thus impairing respiratory metabolism. Schubert reports several items of indirect evidence in support of this view. He finds that by stabilizing the copper in the cuprous state, by destroying the peroxides or by reducing the oxygen level in the tissues he can provide animals with some protection against ionizing radiation, even after they have been exposed. Conversely, he has found that he can heighten tissue sensitivity to radiation by chemical treatment that fixes the copper in the cupric state.

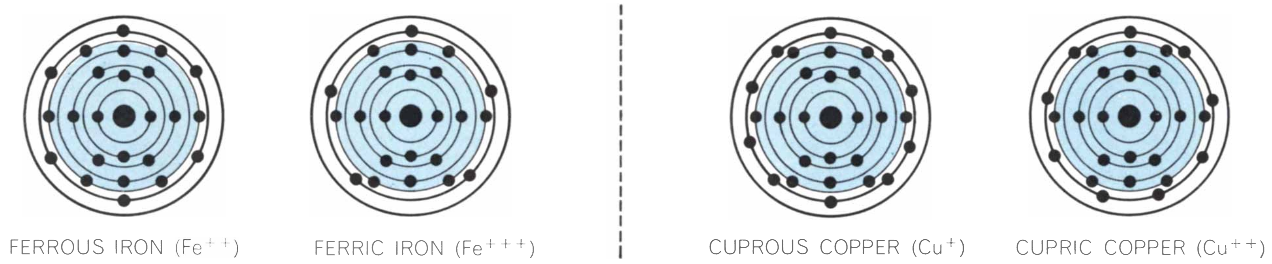
Schubert also reports that in his studies an organism's sensitivity to radiation is correlated with the amount of copper in the tissues: the lower the copper content, the greater the sensitivity to radiation damage. For example, the most radiosensitive tissues in man are the ones that contain the least copper and the least cytochrome oxidase: the spleen, the pancreas and the cells that produce leukocytes. In cultures of yeast it has been found that the cells' resistance to radiation increases with an increase in the amount of copper taken up by the cells from the medium. On the other hand,



OXIDATIVE METABOLISM, whereby energy from food is utilized to produce the high-energy phosphates ($\sim PO_4$) required to sustain life, depends on copper. Shown here is the final series of oxidative reactions, following the order proposed by Quentin H. Gibson of Cornell University. It begins with the capture of hydrogen from partially metabolized substrates by nicotine adenine di-



that play a vital role in life processes. They are (in addition to copper) manganese, iron, cobalt, zinc and possibly vanadium and chromium. Although they share many properties, each of these metals is highly specific in its biochemical reactions and biological functions.

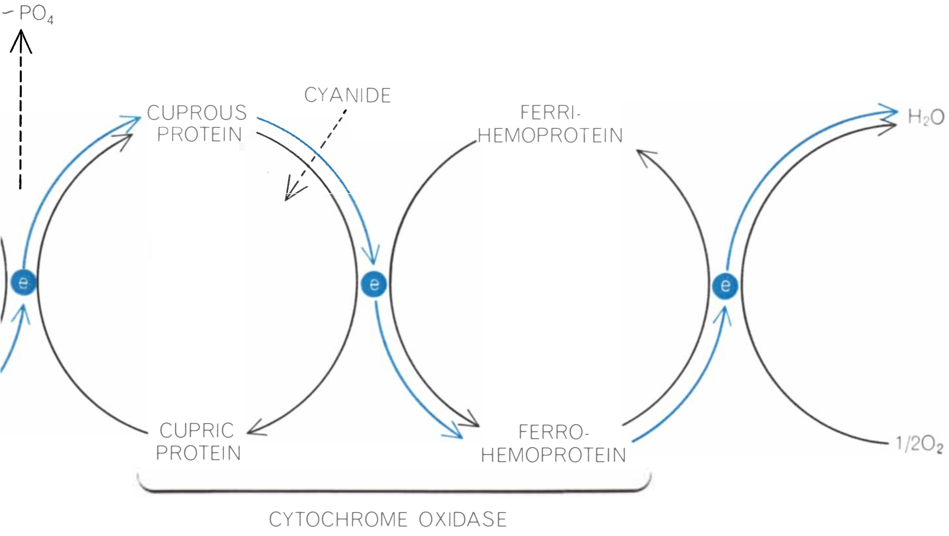


IONIZATION STATES OF IRON AND COPPER qualify them for metabolic functions. Both metals easily assume two ionization states. Copper loses one electron to become singly charged or two electrons to become doubly charged. The ease with which the doubly charged copper ion (cupric copper) accepts an electron adds to the versatility of copper. Acting as an oxidative catalyst, cupric copper temporarily gains an electron; it is then restored to the cupric form by oxygen (*see illustration at bottom of these two pages*).

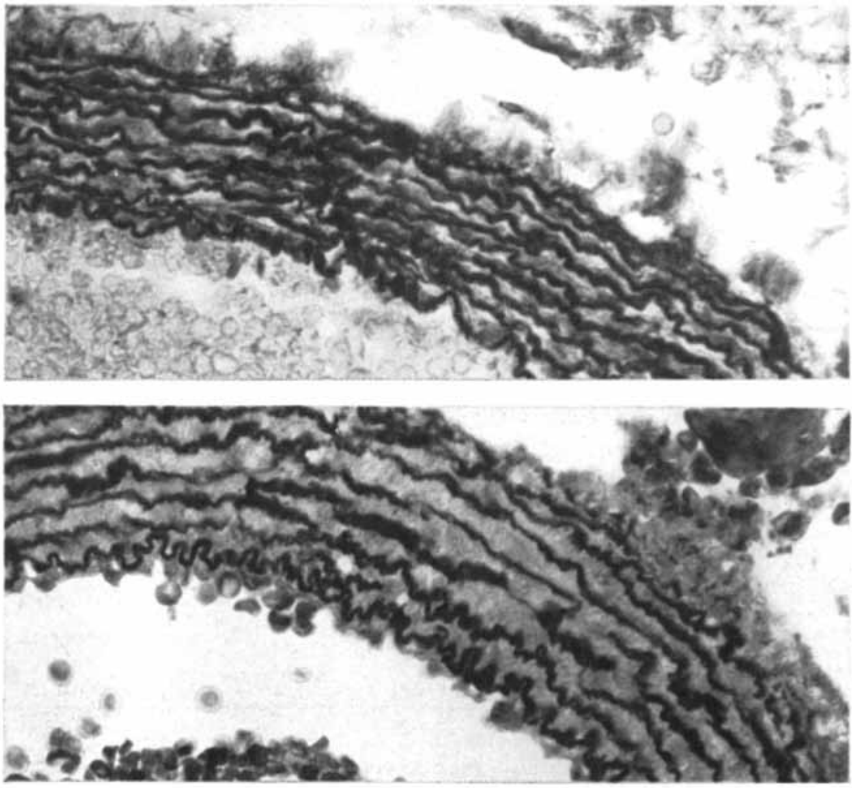
recent studies on melanomas suggest that the removal of copper from these tumors makes them more vulnerable to attack by treatment with radiation.

A copper deficiency can result in the weakening of the walls of certain blood vessels, notably the aorta, rendering the vessels susceptible to aneurisms and rupture. This was first observed in copper-deficient pigs by a group of investigators, including George E. Cartwright and M. M. Wintrobe, at the University of Utah College of Medicine. Charles H. Hill, Jr., and his co-workers at North Carolina State University eventually traced the specific defect to the lack of a copper enzyme called amine oxidase. This enzyme is necessary for the oxidation of the amino acid lysine and the eventual production of desmosine, a substance providing cross-links that probably are largely responsible for the elasticity and stability of elastin, the main protein of the aortic wall. Thus a deficiency of copper, and consequently of amine oxidase, may result in weakening of the wall.

Although chemical investigations have amply demonstrated copper's biological importance, the metal has proved to be an unusually elusive object in the search for its precise forms and locations in living systems. Very little inorganic copper (in the form of salts, for instance) is ever found in the body, even in the bloodstream. It is known that almost all of the 100 milligrams of copper in the human body is incorporated in proteins, and possibly a small amount is complexed with ribonucleic acid. Locating the copper in the proteins, however, is a difficult matter. In the case of iron the locations of the metal are better established: most of the iron in animals is embodied in the substances known as porphyrins, which form the basic structure of hemoglobin, the red protein of the blood, and of the cytochromes, the red proteins of the respiratory system. These iron-containing compounds are complex, but biochemists have managed to analyze and read their structure in some detail. Not so with copper. It is almost never found in any biological compound less complicated than a protein. The only known copper porphyrin is a brilliant red pigment, called turacin, that has been discovered only in the wings of the touraco, a beautiful African bird. Curiously,



nucleotide (NAD). The electron pair (*color*) of hydrogen is passed to flavine adenine dinucleotide (FAD) and ultimately to cytochrome oxidase, which reacts with oxygen and protons to form water. Cyanide reacts with cuprous protein to block metabolism at final stage.



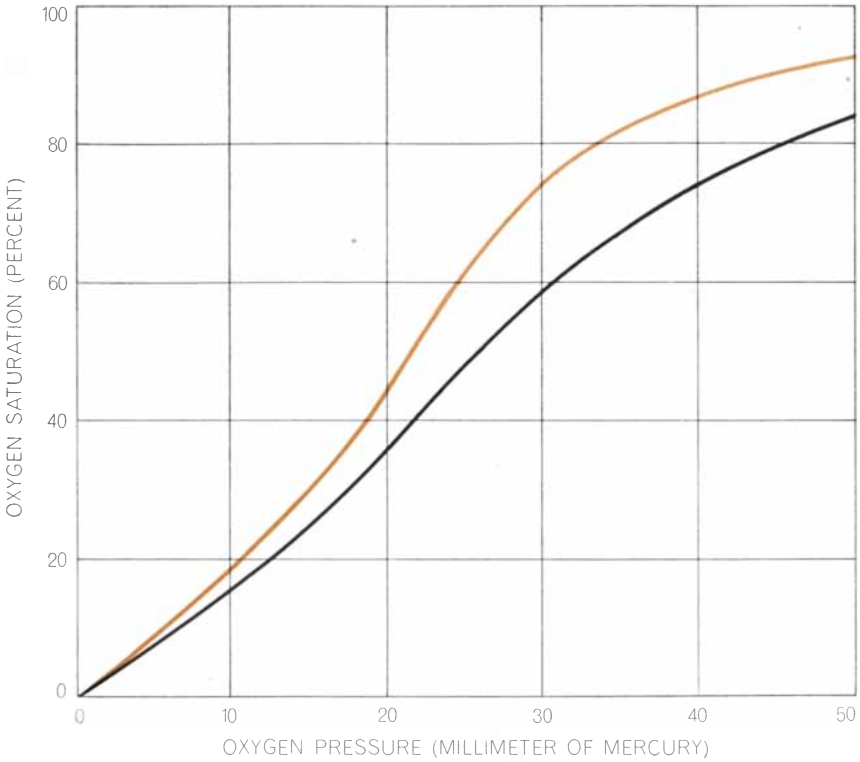
AORTIC WALL loses elasticity and weakens in an animal deficient in the copper enzyme amine oxidase. At top appears the normal aorta of a newborn rat in transverse section. The layers of elastic tissue forming the aortic wall (*dark wavy lines*) are closer together than those in the aorta from a copper-deficient rat shown below it. The photomicrographs were made by Boyd L. O'Dell of the University of Missouri; magnification is about 600 diameters.

it has been found that this pigment can be washed out of the feathers by water, but the configuration of the bird's feathers shields the pigment against rain, so that the wings do not lose their color.

The presence of copper in living matter was first detected in a respiratory blood protein. It had been known for some time that certain mollusks (such as snails and octopuses) and arthropods (horseshoe crabs and scorpions) were distinguished by blue blood. (These two phyla of animals are almost the only true blue bloods!) In the 19th century investigators found that the blue color was attributable to a copper-containing protein that serves as an oxygen carrier in the blood of these animals in place of hemoglobin. The French biologist Leon Fredericq therefore named the protein hemocyanin (actually a misnomer, because it contains no heme).

Although hemocyanin can easily be isolated and has been studied extensively, its chemistry is still obscure. This is due in part to the fact that the hemocyanins are among the largest protein molecules known, their molecular weight ranging from 450,000 to 6,680,000. The molecule is so huge and complex that it is extremely difficult to obtain detailed knowledge of its structure or to determine precisely where the copper is located in the molecule. It has been established that copper constitutes one atom for every 250 amino acids in mollusks and one atom for every 370 in arthropods. In order to bind oxygen as tenaciously as hemoglobin does, the copper atoms must occur in pairs. Very likely the copper is attached to certain amino acids, such as histidine, for which copper has a particular affinity. Apparently copper is complexed with the protein in both the singly and the doubly ionized forms, but direct evidence on this point has proved difficult to find; attempts to detect the presence of unpaired electrons, for example, have failed.

Several interesting questions have been raised about hemocyanin. Why are the mollusks and the arthropods the only blue bloods? Why is hemocyanin not used more widely in the animal kingdom as the blood's oxygen carrier? There are clear indications that evolution provided a choice between copper and iron as the oxygen-bearing agent. In fact, the hemocyanin animals actually use both kinds of metalloprotein for this function; although they depend on the copper protein as their blood pigment, they employ



OXYGEN-BINDING CAPACITY of hemoglobin (*black*) is surpassed by the copper protein hemocyanin (*color*). Hemocyanin is the oxygen carrier in the blood of certain blue-blooded arthropods and mollusks. These animals have a lower concentration of pigment in the blood than red-blooded animals and therefore a lower overall oxygen-carrying capacity.

myoglobin, an iron protein, to supply oxygen to their muscle tissues and utilize the cytochromes, which are also iron proteins, for their oxidative metabolism. A plausible speculation suggests that the preferred blood pigment for most animals may originally have been hemocyanin, because of the strong chemical attraction between protein and copper, but that hemoglobin later gained favor because a mechanism developed that could achieve a much higher concentration of protein in the blood (up to 16 percent). For some reason the hemocyanins never became incorporated within cells; these giant molecules are found only in the plasma. Hemoglobin, on the other hand, is concentrated in the red blood cells, and as a consequence it provides the blood with a much greater total capacity for transporting oxygen. It is conceivable, therefore, that the higher animals turned from hemocyanin to hemoglobin as their oxygen need increased, whereas the mollusks and arthropods stayed with hemocyanin because it is adequate for their requirements.

The principal function of copper in the higher animals, as was mentioned earlier in this article, is to act as a catalytic agent in metabolism. Let us trace the element's chemical behavior and roles in the body. When a copper salt, labeled with radioactivity so that the element can be traced, is injected into the human body, the copper turns up first in combination with the serum albumin in the blood serum. It is then absorbed rapidly by the liver, and thereafter it reappears in the serum in the form of the blue copper protein called ceruloplasmin.

Ceruloplasmin, first isolated by the Swedish biochemists C. G. Holmberg and C. B. Laurell in 1947, has been found to be of central importance in the storage and transport of copper in the higher animals, and this may well be the case in the lower animals also. More than 98 percent of the copper in normal human serum is concentrated in ceruloplasmin, and this one protein accounts for about 3 percent of all the copper in the body. Serum ordinarily has a faintly yellow tinge, but after it has been shaken or allowed to stand, so that its reducing agents are used up and oxidation of the ceruloplasmin can proceed, the presence of that substance is signaled by an emerging faint blue color that turns the color of the serum to a faint green.

The importance of ceruloplasmin as a controlled reservoir for copper is illustrated by Wilson's disease, named after

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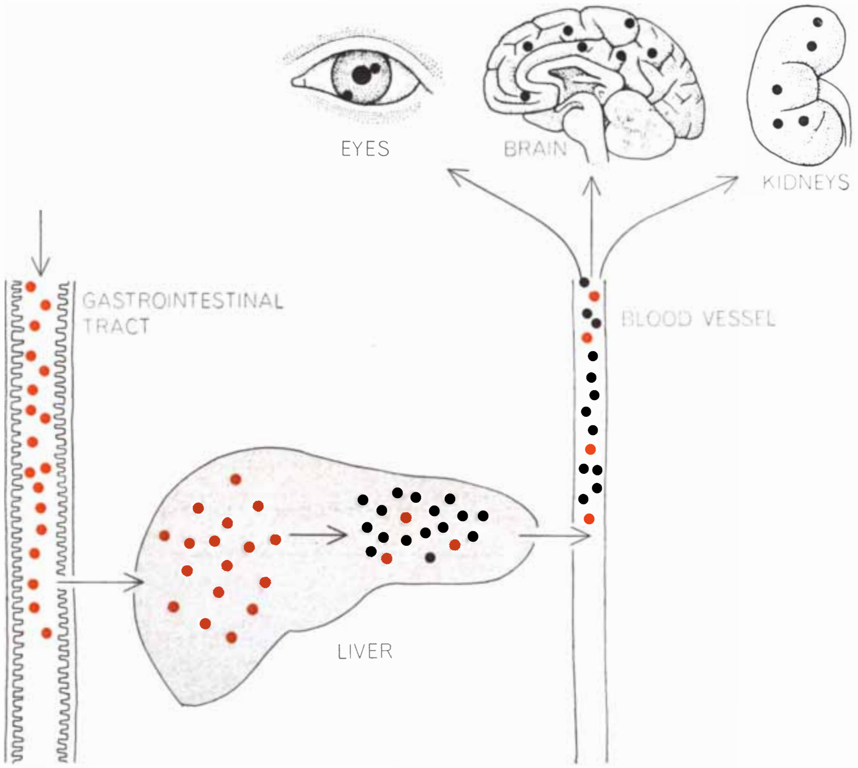
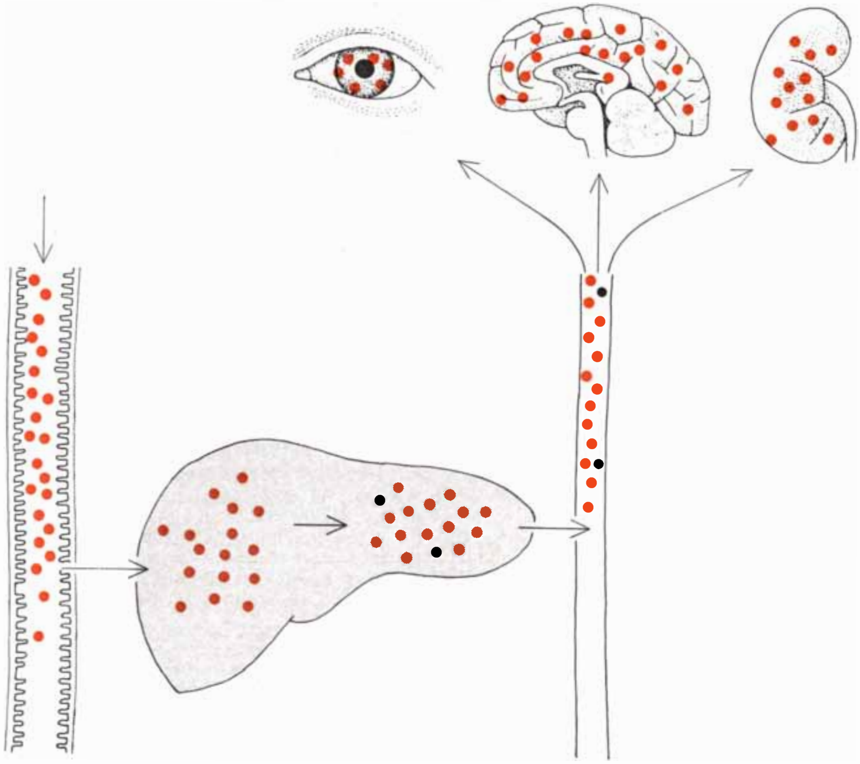
the British physician Kinnier Wilson, who first described it. In this disease the serum is largely depleted of ceruloplasmin, and the copper diffuses into the tissues, where it may accumulate to a high level, particularly in the liver and the brain. It can produce severe mental illness and death. Investigators of the disease, notably I. H. Scheinberg and Irmin Sternlieb of the Albert Einstein College of Medicine in New York, have suggested that anyone with a low level of ceruloplasmin in the blood should have the copper concentration in the tissues tested by means of a liver biopsy. The disease can be treated by two methods: (1) reduction of the copper in the diet by eliminating foods such as liver, mushrooms, nuts and oysters, and (2) the use of a chelating drug, such as penicillamine, that leaches the copper out of the tissues. The second method was devised by J. M. Walshe of the University of Cambridge.

Recent studies have shown that ceruloplasmin not only serves as a nontoxic storage reservoir for copper but also acts as a catalyst for certain reactions. Indeed, ceruloplasmin, acting as an enzyme, may play a part in the synthesis of hemoglobin and other iron-containing proteins. Several years ago a talented British biochemist, Geoffrey Curzon, reported that ceruloplasmin could catalyze the oxidation of ferrous iron to ferric iron, the common oxidizing form of the metal. Later Shigemasa Osaki, Donald A. Johnson and I at Florida State University found that the oxidation of iron was in fact the most prominent catalytic activity of ceruloplasmin (which can therefore be called a "ferroxidase"). We learned that this enzyme may be involved in the formation of a red, iron-bearing protein in the blood plasma called transferrin, which donates its iron to the bone-marrow cells that produce the red blood cells that in turn synthesize hemoglobin. We found that without the aid of ceruloplasmin animals did not synthesize iron transferrin fast enough to supply the iron required for the formation of hemoglobin and other iron-containing proteins.

Further indications of the possible involvement of ceruloplasmin in hemoglobin synthesis have been discovered. M. Shimizu and his co-workers in Japan report that they have found the injection of ceruloplasmin to be effective in treating certain types of anemia. Gennard Matrone and his associates at North Carolina State University have noted that zinc poisoning produces a rapid fall in the concentration of ceruloplasmin in the blood plasma, and this in turn is fol-



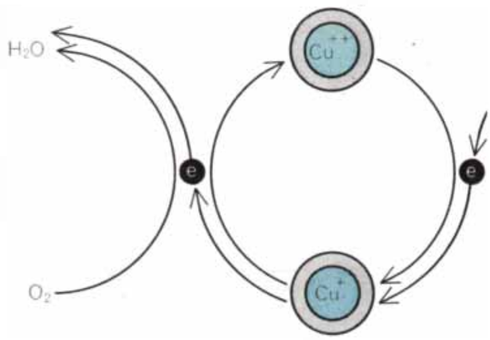
NORMAL DIFFUSION OF COPPER from the diet (*colored dots*) brings the element to the liver. There most of the copper is converted to ceruloplasmin (*black dots*), which enters the bloodstream; it is probably distributed to tissues as needed. This diagram and the one below are based on the work of I. H. Scheinberg of the Albert Einstein College of Medicine.



ABNORMAL DIFFUSION OF COPPER may result in Wilson's disease (named for the British physician Kinnier Wilson). In this condition the conversion of copper to ceruloplasmin is impaired. As a result some excess free copper enters the blood and then diffuses to tissues such as the eye, the brain and the kidney. It also accumulates in the liver.

lowed by anemia and other disturbances of iron and copper metabolism. On the other hand, in our laboratory Takashi Inaba and I have observed that in the metamorphosis of tadpoles to frogs there is a remarkable increase of ceruloplasmin in the plasma before the animals begin to synthesize the nonlarval, or adult, form of hemoglobin. As I have already mentioned, it has been known for some time that animals with a severe copper deficiency suffer a considerable loss in their ability to produce hemoglobin. This new evidence for the role of ceruloplasmin now promises to lead to information that will clarify the link between copper and iron metabolism.

Of all the copper enzymes none is more interesting than tyrosinase, which, among other functions, controls the pigmentation of man's skin. One of the first oxidative enzymes to be discovered, tyrosinase was originally detected in mushrooms by E. Bourguelot and Gabriel Bertrand of France in 1895. Its chemistry and biological activity have been studied intensively, particularly by Dennis J. Kertesz of the Food and Drug Administration and Howard S. Mason of the University of Oregon Medical School. A tyrosinase from the bread mold Neurospora is now available in crystalline form, having been crystallized in 1963 by Marguerite Fling, Norman H. Horowitz and Stephen F. Heinemann of the California Institute of Technology. Tyrosinase catalyzes the oxidation of the amino acid tyrosine and other phenolic compounds to produce the black pigment melanin. Besides its effect in darkening the skin of higher animals, tyrosinase is involved in the darkening of bruised potatoes, apples and



OXIDATION OF IRON by ceruloplasmin may play a role in the formation of transferrin, the iron-carrying protein of plasma. In the oxidation copper (*blue*) removes an

other fruits. It may also be responsible for the darkening of ripe bananas. Insects that have a hard coat protecting them against mechanical injury and dehydration owe this protective coat to a copious production of a hard melanin by tyrosinase.

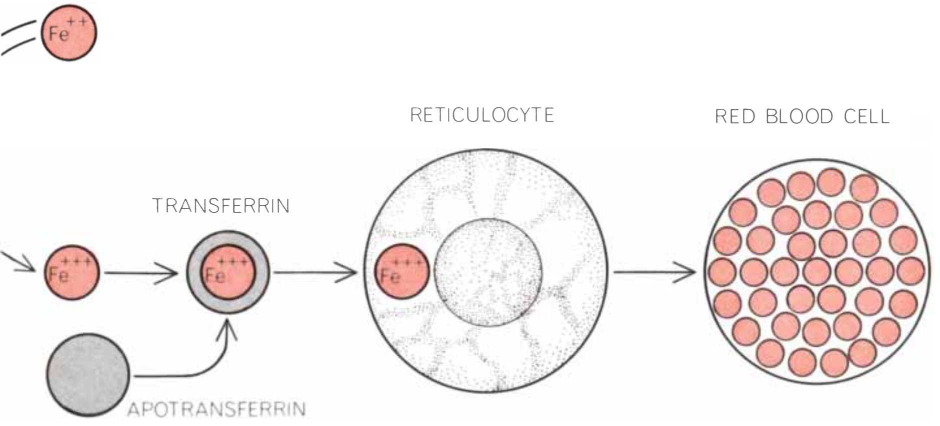
The same copper enzyme has been implicated in two distinctive animal aberrations: albinism and the type of skin cancer called melanoma. Albinism, on the one hand, seems to be associated with an absence or inactivity of tyrosinase; on the other hand, overactivity of this enzyme is observed in malignant melanomas. It has long been known that albinism is due to an inborn error of metabolism that deprives animals of the ability to produce the black pigment melanin. Lack of this pigment in the hair, the skin and the retina of the eye not only decolorizes those organs but also results in acute sensitivity of the eye to light, hypersensitivity of the skin to sunburn and a general shortening of life. The specialized cells ("melanocytes") that normally synthesize melanin fail to do so in animals afflicted with this defect. Instead the cells produce colorless granules, as N. A. Barnicot and M. S. C. Birbeck discovered by examination of the cells with the electron microscope.

In albino rabbits, mice and guinea pigs the melanocytes appear to be completely devoid of the enzyme tyrosinase. Thomas P. Kugelman and E. J. Van Scott of the National Institutes of Health did find some evidence for the presence of tyrosinase in the melanocytes of a number of albinic human patients. The failure of the cells to produce melanin in human beings may therefore be due either to a deficiency of the amino acid tyrosine in these cells or, more likely, to some substance or defect that inhibits the activity of tyrosinase.

Malignant melanomas occur in a wide range of animals, from fishes to human beings. In these diseases the concentration of melanin rises to such a high level that it blackens the skin around the tumors, and dark precursors of the pigment can be found even in the blood and the urine. It has now been demonstrated that the melanocytes of animals afflicted with this malignancy show a hyperactivity of tyrosinase.

Tyrosinase has the unique ability to catalyze the oxidation of tyrosine even when the amino acid is embodied in a protein molecule; no other enzyme known is capable of similar action on a substrate that is combined in an intact protein. Irwin W. Sizer of the Massachusetts Institute of Technology, who was among the first to discover this unusual property of tyrosinase, showed that the enzyme could seek out and oxidize tyrosine in many different proteins. The protein insulin seemed to be impervious to attack by tyrosinase. Charles C. Bigelow, Joseph G. Cory and I have found, however, that the enzyme is in fact capable of acting on the tyrosine in insulin under suitable conditions. Using tyrosinase prepared differently from Sizer's, we succeeded in oxidizing each of the four tyrosines present in the insulin molecule. Later Cory and I found that one of the tyrosines was oxidized more rapidly than the other three. Taking advantage of the fact that the insulin molecule can be separated into two long peptide chains, called *A* and *B*, we learned that the particularly susceptible tyrosine was amino acid No. 26 of the *B* chain.

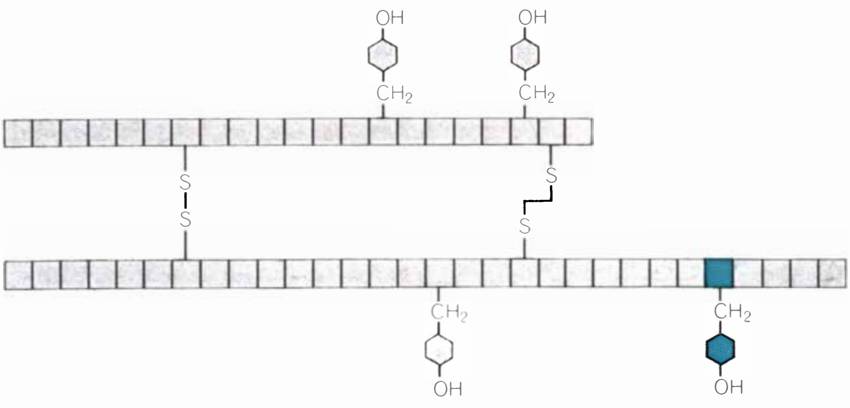
So far only three copper proteins—cytochrome oxidase, hemocyanin and



electron from iron (*red*), temporarily changing its own ionization state and converting iron to ferric iron. Transferrin is known to contribute its iron directly to the reticulocyte cells of the bone marrow. These cells eventually produce the young red blood cells that make hemoglobin. Apotransferrin is an iron-free protein that circulates in the plasma.

PIGMENT IN SKIN AND HAIR is synthesized in reactions catalyzed by the copper enzyme tyrosinase. Under normal conditions (*left*) synthesis of the pigment melanin (*gray*) takes place in melanocytes in the skin and other cells at the roots of the hair (*black*). In albinism (*right*) melanin granules are colorless owing to impaired tyrosinase activity.

tyrosinase—have been investigated thoroughly enough to elucidate their catalytic activity and their roles in metabolism. Doubtless there are many other biological catalysts that owe their activity to copper, but the copper is buried so deep in these huge protein molecules that they are extremely difficult to explore. The few cases already examined, however, show that copper plays remarkably dramatic roles in the machinery of life, and these copper proteins therefore offer an important and fascinating challenge to biochemists.



TYROSINE IN INSULIN is oxidized by tyrosinase, which has the unique ability to catalyze oxidation of the amino acid tyrosine even when it is an integral part of a protein. By splitting the insulin molecule into two peptide chains the author and his co-workers identified the tyrosine unit (*color*) that oxidizes more rapidly than the other three units.

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Territorial Marking by Rabbits

The wild rabbit of Australia lives in colonies from which the rabbits of other colonies are excluded. The rabbits mark their home territory by means of odorous substances that are secreted by specialized glands

by Roman Mykytowycz

Over the past few years it has become increasingly apparent that one of the principal ways animals communicate is by means of odorous glandular secretions that have been given the name pheromones. The best examples of such chemical communication are found among the ants, some species of which use pheromones to lead their fellows to food, to warn them of danger and to organize social behavior in the nest [see "Pheromones," by Edward O. Wilson; SCIENTIFIC AMERICAN, May, 1963]. It has also been shown that pheromones play an important role in the social behavior of mammals (perhaps including man), although exactly how they do so has been somewhat obscure. My colleagues and I have been investigating such mechanisms in the wild rabbit of Australia (*Oryctolagus cuniculus*), and we have been able to demonstrate a clear-cut relation between the animal's social behavior and pheromone-secreting glands.

As is well known, the rabbit was introduced into Australia about 100 years ago, and since that time it has become a serious pest. Over the past two decades the Division of Wildlife Research of the Australian Commonwealth Scientific and Industrial Research Organization has conducted a broad ecological study of the wild rabbit in order to gain a better understanding of the life of the species and to provide a basis for the development of more effective methods of controlling the rabbit population. One result of this study is that we have been able to detect a distinct social organization within the rabbit colony. The role individual animals play in such a society is reflected both in the size of certain glands and in the extent to which the glands secrete pheromones. These substances probably serve a number of functions. They may communicate information about age, sex, reproductive stage and group membership. They may also warn of danger, and they definitely serve to define the "territory" of the rabbit.

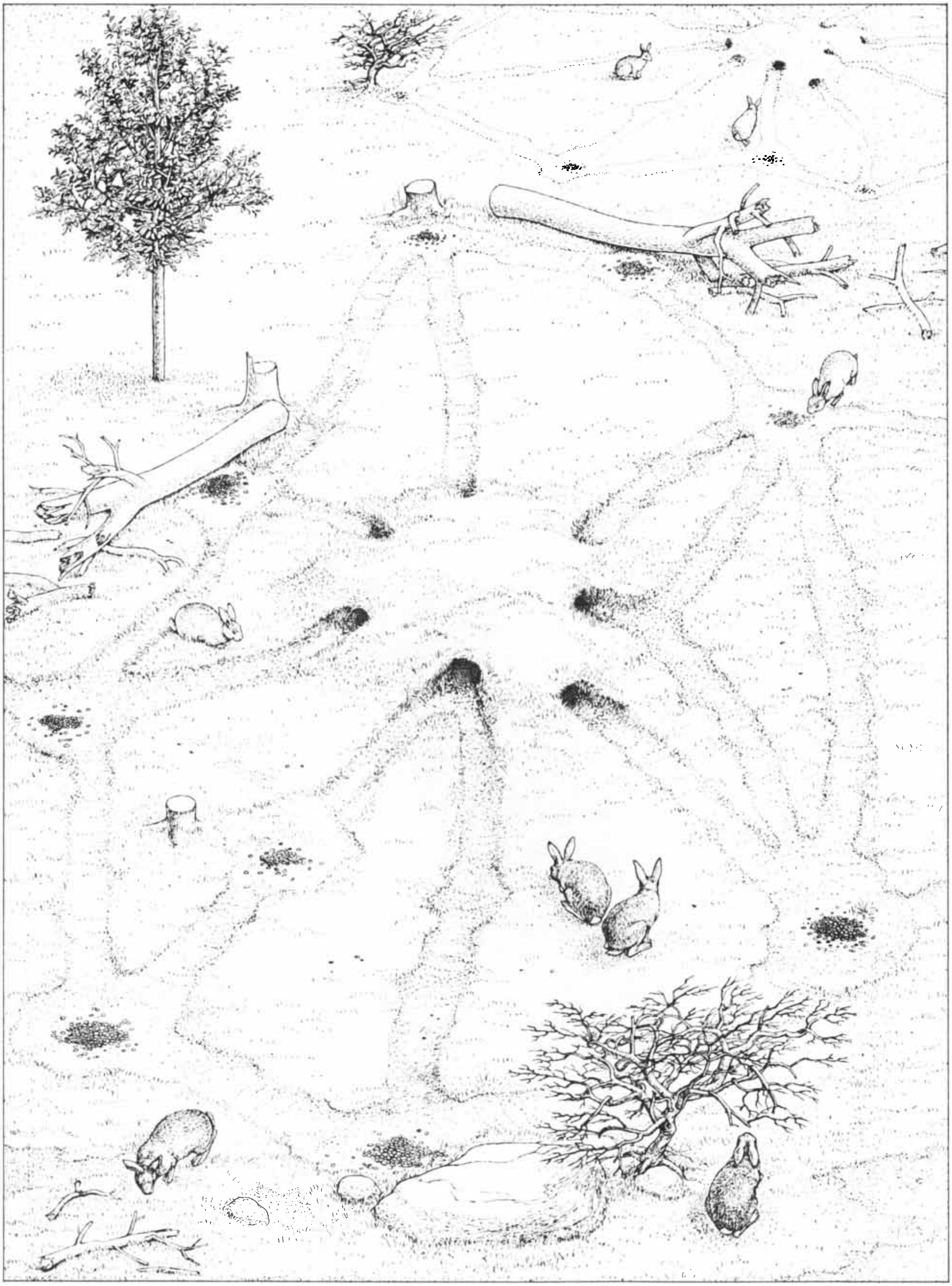
The area within which an animal confines its activities is not necessarily the same as its territory; in a strict sense the term territory refers to that part of an animal's home range which it protects, sometimes by fighting. The size, form and character of a territory of course vary according to the animal's way of life. Some animals occupy a territory permanently; others hold it only during a particular season when, for example, breeding or nesting takes place. The possession of a territory, and therefore available shelter and food, makes breeding possible for some individuals of a species and prevents breeding by other individuals. Hence territoriality is an important factor regulating the density of a population.

Many mammals are known to mark out a territory with substances manufactured by specialized glands. Indeed, nearly all species of mammals possess scent-producing glands, often in several places on the body. In the dromedary the glands are at the back of the head, in the elephant at the temples, in a number of deer species below the eyes (the American deer and some other species have such glands near the hoof and on the leg). The chamois's glands are around the horns, the golden hamster's between the ribs, the peccary's in the loin. The pika (mouse hare) and marmot (woodchuck) employ glands behind and under the eyes and on the cheek for territorial marking. We have identified odor-producing glands on the chest of the kangaroo, and other workers in Australia have found similar glands on the chest of the koala and the brush-tailed possum. The rabbit has scent glands in the anal region, in the groin and under the chin.

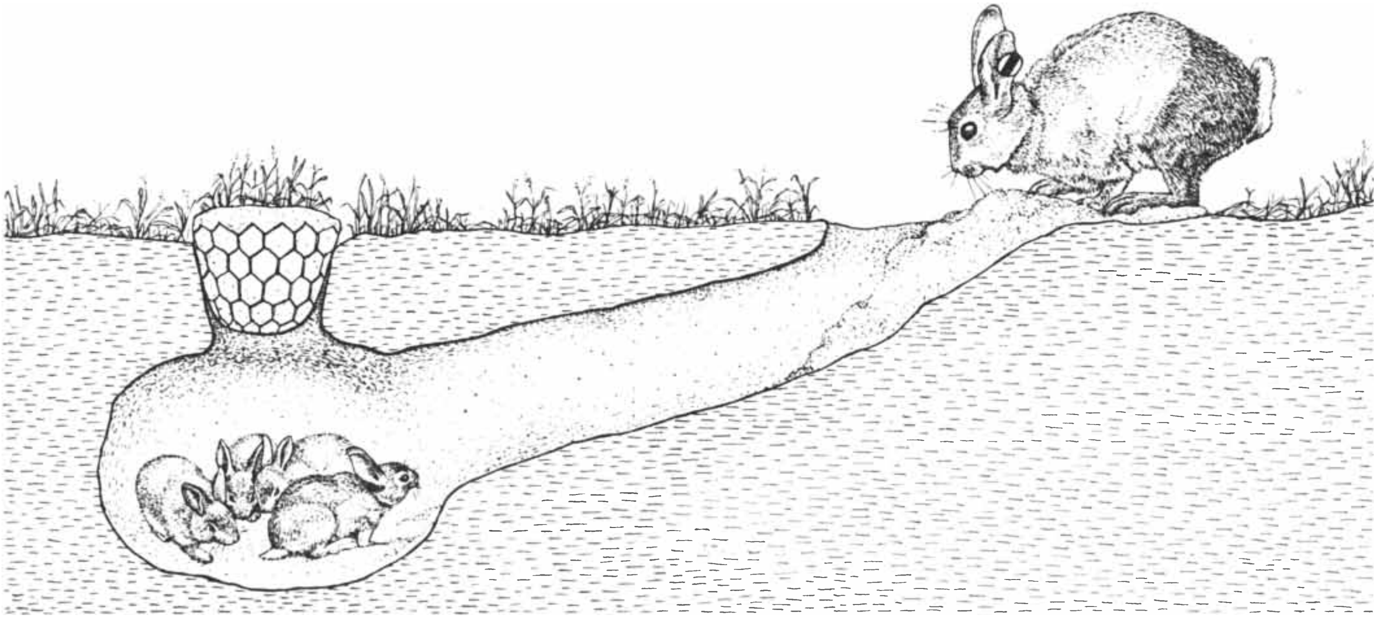
In order to study the territorial behavior of the rabbit it was necessary to follow the activities of individual free-living animals. As in the study of other wild animals, there were certain difficulties. It is not easy to identify individual rabbits, even in daylight, and the animal is largely nocturnal. Live rabbits are hard to catch, and it was necessary to examine them regularly. To minimize these problems we confined our rabbit colonies within fenced areas. Each enclosure was small enough to allow close observation (from an elevated hiding place nearby) but not so small as to interfere with the rabbit's normal behavior. To facilitate the recognition of individual animals each one was marked with black dye in a distinctive pattern; tags of different shapes were also affixed to the rabbits' ears. We used a colored light-reflecting tape to mark the tags in a variety of patterns; at night under spotlights the rabbits could easily be identified. To keep track of the animals' movements in their burrows we drilled a few holes down to the burrow tunnels. When we were not using the holes to check the location of rabbits underground or to catch them, they were plugged with earth enclosed in wire netting.

When a rabbit was born in an enclosure, its ears were permanently marked by tattooing; in this way the behavior of the animal could be followed for its lifetime. The rabbits were observed every day and on certain occasions continuously for a 24-hour period. Some studies were continued for three years, which is twice the average lifespan of a free-living wild rabbit in Australia.

It was established by these observa-



RABBIT TERRITORY, somewhat idealized in this drawing, lies around a central warren. Radiating from the entrances are intersecting runs. On the runs are small mounds of fecal pellets deposited by the rabbits of the colony. At top right a rabbit from another colony sniffs at a mound of pellets. It is warned by odor of an anal-gland secretion on the pellets that the territory is occupied.



RABBIT EXPERIMENT followed the behavior of individual wild rabbits (*Oryctolagus cuniculus*) aboveground and underground. Holes dug down to the burrow tunnel gave access to the animals; when not in use, the holes were plugged with earth enclosed in wire

tions that the rabbit lives in small groups, each consisting of eight or 10 animals, depending on the density of the overall rabbit population. A group of rabbits occupies a distinct territory, with a warren—a burrow with a number of entrances—as its center. At the onset of the breeding season the males establish a hierarchy of descending dominance by fighting. The same is done by the females. The most dominant male and female rule over the group and its territory, which is defended by its occupants and recognized by rabbits of other groups. The rabbit hierarchy is constantly reinforced by chasing and submission.

The advantages of having a territory were evident in the different breeding patterns of female rabbits. High-ranking females give birth frequently and regularly, housing the young in a special breeding chamber dug as an extension to the burrow. Their young have a much higher survival rate and growth rate than the young of low-ranking females. Some of the subordinate females are chased away from a warren and forced to drop their litters in isolated breeding "stops"—short, shallow burrows dug at a distance of 10 to 50 yards from the warren. Both in the stop and later, when they come out of it, the young of such litters are vulnerable to predators, particularly foxes and crows. When they try to enter the central warren, they are attacked by the resident females and their young. Some subordinate females, although they are physiologically fit, never give birth; the embryos they conceive do not develop to full term but are absorbed in the uterus.

It could also be seen that not all rabbit territories are of equal quality: some offer more protection and a better food supply than others. The most dominant animals tend to occupy the better territories. The breeding stops of subordinate females are often in places that are susceptible to flooding, another factor that contributes to the lower survival rate of their young.

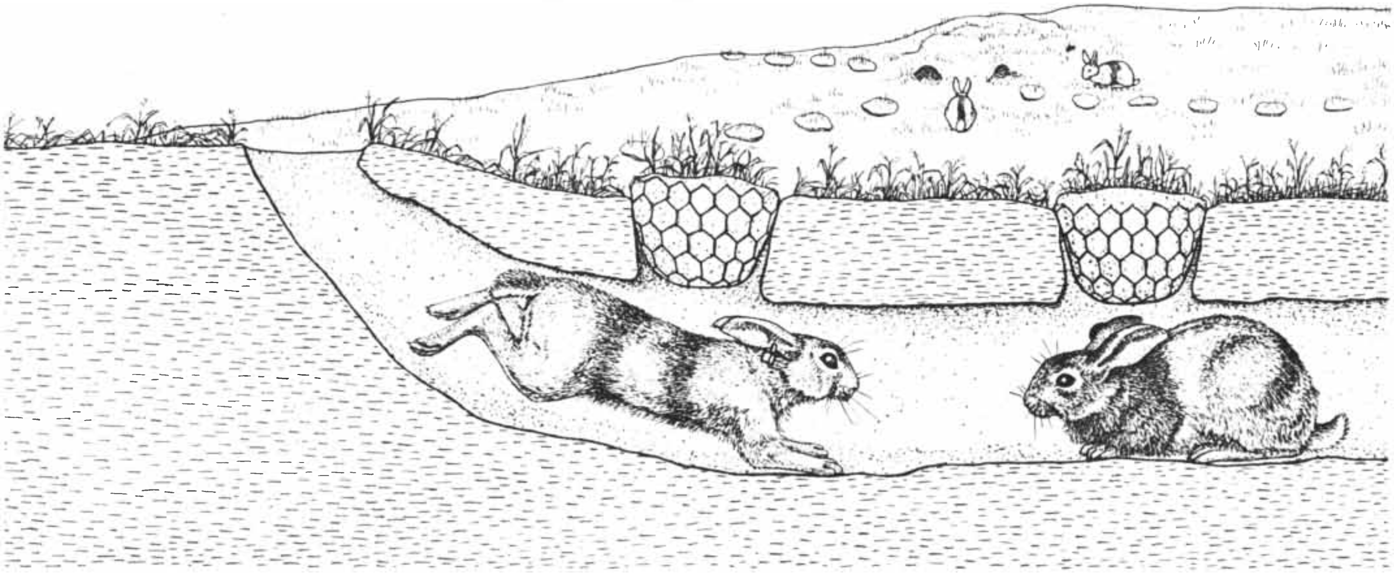
A rabbit that crosses the border between its own territory and a neighboring one is immediately aware that it has done so. No matter how frequent and regular the visits, the animal's behavior changes. In its own territory it moves freely; it feeds and examines objects confidently. In a foreign territory the animal seems always on the alert. Its neck is stretched, the movement of its nostrils indicates that it is sniffing continuously and it does not feed. Although the interloper may be dominant in its own territory, when it is challenged outside by a rabbit permanently attached to the foreign territory, it will offer no resistance. It will not resist even if the challenger is half-grown.

It is not difficult to believe that a rabbit territory becomes saturated with the characteristic smell of the group and that within the area in which this group smell prevails the animals feel at home, much as a man may be able to perceive the odor of another man's home as being strange in contrast to the familiar smell of his own. Specific odors associated with an individual group or colony have been demonstrated in many social insects and also in some fishes. Apart from the effect on the odor of the food eaten by the animals, genetic factors are undoubtedly involved as well.

One component of a rabbit territory's odor is the smell of urine. During amatory behavior the males can be seen urinating on the females, and the animals also urinate on each other during aggressive displays. Young rabbits so marked by adult members of their group are identified with it. The smell of foreign rabbit urine releases aggression; females may even attack their own young when they have been smeared with foreign urine.

Another component of the territory odor comes from feces. The marking out of territory with feces seems to be common among animals, as has been pointed out by Heini Hediger of the University of Zurich. Among certain animals the odor of the feces comes not from the excrement itself but from the pheromone of anal glands; such glands have been identified in more than 100 species of mammals. Some animals whose anal glands are highly developed—for example the gray squirrel, the marten, the dormouse and the hyena—use the anal pheromone alone, rather than in combination with feces, for territorial marking.

The anal glands of the rabbit are well developed. They consist of two clusters

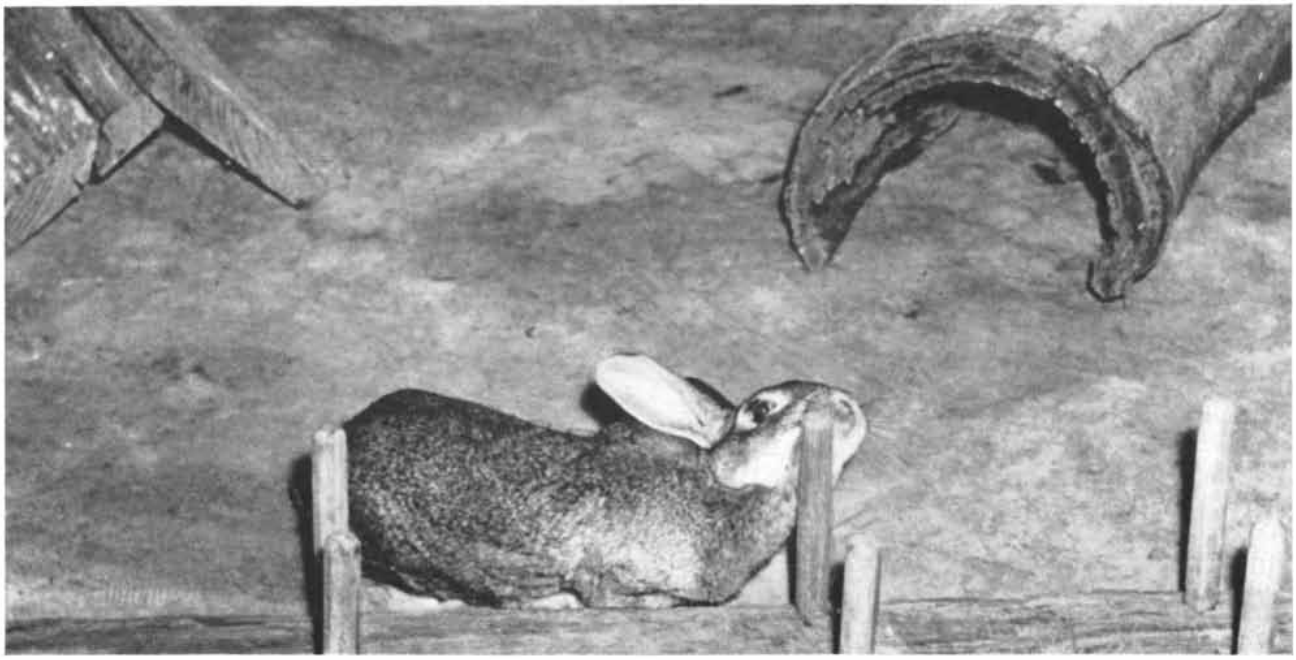


netting. Each adult animal was marked with dye in a distinctive pattern and wore an identification tag in its ear. The ears of rabbits born during the experiment were tattooed. To house their young, rabbits dig special breeding chambers as extensions to the burrow.

of brownish tissue forming a saddle-like mass around the end of the rectum. The secretions of the glands flow through a few ducts into the rectum, where they coat the pellets of feces passing out of the anus. Until recently it was generally accepted that the secretion facilitated the passage of the hard fecal pellets. We have found, however, that when the rabbit's anal glands are removed, defecation is not affected. Our studies indicate that the fecal pellets serve to distribute the rabbit's anal pheromone.

When one examines a rabbit territory, one can see a number of places in which the animals have repeatedly deposited feces. Around a typical warren it is usual to find about 30 of these small dunghills. They are interconnected by paths that all the rabbits use in moving around the area. When a strange rabbit enters the territory, it inevitably encounters a dunghill—a warning signal that the area is occupied. It then displays the wary behavior I have described.

A similar warning is deposited at the entrances to breeding stops. When a stop contains young, it is sealed by the female with soil. Once a day the female reopens the burrow, enters it and suckles the young. When the entrance



CHINNING rabbit enclosed in an experimental pen was photographed at night, when the animal is active. As the rabbit presses against a wooden peg, droplets from its submandibular (underchin) glands are forced through pores of the skin, "marking" the object.

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Every 25 milliseconds the analyzer breaks sound up into 20 channels of ⅓ octave or its multiples. It registers the intensity in each channel and displays the spectrum in the form of a Zwicker diagram. Total loudness is registered on a meter in sones, a unit proportional to the loudness sensation perceived by the ear.

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More information on the Hewlett-Packard loudness analyzer is available in the HP Journal, November, 1967, Vol. 19, No. 3. A copy is yours by writing Hewlett-Packard, Palo Alto, California 94304; Europe: 54 Route des Acacias, Geneva.

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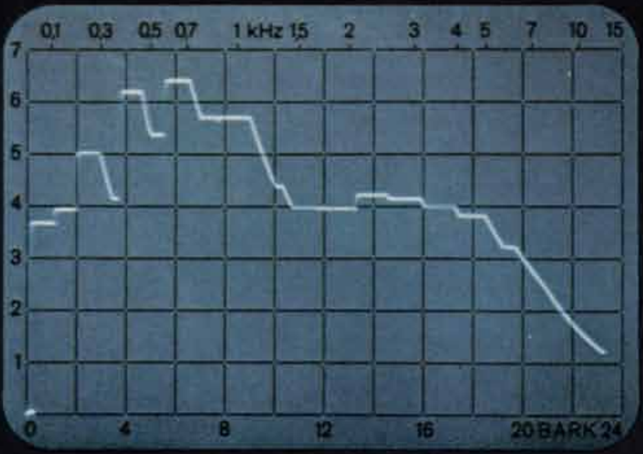
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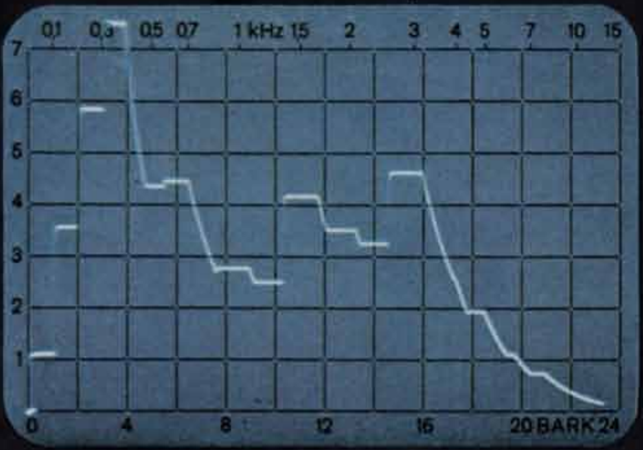
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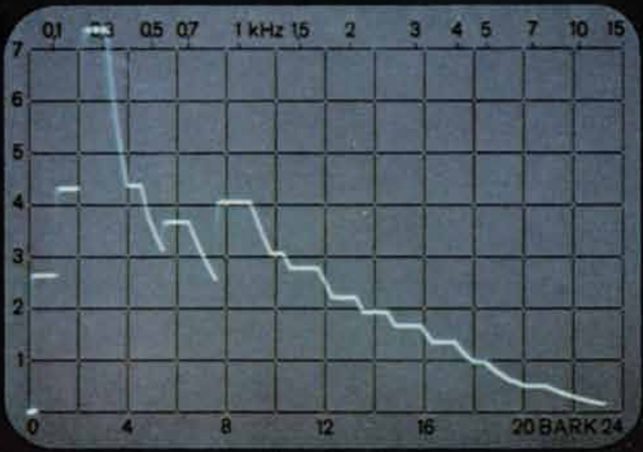
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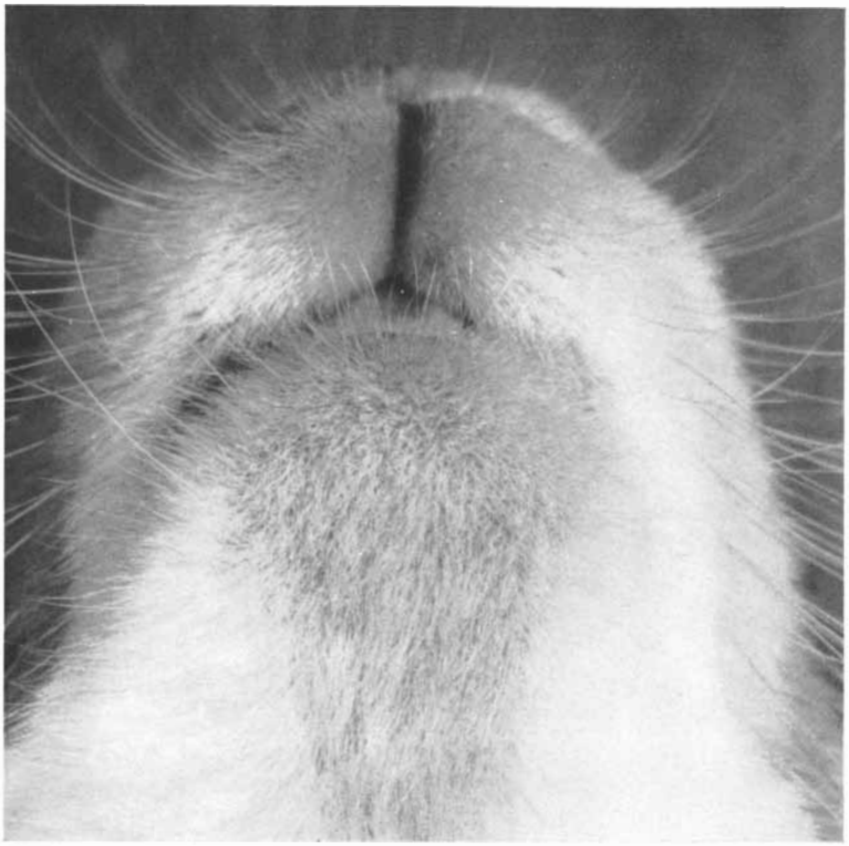
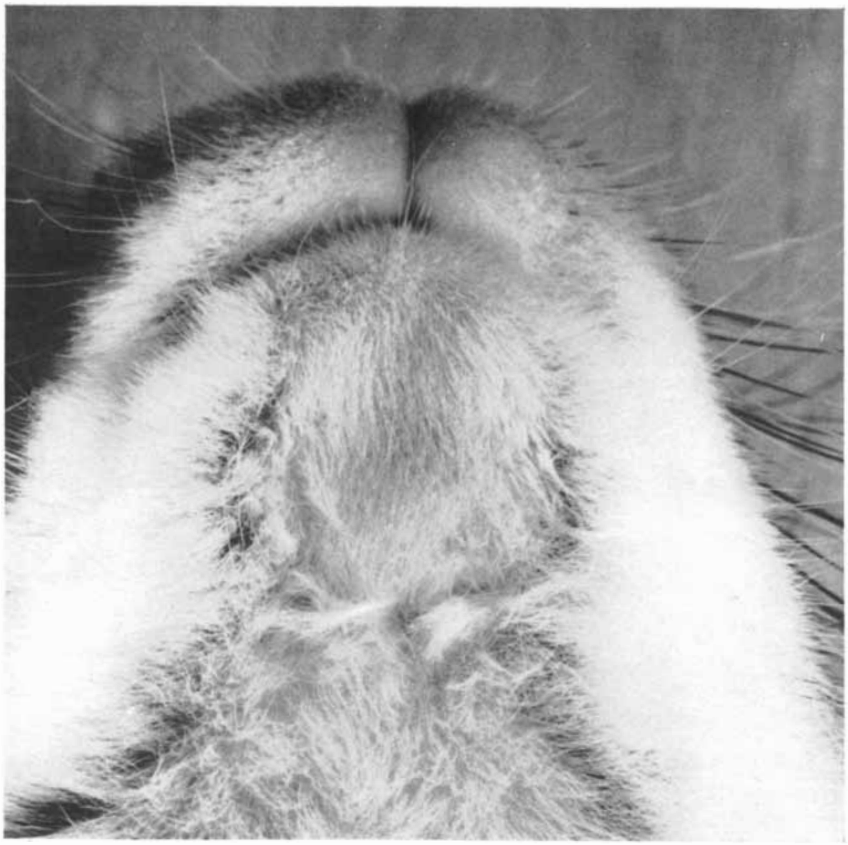
is resealed, the female is likely to deposit a few fecal pellets and some urine on top of the seal. It is remarkable that these earth seals are almost never disturbed by other rabbits. (The exceptions occur under abnormal circumstances, such as when the density of a confined population becomes exceptionally high and competition for breeding sites is intensive.)

Certain of our experiments support the idea that the rabbit's feces serve a communicative function, and indicate that the pellets of a dunghill differ from those that are randomly deposited around a territory. We presented a group of rabbits with artificial dunghills consisting of turf sprinkled with some of the pellets found at random locations in the territory of other rabbits. Around these artificial dunghills (and also on pieces of turf used as a control) the animals engaged mainly in digging and eating. When they were confronted with an actual dunghill from foreign territory, however, they did not eat, they sniffed intensely and they produced marking feces of their own. These pellets were similar to dunghill pellets in that their "rabbity" odor was (according to 30 human judges) decidedly stronger than the odor of the randomly distributed pellets. Presumably the difference between the two odors is perceived even more sharply by rabbits.

There is a highly significant relation between the size of a rabbit's anal gland and the place of the animal in the social hierarchy of a warren. The largest glands belong to dominant individuals, the smallest to subordinate animals. (Body weight is not the main factor determining glandular size.) The secretory activity of the anal gland also is higher in the dominant animals. Indeed, we found that the social rank of an individual rabbit could be guessed with a fair degree of accuracy merely from the appearance of the gland in section. It is also significant that the size and secretory activity of the gland were greatest during the breeding season—the period when territorial activity is most intense.

Male rabbits are mainly responsible for establishing dunghills (in Australia about 80 percent of the animals caught in traps set on dunghills are males), and the anal gland of the male rabbit is larger than the anal gland of the female. Our experiments indicate that the activity of the gland is under the control of sex hormones. When male rabbits were castrated before puberty, the growth



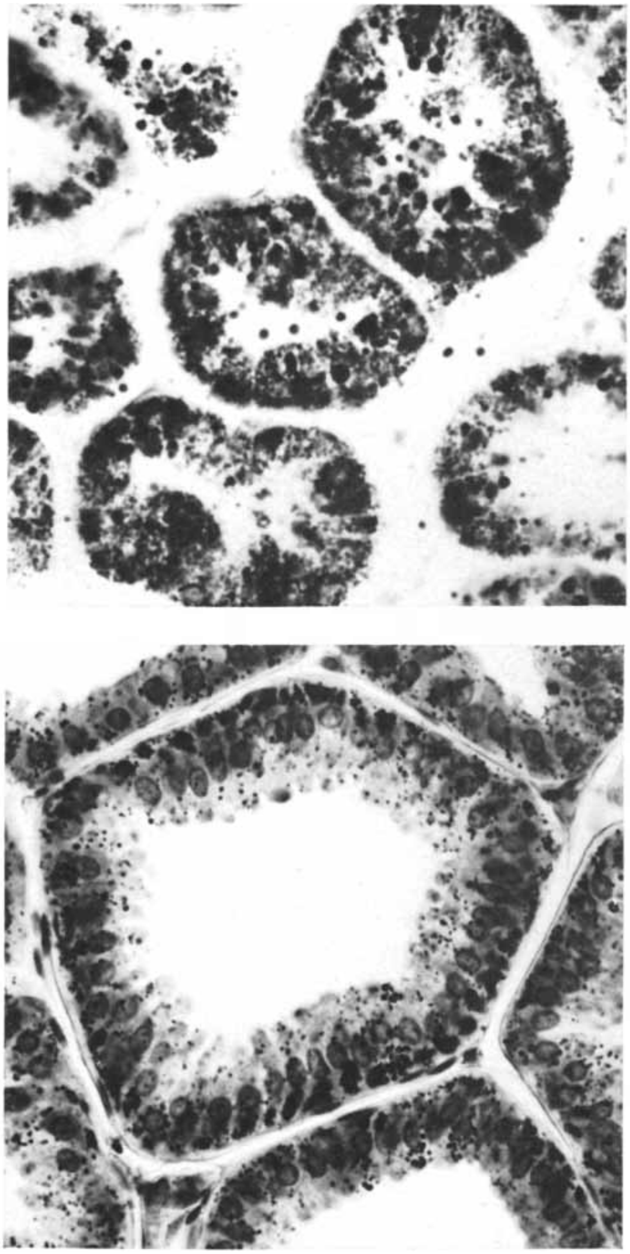


UNDERCHIN of the rabbit is the site of the subcutaneous glands that, together with the anal glands, function in territorial marking. The fur under the chin of the female rabbit (*top*) displays no trace of a glandular secretion. Under the male rabbit's chin (*bottom*) the fur is matted from the secretion, which the male produces more copiously than the female.

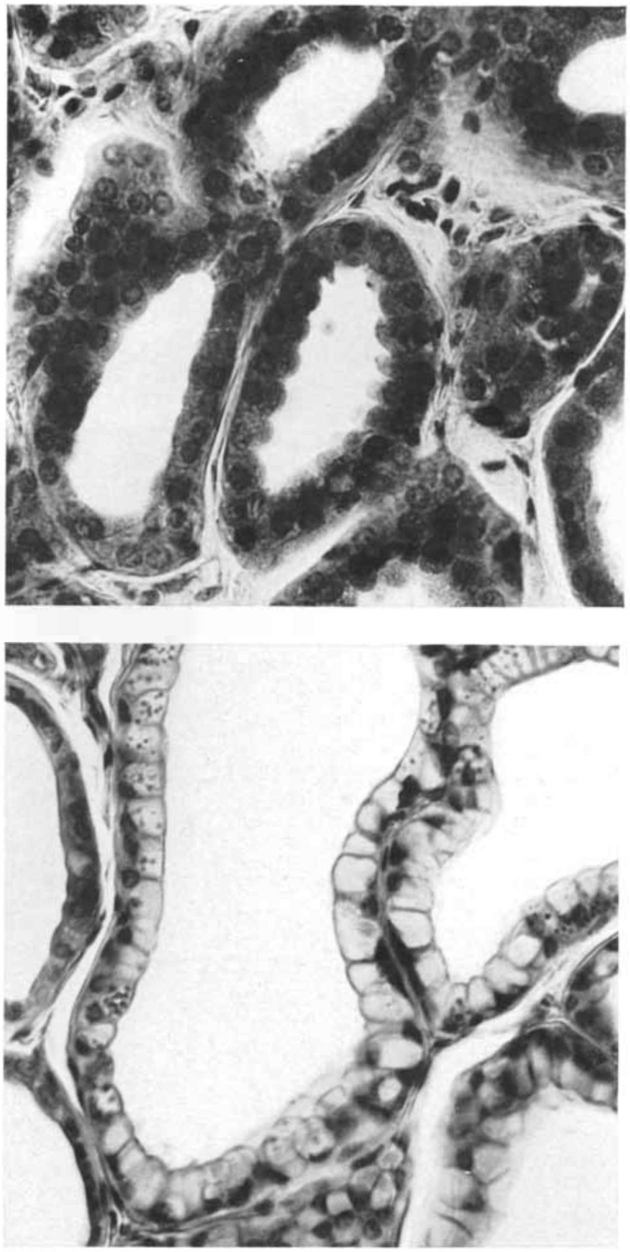
and activity of the anal gland were inhibited; when the ovaries were removed from female rabbits, the size and activity of the gland were somewhat enhanced. When male sex hormones were given to both male and female rabbits, the gland grew larger and produced more secretion.

The rabbit's anal pheromone and its urine thus serve to establish its overall territory. For marking localized features such as logs, branches and blades of grass the animal employs a pheromone secreted by its chin gland. If one looks under the chin of a female rabbit, one cannot find any conspicuous marks, although the fur may be slightly moist or matted. Under the male rabbit's chin, however, there is a distinct yellowish encrustation and matted fur. One can feel the glands under the skin, and if pressure is applied, droplets of secretion can be forced out through a semicircular row of external pores. With this secretion (which is odorless to humans) the male rabbit marks not only objects that would be difficult to mark with feces or urine but also the entrances to its burrows, the fecal pellets of other rabbits, its own weathered pellets and its females and young. To describe marking with this gland we use the term "chinning."

Within its own territory a rabbit chins freely and frequently, particularly if it is a male. When it is in a foreign territory, it does not chin; when it is confronted on its own ground with foreign feces, it chins intensely. We have found that the individuals in a rabbit hierarchy that are most dominant chin more often than the subordinate animals. In fact, the frequency of chinning can



ANAL-GLAND ACTIVITY can be determined from the appearance of the gland in section. In the less actively secreting gland shown at top the tubules (*dark areas with light centers*) are smaller than those in the intensely secreting gland that appears below it.



CHIN-GLAND ACTIVITY is also reflected in contrasting size of tubules in less active gland (*top*) and more active one (*bottom*). These four photomicrographs were made by E. C. Slater of the Commonwealth Scientific and Industrial Research Organization.

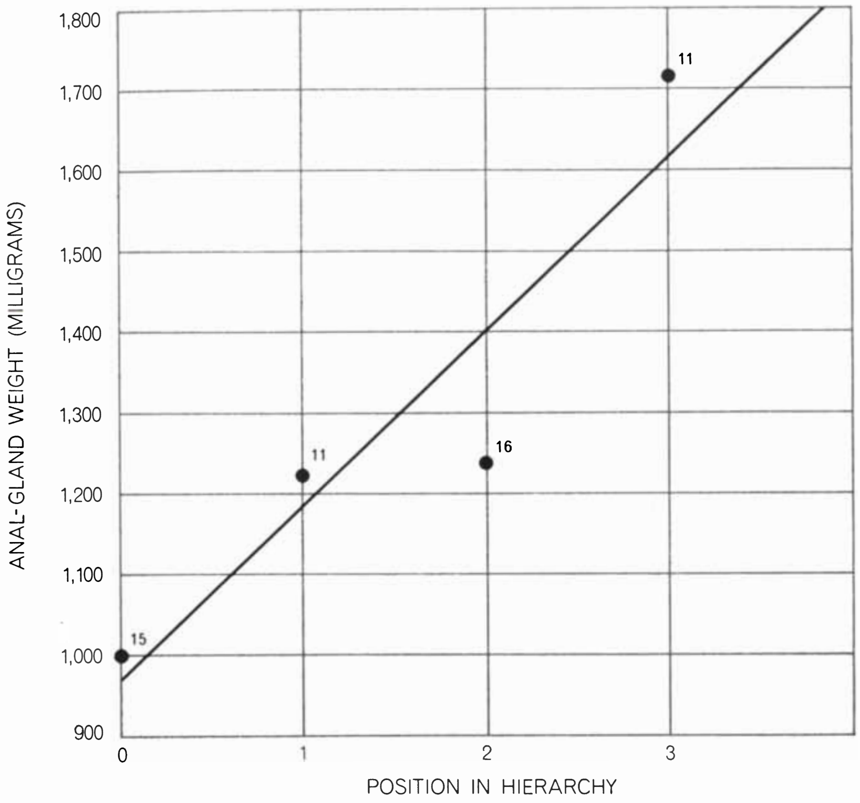
be used as an indication of potential dominance: when two males completely strange to each other were brought together, the male with the highest chinning score always established his dominance over the other animal.

The rabbit's chin gland, like its anal gland, is larger and secretes more abundantly in dominant animals than in subordinate ones. This gland too, being larger in males than in females, appears to be under the control of sex hormones. Moreover, its activity, like that of the anal gland, fluctuates with the seasons; it secretes most freely at the time when the rabbit's territorial activity is at its most intense. Thus the animals that are dominant in the hierarchy are the ones most concerned with the demarcation and defense of territory. Indeed, their territorial behavior is rooted in their physiology.

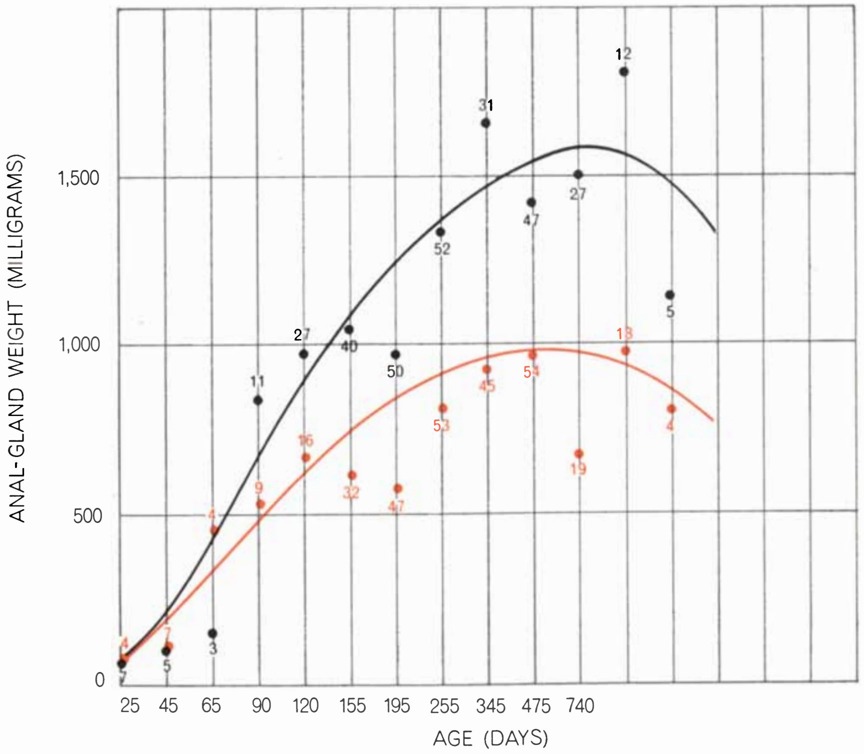
Additional support for the territorial function of the anal and chin glands has come from the study of an animal that is closely related to the rabbit but that behaves differently with respect to territory. This animal is the European hare (*Lepus europaeus*), which like the rabbit has become widely distributed throughout Australia since being introduced there. Although a fully grown hare is four times as heavy as a rabbit and most of its glands (such as the thyroid and lachrymal glands) are larger, the anal and chin glands of the hare are only a tenth the size of those in rabbits.

This difference between the two animals reflects a difference in their territorial behavior. Unlike the rabbit, the hare does not live in a social group; it is a solitary animal and its home area is large. The hare protects only that part of its home range which is in its immediate vicinity, and it does not retain such a territory permanently. Although the animal makes dunghills (apparently at the sites it visits most frequently), the number of them is small compared with the number in a rabbit territory. There is no difference between the anal gland of the male hare and the gland of the female. In short, it appears to be unnecessary for the hare to mark its territory by odor.

Another difference in the glandular makeup of the hare and the rabbit also appears to have behavioral significance. The animals have similar glands in the groin, but in the hare these glands are larger than they are in the rabbit (and they are somewhat larger in the female hare than they are in the male). Observations of the hare's mating behavior



RELATION BETWEEN ANAL GLAND AND SOCIAL BEHAVIOR was established from observations of the activities of rabbits. The most dominant animals of a warren hierarchy (*here given the rating "3"*) were found to possess the heaviest anal glands. The number above a dot indicates the number of rabbits in the sample; the trend is indicated by a line.



SEXUAL DIFFERENTIATION appears when the weight of the anal gland of male rabbits (*black*) is compared with that of female rabbits (*color*). The number of animals sampled is shown adjacent to a dot; the curves indicate the trend in the measurements. Age of the rabbits was estimated from the weight of the eye lens and is uncertain beyond 740 days.

suggest that the glands in the groin are the source of a powerful sexual attractant: when the solitary-living female hare is in estrus, she attracts males from some distance. The female of the gregarious rabbit species obviously has no need of a long-range attractant.

What we have learned about the wild rabbit in Australia is supported by studies of American species. The swamp rabbit (*Sylvilagus aquaticus*), a strongly territorial species, chins more frequently than the weakly territorial cottontail rabbit (*Sylvilagus floridanus*). Our examination of gland tissue from these species indicates that the anal and chin glands are larger in the swamp rabbit than in the cottontail. The social behavior of the two species was studied by Halsey M. Marsden and Nicholas R. Holler of the University of Missouri.

The pheromones of rabbits and other mammals have not yet been chemically separated and identified, as has been done with certain insect pheromones. With knowledge of the composition of specific odors it will be possible to establish their role in the life of a mammalian species. This will undoubtedly lead to a better understanding of the species' behavior. Some insect pheromones have even been synthesized; incorporated in traps, they have been used successfully in pest control. The synthesis of mammalian pheromones would no doubt be helpful in developing effective controls for mammals that are economically undesirable.

The existence of glands that function specifically and solely for territorial marking emphasizes the importance of territory and social organization in the life of an animal. In today's crowded world the question of space and territory is of interest not only to students of animal biology but also to all who are concerned with man's problems of overpopulation. The theory that in animals population control is achieved through social behavior of which territoriality is an integral part has been advanced by V. C. Wynne-Edwards of the University of Edinburgh [see "Population Control in Animals," by V. C. Wynne-Edwards; SCIENTIFIC AMERICAN, August, 1964]. More and more we are coming to realize that it is not only the availability of food that determines the size of a human population but also our own behavior and spacing, and that these factors must be considered in speculating on the fate of the human species. Every animal has, in addition to minimum requirements of things such as food, minimum requirements of living space and distance from others of its own species.

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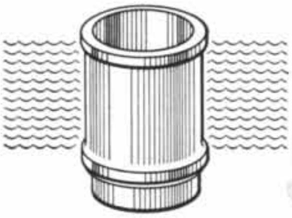

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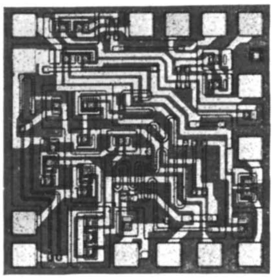

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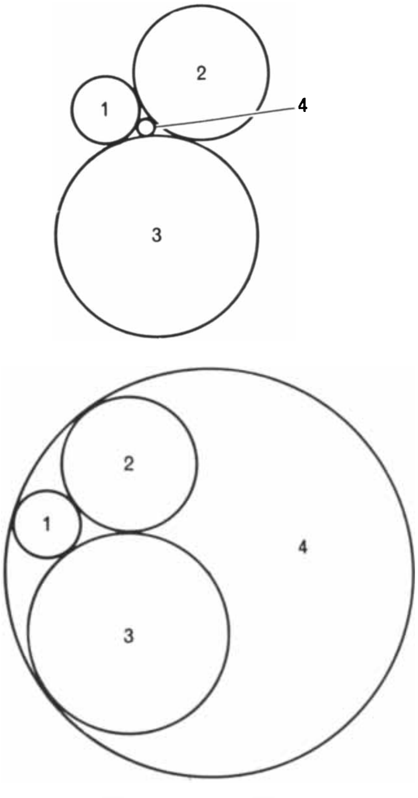
"Shut up or I'll nail your other foot to the floor."

—Children's sick joke, circa 1955

A circle, as the demonstration cited above makes clear, is the locus of all points on the plane at a given distance from a fixed point on the plane. Let us extend this to Euclidean spaces of all dimensions and call the general n-sphere the locus of all points in n-space at a given distance from a fixed point in n-space. In a space of one dimension (a line) the 1-sphere consists of two points at a given distance on each side of a center point. The 2-sphere is the circle, the 3-sphere is what is commonly called a sphere. Beyond that are the hyperspheres of 4, 5, 6... dimensions.



Find radius of fourth circle

Imagine a rod of unit length with one end attached to a fixed point. If the rod is allowed to rotate only on a plane, its free end will trace a unit circle. If the rod is allowed to rotate in 3-space, the free end traces a unit sphere. Assume now that space has a fourth coordinate, at right angles to the other three, and that the rod is allowed to rotate in 4-space. The free end then generates a unit 4-sphere. Hyperspheres are impossible to visualize; nevertheless, their properties can be studied by a simple extension of analytic geometry to more than three coordinates. A circle's Cartesian formula is $a^2 + b^2 = r^2$, where r is the radius. The sphere's formula is $a^2 + b^2 + c^2 = r^2$. The 4-sphere's formula is $a^2 + b^2 + c^2 + d^2 = r^2$, and so on up the ladder of Euclidean hyperspaces.

The "surface" of an n-sphere has a dimensionality of $n - 1$. A circle's "surface" is a line of one dimension, a sphere's surface is two-dimensional and a 4-sphere's surface is three-dimensional. Is it possible that 3-space is actually the hypersurface of a vast 4-sphere? Could such forces as gravity and electromagnetism be transmitted by the vibrations of such a hypersurface? Many late-19th-century mathematicians and physicists, both eccentric and orthodox, took such suggestions seriously. Einstein himself proposed the surface of a 4-sphere as a model of the cosmos, unbounded and yet finite. Just as Flatlanders on a sphere could travel the straightest possible line in any direction and eventually return to their starting point, so (Einstein suggested) if a spaceship left the earth and traveled far enough in any one direction, it would eventually return to the earth. If a Flatlander started to paint the surface of the sphere on which he lived, extending the paint outward in ever widening circles, he would reach a halfway point at which the circles would begin to diminish, with himself on the *inside*, and eventually he would paint himself into a spot. Similarly, in Einstein's cosmos, if terrestrial astronauts began to map the universe in ever expanding spheres, they would eventually map themselves into a small globular space on the opposite side of the hypersphere.

Many other properties of hyperspheres are just what one would expect by analogy with lower-order spheres. A circle rotates around a central point, a sphere rotates around a central line, a 4-sphere rotates around a central *plane*. In general the axis of a rotating n-sphere is a space of $n - 2$. (The 4-sphere is capable, however, of a peculiar double rotation that has no analogue in 2- or 3-space: it can spin simultaneously around two fixed planes that are perpendicular to each other.) The projection of a circle on a line is a line segment, but every point on the segment, with the exception of its end points, corresponds to two points on the circle. Project a sphere on a plane and you get a disk, with every point inside the circumference corresponding to two points on the sphere's surface. Project a 4-sphere on our 3-space and you get a solid ball with every internal point corresponding to two points on the 4-sphere's hypersurface. This too generalizes up the ladder of spaces.

The same is true of cross sections. Cut a circle with a line and the cross section is a 1-sphere, or a pair of points. Slice a sphere with a plane and the cross section is a circle. Slice a 4-sphere with a 3-space hyperplane and the cross section is a 3-sphere. (You can't divide a 4-sphere into two pieces with a 2-plane. A hyperapple, sliced down the middle by a 2-plane, remains in one piece.) Imagine a 4-sphere moving slowly through our space. We see it first as a point and then as a tiny sphere that slowly grows in size to its maximum cross section, then slowly diminishes and disappears.

A sphere of any dimension, made of sufficiently flexible material, can be turned inside out through the next-highest space. Just as we can twist a thin rubber ring until the outside rim becomes the inside, so a hypercreature could seize one of our tennis balls and turn it inside out through his space. He could do this all at once or he could start at one spot on the ball, turn a tiny portion first, then gradually enlarge it until the entire ball had its inside outside.

One of the most elegant of the formulas that generalize easily to spheres of all dimensions is the formula for the radii of the maximum number of mutually touching n-spheres. On the plane, no more than four circles can be placed so that each circle touches all the others, with every pair touching at a different point. There are two possible situations (aside from degenerate cases in which one circle has an infinite radius and so becomes a straight line): either three circles surround a smaller one [*at top in illustration on opposite page*] or three circles are inside a larger one [*bottom*]. Frederick Soddy, the British chemist who received a Nobel prize in 1921 for his discovery of isotopes, put it this way in the first stanza of *The Kiss Precise,* a poem that appeared in *Nature* (Vol. 137, page 1021; June 20, 1936):

For pairs of lips to kiss maybe
Involves no trigonometry.
'Tis not so when four circles kiss
Each one the other three.
To bring this off the four must be
As three in one or one in three.
If one in three, beyond a doubt
Each gets three kisses from without.
If three in one, then is that one
Thrice kissed internally.

Soddy's next stanza gives the simple formula. His term "bend" is what is usually called the circle's curvature, the reciprocal of the radius. (Thus a circle of radius 4 has a curvature or "bend" of 1/4.) If a circle is touched on the inside, as it is in the case of the large circle enclosing the other three, it is said to have a concave bend, the value of which is preceded by a minus sign. As Soddy phrased all this:

Four circles to the kissing come.
The smaller are the benter.
The bend is just the inverse of
The distance from the center.
Though their intrigue left Euclid dumb
There's now no need for rule of thumb.
Since zero bend's a dead straight line
And concave bends have minus sign,
The sum of the squares of all four bends
Is half the square of their sum.

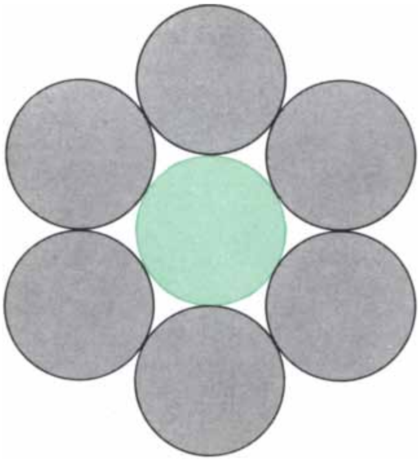
Letting a, b, c, d stand for the four reciprocals, Soddy's formula is $2(a^2 + b^2 + c^2 + d^2) = (a + b + c + d)^2$. The reader should have little difficulty computing the radii of the fourth kissing circle in each illustration. In the poem's third and last stanza this formula is extended to five mutually kissing spheres:

To spy out spherical affairs
An oscular surveyor
Might find the task laborious,
The sphere is much the gayer,
And now besides the pair of pairs
A fifth sphere in the kissing shares.
Yet, signs and zero as before,
For each to kiss the other four
The square of the sum of all five bends
Is thrice the sum of their squares.

The editors of *Nature* reported in the issue for January 9, 1937 (Vol. 139, page 62), that they had received several fourth stanzas generalizing Soddy's formula to n-space, but they published only the following, by Thorold Gosset of the University of Cambridge:

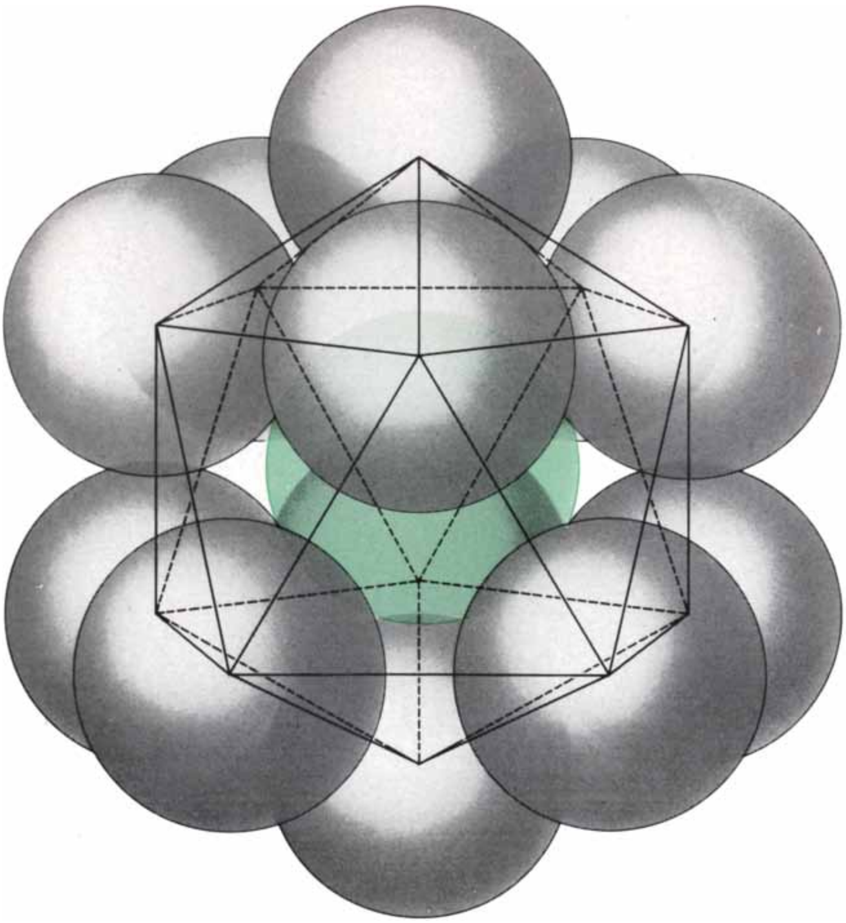
And let us not confine our cares
To simple circles, planes and spheres,
But rise to hyper flats and bends
Where kissing multiple appears.
In n*-ic space the kissing pairs*
Are hyperspheres, and Truth declares—
As n + 2 *such osculate*
Each with an n + 1*-fold mate.*
The square of the sum of all the bends
Is n times the sum of their squares.

In simple prose, for n-space the maximum number of mutually touching spheres is $n + 2$, and n times the sum of the squares of all bends is equal to the square of the sum of all bends. It later developed that the formula for four kissing circles had been known to René Descartes, but Soddy rediscovered it and seems to have been the first to extend it to spheres.

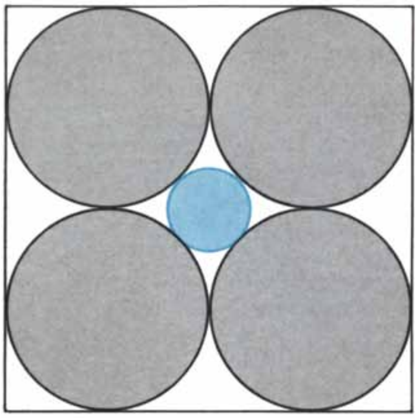


Six unit circles touch a seventh

Note that the general formula even applies to the three mutually touching two-point "spheres" of 1-space: two touching line segments "inside" a third segment that is simply the sum of the other two. The formula is a great boon to recreational mathematicians. Puzzles about mutually kissing circles or spheres yield readily to it. Here is a pretty prob-



Twelve unit spheres touch a 13th



Four circles around one of radius $\sqrt{2}-1$

lem for readers to work on before the answer is given next month. Three mutually kissing spherical grapefruits, each with a radius of three inches, rest on a flat counter. A spherical orange is also on the counter under the three grapefruits and touching each of them. What is the radius of the orange?

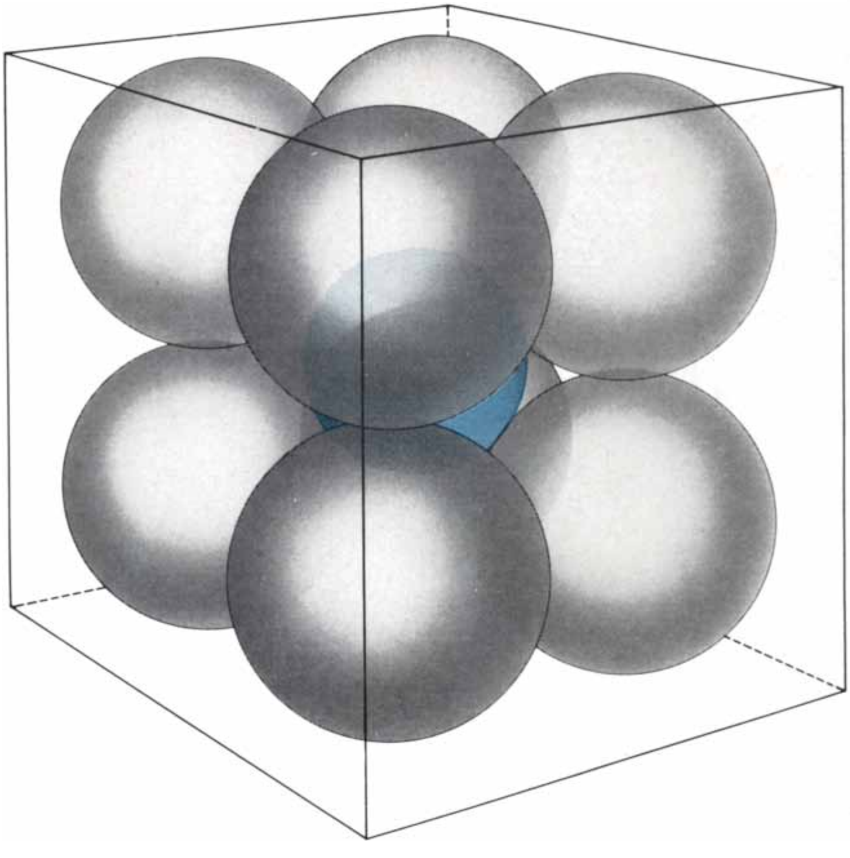
Problems about the packing of unit spheres do not generalize easily as one goes up the dimensional ladder; indeed, they become increasingly difficult. Consider, for instance, the problem of determining the largest number of unit spheres that can touch a unit sphere. For circles the number is six [*see top illustration on preceding page*]. For spheres it is 12, but this was not proved until 1874. The difficulty lies in the fact that when 12 spheres are arranged around a 13th, with their centers at the corners of an imaginary icosahedron [*see bottom illustration on preceding page*], there is space between every pair. The waste space is slightly more than is needed to accommodate a 13th sphere if only the 12 could be shifted around and properly packed. If the reader will coat 14 ping-pong balls with rubber cement, he will find it easy to stick 12 around one of them, and it will not be at all clear whether or not the 13th can be added without undue distortions. An equivalent question (can the reader see why?) is: Can 13 paper circles, each covering a 60-degree arc of a great circle on a sphere, be pasted on that sphere without overlapping?

H. S. M. Coxeter, writing on "The Problem of Packing a Number of Equal Nonoverlapping Circles on a Sphere" (in *Transactions of the New York Academy of Sciences*, Vol. 24, No. 3, pages 320–331; January, 1962), tells the story of what may be the first recorded discussion of the problem of the 13 spheres. David Gregory, an Oxford astronomer and friend of Isaac Newton, recorded in his notebook in 1694 that he and Newton had argued about just this question. They had been discussing how stars of various magnitudes are distributed in the sky and this had led to the question of whether or not one unit sphere could touch 13 others. Gregory believed they could. Newton disagreed. As Coxeter writes, "180 years were to elapse before R. Hoppe proved that Newton was right." Simpler proofs have since been published, the latest in 1956 by John Leech, a British mathematician.

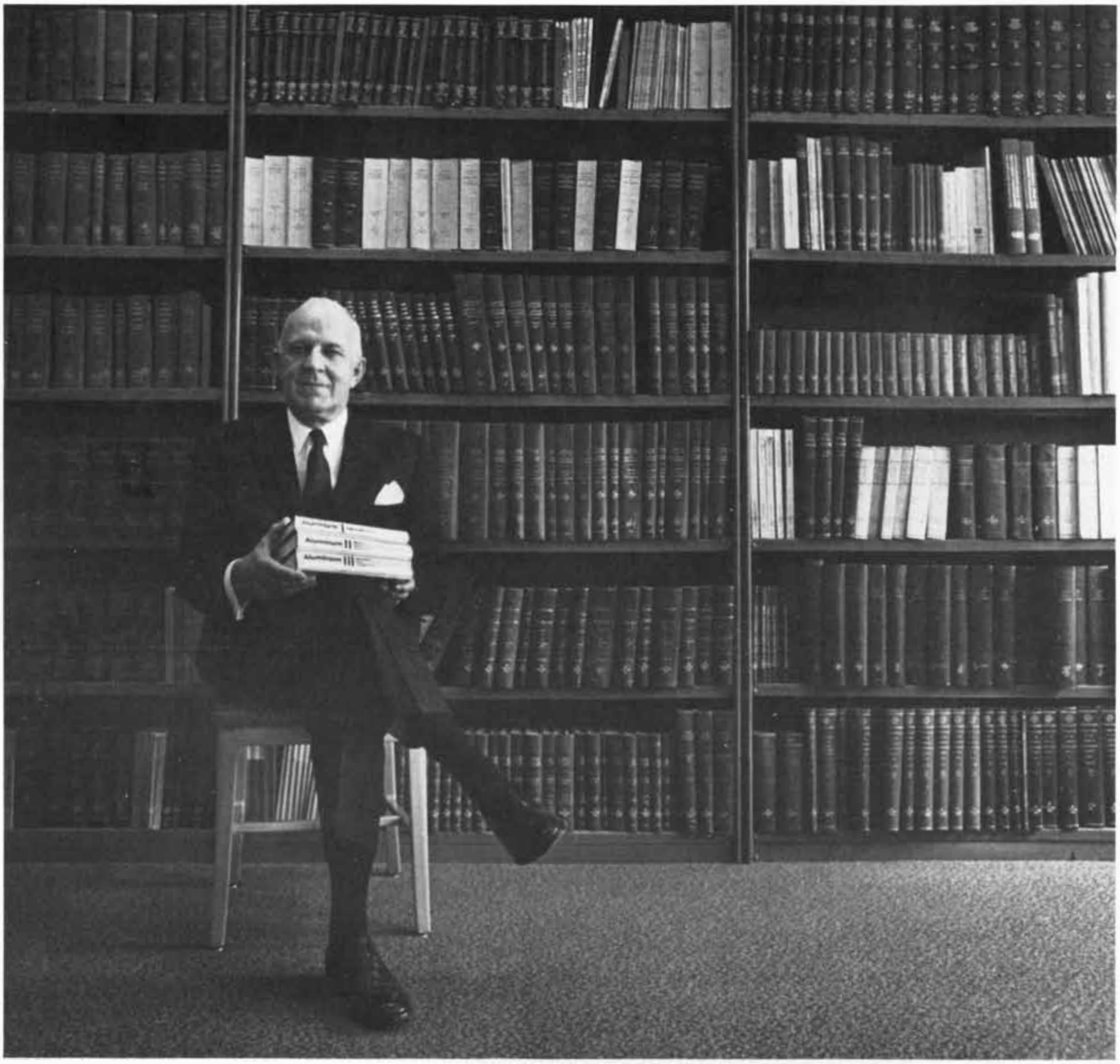
How many unit hyperspheres in 4-space can touch a unit hypersphere? This is not yet known unless one specifies that the centers of all the spheres belong to the points of a regular, infinite lattice. With this honeycomb proviso the answer is supplied by the densest possible packings, which are known through 8-space. In such packings the maximum numbers of unit n-spheres that can touch another sphere of the same size are 24, 40, 72, 126 and 240 for spaces of four, five, six, seven and eight dimensions respectively. The 9-space solution is not yet exactly known, although formulas have been worked out for upper bounds in it and all higher spaces.

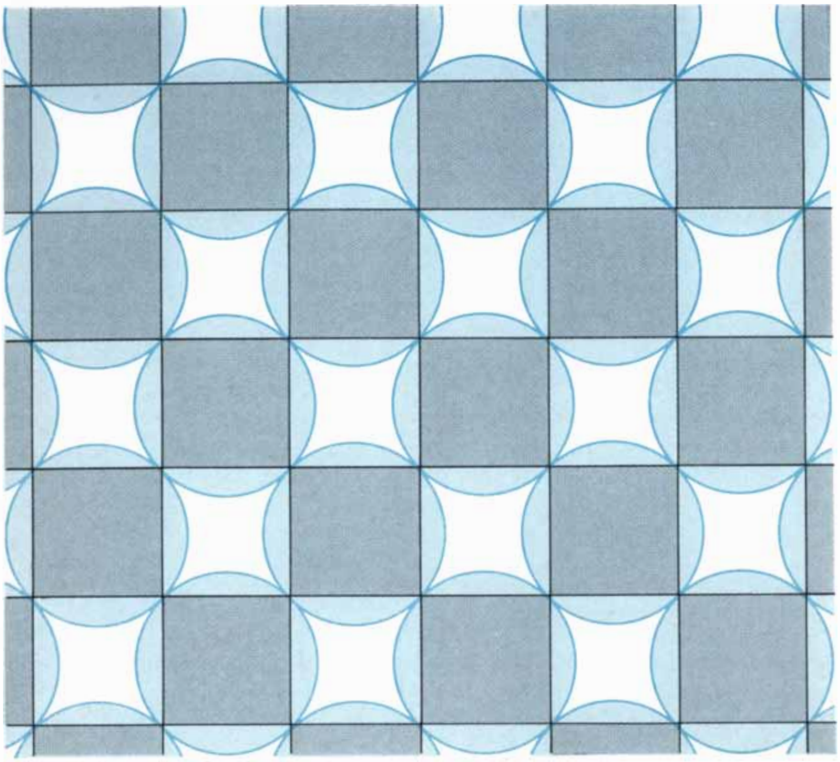
Why the difficulty with 9-space? A consideration of some paradoxes involving hypercubes and hyperspheres may cast a bit of dim light on the curious turns that take place in 9-space. Into a unit square one can pack, from corner to diagonally opposite corner, a line with a length of $\sqrt{2}$. Into a unit cube one can similarly pack a line of $\sqrt{3}$. The distance between opposite corners of an n-cube is $\sqrt{n}$, and since square roots increase without limit it follows that a rod of *any* size will pack into a unit n-cube if n is large enough. A fishing pole 10 feet long will fit diagonally in the one-foot 100-cube. This also applies to objects of higher dimension. A cube will accommodate a square larger than its square face. A 4-cube will take a 3-cube larger than its cubical hyperface. A 5-cube will take larger squares and cubes than any cube of lower dimension with an edge of the same length. An elephant or the entire Empire State Building will pack easily into an n-cube with edges the same length as those of a sugar cube if n is sufficiently large.

The situation with respect to an n-sphere is quite different. No matter how large n becomes, an n-sphere can never contain a rod longer than twice its radius. And something very queer happens to its n-volume as n increases. The area of the unit circle is, of course, π.



Eight unit spheres leave room for one with a radius of $\sqrt{3}-1$

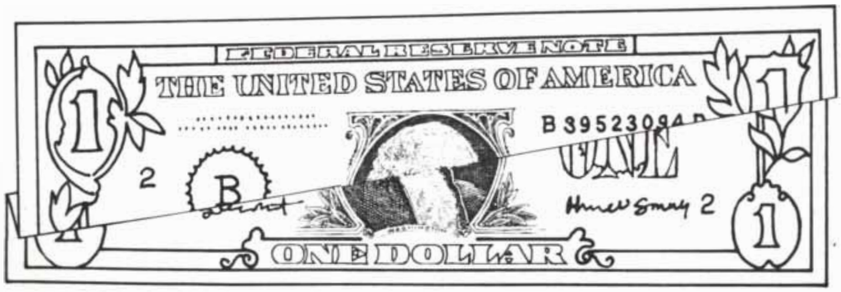




Leo Moser's hyperchessboard problem

The volume of the unit sphere is 4.1+. The unit 4-sphere's hypervolume is 4.9+. In 5-space the volume is still larger, 5.2+, then in 6-space it decreases to 5.1+ and thereafter steadily declines. Indeed, as n approaches infinity the hypervolume of a unit n-sphere approaches zero! This leads to many unearthly results. David Singmaster, writing "On Round Pegs in Square Holes and Square Pegs in Round Holes" (*Mathematics Magazine,* Vol. 37, No. 5, pages 335–337; November, 1964), decided that a round peg fits better in a square hole than vice versa because the ratio of the area of a circle to a circumscribing square ($\pi/4$) is larger than the ratio of a square inscribed in a circle ($2/\pi$). Similarly, one can show that a ball fits better in a cube than a cube fits in a ball, although the difference between ratios is a bit smaller. Singmaster found that the difference continues to decrease through 8-space and then reverses: in 9-space the ratio of n-ball to n-cube is *smaller* than the ratio of n-cube to n-ball. In other words, an n-ball fits better in an n-cube than an n-cube fits in an n-ball if and only if n is 8 or less.

The same 9-space turn occurs in an unpublished paradox discovered by Leo Moser, formerly chairman of the mathematics department at the University of Alberta. Four unit circles will pack into a square of side 4 [*see top illustration on page 132*]. In the center we can fit a smaller circle of radius $\sqrt{2}-1$. Similarly, eight unit spheres will pack into the corners of a cube of side 4 [*see bottom illustration on page 132*]. The largest sphere that will fit into the center has a radius of $\sqrt{3}-1$. This generalizes in the obvious way: In a 4-cube of side 4 we can pack 16 unit 4-spheres and a central 4-sphere of radius $\sqrt{4}-1$, which equals 1, so that the central sphere now is the same size as the others. In general, in the corners of an n-cube of side 4 we can pack 2^n unit n-spheres and presumably another sphere of radius $\sqrt{n}-1$ will fit at the center. But see what happens when we come to 9-space: the central hypersphere has a radius of $\sqrt{9}-1=2$, which is equal to half the hypercube's edge. The central sphere cannot be larger than this in any higher n-cube because it now fills the hypercube, touching the center of every hyperface, yet there is space at $2^9=512$ corners to take 512 unit 9-spheres!



How to fold a $1 bill to make a mushroom

A related unpublished paradox, also discovered by Moser, concerns n-dimensional chessboards. All the black squares of a chessboard are enclosed with circumscribed circles [*see top illustration at left*]. Assume that each cell is of side 2 and area 4. Each circle has a radius of $\sqrt{2}$ and an area of 2π. The area in each white cell that is left white (is not enclosed by a circle) is $8-2\pi=1.71+$. In the analogous situation for a cubical chessboard the black cubical cells of edge 2 are surrounded by spheres. The volume of each black cell is 8 and the volume of each sphere, which has a radius of $\sqrt{3}$, is $4\pi\sqrt{3}$, but the volume of the unenclosed portion of each white cube is not so easy to calculate because the six surrounding spheres intersect one another.

Consider now the four-dimensional lattice of hypercubes of edge 2 with cells alternately colored as before so that each cell is surrounded by eight hypercubes of opposite color. Around each black hypercell is circumscribed a hypersphere. What is the hypervolume of the unenclosed portion within each white cell? The surprising answer, which can be determined quickly without knowing the formula for the volume of a hypersphere, will be given next month.

The first of last month's dollar-bill problems was to fold a bill twice and produce a mushroom. It is done as in the bottom illustration at the left.

The second problem concerned the sum of a bill's serial number and its reversal. When any number with an even number of digits is added to its reversal, the sum is always a multiple of 11. And all multiples of 11 have the following property: either the sum of the digits in the odd positions equals the sum of the digits in the even positions or the sums differ by a multiple of 11. This provides a technique for determining the digit

RECENT FINDINGS

RESEARCH LABORATORIES

Ford

Superconducting Point Contact Devices

A new type of quantum mechanical device has been developed which utilizes small area or point contacts between superconducting materials. A first cousin to the Josephson tunneling junction, these point contacts, with areas estimated at $10^{-12}cm^2$, have been incorporated into appropriate low impedance circuits to produce new highly sensitive devices.

Such a device recently developed at Ford Motor Company research laboratories consists mainly of a sharp-pointed, finely threaded screw made of niobium. When this point is adjusted to touch a superconducting flat niobium anvil over a very small area (the radius of the contact area may be as small as 100 angstroms), the resulting electrical contact shows characteristics similar, but not identical, to the Josephson junction.

One of the first uses of the point contact was to make a very sensitive magnetometer. As part of a superconducting ring in a magnetic field, the point will go into the normal state every time a quantum of flux flows into or out of the ring. For a ring with an inscribed area of one square centimeter, this process occurs with every 2.07×10^{-7} gauss change in the applied magnetic field.

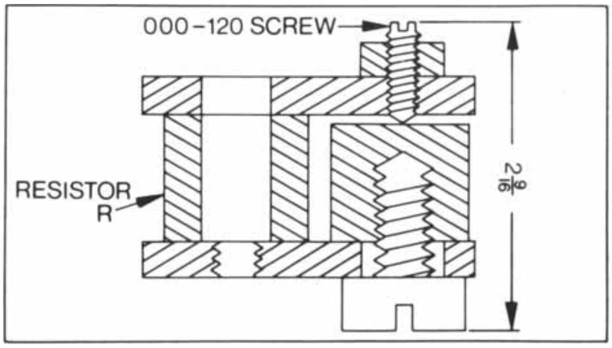


Figure 1
Circuit for developing a voltage across a superconducting point contact. Oscillating currents through the point couple to a pick-up coil for measurement.

More recently, point contacts have been shown to exhibit the Josephson frequency conversion characteristic by which a d-c voltage, V, can be used to generate an a-c signal at a frequency, f, related to the d-c voltages by the formula $V = \frac{h}{2e}f$ where h is Planck's Constant and e is the charge on the electron. Figure 1 shows one configuration used for these experiments. A battery supplies a current through the 10^{-10} ohm resistor and a potential difference equal to 10^{-10} times the current appears across the point contact. An oscillating current, flowing around the loop consisting of the superconducting plates, the resistor, and the screw, is picked up in a pick-up coil for measurement. The frequency versus voltage plot shown in Figure 2 was obtained using apparatus like that shown in Figure 1. The constant of proportionality was measured and found to be 2.07×10^{-15} volts/cycle which is h/2e to an accuracy of 3%.

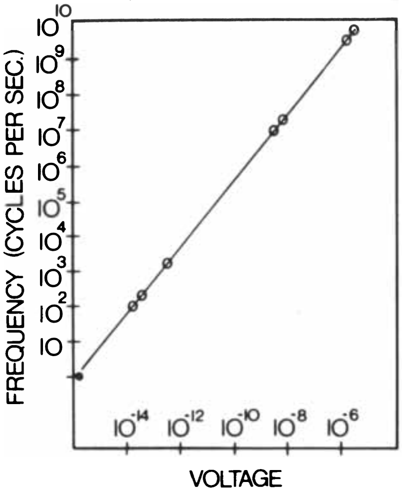


Figure 2
Experimental data showing relationship between voltage across the point contact and frequency generated.

These studies have not only led to a better understanding of the nature of super-conductivity, but may lead the way to the development of a family of cryogenic devices such as galvanometers, magnetometers, voltmeters, voltage standards, thermometers, radiation detectors, and spectrometers with very high sensitivity at very low power.

Reference: J. E. Zimmerman, A. H. Silver, J. A. Cowan, "Coherent Radiation from Voltage-Biased Weakly-Connected Superconductors, Appl. Phys. Lett., vol. 9, p. 353, 1966.

PROBING DEEPER FOR BETTER IDEAS

Ford

that is omitted from the sum of the serial number and its reversal. Simply obtain the sum of the even-position digits and the sum of the odd-position digits, then give x (the omitted digit) a value that will make the difference between those two sums either 0 or a multiple of 11. In last month's example the spectator calls out 72722x17. The odd-position digits here add to 17, the even-position digits to 11. Since x belongs to the even set, x must have a value that will raise 11 to 17. Therefore x equals 6. If the set containing x has a sum greater than 17, say 19, you add 11 to 17, making 28, then subtract 19 to arrive at 9 for the missing digit. (Alternatively, you could subtract 11 from 19 to get 8, then take 8 from 17 to arrive at 9.) If the set containing x has a sum that is less than the other sum and that differs from it by more than 11, add 11 to it and subtract. If the sums of the two alternating sets are equal, the missing digit is 0.

Answers to last month's short questions follow:

1. A word for "1" appears nine times on a $1 bill. Did you overlook "unum"?

2. The word "ten" appears 12 times on a $10 bill. Did you overlook "ten" in "*ten*der" and "sep*tent*"?

3. The date 1776 appears in Roman numerals at the base of the pyramid.

4. The door key is in the green seal on the bill's face.

5. The anagram of "poetics" is "coeptis" (above the pyramid).

6. "Washington" is the anagram of "a night snow."

7. "Sofa" appears in "United State*s of* America." "Dose" is found in the Latin phrase below the pyramid. "Shin" is in "Wa*shin*gton." "Oral" is in "f*or al*l debts."

8. "Esau" is in "Th*esau*r" (in the green seal). "Iva" is in "pr*iva*te."

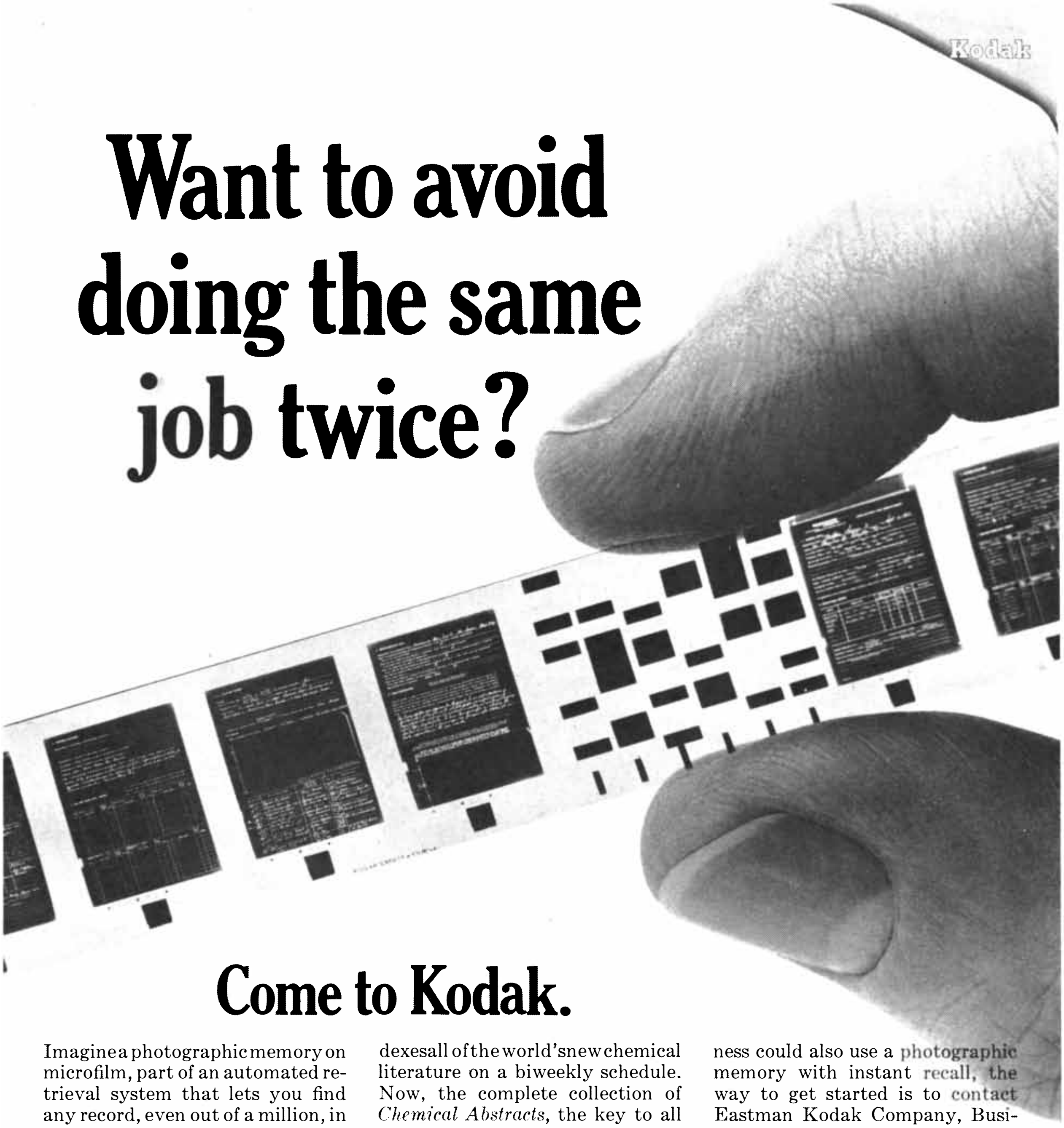
9. "At sea" is in "gre*at sea*l."

10. The inverted Spanish word is "si" (in "This note *is*...").

11. "One" contains "O" pronounced as a "W."

12. The eye above the pyramid is the "Eye of Providence." It was proposed by Benjamin Franklin to emphasize that the Union, symbolized by the 13-step pyramid, should always be under the watchful eye of God.

13. On a $5 bill "New Jersey" is the state name above the third and fourth columns of the Lincoln Memorial. You'll need a magnifying glass to see it. The number 172 can be seen as large dark numerals in the foliage at the base of the memorial, on the left. The number can be taken as 3172, but the 3 is not as distinct as the other numerals are.



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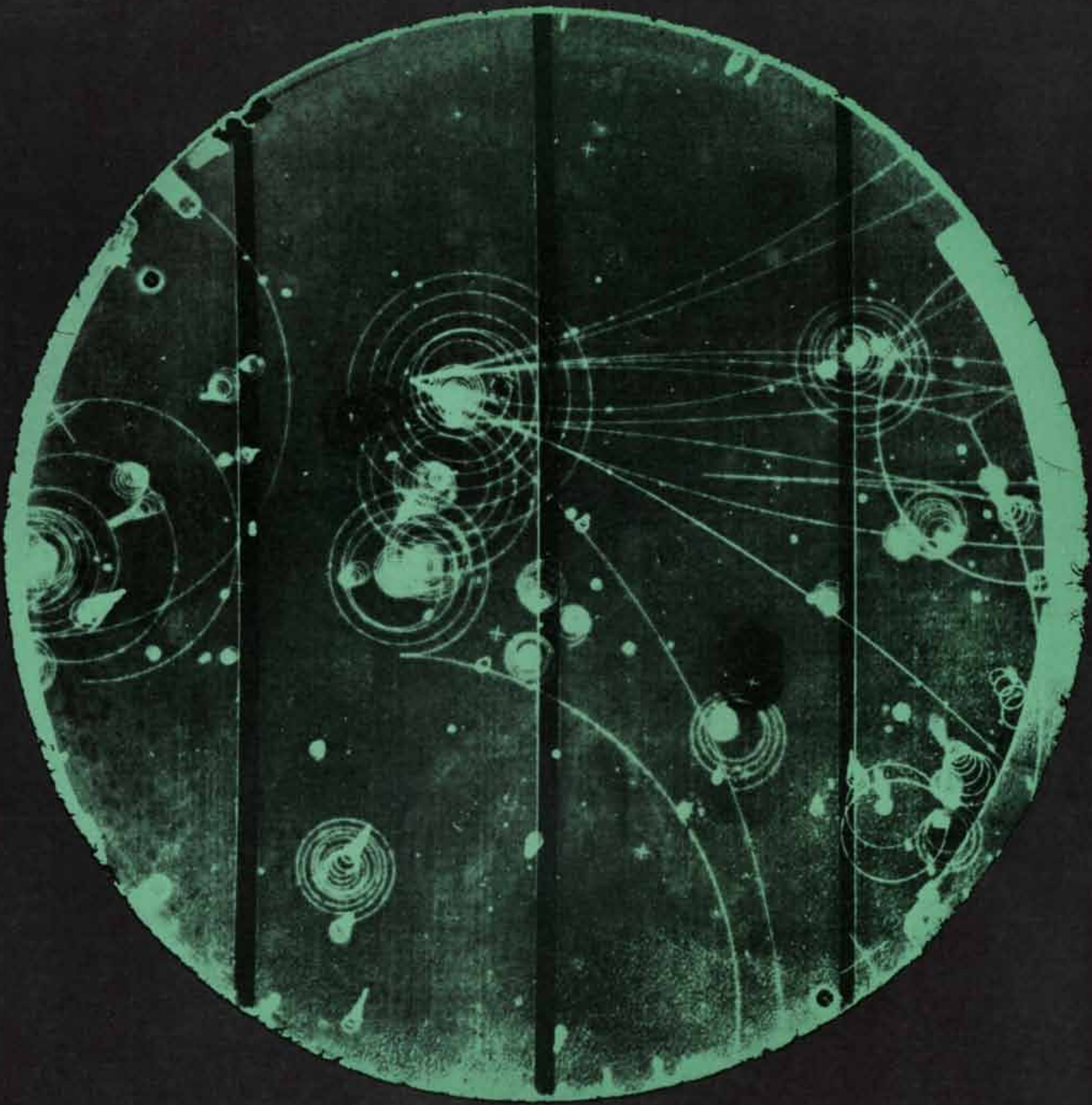


Probing ever deeper into nature and the basic structure of all matter, physicists are applying Einstein's formula equating energy to the product of mass times the square of the velocity of light and Maxwell's second equation of electromagnetic theory. Shown here is the result of one such experiment as viewed in a hydrogen bubble chamber. In order to refine such experiments, one goal of scientists is the production of particle beams whose energy approaches the levels found in nature's cosmic radiation. The devices used to develop high-energy beams are particle accelerators. The sources of the super power required are electron tubes.

RCA knows how

to rival cosmic radiation

Ever since the discovery of cosmic rays, the high-energy sub-atomic particles that bombard the earth from outer space, physicists have been probing into the structure of the atom. They are searching for further knowledge about the sub-atomic particles within the nuclei of various atoms, using the process popularly called "atom smashing".

These sub-atomic particles are believed to play a vital role in the organization of nature. While dozens of sub-atomic particles already have been found to exist, others which may account for some forms of radioactivity are still being sought.

To carry out the search under controlled conditions, physicists are using devices known as "accelerators". These require the generation and manipulation of particle beams of extremely high energy, measured in electron volts—each the force of a single volt propelling a single electron. As the high-energy physics program has progressed far beyond modest beginnings in the laboratory, the energy required in the apparatus used today has increased from a few hundred electron volts to millions of volts (MeV) to the billions (BeV). RCA Engineers, with their years of experience in the design and construction of electronic components and devices, have been deeply involved in working with nuclear physicists in this continuing program.

From the start, there was a need to generate a stream of electrons, first met by the use of Van de Graaff generators and other high-voltage machines. Once the stream of particles was generated, amplifiers of ever-increasing power were needed to provide additional velocity—and hence energy, as stated by Einstein—to the protons, to other ions and to electrons making up particle beams. To work experimentally with such beams, physicists had to be able to control the beams and unleash them to bombard individual atoms in an effort to drive off measurable sub-atomic particles.

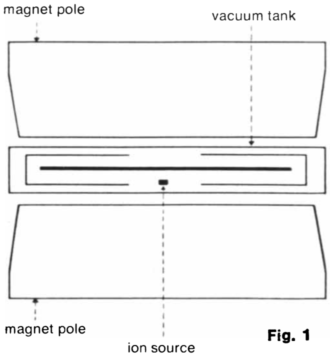


Fig. 1

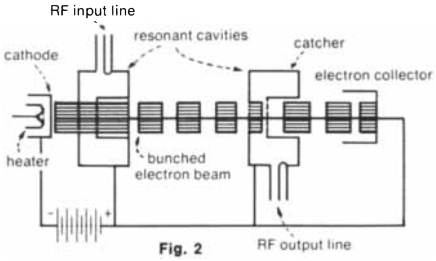


Fig. 2

Interpretation of Maxwell's second equation shows that a magnetic field can be used to influence the motion of a beam of particles. An early means used to provide this magnetic field was to pass the beam through the field of huge magnets, as in the accelerator known as the "cyclotron", which is shown in cross-section in *Fig. 1.*

The production of energies of needed magnitude was difficult to accomplish in magnet-type accelerators because of the sheer size and weight of the magnets required. Physicists wanted beams of several hundred MeV and multi-BeV kinetic energies. To produce high-energy proton beams, the open-magnet synchrotron was developed. For high-energy electron beams, the linear electron accelerator was developed, requiring extremely-high-powered magnetic fields generated by a type of microwave amplifier-oscillator known as the *klystron,* shown in schematic cross-section in *Fig. 2.*

Fig. 3

Largest electron linear accelerator built to date in any country is located at the Stanford Linear Accelerator Center (SLAC). Shown in *Fig. 3* are a few of the more than 100 RCA-built klystrons used by SLAC to help control an electron beam developing over 20 BeV of usable kinetic energy. Still more powerful accelerators are now on the drawing boards, including a proton synchrotron expected to operate at over 200 BeV.

Today, many high-powered accelerators use RCA-built klystrons as an integral part of the apparatus. For example, at SLAC, up to a hundred or more of these super-power tubes, installed as shown in the diagram in *Fig. 4,* direct and control the electron beam from its origin to a target area at the end of the accelerator. There the impact of the beam causes various particles to be driven from the nuclei of struck atoms. The life of these sub-atomic bits of energy is in the order of nanoseconds, but they can be observed through the use of such devices as RCA-made photomultiplier tubes, or cryogenic hydrogen bubble chambers. The photographic record of a nine-pronged experiment performed at SLAC is shown at left.

In the study of high-energy physics, man probes deeper into the atom, hoping to determine the nature of the most fundamental constituents of all matter, and the basic laws governing its structure and behavior. Ultimately, the continuing study of the atom by nuclear physicists may well lead to knowledge linking the behavior of microparticles to the large-scale world which is built up from them. Helping to make this possible will be thermionic electron sources, high-power gridded tube amplifiers and super-power klystrons—all built by RCA. For further details on RCA's line of power devices, write RCA Electronic Components, Commercial Engineering, Section E95DC, Harrison, New Jersey 07029.

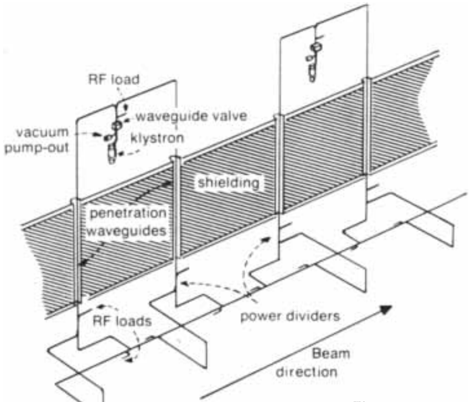


Fig. 4

RCA

THE AMATEUR SCIENTIST

A spectrophotometer is built for less than $75

Conducted by C. L. Stong

Color can serve as a powerful clue to the identity, nature and even the behavior of many substances if the observer can recognize a characteristic shade and perceive small differences of hue. Unfortunately color is difficult to judge by eye and even more difficult to specify precisely in terms of hue. For example, a popular instruction for applying silver to glass when making a mirror calls for adding ammonia to a solution of silver nitrate until the mixture becomes the color of "weak tea." How yellow is weak tea? I learned to recognize the desired shade by mixing, observing, testing and discarding several quarts of costly chemicals until at last a brightly silvered mirror emerged from a solution of the correct color.

Time and money would have been saved if I had owned a spectrophotometer, which is an instrument that measures colors and mixtures of colors in terms of the wavelength of light transmitted by the specimen and also records the intensity of the colors in terms of the percentage of light that is transmitted. Until a few years ago spectrophotometers cost more than I could afford; those of the highest performance still do. The advent of inexpensive electronic and optical parts, however, has made it possible for anyone who is reasonably handy to build a serviceable spectrophotometer at home. One simple design that can be assembled for less than $75 is described by R. C. Dennison of Westmont, N.J. He writes:

"The spectrophotometer can be one of the most useful instruments in an amateur's shop, particularly for the analysis of chemicals. I use mine for determining properties as diverse as the color of glasses and plastics, the transmission of light by neutral-density filters and semisilvered mirrors, the percentage of chlorine and other substances in water, the kind of metals that may be present in specimens of rock and the composition of alloys. Essentially the instrument disperses light that is transmitted by the specimen into the rainbow hues of the visible spectrum and measures the intensity of the emerging colors one by one.

"The physical scheme of the instrument is simple. Diverging rays from an incandescent lamp pass through a thin mechanical slit, known as the entrance slit, and through a collimating lens that makes the rays parallel [*see top illustration on opposite page*]. The parallel beam passes through the specimen, where certain colors may be fully or partially absorbed, depending on the nature of the specimen. Colors that remain in the beam enter a prism that disperses them into the orderly array of the spectrum.

"The spectrum is focused by a second lens, called the telescope lens, as a band of rainbow colors on an opaque white screen that is perforated with the exit slit. This slit transmits one narrow band of color or another, depending on its position in relation to the spectrum. The transmitted rays fall on a photoelectric cell and induce in it an electric current that varies in magnitude with the intensity of the colored light. The current is measured by a microammeter.

"The amount of light that reaches the specimen is controlled by the position of a wedge-shaped diaphragm that in effect determines the length of the entrance slit. The photocell, the exit slit, the telescope lens and the prism are assembled on a carriage of sheet metal that is attached at the prism end to a vertical shaft. By turning the shaft the operator can move the exit slit across the spectrum in order to select a desired color. A dial fixed to the shaft indicates the position of the slit in terms of the wavelength of light. The microammeter is calibrated to indicate the percentage of light transmitted by the specimen. All parts are housed in a cabinet equipped with a light-tight lid for shielding the photocell from room light when measurements are made.

"The parts are assembled on the bottom and one side of a steel radio chassis (Bud CB-643) that is 17 inches long, 13 inches wide and four inches deep. A second chassis of the same size is hinged to the first as a dust cover and light shield. The lamphouse is made of cookie-sheet aluminum and is 2¾ inches long, 2⅛ inches wide and 2½ inches high. A hole 5/8 inch in diameter in one wall of the box is partly closed by a pair of double-edged razor blades spaced .0045 inch apart to form the vertical entrance slit. A socket that fits a General Electric No. 93 incandescent lamp is mounted on the wall opposite the slit. The lamp is installed with its filament in the vertical plane. The housing is ventilated by a one-inch hole in the chassis and several quarter-inch holes in the top. A baffle of sheet aluminum inside the lamphouse near the top prevents the escape of stray light.

"The collimating lens is mounted on a rectangle of sheet aluminum 2⅜ inches square that contains in the center an aperture 5/8 inch in diameter. Two 1/8-inch tabs cut from the upper corners of the rectangle are bent over as supports for the upper edge of the lens. The lower edge is supported by a tab of aluminum attached to the rectangle by a machine screw.

"The assembly is mounted on a bracket of sheet aluminum 2½ inches wide and 2¾ inches high that is perforated with a centered hole one inch wide. The bracket is attached to the chassis by screws passing through slots in the foot that enable the collimating lens to be moved toward or away from the lamphouse when the lens is focused. The optical axis of all elements of the optical train is 1½ inches above the base.

"The carriage, which includes the photocell, the exit slit, the telescope lens and the prism, is made of sheet brass 1/16 inch thick, 2⅜ inches wide and nine inches long. One edge is bent up 5/16 inch to provide stiffness. The photocell housing is similar to the one for the lamp but consists of a Bud CU-3000 A Minibox. One wall contains the vertical exit slit, made with razor blades spaced .003 inch apart. They face the photocell. The photocell (RCA Type 7117) was designed for automatically dimming automobile headlights. I bought one at an automobile junkyard for a fraction of the list price.

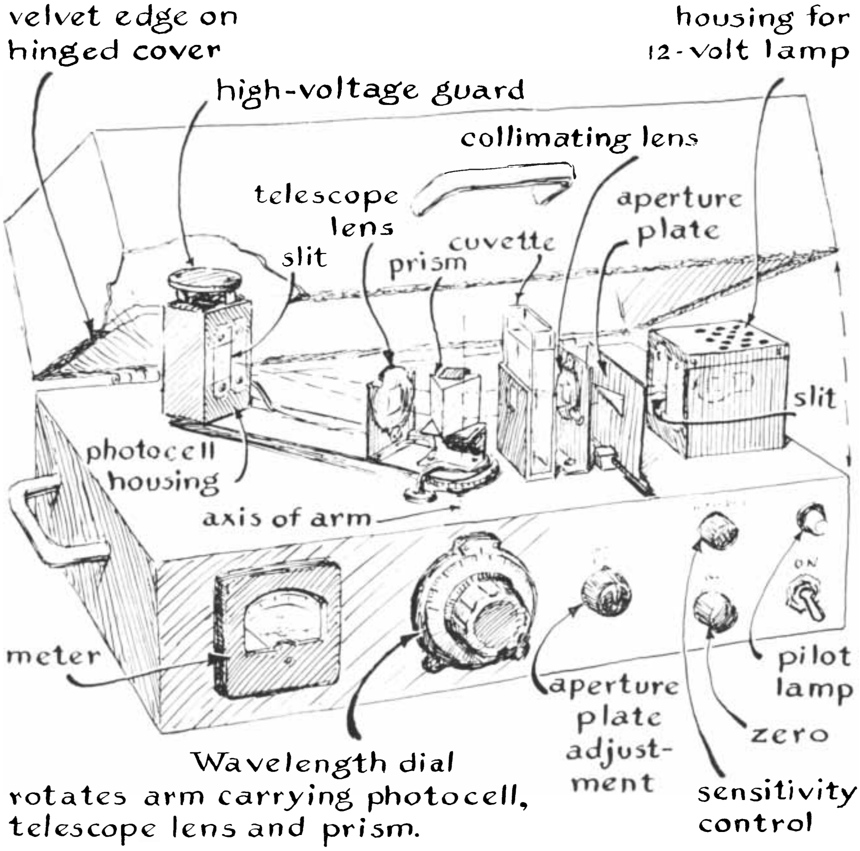
"The cover of the photocell housing consists of a rectangle of Bakelite 1/8 inch thick to which an Amphenol socket (Type 77MIP11) is attached by screws. Nine 33-kilohm resistors that supply voltage to the photocell are soldered directly to the lugs of the socket. A thin sheet of Bakelite, supported by standoff pillars, is mounted over the lug side of the socket to prevent accidental contact with the high voltage.

"The inverted photocell projects downward into the box. The socket must be oriented so that the photocathode faces the exit slit. (Point the keyway of the socket toward the exit slit.) The completed assembly is attached to the carriage arm by machine screws in the position illustrated. Apply a strip of flat white paint to the razor blades and the front of the housing.

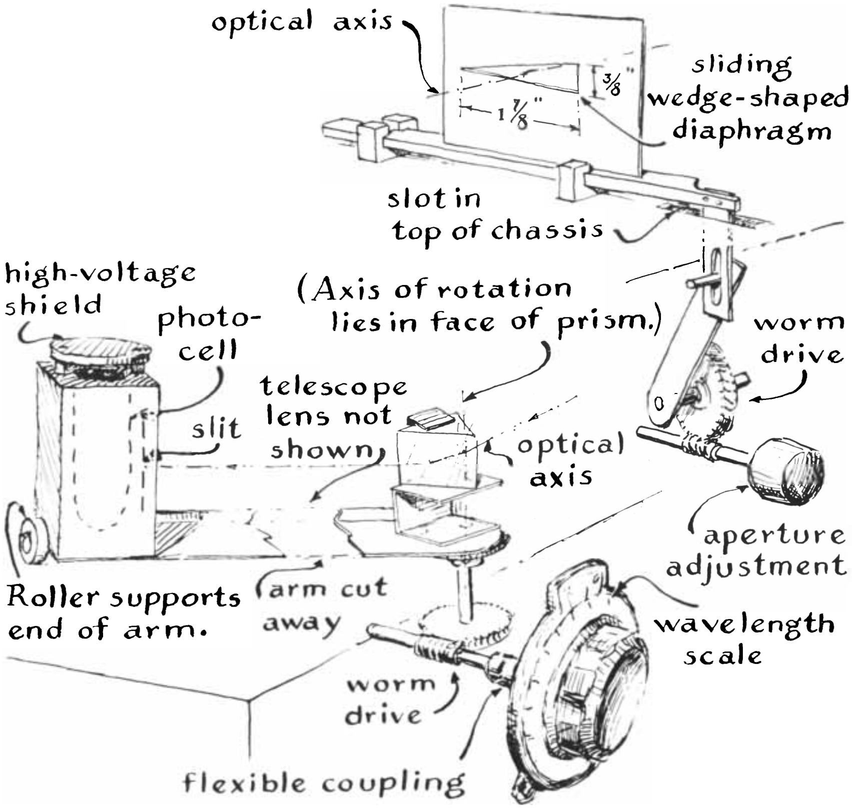
"A 1/4-inch vertical shaft is attached by machine screws to the end of the carriage arm opposite the photocell by means of a flange in the form of a brass gear that happened to be on hand [*see bottom illustration at right*]. Any equivalent flange would serve as well. The distant end of the carriage is supported by a wheel that rides on top of the chassis. The wheel was made by soldering a short hollow rivet into a 3/4-inch washer. The axle of the wheel consists of a machine screw that enters the rear of the photocell housing near the base on the center line of the carriage.

"The vertical shaft is supported and driven by a modified worm gear from a surplus gunsight. An equivalent mechanism could be constructed with a Millen Type 10000A worm-gear drive of the kind designed for rotating the tuning capacitors of radios. This unit is available from dealers in radio supplies. It is made in gear ratios of 16 to one and 48 to one. A gear of the latter ratio should be used.

"The horizontal shaft of the worm gear extends through the front of the chassis. It should be equipped with a planetary dial that has a drive ratio of eight to one (Lafayette Radio Electronics stock No. 99 H 6029). When this dial is turned through 240 angular degrees, the carriage sweeps the exit slit com-



R. C. Dennison's spectrophotometer



Details of dial and diaphragm mechanisms pletely across the spectrum. The dial is designed for only 180 degrees of rotation, but the plastic stops that limit the rotation can be sawed off by disassembling the unit.

"A small table of sheet metal was improvised to support the prism on the optical axis of the instrument above the end of the vertical shaft. The prism (Edmund Scientific Co. stock No. 30,143) is held in place on the table by a clip made of spring brass. The telescope lens is attached to the carriage arm by a fixture similar to the one that supports the collimating lens.

"The amount of light that reaches the specimen is controlled by a triangular diaphragm cut into a plate of brass that moves across the path of the rays emerging from the entrance slit. One edge of the plate is bent at right angles to form a foot 1/8 inch wide. This foot is soldered to a rectangular brass bar, of about the same width and thickness, six inches long. The bar moves in slotted guides made from two small blocks of Bakelite that are attached to the chassis by machine screws. The bar is driven by a mechanical linkage consisting of a Millen No. 10,012 right-angle drive, a bell crank and a slotted brass arm.

"The right-angle drive is mounted on the inner face of the front wall of the chassis. An arm of sheet brass, soldered to the outer end of the rod that supports the triangular aperture, projects down through a slot in the chassis. A slot about 1/2 inch long in the arm engages a bell crank that is driven by the right-angle drive. The bell crank, when turned by the right-angle drive, advances or retards the triangular aperture. By advancing or retarding the aperture the microammeter can be adjusted to full-scale deflection without altering the current that is normally present in the photocell when the photocathode is in darkness.

"Specimens are inserted in the light path at a point between the collimating lens and the prism. A fixture improvised from sheet metal is attached to the chassis at this point for supporting a rectangular glass box that is called either a cuvette or an absorption cell. Fluid specimens are placed in the cuvette for measurement.

"Cuvettes are priced at $15 and up because they must be made of reasonably flat, well-annealed glass. Glass of the quality used for photographic plates is adequate and can be bought from distributors of photographic supplies. The inside dimensions of the cuvette should be about 75 millimeters, 35 millimeters and 10 millimeters. The ends, sides and bottom piece can be cut with a glass cutter of the wheel type and assembled with epoxy cement. Solid specimens such as colored glasses, filters and semitransparent mirrors are inserted for measurement in the position normally occupied by the cuvette.

"I followed conventional techniques when building the electronic portion of the instrument. Small components were mounted on stiff sheets of perforated plastic known as Vector board. The transistors specified in the accompanying schematic illustration [*opposite page*] were used because they were on hand; they do not necessarily represent either the best or the least costly design. The 2N1702 transistor is mounted on the chassis, which acts as a heat sink, and is insulated from the chassis by a thin mica washer supplied by the manufacturer. The 1N1204RA diodes are mounted directly on the chassis, which again acts as the heat sink. (Incidentally, the anodes of diodes that bear the suffix 'RA' connect to the mounting stud and do not need to be insulated from the chassis.)

"The conventional scale of the microammeter was replaced by one calibrated in intervals from 0 to 100 for indicating the transmission of light in percent. It was also calibrated in units of density, according to the relation: density equals the logarithm, to the base 10, of the ratio 100 divided by the transmission in percent. For example, at 50 percent transmission the density of the specimen is equal to $\log_{10} 100/50$, or .3.

"In order to align and focus the optical system and calibrate the dial that controls the position of the exit slit I first removed the prism and the collimating lens of the fully assembled instrument. The lamphouse was then positioned to center the wedge of light that emerges from the entrance slit on the optical axis of the instrument. The lamphouse was locked in this position by its mounting screws.

"The simple plano-convex collimating lens (1¾ inches in diameter with a focal length of three inches) is mounted with its plane side toward the lamphouse at a point that causes the diverging rays from the slit to become parallel after they have passed through the lens. To locate this position I first focused a pair of binoculars on an object about a mile away. The binocular was then positioned so that the objective lens of one half of the instrument was on the optical axis of the spectrophotometer and faced the collimating lens, looking toward the entrance slit. (A sheet of white paper can be placed between the lamp and the slit to reduce the intensity of the light.) The position of the collimating lens was now adjusted until a sharp image of the slit appeared in the binocular. Any small, low-power telescope can be substituted for the binocular. When the collimating lens was focused, it was locked to the chassis by tightening the mounting screws.

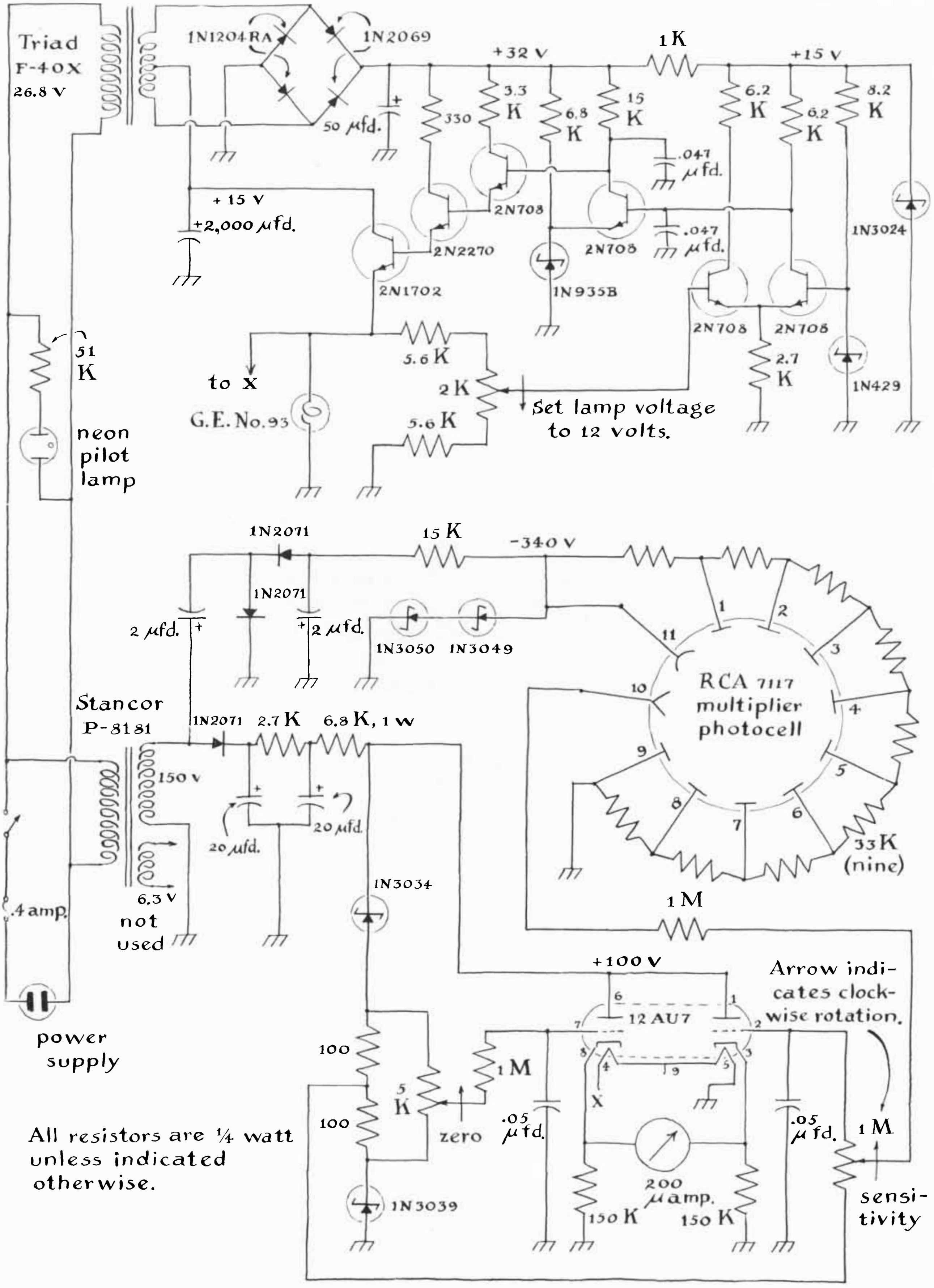
"The telescope lens is assembled in its holder with its plane side facing the exit slit. Again, with a small telescope focused on infinity, adjust the position of the telescope lens on the carriage until a sharp image of the exit slit appears. (Light the slit in front with the beam of a 35-millimeter projector.) Lock the telescope lens in this position.

"Release the setscrew on the rear hub of the dial that drives the carriage. Mount the prism on its table, light the incandescent lamp and slowly rotate the prism back and forth until the spectrum appears on the white surface of the exit slit. Turn the prism back and forth on its table and observe that at one position the angular deflection of the spectrum is at a minimum. The prism is now set at the angle of minimum deviation. Turn the shaft of the worm-gear drive and shift the position of the prism by trial and error until at minimum deviation the center of the yellow band of the spectrum falls on the exit slit. Rotate the shaft to move the slit to the red end of the spectrum, position the dial at the limit of its excursion and lock it to the shaft.

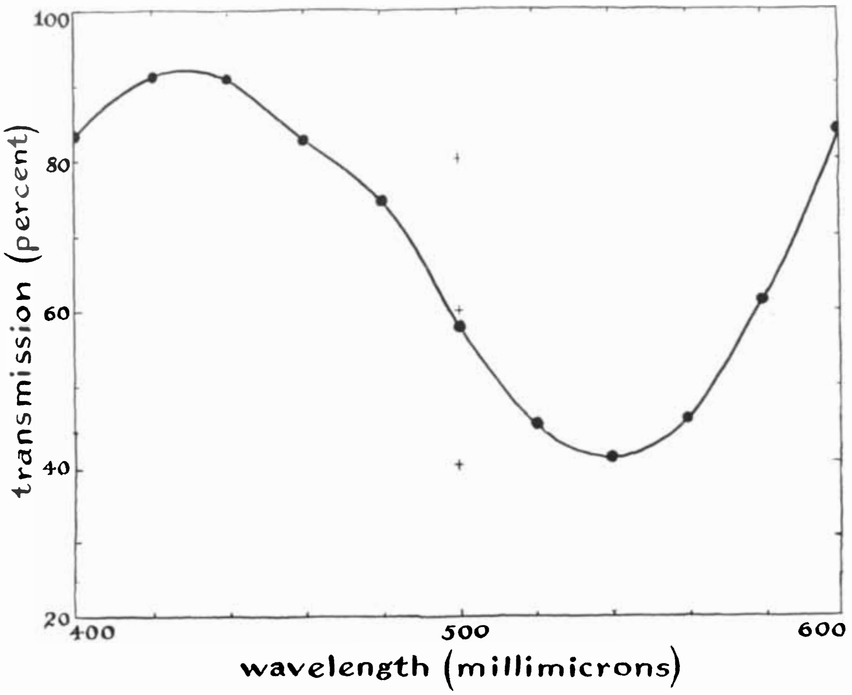
"The dial must now be calibrated to indicate wavelength. If possible, borrow a set of narrow-band interference filters that transmit light of known wavelength. With the exit slit at the red end of the spectrum, insert the interference filter of longest wavelength in the cuvette holder at right angles to the light beam and rotate the dial for maximum photocurrent.

"Record the arbitrary indication of the dial and repeat the procedure for each filter. On linear graph paper plot the arbitrary indications of the dial against the corresponding wavelengths. From these data make a scale for the dial calibrated in millimicrons. The scale will be crowded at the red end.

"If interference filters are not available, the instrument can be calibrated with reasonable accuracy by means of didymium glass. A didymium filter accompanied by a curve of spectral transmittance can be bought from the Arthur H. Thomas Company, P.O. Box 779, Philadelphia, Pa. 19105. The item is listed as didymium filter No. 9104-N20 and costs less than $2. The transmittance



Schematic circuit diagram for the spectrophotometer



Spectral response of potassium permanganate solution

curve supplied with the filter displays nine dips and peaks between 400 and 700 millimicrons. Mount the filter and make a series of readings in which the dips and peaks are correlated with arbitrary dial readings. Convert the arbitrary readings to wavelengths by referring to the calibration curve supplied with the filter and make a corresponding wavelength scale for the dial.

"When the photocurrent of the spectrophotometer is plotted against wavelength, the resulting graph takes the form of a bell-shaped curve that peaks at approximately 550 millimicrons and drops to about 5 percent of the maximum reading at 380 and 660 millimicrons. The graph depicts the intrinsic response (I) of the instrument.

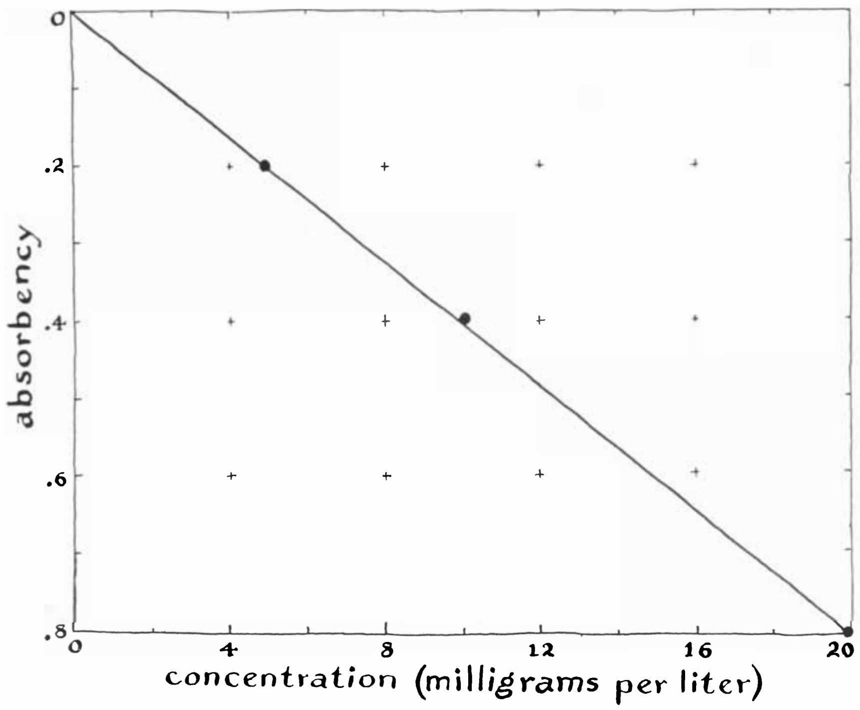
"Intrinsic response must be known before an unknown color can be determined. For maximum accuracy of measurement the intrinsic response should be redetermined prior to measuring each unknown specimen. For example, to measure the spectral response of a piece of colored glass, find the wavelength at which the photocurrent is maximum. Remove the specimen and adjust the intensity of the light (by altering the position of the wedge-shaped diaphragm) until the pointer of the meter swings to full scale (the 100 percent indication). Turn the wavelength dial to its limit at the red end of the spectrum. Replace the specimen. Record the meter indication at this wavelength and designate the response R. Remove the specimen and designate the resulting response I. Make similar pairs of readings at intervals of five or 10 millimicrons across the spectrum to the limit at the blue end.

"When the readings of R and I drop below 20 percent of full-scale meter deflection, as they will doubtless do at the red and blue ends of the spectrum, the instrument will lose some accuracy. This loss can be compensated for by increasing the sensitivity of the instrument. The sensitivity can be increased by turning up the sensitivity control until the limit of usable gain is reached.

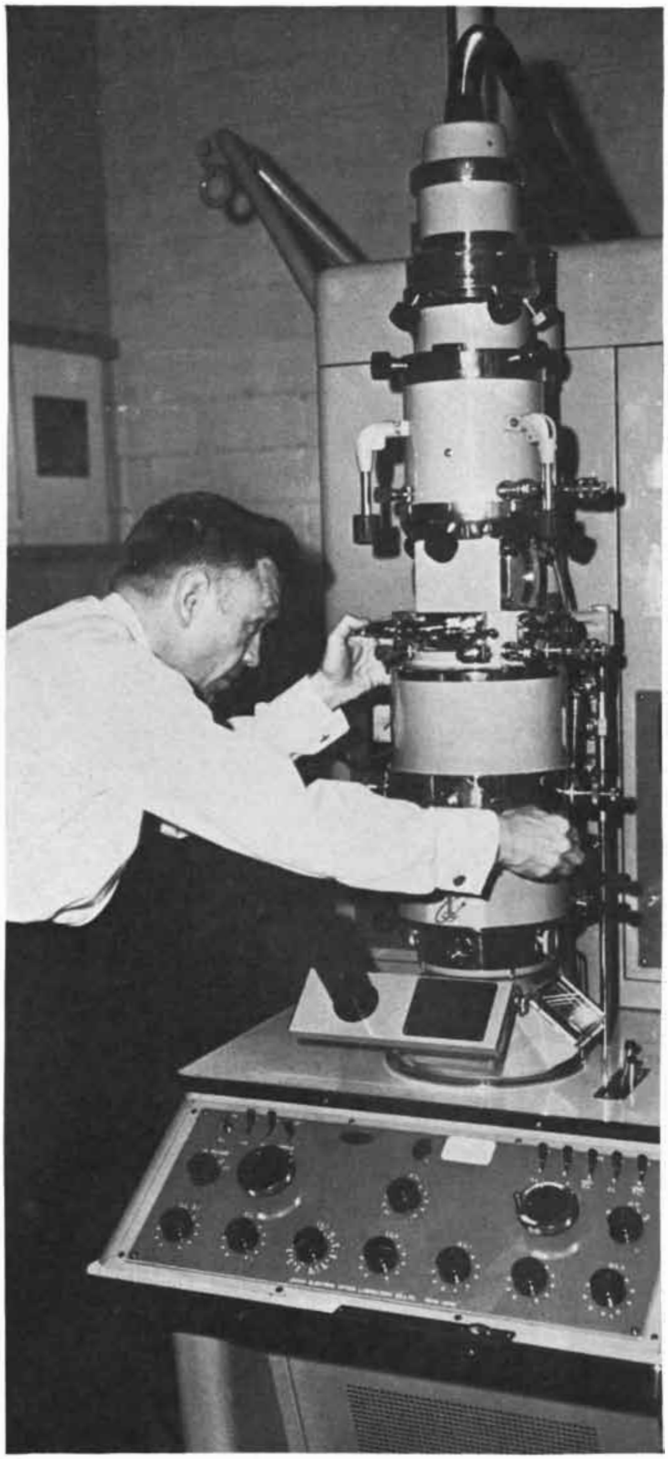
"The transmittance (T) of the specimen is equal at each interval of wavelength to R divided by I. Calculate the transmittance at each interval of wavelength and from the tabulated computations prepare a graph of the spectral response. The response of unknown solutions is also measured. The intrinsic response of solutions is determined by replacing at each interval of wavelength the cuvette containing the specimen with an identical cuvette that contains only solvent.

"Experience in the use of the instrument and confidence in the reliability of the measurements can be gained easily by making graphs of the spectral responses of Wratten filters and comparing the results with graphs supplied by the manufacturer. These inexpensive filters and their graphs can be bought from dealers in photographic supplies. Simple experiments for beginners also include the measurement of various dyes, food colors and other colored solutions [see "The Amateur Scientist," SCIENTIFIC AMERICAN; February, 1965].

"A more advanced experiment that demonstrates the usefulness of the spec-



Calibration graph of spectrophotometer for permanganate ion



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GENERAL DYNAMICS

Fort Worth Division

trophotometer as an analytical instrument consists of the analysis of steel for the presence of manganese. The procedure is based on the magenta color that appears when a solution of manganous salts is oxidized. The amount of manganese in the steel is calculated by comparing the absorbency of the colored solution with the absorbency of a standard solution of potassium permanganate. (Absorbency, like density, is equal to the logarithm, base 10, of 100 divided by the transmission in percent.)

"To prepare the standard solution dissolve 72 milligrams of potassium permanganate in water and dilute the solution to 250 milliliters. In this step and all following procedures use only distilled water and reagent-grade chemicals. Weights and volumes must be accurately determined.

"Transfer four milliliters of the standard solution to a clean container and dilute to 40 milliliters. As thus diluted the solution contains 10 milligrams of manganese per liter. Transfer the diluted solution to a cuvette and make a graph of the spectral response [*see top illustration on page 144*]. Maximum absorbency occurs at 540 millimicrons. My instrument indicated a transmission at this wavelength of 40.5 percent, from which the absorbency was calculated to be .393. ($100/40.5 = 2.47$. $\text{Log}_{10}\ 2.47 = .393$.) From the stock solution make similar dilutions that contain five milligrams and 20 milligrams of manganese per liter and tabulate the absorbencies. A calibration curve for use in the subsequent analysis can now be drawn by plotting the absorbencies of these three measurements against concentration in milligrams [*see bottom illustration on page 144*].

"Saw a small piece of steel, weighing about 200 milligrams, from a bar or rod. Place the sample in a 100-milliliter volumetric flask and add five milliliters of water and five milliliters of nitric acid. Warm the solution until the sample has dissolved. While the solution is warm add sodium bismuthate until a slight excess remains. Dilute to 100 milliliters.

"Transfer 10 milliliters of this solution to a clean vessel and dilute to 100 milliliters. Transfer a specimen of the latter solution to a cuvette. Measure the transmittance and calculate the absorbency. Determine the concentration of manganese by referring to the calibration chart. Assume, for example, that the concentration turns out to be 1.5 milligrams of manganese per liter. Before the dilution the concentration was 15 milligrams per liter. The volume of the original (undiluted) solution was 100 milliliters. Therefore it contained 1.5 milligrams of manganese. The specimen of steel weighed 200 milligrams. Hence the steel contains $1.5/200 \times 100$, or .75, percent manganese.

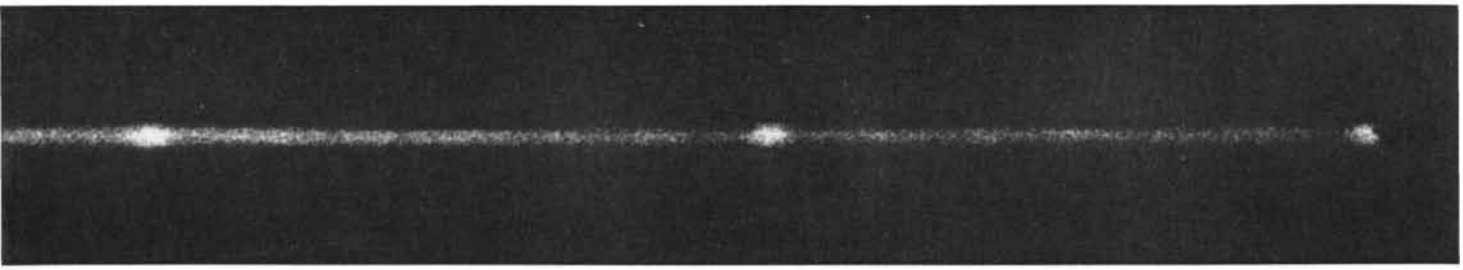
"Another interesting experiment involves a test for cobalt. To make it you will need the following materials: (1) a few grams of sodium pyrophosphate, which can be made by fusing disodium hydrogen phosphate in a crucible; (2) a 60 percent solution of ammonium thiocyanate, made by dissolving 30 grams of the salt in water and diluting to 50 milliliters; (3) acetone; (4) a standard cobalt solution containing 100 milligrams of cobalt per liter, made by dissolving 49.36 milligrams of cobalt nitrate hexahydrate in water and diluting to 100 milliliters, and (5) another cobalt salt, such as cobalt chloride.

"Transfer 10 milliliters of the standard cobalt solution to a graduated cylinder and add 1/2 gram of sodium pyrophosphate. The sodium pyrophosphate prevents any iron that may be present from discoloring the solution. Add 2.5 milliliters of 60 percent ammonium thiocyanate and mix. Dilute to 25 milliliters with acetone and mix. The clear solution will turn blue.

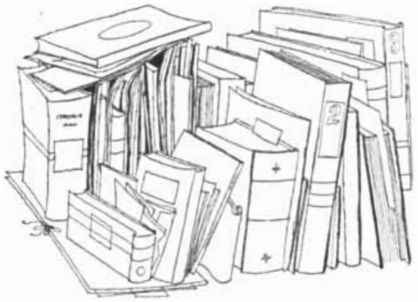
"Place a specimen of the colored solution in the cuvette, measure the transmission and plot the spectral response. Determine the absorbency at the wavelength of maximum absorption and, by serial dilution and subsequent measurement, tabulate data for plotting a calibration graph, as in the analysis of steel. Check the results by measuring the percentage of cobalt in a solution of cobalt chloride by weight.

"Finally, determine the amount of cobalt in an alloy, such as Alnico. Wrap a small Alnico magnet in cloth and, with a hammer and chisel, break off a few fragments. Weigh a specimen of about 200 milligrams. Dissolve the specimen in 10 milliliters of hot nitric acid. Dilute to 100 milliliters. Transfer 10 milliliters of the solution to a clean vessel and add 1/2 gram of sodium pyrophosphate and 2.5 milliliters of 60 percent ammonium thiocyanate. Mix and filter the solution. Dilute the filtrate with an equal volume of acetone. Measure the absorbency and calculate the percent (in weight) of cobalt in the specimen.

"Caution: Most of these chemicals are toxic. Acetone is highly flammable. Avoid contact with the substances. Do not inhale the fumes of reacting mixtures. Be sure to work in a well-ventilated room."



THE SHORTEST LASER PULSES EVER PHOTOGRAPHED, EACH LASTING LESS THAN A TRILLIONTH OF A SECOND. BELL TELEPHONE LABORATORIES.



BOOKS

The balance of knowledge and the balance of power

by R. M. Fano

Privacy and Freedom, by Alan F. Westin. Atheneum ($10).

The primary effects of technological progress on society are the opening up of new opportunities and the lessening of existing constraints on human activities. The new opportunities and the lesser constraints perturb the existing equilibrium in the operation of society and trigger a process of evolution toward a different mode of operation consistent with the new technological environment. The resulting changes in society are the most important effects of technological progress, yet their character depends largely on social forces and goals unrelated to the technological developments that initiated them.

The pace of technological progress was for a long time sufficiently slow as to enable society to learn pragmatically how to exploit new technology and prevent its abuse, with society maintaining its equilibrium most of the time. More recently the rate of technological progress seems to have exceeded the rate at which society can evolve pragmatically while maintaining its balance. It was largely in response to this challenge that in 1959 the Association of the Bar of the City of New York organized a special Committee on Science and Law. In the words of its chairman, Oscar M. Ruebhausen, "the scope of [the committee's] concern was as broad as the whole interface between the disciplines of science and the aspirations of society. Unlike many conventional bar-association committees, it did not concern itself primarily with substantive legal issues or with their resolution, but, rather, with the interrelationships between man, science, and society and the concessions which each sought to exact from the others."

The Committee on Science and Law eventually focused its attention on the erosion of individual privacy resulting from modern technology, and early in 1962 it obtained the support of the Carnegie Corporation of New York for a formal study in this area. The study, which was conducted over a four-year period, was organized and directed by Alan F. Westin, professor of public law and government at Columbia University. *Privacy and Freedom* is a direct result of the study.

By the time the book appeared in print last year the alarm on the invasion of privacy had been sounded loud and clear in the daily press, in magazines, in Congressional hearings and in popular books describing privacy-invading practices on the part of government, business and private individuals. After hearing the alarm bells ringing from so many quarters, mixed with charges and countercharges from opposing groups, it is particularly refreshing to be able to read a scholarly, well-written and well-documented analysis of the problems involved. Professor Westin is director of the Center for Research and Education in American Liberties of Columbia University and Teachers College, and he is also a member of the National Board of Directors of the American Civil Liberties Union, the National Civil Rights Committee of the Anti-Defamation League and the Commission on Law and Social Action of the American Jewish Congress. His personal concern with the preservation of privacy is evident throughout the book, and the importance he attaches to privacy is clear from the title *Privacy and Freedom.*

The aspects of the book on which I shall concentrate here, and the point of view from which I shall comment on them, will reflect my own professional interests. They have been focused during the past five years on multiaccess computer systems ("time-sharing" systems) and on ways and means of making computers available to people on an individual basis, in a manner intended to augment their intellectual capacities and to facilitate communication among them. Because of these professional interests I have become increasingly concerned about the potential impact of computers on society, and in particular about policy decisions and technical choices that may critically affect the future. Thus the protection of privacy in the exploitation of computers is a major concern that I share with Professor Westin. I found his book very illuminating, not only in this regard but also with respect to the whole process of social experimentation and readjustment in response to technological innovation.

The book is divided into four parts titled "The Functions of Privacy and Surveillance in Society," "New Tools for Invading Privacy," "American Society's Struggle for Controls: Five Case Studies" and "Policy Choices for the 1970's."

Professor Westin's view of privacy is presented in two stage-setting paragraphs at the beginning of Part One. "In my view, the modern claim to privacy derives first from man's animal origins and is shared, in quite real terms, by men and women living in primitive societies. Furthermore, the approach to privacy taken by Americans today developed from a tradition of limiting the surveillance powers of authorities over the private activities of individuals and groups that goes back to the Greeks in Western political history."

"Privacy is the claim of individuals, groups, or institutions to determine for themselves when, how, and to what extent information about them is communicated to others.... The individual's desire for privacy is never absolute, since participation in society is an equally powerful desire. Thus each individual is continually engaged in a personal adjustment process... in the face of pressures from the curiosity of others and from the processes of surveillance that every society sets in order to enforce its social norms."

Several important points are raised in these two paragraphs, and in the rest of Part One. The claim to privacy is regarded as a "natural right" of man, because of the crucial biological and psychological roles that privacy plays in the life of each individual. On the other hand, the specific forms in which privacy is demanded or observed vary from culture to culture and depend on the environment in which the individual lives. Privacy may take the form of a physical area from which other people are excluded, of a minimum "personal distance" in interpersonal relations, of aloofness from one's neighbors, of anonymity or of secrecy about certain aspects of one's personal life. The point is that every human being needs some physical and psychological "living space" of his own. This view of privacy differs from the one held by many social scientists, who regard privacy as a distinctly modern notion. Perhaps the disagreement stems from a difference in the breadth of the definition of privacy. Another point worth stressing is that privacy is a dynamic rather than a static concept, because what counts is one's ability to decide for oneself at any given time what is private. Therefore privacy is akin to personal autonomy and to being in control of one's own immediate environment. The same dynamic character of privacy is evident in the process of balancing one's desire for privacy with other desires and with the requirements of society. This implies that protecting the privacy of specific aspects of a person's life is not sufficient. What needs to be protected is the right of the individual to decide for himself what is to remain private and when.

The following three examples will illustrate different and important functions of privacy. Most, if not all, people are affected by personal problems and conflicts that they manage to keep under control throughout their lives. These problems and conflicts may not warrant medical attention, or they may persist in spite of it. Forcing a person through personality tests, lie-detector tests or other means to expose his inner self may cause irreparable emotional damage. The right to maintain the privacy of one's personality can be regarded as part of the right of self-preservation. Similarly, "blowing off steam" or relaxing under the protection of privacy seems essential to an individual's mental health.

The second example has to do with diversity in society. Whereas the enforcement of social norms may be essential to the effective operation of society, it is practically impossible to establish social norms that are reasonable for all people in all situations. Some deviations from social norms are to be expected and tolerated. Furthermore, they are essential to social experimentation and therefore to social progress. Privacy is the mechanism that enables society to ignore deviations it regards as permissible while still upholding social norms and punishing flagrant violations of them. It is also the mechanism that permits the gradual evolution of social norms.

The third example concerns the preservation of independence and diversity of thought and action on the part of organizations as well as individuals. Sheltered experimentation and rehearsal of conduct are essential to the development of independent thought and to the planning of independent activities. This implies the right to remain silent and to communicate in private with other people until ready to expose oneself to public criticism. The role of privacy here is reminiscent of the need for decoupling measuring instruments from the physical system on which the measurements are to be performed; without sufficient decoupling the presence of the instruments would change the state of the system and lead to erroneous results. In a sense privacy decouples the individual from the rest of society. It is a social function needed to keep his thoughts and actions from being distorted by society's reaction to them.

In spite of my familiarity with the underlying technology, I was very surprised, in reading Professor Westin's book, by the sophistication of commercial devices made specifically for the purpose of spying on other people, and by the extent to which such devices are openly advertised, sold and used. I was equally surprised by the extent to which objectionable privacy-invading practices, such as lie-detector tests and personality tests, have been used by government agencies and private organizations in the selecting and monitoring of employees. The situation is particularly alarming in view of the vested interests that already exist with respect to the development and sale of privacy-invading devices and procedures. Perhaps even more alarming are two attitudes that, it seems to me, underlie the speed with which some of the privacy-invading practices have taken root, and that are likely to be the basis for a continuing demand for them.

The first attitude can be characterized as an infatuation with gadgets and procedures that appear, at least to the layman, to be scientific. This attitude seems to lead people to fit problems and objectives to the tools that happen to be available. The second attitude, encouraged by an all too human desire to avoid personal responsibility for decisions, is a preference for data and procedures that lend themselves to mechanization, in the belief that the elimination of human judgment is in itself desirable. I am reminded here of what the late Norbert Wiener used to say (as far back as 1950) with regard to the use of computers. He stressed that the greatest danger lies in our delegating to computers, out of ignorance or mental laziness, decisions that should remain ours. He would illustrate the point with various tales of magic, such as the fable of the monkey's paw, and would warn: "The agencies of magic are literal-minded; if we ask for a boon from them, we must ask for what we really want and not for what we think we want." Indeed, solutions to improperly formulated problems are not only worthless but also often dangerous, and we never know in advance if a problem has been properly formulated. Frequently it is just by reflecting on a solution that is logically correct but unacceptable for one reason or another that we become conscious of constraints that have not been explicitly stated and of special situations in which the decision criteria employed are inappropriate.

The dangers to privacy arising from the widespread use of computers deserve to be singled out for special consideration for at least two reasons. In the first place, the dangers are inherent not only in uses such as surveillance but also in uses that may be very beneficial (and possibly even essential) to the operation of a complex society. It is feasible to outlaw or place under strict controls various privacy-invading devices and practices, but it would be foolish to outlaw computers, and it is obviously very difficult to devise strict controls on their use that would not hamper desirable applications. In the second place, knowledge is power, and any computer-created change of relative power between organizations and individuals or between different segments of society will have far-reaching consequences transcending the issue of privacy.

Our daily activities generate a stream of data about ourselves that are recorded and preserved by government and private organizations. Credit cards in particular record events in our daily lives that once were unnoticed and anonymous. Furthermore, we constantly give personal information to government and private agencies for the purpose of obtaining special authorizations and services such as licenses, loans, insurance and credit. The same computers that make it possible to process all these data for the purposes for which they are given or collected also make it practical to create dossiers on each individual for surveillance or other purposes. In addition to the dossiers kept by local, state and Federal agencies, there are many private agencies that collect information about individuals for purposes such as credit and industrial security. For instance, *The Washington Post* has reported that the Retail Credit Company maintains dossiers on 42 million people, and that its annual gross income from selling this information is more than $100 million. There are two aspects of these dossiers that are particularly disturbing. First, "this situation creates a potential 'record-prison' for millions of Americans, as past mistakes, omissions, or misunderstood events become permanent evidence capable of controlling destinies for decades." Second, few individuals are aware of the existence of such dossiers about them, or of the purposes for which the data are used, and in any case they have no way of challenging the accuracy of the data. It is important to remember in this connection that facts often require interpretation, and that evaluations and opinions may be grossly misleading when they are used in a context for which they were not intended.

Public reaction to the threats to privacy arising from the use of computers has been more vocal and more emotional than to those arising from other sources. At the root of most people's fear of computers probably is the feeling of being at the mercy of a machine. To make matters worse, it is a machine whose capabilities they do not understand, working on information they cannot check. Strong objections have been raised by Congressional committees to the establishment of a National Data Center to coordinate the preservation and use of socioeconomic information. It became clear in Congressional hearings that the identity of individuals and businesses would have to be preserved in order to keep data current and to check their validity. The threat to privacy is real indeed, but the committees seemed to have missed the point that the threat exists regardless of the establishment of the National Data Center; the fact is that computers can communicate with one another and the physical location of the data is largely immaterial. Furthermore, computerized information systems containing personal data exist at the local and the state level, and even more data about millions of Americans are being accumulated in the commercial information systems.

How can privacy be adequately protected? Professor Westin believes the intent to protect privacy from unreasonable surveillance is expressed in the Federal Constitution, although the manner in which protection is provided is keyed to the realities of the 18th century. Recent Supreme Court decisions have extended the protection to various aspects of privacy, and "the Court seems on the brink of a landmark ruling defining a comprehensive, positive right of privacy from unreasonable surveillance." Meanwhile various measures are suggested for controlling privacy-invading practices. The emphasis is on the recognition of privacy as a basic right, with the burden of proving the necessity of any proposed violation of privacy resting on the party that intends to take such action.

With respect to data processing Professor Westin believes that "personal information, thought of as the right of decision over one's private personality, should be defined as a property right, with all the restraints on interference by public or private authorities and due-process guarantees that our law of property has been so skillful in devising. Along with this concept should go the idea that circulation of personal information by someone other than the owner or his trusted agent is handling a dangerous commodity in interstate commerce, and creates special duties and liabilities on the information utility or government system handling it." On the basis of such a definition of personal information an individual would have to be notified of what information existed about him and where, and he would be able, if he so wished, to examine the information, challenge its accuracy and add explanations to it. Any agency or private company operating an information system would also have the responsibility of protecting the information contained in it. In particular, it would have the responsibility of specifying what information would be open to access, by whom, for what purpose and under what circumstances, and also of taking all necessary precautions to protect the security and integrity of the system. It is well to remember in this connection that unauthorized changes or additions to personal information may have more serious consequences than violations of its privacy.

Although such a definition of private information would be very helpful, various additional measures would be needed to ensure that the protection to privacy the definition intends to provide would be realized in practice. For instance, although it is clear that banks are responsible for any money deposited by the public, they are still subject to various regulations and to periodic inspection because the individual depositor would be unable to ascertain for himself whether or not his money was being properly protected. By analogy it would seem desirable to have information systems certified and inspected periodically by a public body. The question of whether and how information systems should be regulated to protect the privacy of the information they contain will be considered in a forthcoming inquiry of the Federal Communications Commission into "Regulatory and Policy Problems Presented by the Interdependence of Computer and Communication Services and Facilities."

I should like briefly to examine some of the implications of the statement "knowledge is power" that appears in a number of places in Professor Westin's book. The relative power of government, private organizations, individuals and different segments of society greatly affects the degree of autonomy that individuals and institutions enjoy in practice. Any significant change in the balance of power is bound to distort the operation of society and the process by which social decisions are made. If knowledge is power, the balance of knowledge is as important to the preservation of a free society as privacy. "Knowledge" implies much more than mere access to facts or raw data. It presupposes the availability of means for extracting useful information from them, for building models of the reality they describe, for testing their validity and for exploring the consequences of possible courses of action. Thus preserving the balance of knowledge within a society requires that the public have convenient and economical access not only to raw data but also to the computer facilities and specialized programs necessary to perform such tasks.

Recent experimentation with multi-access computer systems [see "Time-sharing on Computers," by R. M. Fano and F. J. Corbató; SCIENTIFIC AMERICAN, September, 1966] has indicated the feasibility of bringing the power of computers within the reach of individuals. An individual could then have at his disposal the equivalent of a very knowledgeable and skillful assistant, ready to serve him with respect to such diverse matters as buying consumer goods, managing financial affairs or meeting legal problems. The first steps in this direction have already been taken, but much remains to be done. A wide spectrum of possibilities is open for the future. At one end is the rapid development of computer utilities keyed to provide a variety of computer-based services to the public at large, as well as to government and private organizations. Such a development would tend to preserve the relative balance of knowledge and power within a society. At the opposite end of the spectrum is the continuing development of computers keyed specifically to meeting the data-processing needs of government and private organizations. This tends to keep computers largely out of reach of the public, thereby creating a dangerous imbalance of knowledge and power in the society.

Technology is still largely neutral with respect to this spectrum of choices for the future. Nonetheless, decisions as to the technical developments to which resources will be allocated in the next few years may well bias the technology in a particular direction, perhaps irreversibly so. Large economic forces are at play; both the communications industry and the computer industry are involved. The outcome will depend on many factors and decisions whose implications are still very poorly understood. The forthcoming inquiry of the Federal Communications Commission, the scope of which appears to be unusually broad and open-ended, will certainly help. The computer and its uses are evolving very rapidly, and public discussion of the underlying issues is urgently needed to prevent society from becoming a prisoner of a course it did not consciously select.

Short Reviews

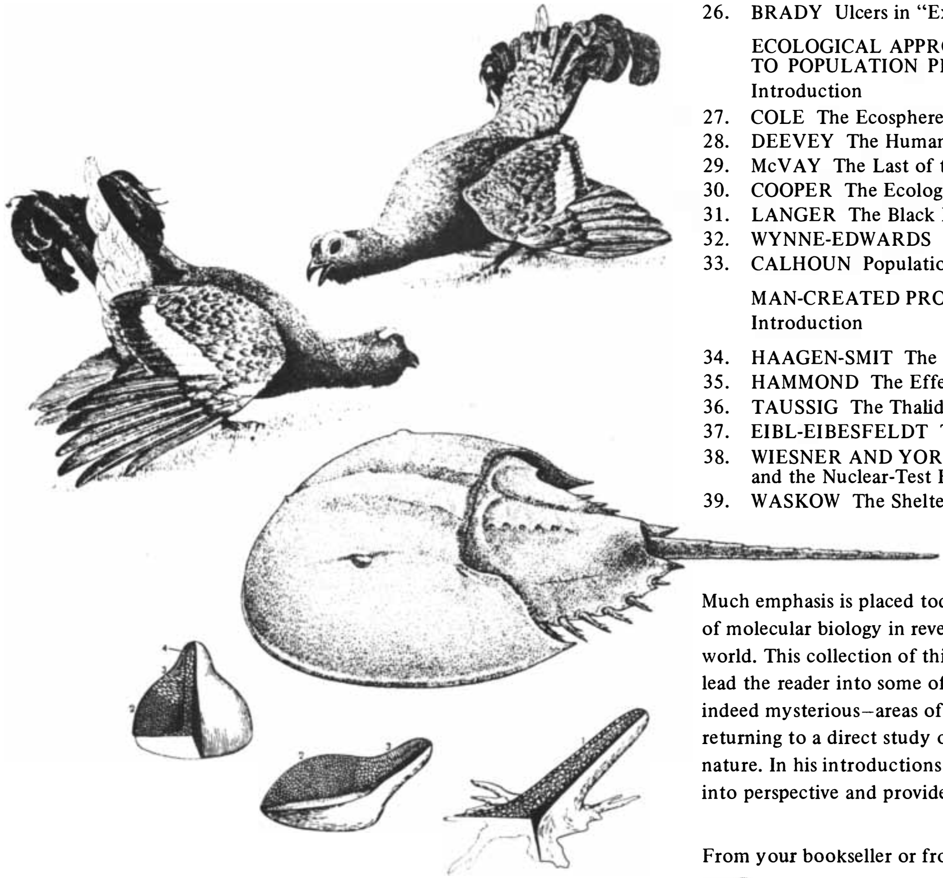
JANE'S FIGHTING SHIPS: 1967–1968, edited by Raymond V. B. Blackman. McGraw-Hill Book Company ($47.50). Once again we have the annual compendium of the great war engines, in all their folly and splendor. This year the directory of advertisers is done for the first time in English, French, German, Spanish and Russian (it is *radar* in four languages but a Cyrillic *radiolokatsionnie* in the other), and *Jane's* celebrates its 70th year by including 30-odd facsimile pages from the past. There is a pen-and-ink drawing, done for the 1897 annual by Fred Jane himself, of the U.S.S. *Nantucket,* a cheesebox monitor of Civil War vintage, with the rather candid comment on her and her class: "Most of these ships are unseaworthy." The U.S.S. *Pueblo* is listed for the first time in 1967; she is one of five "light cargo ships" taken over from the Army. Candor is uncommon today even in *Jane's;* readers fluent in intelligence talk may see a clue in the comment that one of the class was "converted to a special-project ship." The *Pueblo's* North Korean captors are here too; they are aluminum-hulled motor torpedo boats of Russian manufacture, a score of them comprising a third of the North Korean navy. The huge black nuclear-powered missile submarines look very much alike, whether named *Lafayette* and built in Connecticut or *Le Redoutable* and built in Cherbourg; their Russian counterparts

Readings from **SCIENTIFIC AMERICAN**

39 Steps to Biology

With Introductions by GARRETT HARDIN,
University of California, Santa Barbara

Publication date: May 1968



Much emphasis is placed today on the recent triumphs of molecular biology in revealing important unities in the living world. This collection of thirty-nine readings is intended to lead the reader into some of the more unsettled—indeed mysterious—areas of biology that can be seen by returning to a direct study of the diversities and unities of nature. In his introductions Professor Hardin puts the readings into perspective and provides insight into their significance.

From your bookseller or from

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carry not names but numbers and appear only in rather murky unofficial photos. The American taxpayer has invested about $7 billion in nuclear submarines. There are two sections given over to the flying hardware that ships carry: aircraft of all kinds and guided missiles. One smiles on noting amidst all this cruel power a few lofty training square-riggers, an occasional trim yacht and a U.S. Coast Guard tender named *Cowslip*.

SUBMARINE CANYONS AND OTHER SEA VALLEYS, by Francis P. Shepard and Robert F. Dill. Rand McNally & Company ($9.75). THE EARTH BENEATH THE SEA, revised edition, by Francis P. Shepard. The Johns Hopkins Press ($6.95). If geologists had been able to follow the course of the Colorado River only with blimps, dropping sounding lines and recording echo pulses at night from an altitude of 500 feet, they would not know a great deal about the Grand Canyon. They would welcome the new techniques: automatic remote photography and sample-taking routines, "mountaineering" gear that would permit a brave man to wander alone gingerly over the highest parts of the terrain, and real flying saucers that could take trips deep into the canyon and close to its walls. Undersea geology fits the metaphor. The two authors of the first book represent both the veteran and the more modern schools of submarine geology; one photograph by Dill shows a man-tadpole leading the way into a deep granite crevice too narrow to admit the saucer. In Monterey Bay off central California there arises a canyon whose profile is remarkably similar to the air-filled one in Arizona: it is 60 miles long, 10 miles wide and has walls more than a mile high. Off the East Coast of the U.S., about 100 miles out to sea, a vast slope descends a mile in a distance of about 15 miles, forming a smooth escarpment all the way from Cape Hatteras to Georges Bank. A score of canyons, bigger than any in the neighboring Appalachians, notch that smooth slope. In the past few years it has become clear that off New Providence Island in the Bahamas there lies the most spectacular gorge in the world: the perpetually dark Great Bahama Canyon, with walls nearly three miles high and a length of 125 miles. The first of these books lists and describes in lively and specific prose some 100 undersea valleys off all the continents except Australia.

What made the canyons? Here there is no certainty to match the insights of geologists in Arizona. Some of the canyons, notably the ones off Corsica, are plainly drowned gorges cut by rivers long ago *en plein air*. Most of them, however, do not fit river valleys ashore. The most striking of them are apparently still being eroded; slow currents continue to ripple and mold their walls and bottoms. The ingenious theory that during earthquakes catastrophic turbidity currents rush down the submarine slopes, carrying with them a heavy load of abrasive sediment, is badly battered by the analysis. The famous 60-mile-per-hour current that followed the Grand Banks earthquake of 1929 was inferred from the pattern of breaks in the skein of transatlantic cables lying on the bottom. The newer analysis suggests a much slower current, only 15 m.p.h., starting almost simultaneously over a wide area. The conclusion is cautious, cheerful and forward-looking. We simply don't know yet. The second book, more popular and more comprehensive, is a new version of a somewhat older account of submarine geology as a whole, from tidal waves to coral reefs, by the senior author of the first one. The undersea photographs in the first book are awesome.

SAFETY IN THE AIR, by Maurice Allward. Abelard-Schuman Ltd. ($5). Lord Brabazon stood before the B.B.C. cameras in a pool of jet fuel and tried to ignite the liquid at his feet. He had to use a blowtorch, because the material was the kerosene-like world-standard civil jet fuel. His opponent in the debate used JP-4, a standard fuel for land-based military jets that is much more like automobile gasoline and is enough cheaper to save $30,000 per year per big plane. The JP-4 flashed up at the touch of a match, and there were some small explosions. Therein is part of the problem of air safety. There is no doubt that the cheaper fuel adds risk, but how much is safety worth? Since 1965 Pan American and TWA, together with the British airlines, have used kerosene, although except for the Australians no civil air safety authorities have banned the more volatile fuel.

Not all air safety has been won by the careful calculation of risk. Men have had to learn the hard way about faulty design, foolhardy operation and handling errors. Airplanes are complex machines. Here the story is presented in a lively, well-informed little book (unhappily lacking an index) by a British aviation writer with a generation's experience in the industry. The risk of death in an hour's flight on a scheduled airline is nowadays about one order of magnitude greater than in an hour's trip by car. The number of fatal accidents has stayed about the same since 1950, although the crashes are bigger ones and the miles flown have increased tenfold.

We are told the tale of the Electra I, its engines shaken off by a resonance between propeller wobble and wing vibration. We also learn about the DC-6: after two serious fires aloft in the then new type, a determined pilot found that during the transfer of fuel between tanks in flight a small overflow of gasoline was carried by the slipstream 10 feet back and downward to enter the air intake for the cabin heater! The most penetrating of all inquiries was the one started after the second mysterious crash of the Comets flying out of Rome in 1954. The sea bottom off Elba was combed for 100 square miles at a depth of nearly 100 fathoms with trawls and television cameras, and over months almost the entire airplane was dredged piece by piece out of the depths. The pieces recovered were wired to a wooden skeleton to reconstruct the plane. Three other Comets were allotted to the Farnborough Royal Aircraft Establishment for testing. Flying with cabin unpressurized, loaded with instruments, deliberately mishandled, the Comet never failed. A Comet engine was placed on a special moving frame and maneuvered to reproduce the damage seen in the recovered turbine wheels. Nosing down very suddenly did it; the engines must have failed only *after* the Comet had ceased normal flight.

A Comet fuselage immersed in a huge water tank was cycled through the pressure changes of flight, simulating a three-hour trip every five minutes. After thousands of cycles, the cabin suddenly lost its pressure. A tiny fatigue crack widened rapidly into a tear eight feet long. That had wrecked the Comet, that beautiful pioneer of jet flight. By the end of the summer the cabin roof had been salvaged, and the primary fatigue crack could be seen. Zinc-rich Duralumin is not used any more; it is very strong but subject to such crack growth. Stress at window corners is kept low, and special strengthening is put there to impede cracks.

If anything can be assembled wrongly, sooner or later it will be. In one plane a small line was used for pressure equalization. Its open end looked bare. Someone might cap it. Accordingly the designer remembered to put a metal guard across the open end of the tube. A neat mechanic nonetheless reached behind the guard and fitted the cap he thought someone must have forgotten.

Survival equipment, collision alarms, computer-tended ground control, clearer

instrument markings, recorders for post-crash study, design for crashworthiness and fire retardation, slow landing and takeoff are the currently visible steps to safety. More flying will mean more deaths; we need above all to increase the dwindling corps of experienced World War II pilots, and to build "aeroplanes that land slowly and [do] not burn up." We passengers have to be willing to pay for safety too. It might be worth more than the in-flight movies.

Orchid Flowers: Their Pollination and Evolution, by L. van der Pijl and Calaway H. Dodson. University of Miami Press ($12.50). The grasses spread over the wide featureless plains; whole counties are dominated by a handful of species. They sow their pollen on the insensate winds. The flowers of our fields are more discriminating; they are varied in look and habit, and their pollen is carried from plant to plant by bees or beetles. Such carriers, particularly the social bees, visit many plants and mix pollen freely; indeed, they take the pollen as a source of protein, and only by accident does a little of the food remain to serve the flower species. The orchids may be the plant family with the most numerous species; they often dwell in the rain forest, on an extraordinary variety of hosts subtly different in environment. Their self-managed genetics is responsible. Orchid species can differ almost exclusively in the blossom; they will not hybridize away their elegant distinctions, because they remain sexually aloof. Their pollen is not scattered, nor even brushed onto the carrier; it is bound into one tight capsule. They have frugally placed all their seed in one basket and watched that basket.

How have they watched? This book, the first modern reworking of the subject since Darwin that is free of mystical and special pleading, shows us, in 50 beautiful color plates and many drawings and black-and-white photographs. The text is not fully popular, but it is clear, and with some biological background and a judicious use of the careful glossary the general reader will be brought to awe and delight by the arguments as well as by what he sees. Some orchid flowers have transparent windows to direct the motion of the insect within by its instinctual approach to light. Some exude a liquid when properly scratched in the right place by a male bee of the right species. The liquid intoxicates the bee. His motions are slowed, his flight is erratic. Then he is led to fall through a chute, down a slide or into a bucket of water. Sometimes he springs traps, receives the gluey pollen vessel and leaves the flower, which ceases giving off scent at once (noticeably within 15 minutes). The female flowers remain scented for a month longer, until after pollination they too swell shut in hours. Some blossoms mimic the bee's mate, furry body, glistening eyes, blue mirror spots and all; he attempts copulation, only to bear away the pollen capsule, which he transfers to his next false love. One orchid, *Oncidium,* appeals not to hunger or to lust but to bee sovereignty. The territorial bee strikes the wind-tossed blossom of the orchid repeatedly. The action is precise; there is a target on the flower about a millimeter across. Once the bee's head strikes that target, a pollen case sticks to the insect. On the next strike he implants the case precisely in the target plant.

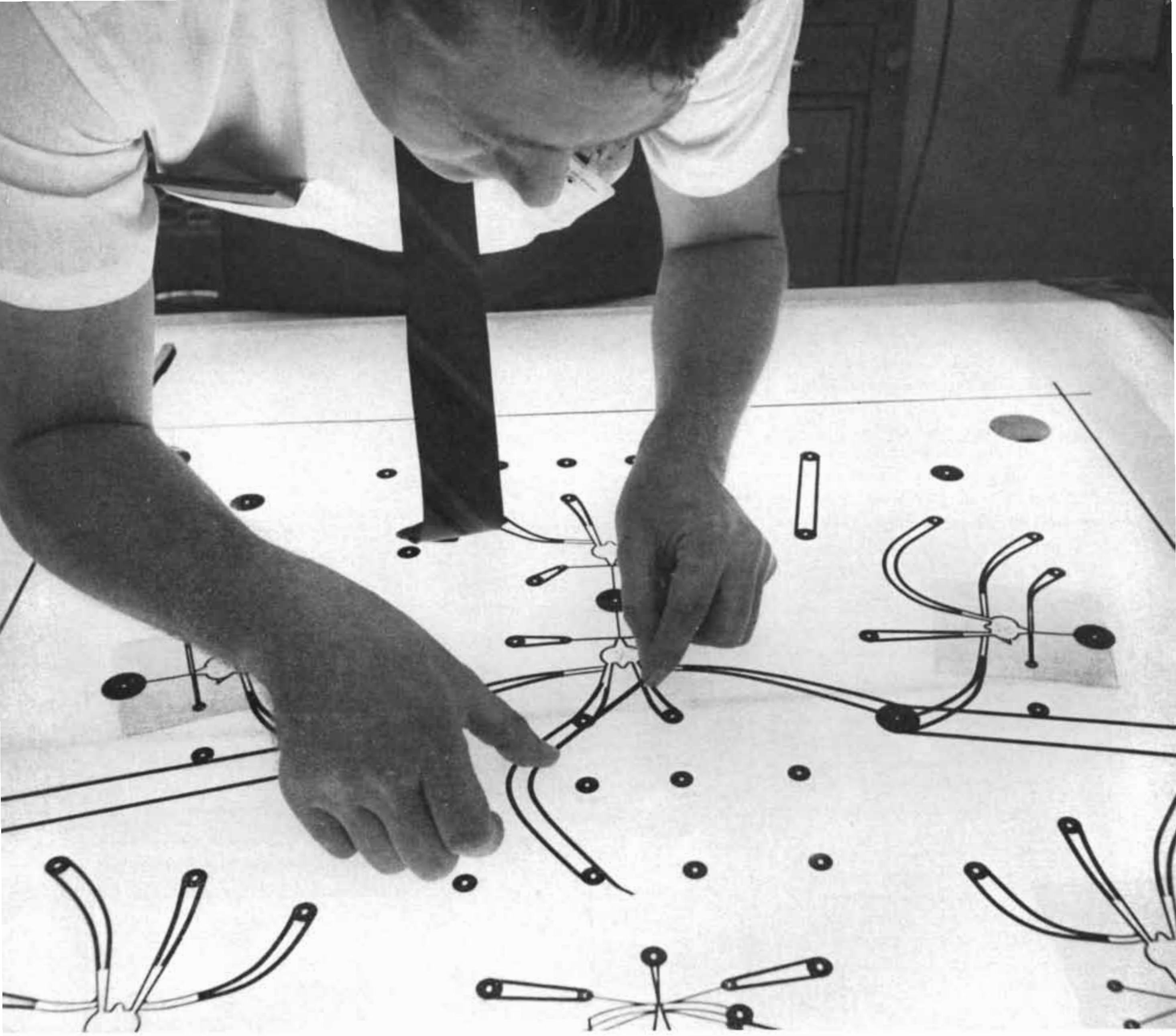
Deceit, not nectar, write the authors, lies in the foundation of the flower-pollinator relationship in the orchids. The whole system, charged with specificity, has had its clear effect. The orchids have made themselves, exploiting the subtler needs of bees. It would appear that this marvelous topic is about ripe for quantitative study by the theorists of evolution. The two authors, one long experienced in Java, the other in tropical America, have produced a book of beauty, cogency and philosophical strength. Their epigraph deserves being cited. It is Darwin speaking: "I carefully described to Huxley the shooting out of the pollinia in *Catasetum* and received for an answer, 'Do you really think I can believe all that?' " One cannot longer doubt it, and perhaps we can see how it arose.

Special Relativity, by A. Shadowitz. W. B. Saunders Company ($6.50). Brief, physical, clear, this is a most appealing member of the set of good books that outlines the special theory of relativity for anyone, be he teacher or graduate student, who has occasion to work with the theory from time to time but is no specialist. There is little formal mathematics in the book, but it emphasizes, and here it is unique, the space-time diagrams originated by Hermann Minkowski, Robert W. Brehme and Enrique Loedel, which make simple and concrete the transformations of covariant and contravariant vectors. With these graphic diagrams, some algebra and very little analysis, the text displays in detail the full kinematics of Einstein, his mechanics and the elementary provinces of electromagnetic theory. An excellent summary of the recent experimental tests of the theory (the idea that light takes on the velocity of its source is now excluded not by Willem de Sitter's old double-star orbits but by the decay of the neutral pi meson) and a remarkably fresh list of problems, paradoxes and references, together with good discussions of knotty points, fill out the book. Undergraduate physics majors, although probably not every student of physics, would much enjoy working at this book.

PLEISTOCENE EXTINCTIONS: THE SEARCH FOR A CAUSE, edited by P. S. Martin and H. E. Wright, Jr. Yale University Press ($12.50). *Aepyornis,* whose real roc eggs held two gallons of omelet, was plentiful on the large sea island of Madagascar when man first arrived. By the 17th century the great bird was rumored to be about, but "people cannot take him; he seeks the most deserted places." The moa, *Aepyornis'* New Zealand counterpart, was reduced to a few small, shy representatives of a plentiful and magnificent genus by the pre-Maori first settlers, carbon-dated by their campfire charcoal at the era of the Norman Conquest. Ten thousand years ago the large fauna of North America, mostly herbivores such as the mammoth, the camel, the pronghorn antelope, the horse, the armadillo, together with their predators such as the saber-toothed cat and the hyena, became extinct rapidly ("about 95% of the North American megafauna").

Who done it? Was it our cousins—the agile, tireless, able hunters, masters of the chase, of the stampede over the edge of the ravine, of fire scorching the dry prairie? They had newly come from old Asia to find a huge plain of tame grazers unafraid of man. Or was it merely the last shrinking of the glaciers? Drought and warmth then reduced the enormous areas that must nourish such large beasts, forcing all animal life through a narrow funnel of survival. Small relict areas of cool, wet grassland can support stocks of little animals, but the large ones go to the wall.

The argument ranges with fascination and no clear resolution in this fine report of an expert international symposium, held in Boulder, Colo., three years ago but supplemented by up-to-date papers on the subject. The fauna-rich East African plains were themselves decimated of genera 40,000 years ago. What remains in all its wonder is only two-thirds as diverse as it was before the time of man. The great extinctions spread continent by continent, in the sequence of man's arrival, reaching finally those island realms where mainland man has only recently arrived. It was the first Darwinian, Alfred Russel Wallace, who



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wrote: "We live in a zoologically impoverished world, from which all the hugest, fiercest, and strangest forms have recently disappeared." One is tempted to add "except for the fiercest, strangest and most wonderful of all."

Americans are the strongest proponents of this responsibility of man. It is admitted, however, that the matter is uncertain. The numbers do not seem clear. Could a small population work faster, without guns and the pressure of the market, than historic man did? The finds of what the hunters took do not include most of the extinct species. The hunter-artists of Europe did not often kill the woolly rhinoceros or the musk ox. The cave bear vanished, yet man did not compete with it for its mountain caverns. The case remains open, although the indictment was brought as long ago as Lucretius.

Whole piles of mammoth bones are shown as they are found on the riverbanks of the Don and the Dnieper, but the Russian workers do not believe the huge beasts were always prey to hunters (although one ravine in the southern Ukraine holds 1,000 bison that were deliberately killed by stampeding). The book begins with an enormously helpful brief "bestiary for Pleistocene biologists" opening many papers otherwise barred to the general reader.

THE REPRODUCTION OF COLOUR, by R. W. G. Hunt. John Wiley & Sons, Inc. ($16). This broad and fascinating technology, depending on the enigmas of our brain, on electronic and retinal networks and on the properties of available commercial dyestuffs, lamps and phosphors, is fully treated in the second edition of a book that has doubled in size in the 10 years since it first appeared. The author is a British expert of the widest experience; American practice seems well represented. How your color transparencies are processed, using exposures semiautomatically controlled on the surprising assumption that on the average the whole color picture, and not merely a gray area, integrates to gray, is only one of a hundred complex and ingenious engineering schemes described. The general reader and user of color reproduction is never neglected in favor of the expert, although ample detail is given. The account of how color letterpress pictures are printed nowadays is a splendid antidote to the "three separation pictures and black" of reference books. To mention only the elements, there are eight colors of dots printed from the three colored inks, because the dots frequently overlap.

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BIBLIOGRAPHY

Readers interested in further reading on the subjects covered by articles in this issue may find the lists below helpful.

THE THREE SPECTROSCOPIES

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