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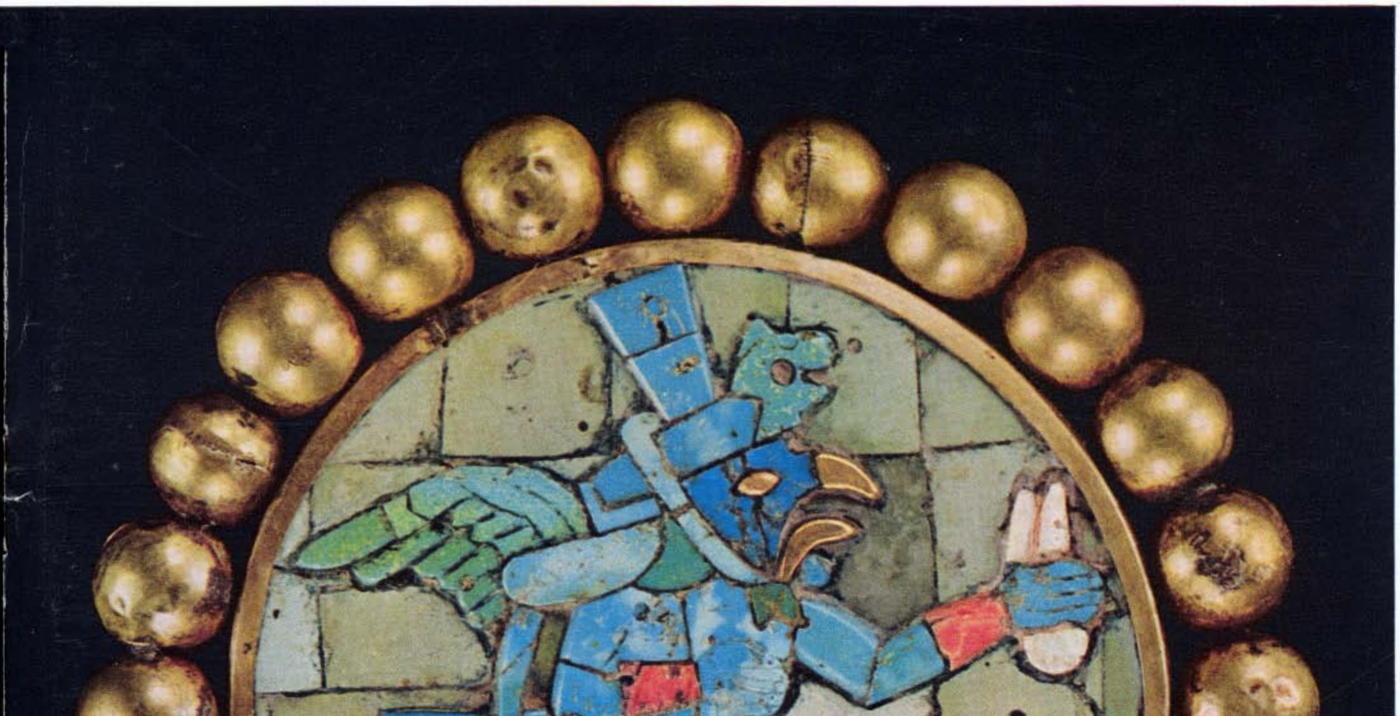

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April 1966

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Established 1845 **SCIENTIFIC AMERICAN** April 1966 Volume 214 Number 4

ARTICLES

DEPARTMENTS

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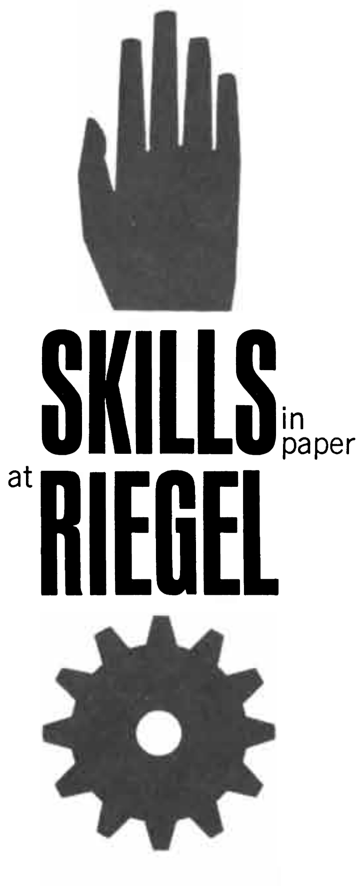

THE COVER

The photograph on the cover shows a gold and mosaic ear ornament made by Peruvian craftsmen at least 800 years before the conquistadors seized and melted into bullion most of the examples of fine metallurgy in gold and silver that filled the native treasuries from Mexico to Chile (see "Early Metallurgy in the New World," page 72). This particular example, executed in Mochica style at some time between A.D. 200 and 700, is slightly more than four inches in diameter. The 24 gold balls that surround the central figure were probably made by pressing sheet gold into a die and soldering the resulting metal hemispheres together. The figure is a mythological "bird messenger"; the mosaic is composed of amethystine quartz, turquoise, shell and the copper silicate chrysocolla. Like many of the surviving pre-Columbian treasures, the ornament is in a private collection.

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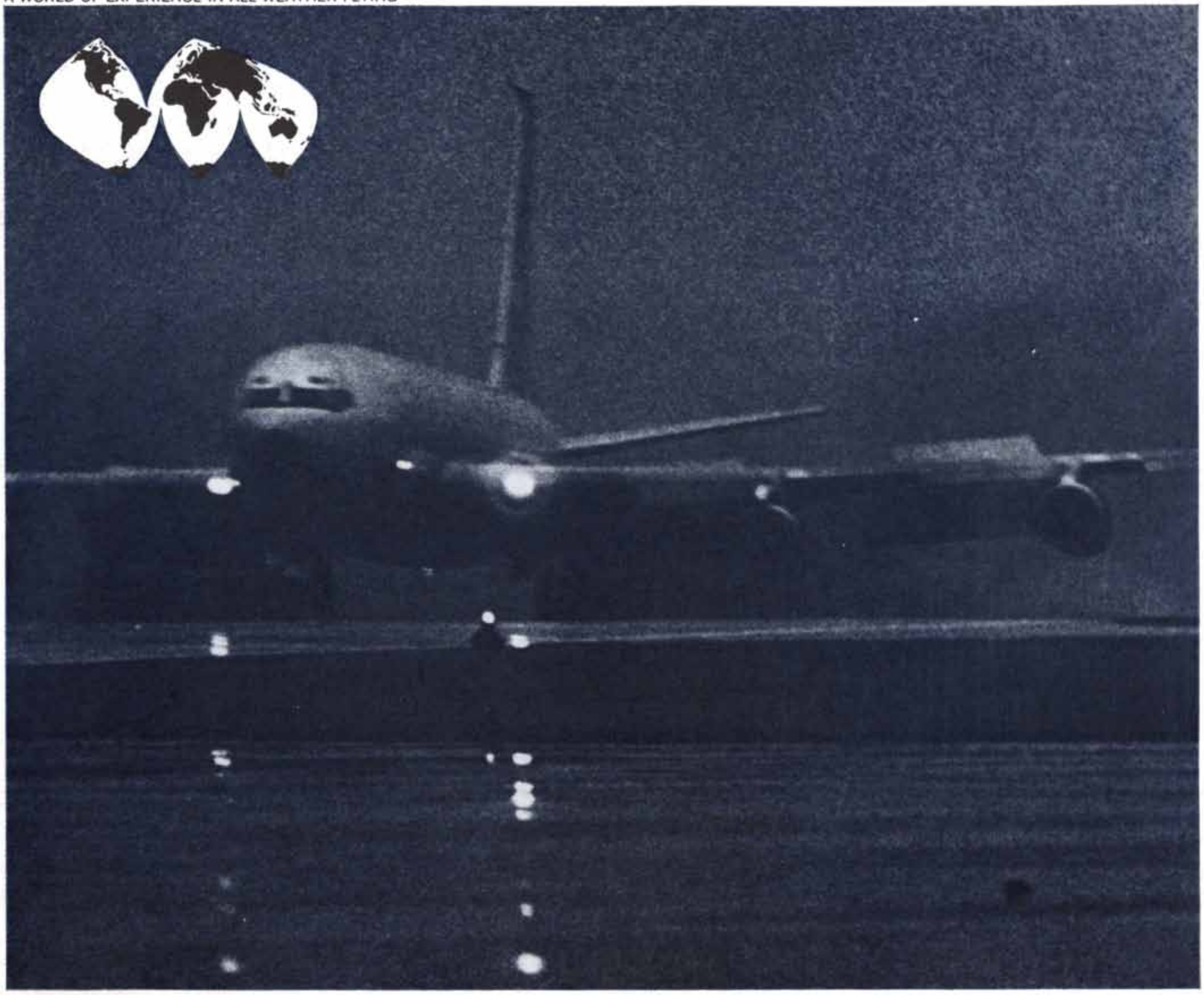

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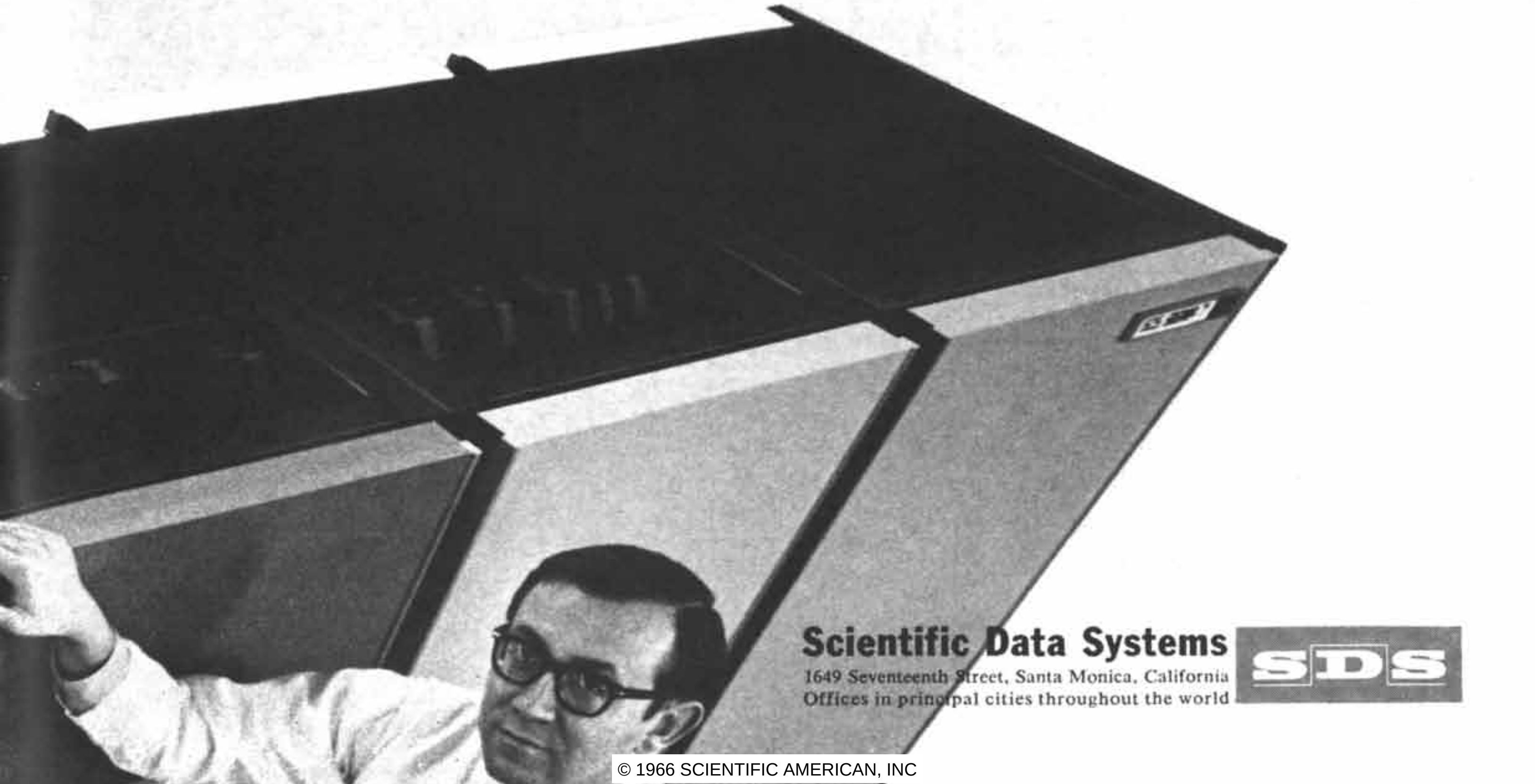

LETTERS

Sirs:

Stephen Toulmin's review of Carl G. Hempel's *Aspects of Scientific Explanation and Other Essays in the Philosophy of Science* [SCIENTIFIC AMERICAN, February] gives such a flagrantly distorted account of the book's aims and contents that it is difficult to believe he read the book with the care required of a responsible reviewer. Three examples, which could be multiplied several times, will suffice to establish the unreliability of his review.

1. Hempel's main objective is to analyze the *logical structure* of scientific explanations rather than to examine the *process* of scientific discovery or the *development* of scientific ideas. To this end he deliberately adopts the familiar strategy, so effective in scientific and logical research, of abstracting from the full complexity of a subject matter and introducing a precise technical vocabulary to formulate admittedly "abstract idealizations" or simplifying assumptions. Toulmin assesses the book by reference to objectives that are not Hempel's, and in consequence his dismissive evaluations are irrelevant to what the book is about. Thus one of his major criticisms is that "the language of science" Hempel analyzes does not refer to any "actual mode of discourse" to be found in technical scientific journals. This is no more pertinent as a criticism of Hempel's book than is the objection to the codification of a proof for a mathematical theorem that the steps in the proof do not correspond to the sequential order in which the theorem or its demonstration was actually discovered.

At one point in his review Toulmin does consider the possibility that Hempel's abstract idealizations are not intended to be descriptions of how scientists actually talk or behave. But he promptly disparages their value on the ground that Hempel does not demonstrate the intellectual profit to be gained from the "wish to *replace* [my italics] our working conceptions of 'validity,' 'confirmation,' 'proof' and the like by formalized substitutes." This is a crude misrepresentation of Hempel's intent. Hempel nowhere proposes such a *replacement*, and he introduces his abstract idealizations simply as instruments of analysis and clarification—a distinction that is apparently beyond Toulmin's grasp.

2. Toulmin reports Hempel as denying that Darwinian theory is genuinely explanatory, on the ground that it does not conform to Hempel's "a priori" requirements for a satisfactory explanation. This is a shocking misstatement of Hempel's views. Hempel's comments on Darwinian theory in the book occur in the context of a brief examination of Toulmin's claim made elsewhere, that the theory is explanatory but has no predictive value (allegedly because it cannot foretell the rise of new biological species). In disputing this claim Hempel notes that it is not the *narrative* of the sequential emergence of organic forms but rather the Darwinian *theory of the underlying mechanisms* of mutation and natural selection, "which provides what explanatory insight we have" into the sequential development, but he also calls attention to what he believes is a "widespread tendency to overestimate the extent to which even the theory of mutation and natural selection can account for *the details of* the evolutionary sequence." In quoting this second passage Toulmin omits the phrase I have here italicized and thereby foists on Hempel a view the latter does not hold. Leading exponents of Darwinian theory, and not only Hempel, recognize limitations in our current ability to account for many *details* of the evolutionary

Scientific American, April, 1966; Vol. 214, No. 4. Published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Gerard Piel, president; Dennis Flanagan, vice-president; Donald H. Miller, Jr., vice-president and treasurer.

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Subscription correspondence should be addressed to Jerome L. Feldman, Circulation Manager, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017.

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sequence, but they cannot therefore be rightly accused of maintaining that the theory has no explanatory value.

3. Toulmin cites three statements that Hempel designates as "laws of nature" but that he does not believe do justice to the "true variety" of explanations in actual science, and he strongly suggests that these statements are the only examples of scientific laws mentioned in the book. This suggestion is not exactly cricket; even a quick leafing of the book reveals that Hempel refers to many other laws (for example on pages 83, 178, 232, 340 and 435) that differ in "form, function, and implications" from those Toulmin quotes with undisguised contempt. Moreover, Toulmin misrepresents the point of Hempel's procedure. Hempel nowhere takes the examples Toulmin cites to be representative of the variety of scientific laws—he uses them in discussing certain logical issues that arise for simple as well as complex laws, for the obvious reason that those issues can be expounded with greater economy and clarity with the help of those simple examples.

ERNEST NAGEL

Department of Philosophy
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New York, N.Y.

Sirs:

By reacting so quickly to my review in the February *Scientific American* (his letter is dated February 3) instead of taking time to think over my argument, Ernest Nagel has let premature indignation blind him to what I actually said. Unfortunately the tone of his letter compels a formal reply, and in places (for example the insinuation that I did not read the book carefully enough to grasp its meaning) is unworthy of him. (That really is not cricket.) In any case, several of the most significant papers in the book have been in circulation for 15 years or more.

Professor Nagel states that I "flagrantly distorted" three aspects of Carl Hempel's views: (1) his belief that symbolic logic provides a suitable notation for the philosophy of science, (2) the status of the two basic "explanation-forms" recognized within his system and (3) his reasons for concentrating on these two idealized forms instead of on the real-life arguments of natural scientists. Yet in fact (with one major reservation discussed below) I do not, and did not, question that Hempel's views are substantially as Professor Nagel declares. If I had done this, the rest of my argument would have made no sense. My central thesis is that *these very views* rest on concealed presuppositions that, when brought to light, appear highly dubious, and nothing in Ernest Nagel's letter meets the substance of my doubts.

Concerning item 1, the "familiar strategy" of using a "precise technical vocabulary" to formulate "abstract idealizations" is not *self-justifying*. The mechanics of Galileo and Newton, for instance, did not carry conviction merely because it fitted simple, everyday motions; it had to be shown, in addition, how the new formalism could be extended to cover also motions of much greater complexity, and—in principle—all motions whatever. So for Professor Nagel to retort that Hempel is "discussing certain logical issues that arise for simple as well as complex laws, [because] those issues can be expounded with greater economy and clarity [using] simple examples" is to stand the real issue on its head. Nobody need challenge Hempel's account of arguments based on everyday generalizations about black ravens and the like. What does need showing is that the issues arising over such "laws"—if we *must* call them that—affect the complex arguments of scientific theory at all. And nothing is achieved in this direction by quibbling over the distinction between "instruments of analysis and clarification" and "replacements." What is "analysis" but the replacement, for philosophical purposes, of allegedly confused terms and notions by explicit, clarified ones?

As for Professor Nagel's item 2, here it is he who fails to grasp the crucial distinction. His defense of Hempel's argument about "historical" theories, such as neo-Darwinism, relies on the obvious truth that current *explanations* of the origin of species *are not as detailed or complete* as we should like.

Addendum

The principal book review in Scientific American for March indicated that *Science in History*, by J. D. Bernal, was published by the British firm C. A. Watts & Co. The book has now been published in the U.S. by Hawthorn Books Inc. ($12.95).

This is beside the point. Hempel's relevant argument (which is directed, incidentally, against Michael Scriven and several others besides myself and involves the entire section from page 364 to page 374) goes far beyond that truism; it contends that, in any proper sense of the term, the Darwinian account *is not and never was an "explanation" at all* but rather "a hypothetical historical narrative *describing* the putative stages of the evolutionary process" (Hempel's own emphasis). About this, the force of the whole passage is unambiguous.

As for item 3: over this point Ernest Nagel, if anyone, "flagrantly distorts" Hempel's views. In the normal acceptation of the term "representative" there can be no doubt that Hempel does regard "All ravens are black" as *a* representative—indeed, as *the* representative—type of a scientific law, and the passing allusions to electromagnetism, Ohm's law and so on cited by Professor Nagel are mere lip service to the complexity and variety of scientific arguments. Hempel's very insistence that the only acceptable modes of scientific explanation proceed by "subsumption under universal or statistical covering laws" *in this sense* is in fact what provokes opposition. If all Hempel had said were "Here is one valid mode of commonsense explanation," nobody would have batted an eyelid—still less a cricket ball!

The logical empiricists (I argue) have taken too much for granted for too long; for example, that which applies to ravens must apply to neutrinos, and that "discussing certain logical issues that arise for simple [generalizations]" necessarily elucidates also the intellectual force of more complex concepts and principles. Forty years seems time enough for a convincing demonstration of these points—which is why my review went beyond the minutiae of Hempel-scholarship to the entire historical context of his work.

Finally, let Professor Nagel send me details of the other "unreliabilities" in my review and I shall see if they carry any more weight than the three in his letter. If so, I shall gladly wear a hair shirt in your columns. For the moment, however, I can only ask him to go back and reread the review more carefully.

STEPHEN TOULMIN

Department of Philosophy
Brandeis University
Waltham, Mass.


5 FOR 1
HIGH
HIGH
4
5
8
NINE
10
Pays Double
2
3
4
9
10
11
Pays Double
12
FIELD
Don't Pass
15 FOR 1
Any Craps

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

APRIL, 1916: "The great German assault upon Verdun has lasted since February 21, apparently with no end yet in sight. The massing of artillery, the rush of storming divisions and the employment of every means of warfare known to the modern day have each been in the superlative; there has been no action in all history that can be compared with the battle of Verdun. It is not a battle, it is not a siege; the two are combined in one, sanguinary in the extreme. Foreign as well as local military writers, soldiers trained in the art of war and strategists of high degree freely confess that they are unable to definitely state what the object of the German General Staff seems to be while whole army corps are being hurled, in the face of huge losses, against the serried guns of Verdun. The point is rather remote from Paris; it scarcely seems to be a drive upon the French capital. And while the Verdun salient without doubt establishes a certain menace against Metz, in the event that the Entente begins a determined drive in the course of time, the German losses so far encountered seem utterly disproportionate to the possible gain of eliminating the menacing salient. It is very evident that for some reason, however, Germany seems willing to pay the price, to make enormous sacrifices at Verdun to gain the city and fortress. What the reason is no one not in the confidence of the German General Staff may know. For 52 days the attack has continued, with brief intervals of inactivity, during which time positions gained were consolidated and preparations were made for resumption of the attack."

"To those who believe that the ultimate victory of the Allies will be due to the exhaustion of the Central Powers' supply of men, the estimate of German losses made by Hilaire Belloc in *Land and Water* will have profound significance. Belloc recently visited Paris for the purpose of obtaining data of an official character, gathered by the intelligence bureau of the French War De-

Report from

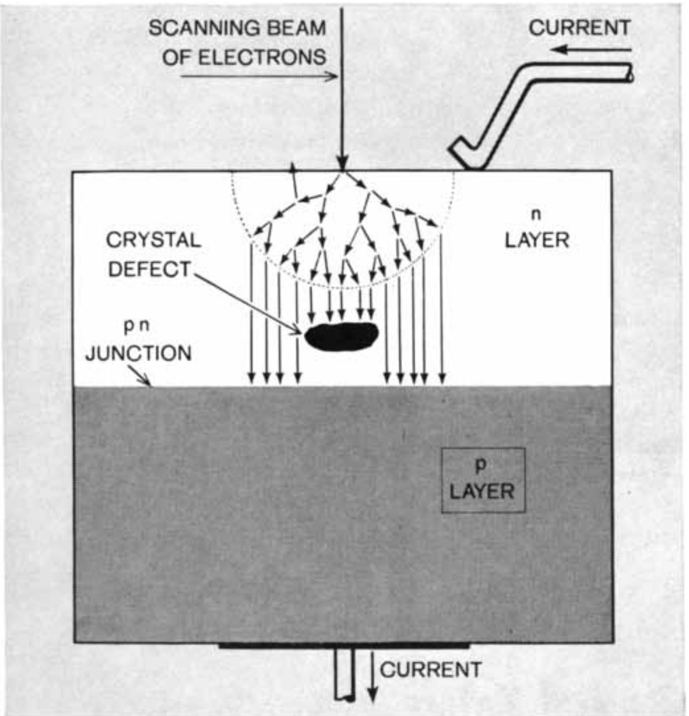
BELL LABORATORIES

New type of microscopy reveals internal structures of crystals

Bell Telephone Laboratories scientists have developed a new type of microscopy that uses a beam of electrons as a probe to investigate the structures of semiconductor crystals. Unlike other electron-probe arrangements or the electron microscope, which are limited to studies of surfaces or very thin layers, the new system is used to reveal features within the body of the semiconductor.

As shown in the drawing below, crystal defects are not probed directly by the electron beam. Instead, the secondary charge carriers created by the beam are used, in effect, to project an image of each imperfection onto the plane of a pn junction. This image is then reproduced on a cathode-ray tube. The process is nondestructive of the crystal, usually does not require special treatment of the crystal surfaces, and has a resolving power higher than that of optical microscopes.

This new type of microscopy reveals both surface and internal structure and allows separate identification of each. It has proved useful in studying crystal defects that may degrade the performance of semiconductor diodes and is also leading to greater understanding of crystalline structures.



Mechanism of new type of microscopy developed at Bell Telephone Laboratories: Beam of electrons is directed onto surface of semiconductor crystal containing pn junction and penetrates crystal a short distance (vertical distance here is exaggerated). Beam creates a "cloud" of secondary electron-hole pairs, indicated by the semicircle of dots. Normally the created charge carriers are collected by the pn junction, giving rise to diode current. If the beam is swept across a crystal defect, however, the diode current drops, apparently because the tendency for electrons and holes to recombine is heightened in the vicinity of the defect. Thus the defect casts a "shadow" on the pn junction. The surface of the crystal is scanned by the electron beam in a series of lines, TV-fashion. The varying diode current, displayed on the face of a cathode-ray tube, results in "pictures" of the defects in the vicinity of a junction. In such pictures (right) the crystal defects appear as dark lines or regions.

Photomicrograph produced on face of cathode-ray tube by new technique. Dark lines show regions of crystal imperfections resulting from strain introduced by diffusing phosphorus into surface of silicon. (620X magnification.)

Large dark areas are regions of crystal damage caused by mechanical indentations in surface of silicon. Heat treatment relieved strain and caused edge dislocations, seen here as radiating lines or arc segments, to move outward from strained region. (800X magnification.)

partment, and it is largely upon the material thus secured that his analysis is based. Adding to a total of one million dead the corresponding number of wounded (as shown by the ratio of wounded to dead established by the statistics of the present war) and making a liberal allowance of between 50 and 60 per cent of the wounded returned as once more efficient to the front, Belloc estimates that, at the very minimum, over three and a half million men had been permanently lost to the German fighting forces by January 1, 1916, leaving only five and a half million out of the original nine million maximum possible recruitment of German men effective for war."

"A recent paper by Professor E. E. Barnard in the *Astrophysical Journal* gives strong support to the belief that just as there are probably many dark stars—more, perhaps, than bright stars—so there are many dark nebulae. Dark stars are necessarily invisible and reveal their presence only by their perturbing effect on the motions of bright stars and by eclipsing their light. Dark nebulae may, however, be visible as silhouettes against a luminous background, supplied by dense star fields as in the Milky Way or by luminous nebulosity or possibly by some faint general luminosity of space (a condition that Professor Barnard thinks may exist). There are in the heavens many dark spots of striking appearance, which have generally been assumed to be merely starless regions. The author presents photographs of some of these and expresses the suspicion that 'most of them are really dark or feebly luminous bodies shown in relief against a brighter background,' though some are doubtless real vacancies."

Scientific American.

APRIL 1866: "The Aeronautical Society of Great Britain was recently formed by the exertions principally of Mr. F. W. Brearey. On the 28th of February a meeting of the society was held at the residence of the Duke of Sutherland, where Mr. Brearey read a paper. The present plan for lowering a balloon in the air is to open a valve at the top and let out a portion of the gas, whereas the balloon is made to ascend by throwing overboard some ballast. Mr. Brearey proposes to carry a quantity of liquefied gas to supply the place of that which is allowed to escape; he also proposes to raise and lower the balloon by beating the air with wings, by means of the muscular force of the aeronauts."

"At a recent meeting of the Polytechnic Association of the American Institute, Professor Charles Joy of Columbia College remarked that the engineering problems involved in providing means of transit between different parts of New York City were not in the line of his studies or of his knowledge, but that the social or humanitarian side of the question, which had been broached, was of interest to every citizen. He wondered that the people of New York City did not rise in their majesty and put an end to the abuses of our horse-railroad system. He had traveled during the past year 6,000 miles in Europe. Five hundred of this was by means other than steam and 5,500 by steam. He had ridden in first-, second-, third- and fourth-class cars; he had traveled under ground and above ground, on water and land, and he had never experienced discomfort approaching that to which he had been subjected that evening in coming down from 49th Street to the Cooper Institute. He had come directly from his laboratory, but he had never had in his laboratory odors so vile—his science was not able to produce so foul a compound of stenches as filled the car in which he rode. If the railroad companies treat us thus above ground, what will they do when they get us into subterranean tunnels? He thought that the principal care of the citizens should be to see that in the granting of franchises ample provision is made for the protection of the community from imposition."

"Rats are as plentiful in Paris as in London, and they are often the victims of physiological experiments. M. Bert, for example, gained the prize in experimental physiology for removing their tails from their natural position and grafting them upon all sorts of odd places—the middle of the back of the animal, for instance, and even in the cavity of the peritoneum. M. Bert made one very curious observation. He succeeded in uniting the small end of the tail to the body and found that the large extremity, which was free, recovered its sensibility, thus showing that the nerves will convey sensation in a direction inverse to that in which they act under normal circumstances."

How many integrated circuit manufacturers shipped more units last December than all others combined?

One.

FAI

THE AUTHORS

ANNE P. CARTER ("The Economics of Technological Change") is a senior research associate in the Research Project on the Structure of the American Economy at Harvard University. She was graduated from Queens College in 1945, received a doctor's degree in economics at Harvard four years later and taught economics at Brooklyn College, Smith College and Wellesley College. "Except for a few lectures here and there," she writes, "I have not taught since my first child was born, but I hope to teach again someday." Her present research involves "a number of problems having to do with the economic impact of changing technology." She adds: "In addition to economic research I devote substantial chunks of time and energy to wifehood and motherhood, to playing the cello in a string quartet and to the demands of the Cambridge community. Each activity really deserves more."

GEORGE C. PIMENTEL ("Chemical Lasers") is professor of chemistry at the University of California at Berkeley. He is a native Californian who did his undergraduate work at the University of California at Los Angeles and his graduate work at Berkeley, where he obtained a Ph.D. in 1949. He has been a member of the faculty at Berkeley since then, becoming professor in 1959. His particular interests are infrared spectroscopy, molecular structure, hydrogen bonding and the thermodynamic properties of hydrocarbons.

ROBERT S. LEDLEY and FRANK H. RUDDLE ("Chromosome Analysis by Computer") are respectively president of the National Biomedical Research Foundation and assistant professor of biology at Yale University. Ledley arrived at his position by an unusual route. At Columbia University he specialized in physics and mathematics, but since "in those days a mathematician or a physicist could not make too much of a living, my parents decided to make a dentist of me." As a dentist Ledley was sent by the Army to do dental research at the National Bureau of Standards. There he had occasion to use a computer, and since he was "not happy using an instrument without knowing how it worked," he became a digital-computer engineer and served for a time as associate professor of electrical engineering at George Washington University. In 1960 he organized the National Biomedical Research Foundation to "apply computers in biomedical research on a full-time basis." Ruddle, who met Ledley during a seminar at Yale, received bachelor's and master's degrees at Wayne State University and a Ph.D. at the University of California at Berkeley.

ROBERT B. LEIGHTON ("The Photographs from *Mariner IV*") is a physicist who has turned his attention to astronomical instrumentation and observation. He has spent many years at the California Institute of Technology, first as an undergraduate, then as a graduate student (he received a master's degree in 1944 and a Ph.D. in 1947) and subsequently as a research worker and member of the faculty. Since 1959 he has been professor of physics. In addition to his astronomical interests he has worked on the theory of solids, high-energy particle physics and lattice vibrations.

DUDLEY T. EASBY, JR. ("Early Metallurgy in the New World"), is secretary of the Metropolitan Museum of Art. He is by profession a lawyer and spent several years in private practice in Philadelphia, with the legal division of the U.S. Department of the Treasury and as assistant general counsel of the office of the Coordinator of Inter-American Affairs; now he is general counsel of the Archaeological Institute of America. Easby is president of the Institute of Andean Research and has described his archaeological work in a number of scientific journals in the U.S., Mexico, Peru and Argentina. He was graduated from Princeton University in 1928 and from the law school of the University of Pennsylvania in 1931.

SEYMOUR LEVINE ("Sex Differences in the Brain") is associate professor of psychology in the department of psychiatry at the Stanford University School of Medicine. A native of Brooklyn, N.Y., he obtained a bachelor's degree at the University of Denver in 1948 and a Ph.D. at New York University in 1952. From 1953 to 1956 he was a postdoctoral fellow and research associate at the Institute for Psychosomatic and Psychiatric Research of the Michael Reese Hospital in Chicago. He then spent four years as assistant professor of psychiatry at Ohio State University and two years as a fellow of the Foundations' Fund for Research in Psychiatry and an associate of Geoffrey W. Harris at the Institute of Psychiatry of the University of London. He took his present position in 1962.

VERNON W. HUGHES ("The Muonium Atom") is professor of physics and chairman of the department of physics at Yale University. He was graduated from Columbia College in 1941, received a master's degree at the California Institute of Technology a year later and then spent four years at the Radiation Laboratory of the Massachusetts Institute of Technology. From 1946 to 1952 he was at Columbia, first as a research associate and later as a member of the faculty; he received a Ph.D. there in 1950. He went to Yale in 1954 after two years as assistant professor of physics at the University of Pennsylvania. "I have spent a good deal of my scientific career," Hughes writes, "in the study of simple atoms and molecules" to examine "modern quantum electrodynamics and other fundamental physical principles." More recently he has become involved in high-energy particle physics, including the design of a very-high-intensity proton linear accelerator.

LUIGI GORINI ("Antibiotics and the Genetic Code") is American Cancer Society Professor of Bacteriology and Immunology at the Harvard Medical School. He is a native of Milan who was graduated from the University of Pavia in 1925 and began a career in scientific research at the University of Milan in 1928. Fascism caused a 20-year interruption of that career. As Gorini puts it: "For political reasons I was unable to hold an academic position in fascist Italy and resumed my scientific research after the war." In 1947 he accepted a research fellowship at the University of Paris (the Sorbonne). He came to the U.S. in 1955 as a visiting investigator at New York University, and in 1957 he joined the Harvard medical faculty. For his work on streptomycin he received last year the Ledlie Prize, which is awarded by Harvard University every two years for "the most valuable contribution to science or in any way for the benefit of mankind."

KENNETH E. BOULDING, who in this issue reviews *The Scientific Estate*, by Don K. Price, is professor of economics at the University of Michigan.

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

We'll study the launching with a laser beam—because it can't be done as accurately with radar. For the first 50 seconds, a rocket is still too near the ground for pinpoint radar tracking. There's too much "clutter."

But with a laser, you can record a rocket's slightest deviation—for split-second correction by computer. The big problem is how to *steer* the beam fast enough to follow the craft.

Sylvania solution: an *electro-optic beam deflector*—that works without mechanical inertia. How? By changing the refraction angles of laser crystals internally, with electrical impulses. The scanning beam moves faster than you can say "countdown"! Such work is being done under contract with NASA's Marshall Space Flight Center.

Sylvania is a leader in laser technology, developing a "wire of light" capable of linking us with other planets. And we offer the world's first *liquid laser*—an accurately reproducible medium that makes advanced optical techniques more practical than ever.

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Tactical Missiles: A report from General Dynamics

Evening the odds against surprise attack:

Even for those who weren't there, newsreels of World War II and the Korean War have made this scene familiar:

Troops are moving along a road or field. Suddenly, an enemy plane swoops out of the sky with machine guns and cannons blazing. Troops scatter for cover. A few fire at the disappearing plane—but in vain.

Today, the foot soldier does not have to head for cover. He has an equalizer. Now the scene would go like this:

An enemy plane is seen in the distance. An infantryman shoulders a weapon that resembles a bazooka. Through an eyepiece he sights the plane, squeezes a trigger and a missile whooshes out of the tube. Seconds later, the plane explodes.

Such a weapon is now moving into the hands of field troops. It is made by General Dynamics and called Redeye. It is a tactical guided missile designed to be used by one man.

The bullet that gets a second chance:

A bullet or shell is affected by gravity and wind, but, by and large, once fired it continues in the direction it was originally pointed.

A sharp eye, a steady arm and an accurate gun are all you need to hit a stationary target.

A moving object has to be "led"—the gunner judges where the moving object will be in a few fractions of a second and points his bullet there.

But to "lead" an airplane traveling at the speed of sound, miles high and able to change its direction in a hurry, you need a guided missile.

An effective surface-to-air weapon must be capable of fast reaction. Its warhead must be powerful enough to destroy an attacking plane. Its speed and range must be enough to reach the attacking aircraft before the plane's offensive weapons can be launched against ground troops.

But the real key is in the word *guided.*

The guided missile, like its evasive target, can be steered and sometimes steer itself. In fact, you might call a tactical guided missile a "bullet that gets a second chance."

Let's take a look at three produced by General Dynamics—Terrier, Tartar as well as Redeye—to see how some tactical missiles work. All are essentially defensive weapons.

Terrier and Tartar are supersonic, solid-fueled missiles used by the United States Navy. Both have what is known as "semi-active homing" guidance. This involves a complex of shipboard radar and computers, combined with sensing, computing and controlling devices within the missile itself.

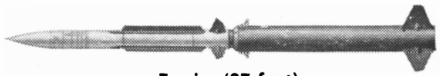
When search radar aboard a ship finds an oncoming target, a radar illumination beam, controlled through a central computer, seeks out the attacking plane. The radar waves reflected from the airplane are picked up by a sensor in the nose of the missile, which will chase its target to intercept even if the plane changes course several times.

Terrier:

Terrier is the bigger of the two. On its launcher aboard a Navy cruiser, it is about 27 feet long. The first 15 feet are the missile proper. The second 12 contain a booster rocket for propulsion.

Terrier is always ready to go. Almost within the instant that the illumination beam fastens on the approaching aircraft, Terrier is triggered.

The booster blasts the missile off the launching rack. The finder is already receiving the reflected beam from the target. Two small charges within the missile have already ignited. Their burning gases turn two small turbines. One provides power for the guidance and control systems. The other operates a hydraulic pump whose fluids move the small guidance fins on the missile's tail.



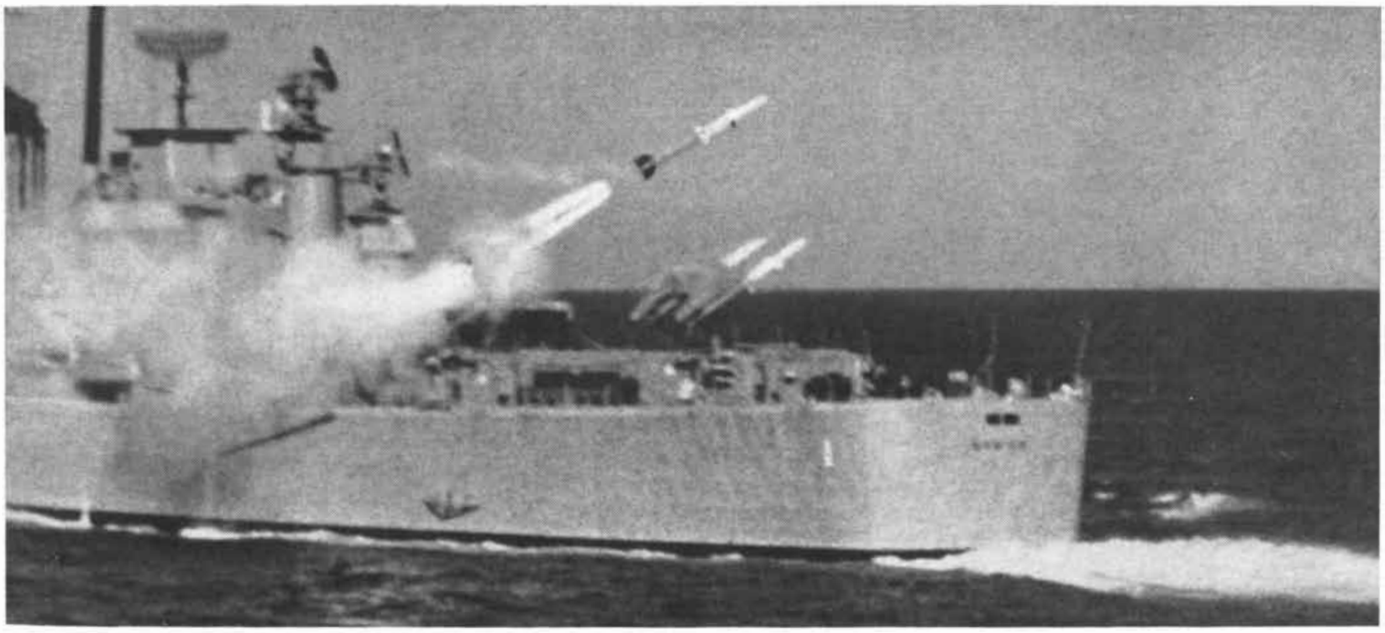
Terrier (27 feet)

As the booster burns out and then drops away, a sustainer rocket within the missile proper commences firing to continue necessary velocity to intercept.

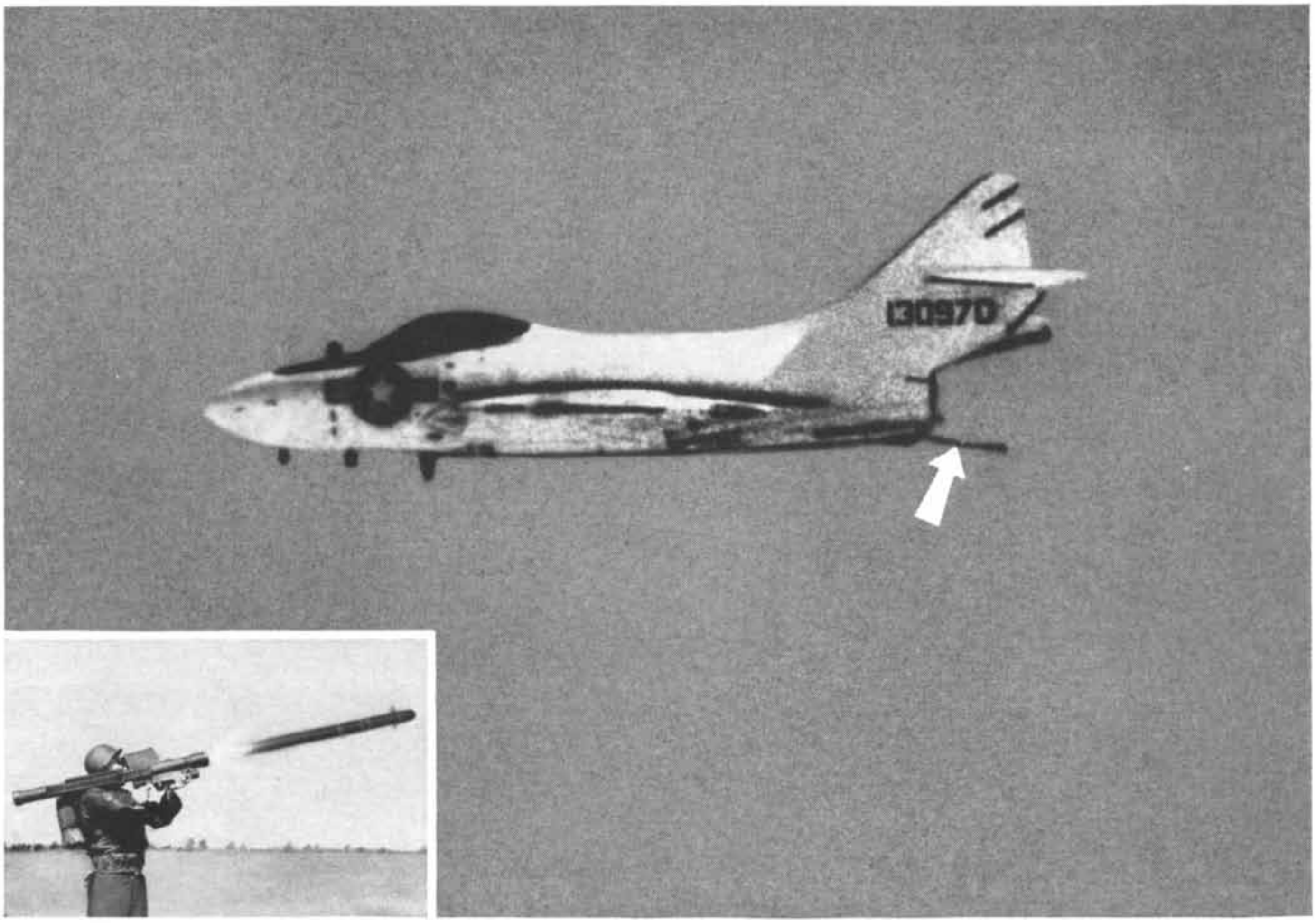
Tartar:

Tartar is similar to Terrier, but more compact (15 feet long and about 1,200 pounds compared to 27 feet and about 3,000 pounds for Terrier).

Its booster and sustainer are combined into a single-rocket engine. When



Above: Cruiser fires a Terrier. **Right:** Diagram shows radar waves sent from a ship and reflected from a plane being received by sensor in nose of the missile. Even if the plane takes evasive action, the missile will change course to intercept.



1. An infantryman (above) fires a Redeye missile at a target drone airplane.

2. This is an actual photo of a Redeye missile (arrow) entering the jet exhaust of a drone airplane. Immediately after this photograph was taken, the plane exploded.

Tartar gets its signal, the engine generates high initial thrust to shoot aloft, then reduces its force to provide the long sustained velocity to reach and chase a distant target.

Both Terrier and Tartar, in spite of their size, can be fired repetitively almost as fast as a bolt-operated rifle.

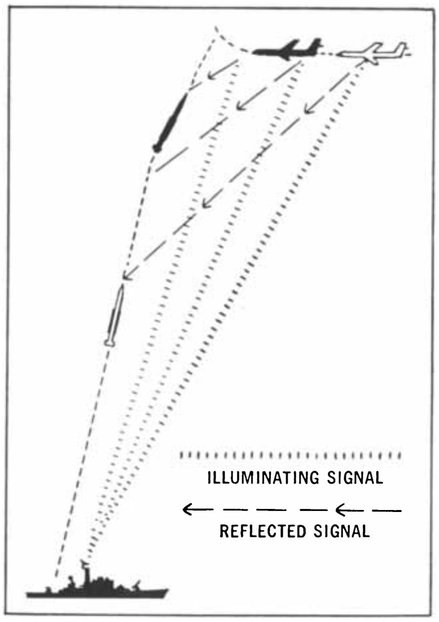


Diagram shows how missile changes course as the target changes course.

Stored in automated magazines, they can be lifted onto a launcher, hooked into the central computer radar control and fired within seconds.

Ships equipped with Terrier or Tartar can defend themselves against an armada of attacking aircraft today far more ef-

Tartar (15 feet)

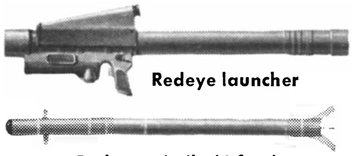
fectively than would have been possible against a single aircraft ten years ago.

Redeye:

Redeye is designed to destroy low-flying aircraft rather than high-altitude supersonic attackers. Four feet long and three inches in diameter, it weighs only 28 pounds complete with its launcher.

Redeye's heat-seeking guidance is wholly self-contained. Reaction time is little more than it takes the soldier to lift the launcher to his shoulder, find the attacking aircraft in the sighting scope and squeeze the trigger. By that time, Redeye's infrared sensor has locked onto the source of heat it must follow.

A small charge projects the missile from its launching tube. At a distance far enough to protect the soldier from rocket blast, a fuse lights the major rocket charge. Miniature computer circuitry within the missile directs a set of



Redeye launcher

Redeye missile (4 feet)

steering fins which enable Redeye to change direction as necessary and chase the target at supersonic speed until it intercepts it.

During the long history of combat, the advantage of surprise has almost invariably lain with the attacker. The modern tactical missile now more than evens the odds for the defender. At General Dynamics we are already developing newer ones with still more punch.

General Dynamics is a company of scientists, engineers and skilled workers whose interests cover every major field of technology, and who produce: aircraft; marine, space and missile systems; tactical support equipment; nuclear, electronic and communication systems; machinery; building supplies; coal, gases.

GENERAL DYNAMICS

Established 1845 SCIENTIFIC AMERICAN April 1966 Volume 214 Number 4

The Economics of Technological Change

The effects of such change are brought out by a comparison of input-output tables listing the transactions among all sectors of industry in the U.S. for the years 1947 and 1958

by Anne P. Carter

Technological change in the U.S. economy currently evokes expressions of both satisfaction and anxiety. According to the National Commission on Technology, Automation, and Economic Progress, reporting to the President and Congress earlier this year, the "vast majority" of people recognize that technological change "has led to better working conditions by eliminating many, perhaps most, dirty, menial and servile jobs; that it has made possible the shortening of working hours and the increase in leisure; that it has provided a growing abundance of goods and a continuous flow of improved and new products." At the same time people are assailed by fears and concerns: "Perhaps the [concern] most responsible for the establishment of the Commission has arisen from the belief that technological change is a major source of unemployment..., that eventually it would eliminate all but a few jobs, with the major portion of what we now call work being performed automatically by machine."

The members of the commission, for their part, concluded "that technology eliminates jobs, not work" and attributed current unemployment to more or less "normal" cyclical processes. This distinguished group of industrialists, labor leaders and economists nonetheless concurred in the recommendation ("directed to making it possible, or easier, for people to adjust to a fast-changing technological and economic world without major breaks in the continuity of employment") that Congress "examine wholly new approaches to the problem of income maintenance [and] give serious study to a minimum income allowance or a negative income tax program."

Clearly there is need for an objective and consistent way to identify and measure the economic consequences of technological change. There is concrete evidence of change all around us. Developments such as the replacement of the steam locomotive by the diesel engine, the transformation of electronics by solid-state physics and the substitution of aluminum for steel or polyethylene for aluminum are explicit and visible enough. Their economic impact, however, is not easy to gauge. The citing of a single example does not exhaust the possible applications of a new technique, and a spectacular example may give an exaggerated idea of its importance. Moreover, for all the evidence of change, the internal-combustion engine under the hood of the 1966 automobile bears considerable resemblance to the engine of 20 or 30 years ago, 50-year-old blast furnaces are still reducing iron, and machinists and secre-

	AGRICULTURE	INDUSTRY	FINAL DEMAND	TOTAL OUTPUT
AGRICULTURE	25 .25 1.46	20 .40 .66	55	100
INDUSTRY	14 .14 .23	6 .12 1.24	30	50
VALUE ADDED	61 .61	24 .48	85	

INPUT-OUTPUT TABLE depicts a hypothetical economy broken down into two sectors: "Agriculture" and "Industry." Reading across the row for one of these sectors, the large figures in each cell show the distribution of its output of intermediate products to itself and to the other sector inside the "interindustry" matrix (*two columns at left and two top rows*), and its delivery of finished products to final demand. Reading down a column, the figures show the input of intermediate products required by the sector plus its "value added": its inputs of labor, depreciation and profit. The final demand and value added for the system as a whole sum to the same gross national product (85 arbitrary units, for example billions of dollars). The total output for each sector redundantly adds its interindustry deliveries to its contribution to the gross national product. The "input-output coefficients" in small figures at bottom left of each cell express the ratio of the input shown to the total ouput of the sector in whose column it appears. Figures at bottom right are "inverse coefficients," showing the direct and indirect requirement for the input per dollar of delivery to final demand.

taries have not all been driven from the labor force by "automation." It is, in fact, difficult to relate the effects of specific innovations to changes in the national indexes of output and productivity; individual changes may reinforce or offset one another. What is wanted to make sense out of the fragmentary and conflicting evidence about change and lack of change in the economy is a technique that will allow us to organize this piecemeal information in the context of the structure of the system as a whole.

One useful approach to the structure of an economic system is provided by "input-output" or "interindustry" analysis. This technique takes account of the fact that the division of labor in a modern industrial economy is embodied in a diversity of highly differentiated and mutually dependent technologies. The production and delivery of the output of any one industry to its final market requires inputs of raw and semifinished materials, components and services from other industries. For any

		FOOD AND TOBACCO		TEXTILES AND APPAREL		DRUGS, CLEANING PREPARATIONS, COSMETICS, PAPER		FURNITURE		CONSUMERS' APPLIANCES (INCLUDING AUTOMOBILES)		CONSTRUCTION		PRODUCERS' DURABLE GOODS (NON ELECTRICAL)		ELECTRICAL EQUIPMENT
		DOLLARS	PERCENT	DOLLARS	PERCENT	DOLLARS	PERCENT	DOLLARS	PERCENT	DOLLARS	PERCENT	DOLLARS	PERCENT	DOLLARS	PERCENT	DO
GENERAL INPUTS	BUSINESS SERVICES	1427	72	111	22	84	9	26	23	841	198	1983	97	347	172	127
	COMMUNICATIONS (INCLUDING RADIO AND TELEVISION)	474	158	81	75	84	87	27	128	179	158	462	131	135	207	35
	ELECTRICITY, GAS AND WATER	590	87	169	84	86	95	49	117	218	100	775	127	181	112	71
	FINANCE, INSURANCE, REAL ESTATE AND RENTALS	703	17	281	38	292	114	82	65	556	123	900	37	466	185	136
	PAPER PRODUCTS AND CONTAINERS	362	16	155	27	118	6	125	155	241	52	549	43	50	16	61
	PETROLEUM REFINING	336	24	1	0	50	37	10	19	9	3	419	26	63	42	1
	WHOLESALE AND RETAIL TRADE	520	12	47	4	186	67	191	114	1045	152	2187	40	647	154	262
	PRINTING AND PUBLISHING	370	43	77	40	72	2	17	42	248	125	554	72	115	111	28
	OTHER SERVICES	29	2	76	34	40	44	28	75	152	96	218	16	117	131	52
	METAL CONTAINERS	238	19	9	25	31	47	1	14	22	43	34	28	5	19	6
	TRANSPORTATION AND WAREHOUSING	508	11	15	2	40	9	15	6	149	13	301	7	167	31	55
	MAINTENANCE CONSTRUCTION	20	2	85	33	2	3	3	8	22	9	23	0	13	10	11
	COAL MINING	211	52	60	50	34	47	12	36	76	30	172	32	36	24	27
	WOODEN CONTAINERS	229	53	18	59	12	74	5	55	31	47	27	34	19	73	7
CHEMICALS	CHEMICALS AND SELECTED CHEMICAL PRODUCTS	434	27	373	61	251	36	42	55	127	29	781	91	77	35	31
	DRUGS, CLEANING AND TOILET ITEMS	143	75	10	6	23	155	3	52	27	71	80	122	20	113	3
	PAINTS AND ALLIED PRODUCTS	3	2	26	45	12	34	2	3	59	29	9	2	3	7	21
MATERIALS	PLASTICS AND SYNTHETIC MATERIALS	89	33	462	61	34	76	41	96	11	3	241	103	34	42	8
	STONE AND CLAY PRODUCTS	28	16	17	48	9	29	4	15	0	0	1496	40	89	64	5
	RUBBER AND PLASTICS PRODUCTS	91	20	199	94	66	149	103	211	348	28	335	72	34	13	42
	LIVESTOCK AND LIVESTOCK PRODUCTS	2750	16	382	53	104	52	0	0	12	17	16	7	27	75	14
	GLASS AND GLASS PRODUCTS	193	23	8	24	111	50	46	102	98	48	105	29	7	14	37
	AGRICULTURAL PRODUCTS (OTHER THAN FOOD)	2375	12	373	26	122	61	9	13	16	14	295	72	22	44	5
	PRIMARY NONFERROUS METAL MANUFACTURING	175	30	44	28	50	38	2	2	502	26	825	22	143	16	219
	LUMBER AND WOOD PRODUCTS, EXCEPT CONTAINERS	163	28	35	21	31	24	91	13	125	38	1401	21	46	30	68
	PRIMARY IRON AND STEEL MANUFACTURING	444	25	80	34	52	25	72	18	1004	26	1167	16	511	17	248
METALWORKING	ELECTRONIC COMPONENTS AND ACCESSORIES	25	372	11	640	6	513	5	777	591	173	83	423	157	941	595
	SCIENTIFIC AND CONTROLLING INSTRUMENTS	15	66	16	210	1	5	38	75	102	60	193	120	33	2	57
	HARDWARE, PLATING AND VALVES AND WIRE PRODUCTS	54	18	31	39	12	12	57	31	255	29	73	4	7	2	21
	HEATING, PLUMBING AND STRUCTURAL METAL PRODUCTS	49	31	13	41	5	29	9	38	39	18	790	16	33	17	19
	ELECTRIC INDUSTRIAL EQUIPMENT	28	52	0	1	7	70	5	70	86	13	317	64	97	23	9
	BATTERIES, X-RAY AND ENGINE ELECTRIC EQUIPMENT	20	24	2	22	0	7	0	3	48	16	22	17	13	19	5
	ELECTRIC-LIGHTING AND WIRING EQUIPMENT	10	14	2	19	2	32	5	131	55	31	27	3	13	26	9
	STAMPINGS AND SCREW MACHINE PRODUCTS	93	24	6	15	1	2	14	25	368	26	140	21	117	23	95

TECHNOLOGICAL CHANGE IN THE U.S. has led to increases or decreases in the inputs required of selected producing sectors listed vertically at left to satisfy 1958 final demand for the categories of end products specified at head of each column. Figures in cells show the difference, in tens of millions of dollars (*cell at left*) and in percentages (*cell at right*), between inputs required to satisfy the same 1958 final demand computed with the coefficients of a 1947 input-output table for the U.S. economy and those provided given industry a detailed accounting of its purchases from other industries tells exactly what inputs it used to make its product and thus describes its production process. Correspondingly the record of interindustry transactions for the entire economy, displayed in the square matrix of an input-output table [*see illustration on page 25*], describes the

	NSPORTATION EQUIPMENT (CEPT AUTOMOBILES)		SERVICES (EXCLUDING UTILITIES)		TOTAL OUTPUT REQUIREMENTS ($) TO MEET 1958 FINAL DEMANDS		DIFFERENCE IN REQUIREMENTS (1958 TECHNOLOGY-1947 TECHNOLOGY)	
PERCENT	DOLLARS	PERCENT	DOLLARS	PERCENT	1958 TECHNOLOGY	1947 TECHNOLOGY	DOLLARS	PERCENT
84	643	189	1654	16	24366	17120	7246	42
73	177	156	1126	16	11278	8499	2779	33
81	311	105	1418	54	20204	15498	4706	30
71	561	125	4294	6	88088	79241	8847	11
29	147	36	684	16	13032	12377	655	5
2	18	5	239	9	17310	16641	669	4
90	1101	187	1972	3	94584	90663	3921	4
32	235	169	1082	19	12582	12102	479	4
96	134	85	425	1	49320	48324	996	2
43	16	36	74	33	2090	2057	33	2
19	196	18	1001	5	32608	34523	1916	6
15	24	9	4108	34	16855	21408	4553	21
44	69	26	800	71	2742	4589	1847	40
71	23	69	43	28	446	879	433	49
20	148	39	225	16	11790	9025	2766	31
22	39	134	422	69	6609	5853	754	13
47	42	22	177	24	1868	2212	344	16
7	70	28	148	39	4222	2993	1230	41
5	58	23	11	2	7484	5854	1629	28
22	246	23	108	10	6820	6146	674	11
64	9	13	218	12	22621	20539	2082	10
61	89	51	85	20	22444	25703	3259	13
16	16	14	670	24	2137	2479	342	14
24	230	13	626	39	9150	11881	2730	23
48	7	2	716	47	7890	10606	2716	26
32	1050	21	1963	57	19080	26081	7002	27
72	171	486	284	276	2646	1458	1189	82
261	40	15	60	14	3511	3020	492	16
11	320	39	243	27	6420	6129	291	5
41	42	21	588	51	8012	7991	21	0
0	127	56	42	13	5068	5440	372	7
1	72	23	209	44	1529	1845	317	17
1	90	113	289	61	2284	2868	584	20
30	143	12	250	42	3683	4812	1129	23

by the 1958 table. Producing sectors are grouped as "General inputs," "Chemicals" (excluding plastics), "Materials" and "Metalworking." Negative numbers are in color.

structure of the underlying technological order.

Input-output tables have now been prepared for the economies of more than 50 nations by the statistical agencies of their governments. With the advent of computers that can manipulate the information quickly and easily these tables are finding a wide range of uses. They have been applied in setting the priorities of capital-investment programs of developing nations, in ordering trade relations among the Common Market countries and in planning the market-development campaigns of large industrial corporations. Comparison of input-output tables for two different countries highlights differences in their industrial systems.

For planners and forecasters an input-output table provides what is in effect a working model of the technological apparatus that helps to make and test economic projections. Investigators in this field, beginning with Wassily W. Leontief of Harvard University, the originator of the technique, have also been intrigued by the insights that input-output analysis might yield into the economics of technological change. Comparison of two input-output tables compiled for the same economy at different times should reveal the structural changes corresponding to the changes in technology that occurred in the interim.

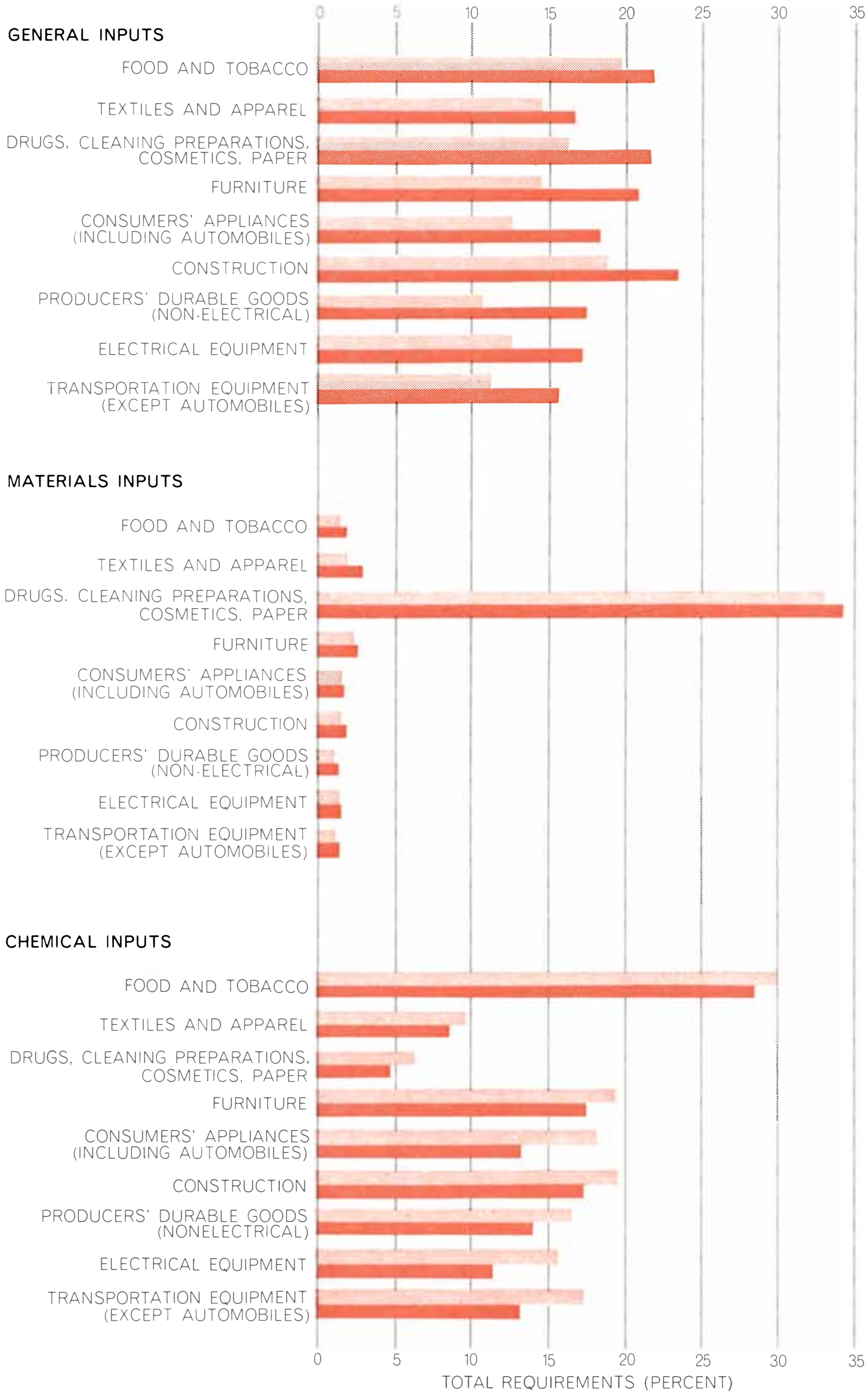
During the past year the author and her colleagues at the Harvard Economic Research Project have been engaged in just such a comparative study of two input-output tables for the U.S. economy. The tables are based on detailed accounting of the interindustry transactions for the years 1947 and 1958, conducted respectively by the Bureau of Labor Statistics of the Department of Labor and the Office of Business Economics of the Department of Commerce. Ideally one could wish for a terminal year other than 1958, because the business recession of that year may have distorted some of the interindustry product flows; furthermore, the passage of eight years would seem to make the comparison descriptive of "history" rather than of current developments. The work has nonetheless prepared the ground for studies of more up-to-date tables that are to come. The present study has also brought out patterns of technological change that persist in the system today.

Comparison of the technologies of 1947 and 1958, as portrayed by the two tables, shows a relative increase in what can be described as "nonmaterial" or "general" inputs. This increase has largely been balanced by decreases in the input of the materials and semifinished goods out of which the system makes its tangible products. The category of general inputs embraces those used in all, or almost all, sectors of the economy: energy, communications, trade, packaging, maintenance construction, real estate, finance, insurance and other business services, printing and publishing, and business machines and their related information technologies. Increased energy consumption results, of course, from the increasing mechanization of productive processes. It also reflects mechanization of office functions and heavy expenditures for air conditioning. Increases in other general inputs are explained by the growth of the relative importance of the coordinating functions required by the logistics of a larger and more complex industrial system. As demand for general inputs rose from 1947 to 1958, diverse sectors of the system developed increasingly similar demands for these inputs.

In the pattern of relatively declining materials inputs there appears a second broad trend of equal significance. The classical dominance of single kinds of material—metals, stone, clay and glass, wood, natural fibers, rubber, leather, plastics and so on—in each kind of production has given way by 1958 to increasing diversification of the bill of materials consumed by each industry. This development comes from interplay between keenly competitive refinement in the qualities of materials and design backward from end-use specifications.

All these changes in the relative importance of sectors imply change in the kinds and numbers of jobs available. Translation of the input figures into man-years shows, in fact, that the sectors producing the general inputs had come to employ more than half of the labor force by 1958.

In order to compare the tables for 1947 and 1958 it was necessary first to make them reasonably compatible. The 1947 table presents a full accounting of interindustry transactions with the U.S. economy broken down into 450 sectors. For intelligibility on the printed page this table was consolidated to 192 sectors and, for publication in the pages of this magazine, to 50 sectors [see "Input-Output Economics," by Wassily W. Leontief; SCIENTIFIC AMERICAN, October, 1951]. The 1958 table is based on analysis of primary data at a comparable level of detail but presents the information conservatively aggregated to 81 sectors [see "The Structure of the U.S. Economy," by Wassily W. Leontief; SCIENTIFIC AMERICAN, April, 1965]. Alignment of the two tables was further complicated by the very process of technological change that was the subject of our study. The waning of older industries and the burgeoning of new ones had necessitated a complete revision of the Standard Industrial Classification by the Office of Statistical Standards in 1957. As a result 45 of the 450-order sectors of the 1947 table had to be split, each into two or three parts, in order to create a set of 1947 81-order industries that would conform to the new "S.I.C." code employed in the 1958 table. To improve the comparability of sectors between the two years the 81-order classification was finally aggregated to a 73-order system. Needless to say, reconciliation of the two tables also required price adjustments (inflation of the 1947 transactions to 1958 prices) and many other accounting adjustments, particularly those occasioned by change in the conventions for defining and measuring outputs in certain sectors and, inevitably, differences in the treatment of taxes.

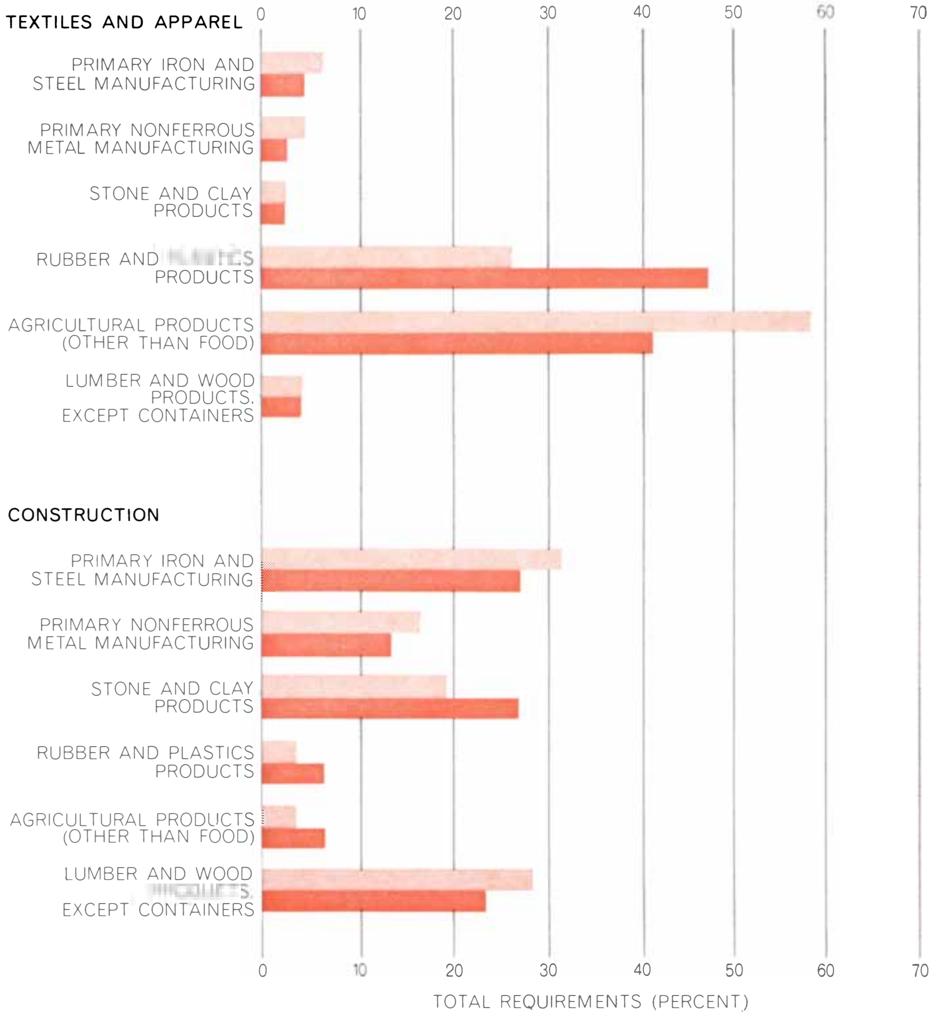


DIFFERENT REQUIREMENTS are made on producing sectors because of changing interindustry relationships. Graph at top shows that "General inputs" contribute proportionately more to output of end-product groups in the 1958 economy (*dark bars*) than they did in the 1947 economy (*light bars*). Chemical industries also play a larger role in the 1958 economy. Bottom graph shows that industries producing materials, however, play a smaller role.

With the interindustry transactions for 1947 and 1958 arrayed in two roughly compatible 73-order tables, the next step was to derive the input-output coefficient matrix for each of the two years. An input-output, or "direct," coefficient expresses the ratio of a given input to the total output of the industry receiving the input. The full column of direct coefficients for an industry shows just how much that industry must draw from each of the other industries in order to produce a unit of its product. Change in a coefficient, from one input-output table to the next, shows the effect of changes in an industry's technology on its requirements for a particular input. Often changes in input coefficients will reflect qualitative as well as quantitative changes in input requirements.

When it comes to comparing changes in the system as a whole, however, direct comparison of two tables, coefficient by coefficient, would be a cumbersome task. Moreover, some coefficient changes are of much greater interest than others, and some may reflect not real changes but minor differences in the techniques of constructing the tables of transactions. In the present study we treated the two complete matrices of coefficients as working models of the system, one for 1947 and one for 1958. We asked each "technology" in turn what outputs of raw materials, intermediate products and services it would have to produce in order to yield the same gross national product.

The total of such outputs, the "gross domestic output," exceeds the gross national product, which is the value of goods and services consumed in their final markets, because each industry delivers more or less of its total output in the form of primary and intermediate inputs to other industries. Gross national product may also be reckoned as the total of the inputs of the prime factors of production, or the "value added," of all the industries [*see illustration on page 25*]. To the gross national product, reckoned either way, the gross domestic output adds the redundant values of the interindustry transactions. Since all of the product of the system is ultimately delivered to final demand, it is the gross national product that is taken as the conventional index of total economic activity. For the purposes of our study we employed the gross national product for 1958, specified by a bill of final demand showing preliminary estimates of actual deliveries to the ultimate markets represented by households, industries (on their inventory and capital accounts), government agencies and so on. (The official estimates for the 1958 final demand, which were published after we had done our work, would change some of the numerical results but not the general conclusions of our study.)



COMPETITION OF MATERIALS is evident in graphs comparing the percentage of materials required by two end-product groups according to 1947 technology (*gray*) and 1958 technology (*black*). The inputs tend to level out, the large 1947 inputs becoming smaller and the small ones becoming larger. In textiles and apparel, natural fibers ("Agricultural products") yield traditional predominance to synthetics ("Plastics, rubber"). In construction, iron and steel ("Ferrous metals") yield to cement and concrete ("Stone and clay products").

To facilitate our comparison of the 1947 and 1958 technologies, we had the Harvard Computation Center "invert" the two 73-order coefficient matrices and furnish us with matrices of what are called Leontief inverse coefficients. These coefficients express the total value of each industry's output required directly or indirectly to satisfy an additional dollar's worth of final demand for the product of a given industry. The inverse coefficient for the output of coal occasioned by the final demand for shoes, for example, tells the total increase in the consumption of coal by the shoe industry, the leather industry, the chemicals industry—by all industries in the economy—that would be required to increase final consumption of shoes by one dollar. Given the inverse coefficient matrix, one can derive the total outputs required to produce any stipulated bill of final demand by simple multiplication and summation.

With the matrix for the 1947 economy, therefore, we derived the outputs of all the goods and services that would have been required to satisfy the 1958 final demand on the basis of 1947 technology. These hypothetical outputs could then be compared with the actual 1958 outputs that satisfied the 1958 demand on the basis of 1958 technology. We found that the 1958 gross national product of $444 billion required a gross domestic output of $786 billion by 1947 technology and $800 billion by 1958 technology. It would appear that technological change (or progress!) had actually added about $14 billion to the task of satisfying the same final demand. Because the difference is accounted for entirely by increase in the interindustry transactions one can say that the productive and distributive process has become somewhat more "roundabout."

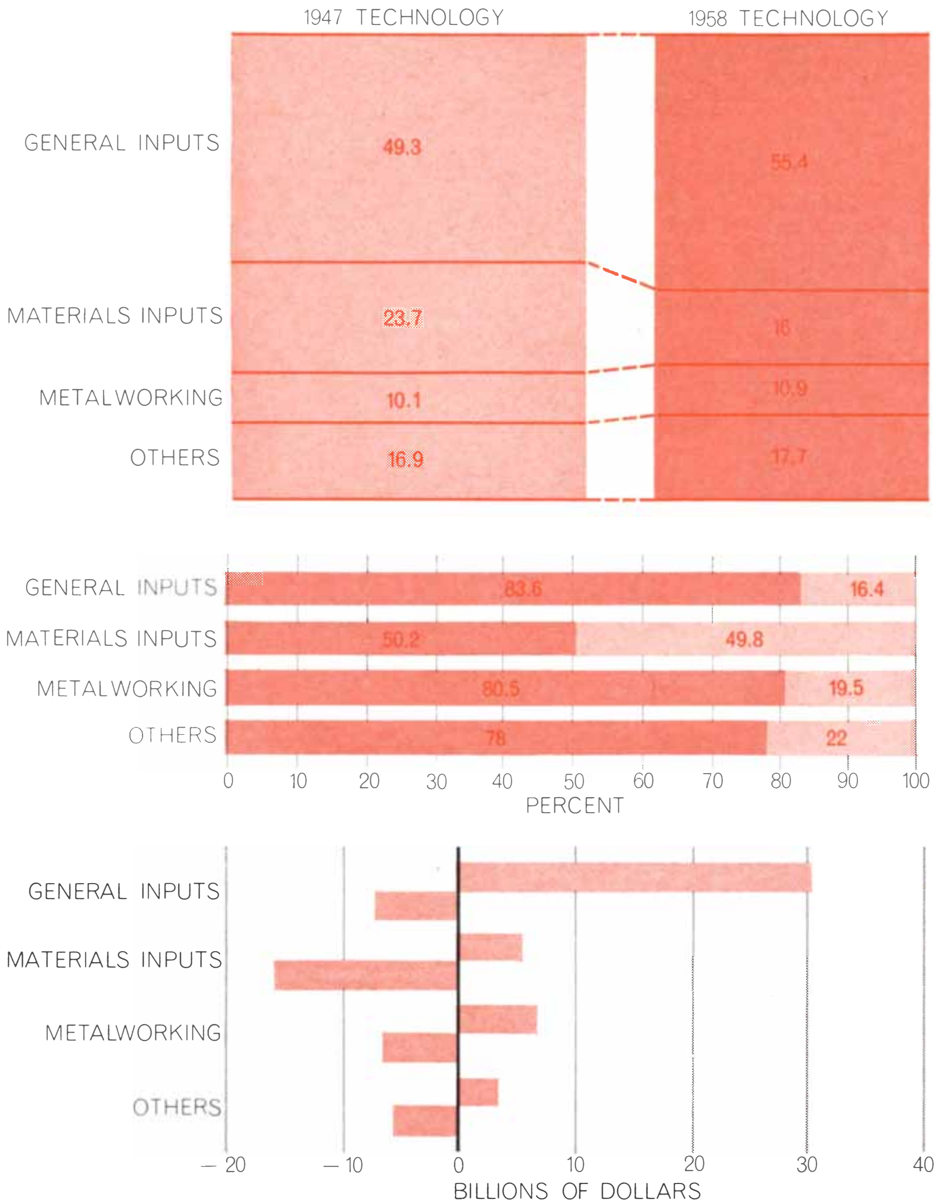
Our figures also showed that the productivity of labor had increased markedly in practically all industries between 1947 and 1958. Roughly 33 percent more labor would have been required to produce the 1958 bill of final demand with 1947 technology.

The differences between the technologies for the two years become more substantial when the gross changes in output are added up, ignoring the plus and minus signs. The gross change comes to $87 billion, or roughly 10 percent of the gross domestic output computed for either system. About half of the total swing is accounted for by the preponderantly positive changes in the general inputs. The principal offset to these increases is provided by the decline in the materials inputs, leaving the small net positive change of about $16 billion. Expressed as percentages of the gross domestic output none of these movements, up or down, appears very large. Clearly the system has considerable inertia; technological change must be regarded not as a revolutionary process but as an evolutionary one.

When the changes are expressed as percentages of the major classes of inputs, however, they loom larger. The gross change of $39 billion in general inputs represents 11 percent of the total inputs from these sectors computed for 1947 technology. The net of the positive and negative changes is an increase of $22 billion, or 6 percent. For materials the gross changes add up to $21 billion, or 19 percent of the total 1947 inputs from these sectors, and the changes net out in a decline of $10 billion, or minus 9 percent.

To calculate the corresponding changes in employment we multiplied the total output for each industry by a "labor coefficient," that is, the man-years required per unit of output in each of the two years. The total swings in the job market estimated in this fashion reflect increases in productivity as well as changes in the requirements for the several classes of inputs considered in our study. Thus the smaller inputs of materials required by 1958 technology generated only about half as many jobs as the hypothetical materials requirements of the 1947 matrix [*see illustration below*]. The larger 1958 total of general inputs required 83.6 percent of the jobs computed to meet the 1947 demand for these inputs. The movement of jobs into the general input sectors indicated by these findings is fully substantiated by comparison of the 1950 and 1960 census figures, which show that the "providers of services" increased from 47 percent of the labor force to 54 percent.

Consideration of the swings in the outputs of a representative sample of individual producing sectors, as shown in detail in the table on pages 26 and 27, brings one still closer to the ferment of technological change and to the level at which change is experienced by the people and the institutions involved. The biggest dollar-and-cents changes occur in sectors that are large to begin with. On a percentage basis one finds large changes affecting relatively small sectors and smaller percentage changes in large sectors. Communications (including radio and television broadcasting), plastics and electronic components show increases ranging from 33 to 82 percent; these fast-growing sectors are still comparatively small, and the absolute increases in the requirement for their products and services range around $1 billion. On the other hand, some large sectors show substantial declines: coal mining by 40 percent, iron and steel by 27 percent and stampings, screw-machine products and bolts by 23 percent. Further disaggregation of the sectors would reveal other significant changes. The decline of nearly $3 billion, or 23 percent, in nonferrous metals represents the net of a substantial increase in the use of aluminum and of declines in other nonferrous metals. In the case of iron and steel the decline reflects not only substitution by plastics and aluminum but also improvements in the performance of various steels and design changes that take advantage of these improvements to reduce the total amount of material used.



EFFECT OF CHANGE ON LABOR FORCE is presented in three graphs. Graph at top shows manpower required to satisfy 1958 final demand according to 1947 technology (*bar at left*) and 1958 technology (*right*). Bars show the percentage of workers employed in each industry group. Width of each bar is proportional to the number of workers called for by the technology of each year. Bars of middle graph show the percentage of workers needed in 1958 compared with 1947 to produce the 1958 bill of goods in each major inputs category. The graph at bottom expresses the changed requirements for major groups of inputs. Extension of bars to the right of zero represents a positive change, extension to the left represents a decline. The positive overall change in general inputs (production of which employs more than half of the 1958 labor force) is accompanied by an overall decline in materials inputs.

Such change in the relative importance of industries brings changes in the distribution of employment. Comparatively rapid growth in the demand for chemicals, plastics and drugs tends to offset reductions in their man-year requirements per unit of output and to moderate the decline in their total labor requirements. In industries such as coal mining, steel and wooden containers "technological" unemployment stems as much from relative decrease in demand for their output originating elsewhere in the system as from decline in their labor coefficients.

Even the largest swings in output and employment disclosed by our study assume a gradual slope when averaged over the 11 years from 1947 to 1958. The replacement of a metal bearing by a nylon one may look like an abrupt change, but it takes time for such substitutions to percolate through the system. Changes in input-output coefficients therefore occur gradually. As it becomes possible to plot them from one input-output table of the U.S. economy to the next it will become increasingly feasible to project the diffusion of new technologies.

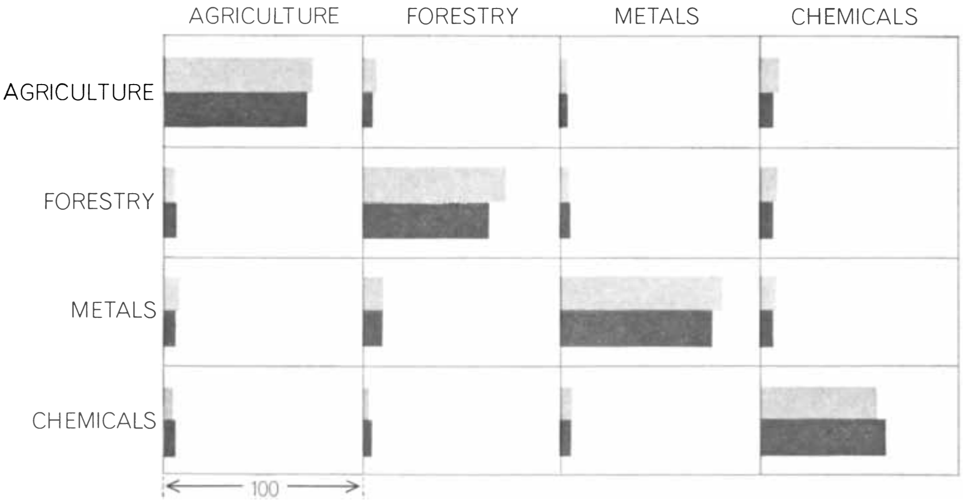
Demand for an industry's product may increase in some markets and decline in others. The net change in the output of a sector may therefore understate the gross change in the requirements of the sectors that consume its product. To show how technological change has affected detailed input requirements for different types of final products, we subdivided the 73-order "vector," or bill of final demand, into 10 "subvectors of final demand," or end-product groups. We then computed changes in direct plus indirect requirements for the various inputs generated by final demand for "Food and tobacco," for "Construction," for "Transportation equipment" and so on when 1958 technology is substituted for that of 1947. The results of this detailed analysis are shown in the table on pages 26 and 27. Reading down the columns, one sees the changes in the input structures for each of the 10 end-product groups. The requirements for the production of durable goods, particularly those involving electrical and electronic technology, change most. The relatively old and mature food and textile groups show correspondingly less change. Reading across the rows in the table, one sees the changes in requirements for a given input. As the figures for the system as a whole suggest, the requirement for general inputs, particularly for services, increases in almost all end uses.

In the energy rows coal requirements decline and the demand for petroleum, natural gas and electricity increases in keeping with the common elements of fuel technology in all sectors. Growth in the packaging sectors reflects the fact that the U.S. economy now packages almost everything except bulk raw materials. The use of paper and paper containers in packaging apparently increases at the expense of wood; metal containers similarly displace glass in the delivery of food, beverages, drugs and cleaning preparations. The general rise in the use of plastic film in packaging is unfortunately obscured in the aggregation of plastics products with rubber.

Although the entries in the materials rows reflect the gross trend downward for these inputs, there are significant departures from the general pattern. The increase in demand for synthetics reflects the parallel diffusion of several technologically distinguishable developments, particularly the new dominance of synthetic fibers in textiles and the increased use of plastics in durable goods. One is impressed to find, however, that the decline in steel requirements shows up in every subvector of final demand and adds up to a cumulative decline six times as great as the rise in plastics and synthetics. The growth of aluminum offsets the decline of other nonferrous metals only in the production of nonelectrical producers' durables.

In the producing sectors grouped under metalworking two major trends can be discerned. The more traditional sectors, such as stamping and screw-machine products, lose markets as fabrication technologies become more specialized and fewer parts are assembled to make a given product. Losses for this group are offset by increases in demand for electrical apparatus and motors, electronic components and instruments in the production of most kinds of consumers' and producers' durable goods.

As between the 1947 and 1958 technologies, the requirement for general inputs in all 10 end-product groups increases from an average of 15 percent to an average of 18 percent of total inputs. Concurrently the requirements for these inputs tend to become still more uniform among the different end-product groups [*see illustration on page 28*]. The inputs of materials show a nearly offsetting decline in all end-product groups. In effect the rapid development of materials technology has brought the replacement of old inputs with new ones of lower value. The changing input pattern shows, however, that these developments have had the more important effect of making materials increasingly interchangeable. In all 10 end-product groups the larger materials inputs tend to become smaller and the smaller to become larger; in the textile industry synthetics displace natural fibers from first place and in the construction industry steel yields to concrete [*see illustration on page 29*]. As a result the familiar materials-oriented industrial complexes—agriculture, forest products, metals and chemicals—show less self-sufficiency and increasing interdependence. The chemicals bloc is an exception to this generalization; it is the least self-sufficient in the 1947 technology and develops increasing reliance on its own, rather than agricultural, raw materials [*see illustration above*].



GROWING INTERDEPENDENCE of its parts has characterized the U.S. economy in recent years. In this matrix for four materials-oriented industrial complexes each cell shows the percent of total direct and indirect requirements on the complex listed at left by the complex listed at top. Gray bar gives figure for 1947 technology; black bar, for 1958 technology. All but the chemicals bloc need a rising percentage of inputs from other sectors.

By and large technological change from 1947 to 1958 tended to reduce the differences in input structure distinguishing the major groups of industries. This may seem an improbable consequence of the increasing specialization and complexity of technology. The fact remains that the proliferation of new materials and new methods tends to increase the variety of inputs to each sector; with greater variety the input columns show more elements in common. The diversification of materials breaks down the primary identity of major industrial blocs. The increase in general inputs that render the same services and deliver such indistinguishable products as kilowatt-hours to all customers makes input structures more alike. Thus as a principal consequence of technological change the diverse major industries in the U.S. economy tend to become interlocked in increasing interdependence. In the job market there is declining demand for people in the "productive" functions, as traditionally defined, and increasing demand for people who can contribute to the coordinative and integrative functions required by the larger and more complex system.

CHEMICAL LASERS

If a laser could be made to work by a chemical reaction, it would need no external source of power. Two experimental chemical-laser systems, both of which emit in the infrared, have now been found

by George C. Pimentel

The current scientific literature reflects a virtual population explosion among the wavelengths at which laser action has been observed. A recent summary lists some 330 such wavelengths; they span the spectrum from the near-ultraviolet region to the far infrared. The rapid growth of the roster of lasers is paralleled by a rising number of applications of these remarkable light sources.

The laser exploits the fact that an atom or a molecule that has been excited by a source of energy can be stimulated to emit some or all of its extra energy in the form of a photon, or quantum of light. The stimulation can be provided by an incoming photon that has precisely the energy of the photon the excited atom or molecule is ready to emit. As a result of the stimulated emission the incoming photon is augmented by the emitted photon. The process is described by the words that give rise to the acronym "laser": light amplification by stimulated emission of radiation.

To be of significant magnitude the process requires a large population of molecules in an excited state. This situation is achieved by injecting energy into the system, a procedure known as "pumping." In most of the lasers designed so far the pumping energy has been supplied by an intense source of light or by electron bombardment. Such lasers obviously require an outside "feed" in the form of electric power. Moreover, the efficiency of these systems is rather poor; the output of energy achieved by the laser effect is much less than the input of energy required for pumping.

An idea that has intrigued a number of investigators for some years is the possibility that the energy released in chemical reactions could be used for pumping. This release of energy is associated with the making and breaking of chemical bonds. In principle the chemical reactions, once initiated, could proceed without an outside source of power. In other words, a chemical laser could be self-pumping. It could also be highly efficient and hence would act as an extremely intense laser: a concentrated source of light at a single wavelength.

By the fall of 1964 interest in this possibility had increased to such an extent that a symposium was organized in California solely for the discussion of chemical lasers. The proceedings of the symposium have been published as a supplement to the journal *Applied Optics;* this valuable document contains 21 articles and is 215 pages long. The authors of these articles represent four countries, seven universities, one government laboratory and 10 industrial laboratories. The articles clearly indicate the important principles—yet the publication is remarkable for the fact that none of the articles describes the successful operation of a chemical laser.

Nonetheless, one editor of the supplement, Kurt E. Shuler of the National Bureau of Standards, felt optimistic enough to express the belief that "the chemical laser has something in common with the four-minute mile: once the barrier is broken, successful operation of chemical lasers will be announced regularly." Only a week before the symposium Jerome V. V. Kasper of our laboratory first operated a chemical laser successfully. We call it a "photodissociation laser"; it is based on the breakdown of organic compounds containing iodine. Shortly thereafter we discovered the second chemical laser. It could be called an "explosion laser," because it involves the violent reaction between hydrogen and chlorine. Now that the chemical laser has achieved its four-minute mile, we are optimistic about the fulfillment of Shuler's prediction. We are also confident that the chemical laser will prove to be an extremely valuable instrument for assessing some aspects of chemical reactions that hitherto have eluded analysis.

The significant feature of a laser is the enormous difference between the character of its light and the light from an ordinary light source such as the sun, a flame or an incandescent lamp. In these thermal light sources atoms and molecules are continuously being excited by collisions, and many of them release their energy by emitting light. When one molecule thus spontaneously emits light, it does so without influence from light emitted by other molecules. Hence this kind of independent and spontaneous emission in a population of molecules consists of photons that encompass a wide range of frequencies. Moreover, the photons possess no wave coherence: the constructive superposition of waves, crest on crest. Wave coherence is a property uniquely associated with lasers.

The high degree of coherence of laser light is obtained because stimulated emission synchronizes the radiation of individual molecules. A photon from an excited molecule stimulates another molecule to contribute a second photon with the same wavelength as the first and precisely in phase, or in step, with it. In a large population of excited molecules the process occurs repeatedly and produces a cascade of emissions, which take the form of an increasingly intense light wave.

This cascade process can be augmented still further if the coherent light is reflected back and forth through the excited molecular population by a pair of mutually aligned mirrors. Such an arrangement of mirrors is called an optical cavity. For a gas laser the cavity could be merely a slender tube with mirrors at each end. A light wave traveling along the axis of the tube will be enhanced by stimulated emission; when it reaches either of the mirrors, it will be reflected back and so will give rise to further stimulated emissions. In a properly designed reflecting system the gain on repeated passages will be greater than the losses. Such losses occur, for example, because mirrors are not perfect reflectors and because some of the light travels at an angle to the axis of the tube and so escapes from the system.

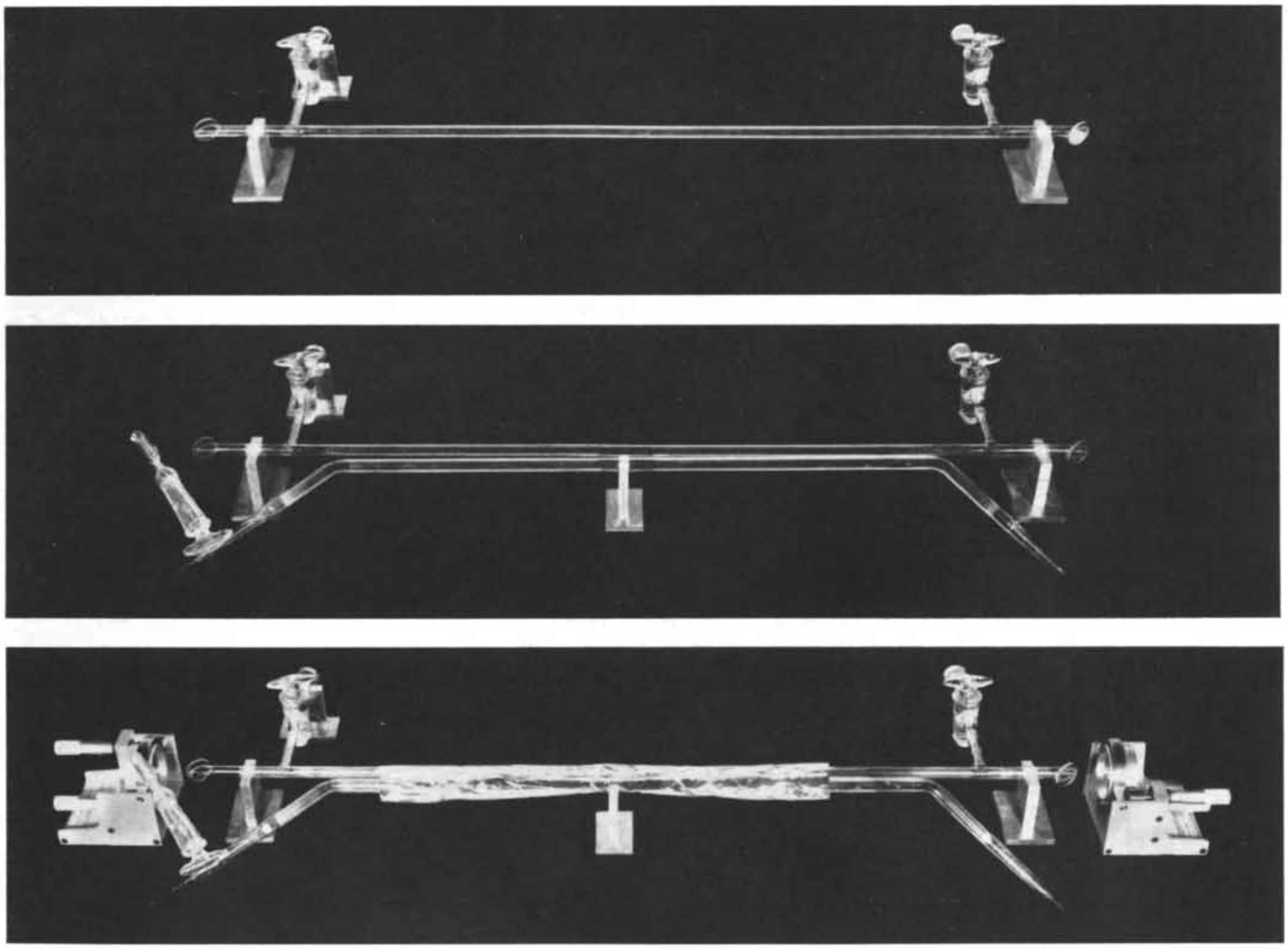
If one of the mirrors is semitransparent, a portion of the wave can escape through it. This is the output of the laser: a beam of light that is markedly directional, powerful, monochromatic and coherent. Light with these characteristics opens up possibilities that do not exist with ordinary light—both in research on the properties and effects of light and in practical applications such as the transmission of signals.

Essentially the laser has three components: a suitable set of energy levels, a pumping system and an optical cavity. The set of energy levels is supplied by an atomic or a molecular system, and it provides a means of storing energy for concerted release in the form of monochromatic light. I have already touched on pumping, but the topic merits closer attention.

In most materials under most conditions nearly all the molecules are in a low energy state, usually called the "ground" state. Such molecules will absorb energy rather than emit it; therefore under ordinary conditions—that is, whenever molecules in the ground state outnumber molecules in excited states—absorption predominates. One of the central problems in designing a laser is to achieve an inversion of the normal situation, so that a preponderance of the molecules are in an excited state. There must be an excess of excited molecules to enable stimulated emission to predominate. It is this excess that must be achieved by pumping.

Much of the current research on lasers is directed toward the first component: the energy-level system. This research seeks to discover new energy systems to fill gaps among the wavelengths now generated by lasers and to extend these wavelengths farther into the ultraviolet and infrared regions of the spectrum [*see illustration on page 39*]. For this purpose, and for their own fundamental interest, new pumping methods are also being sought. The discovery of more effective means of inverting an energy-level population results in lasers with more intense emission of light.

The search for new methods of pumping leads to the chemical laser. Chemical pumping is unique in that the first component of a laser (the energy-level system) intrinsically supplies the second (the pumping). Other tech-



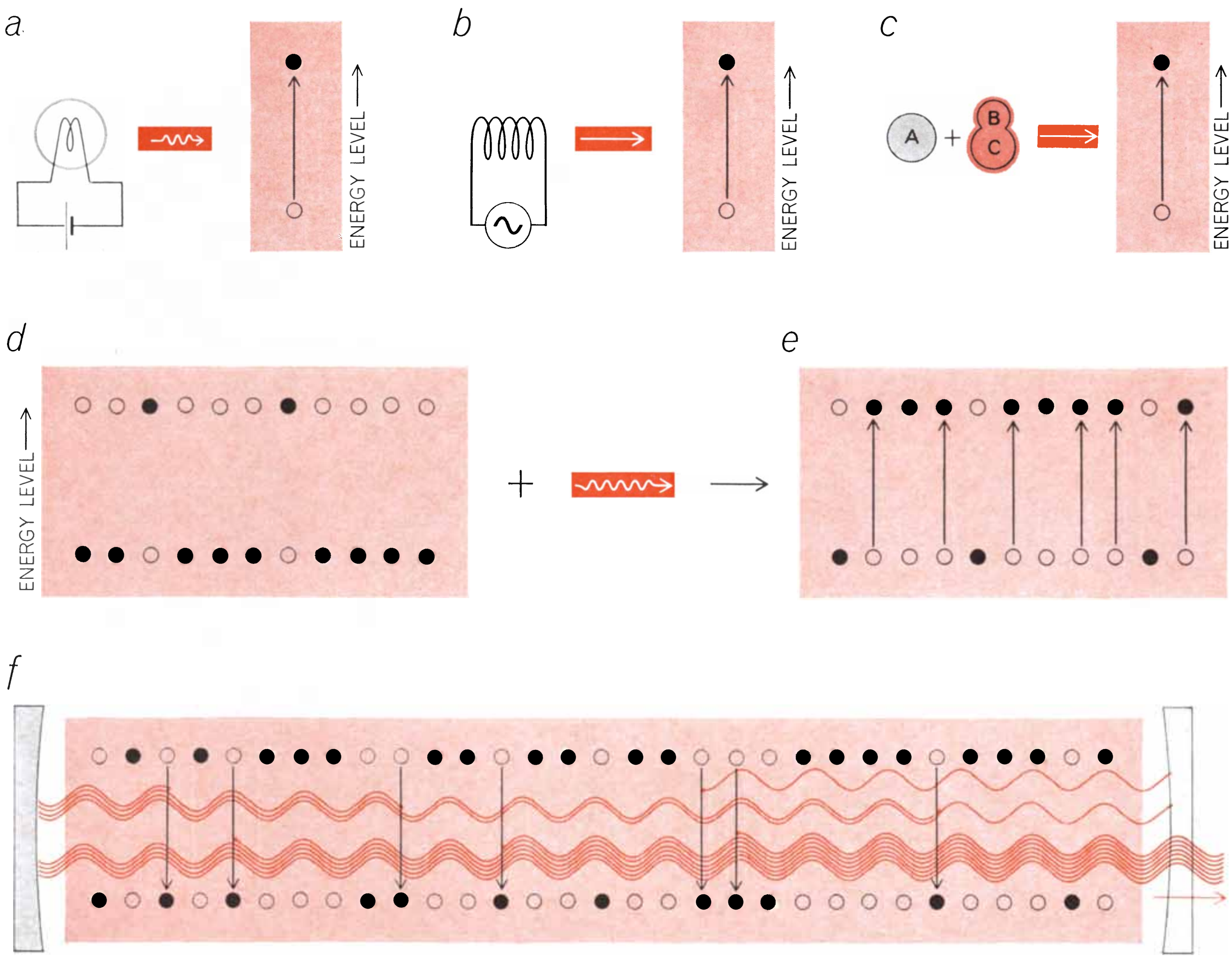
LASER APPARATUS used for investigating chemical-laser effects has as its basic part a quartz tube (*top*). The stopcocks near the tube ends are used to fill it with gas. In investigations of a laser based on the breaking of an iodine bond a flash tube is needed (*middle*) to give a pulse of light that initiates the reaction. The bottom photograph shows the apparatus with the laser mirrors in place opposite the ends of the tube and aluminum foil wrapped around the two tubes. The foil serves as a reflector to concentrate the light flash.

niques start with an energy-level system and pump it with an outside source of energy; in a chemical system the pumping is achieved with energy generated by the reactions that produce the energy-level system.

The chemical reactions that are most promising for laser action are those known as exothermic, meaning that they produce heat. As a general statement the desired kind of reaction can be written $A + BC$ yields $AB + C$ + heat. The letters stand for atoms or molecular fragments. The statement describes a reaction in which the molecular bond between atoms B and C is broken, a new bond is formed between A and B and heat is evolved because the net effect of the breaking and making of these chemical bonds releases energy.

Chemists would like to observe such a reaction in slow motion to see just how this energy is released. Initially all the energy is contained in the product fragments AB and C and is distributed in varying degrees among four forms of excitation: electronic, vibrational, rotational and translational [*see top illustration on opposite page*]. Electronic excitation involves changes in the spatial distribution of the electrons that bind the atoms of a molecule together; achieving it calls for high energy at the frequencies of ultraviolet radiation or visible light and results in emissions at those frequencies. In vibrational excitation the atoms of the molecule vibrate in relation to each other. This kind of excitation requires less energy than electronic excitation; it can be accomplished by energy at the frequencies of infrared radiation and results in emissions at those frequencies. Rotational excitation involves rotation of the entire molecule. The input and output energies of this excitation are still lower, occurring at microwave frequencies. There is always a subcomponent of rotational energy in vibrational excitation. Translational excitation, in which the whole molecule moves from one place to another, is the kind commonly associated with heat.

As the reaction proceeds, collisional processes—the banging of atoms into one another—inevitably redistribute the energy among the four forms of excitation, the system approaches equilibrium and the temperature rises. In the case of electronic and vibrational energy, however, these collisional processes of de-excitation can be rather slow. This is why the energy produced in the reaction is not instantly evolved as heat. The fact that some of the reaction energy remains in the form of electronic and vibrational excitation lies at the heart of chemical-laser systems. It is



ESSENTIAL COMPONENTS of a laser are a pumping system, an energy-level system and an optical cavity. Pumping injects energy into a population of atoms or molecules; it can be done by light (*a*), electron bombardment (*b*) or the energy released in a chemical reaction (*c*). Pumping raises molecules from a state of low energy (*d*) to higher levels (*e*) where each molecule can be stimulated by a photon, or quantum of light, to release part of its energy as another photon of the same wavelength. In the optical cavity (*f*) photons are reflected back and forth many times, stimulating more emissions and producing a growing wave of highly intense light.

this excitation, this brief storage of energy, that makes the atoms and molecules ripe for stimulated emission.

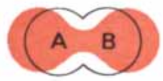
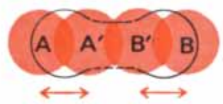
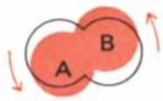
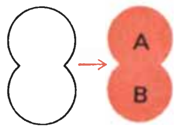
It is now appropriate to recast slightly the general statement about the chemical reactions of interest for lasers so that it reads $A + BC$ yields $AB^* + C^*$. The asterisks represent products in a state of excitation. The statement says that a chemical reaction can yield products that are born excited in an energy-level system suitable for laser action. Here in a shorthand form is the unique aspect of chemical pumping: the energy-level system intrinsically supplies its own pumping.

Two other advantages of the chemical laser can be cited. One is that in principle the excitation of *AB* or *C* is obtained on the initiation of the chemical reaction and without any external power supply. The reaction can be started by the mere mixing of reactants. Alternatively, one can begin with a premixed sample and start the reaction explosively by some means such as a spark or a flash of light.

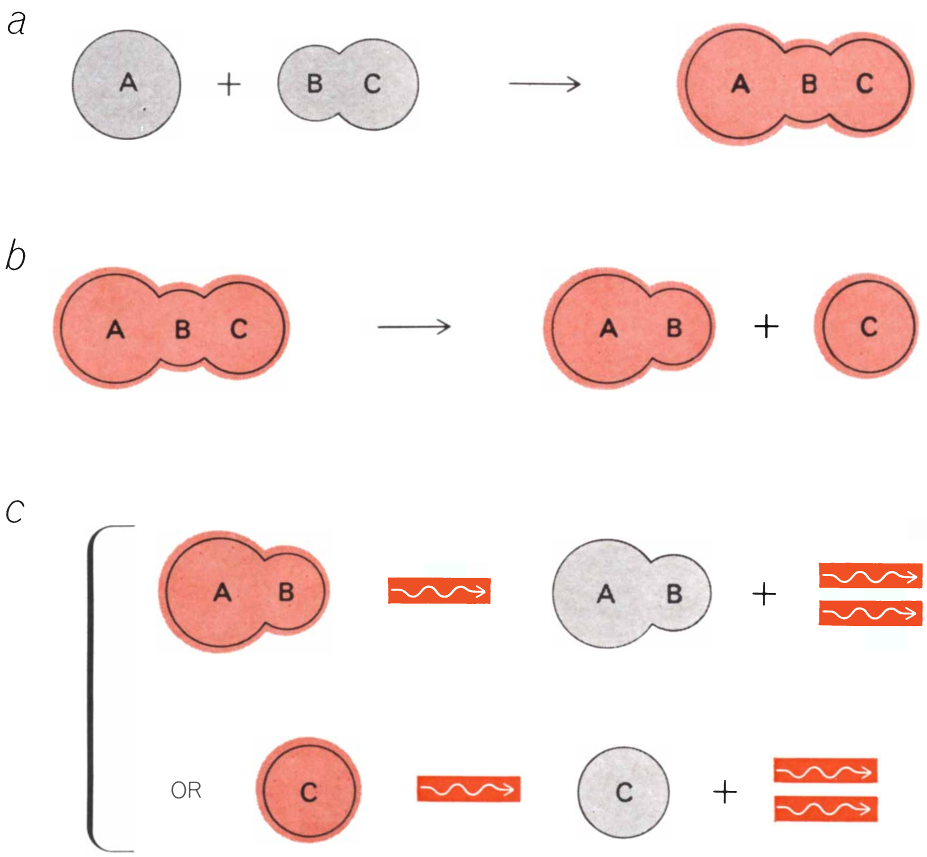
A much more important advantage, however, is the potential population inversion that chemical pumping can achieve in an energy-level system. It is conceivable—indeed, it may be happening in some of our experiments—that the distribution of energy in an energy-level system following a chemical reaction might result exclusively in excited states, either electronic or vibrational. Until the slow de-excitation process occurred there would be no lower-state population at all! The implication is that chemical lasers could be extremely efficient.

The reader may have detected a somewhat tentative quality in these statements. He must remember that the chemical laser is in a very early stage of development, and that its advantages must be stated more as potentialities than as facts. Moreover, it must be recorded that there are some inherent limitations in chemical lasers. If the reaction is set off explosively, the light source is inherently pulsed, or momentary. A second pulse can be obtained only after the vessel in which the reaction occurs has been flushed out and recharged. On the other hand, if the reactants are continuously mixed, the mixing rate and the rate of reaction might be limiting factors.

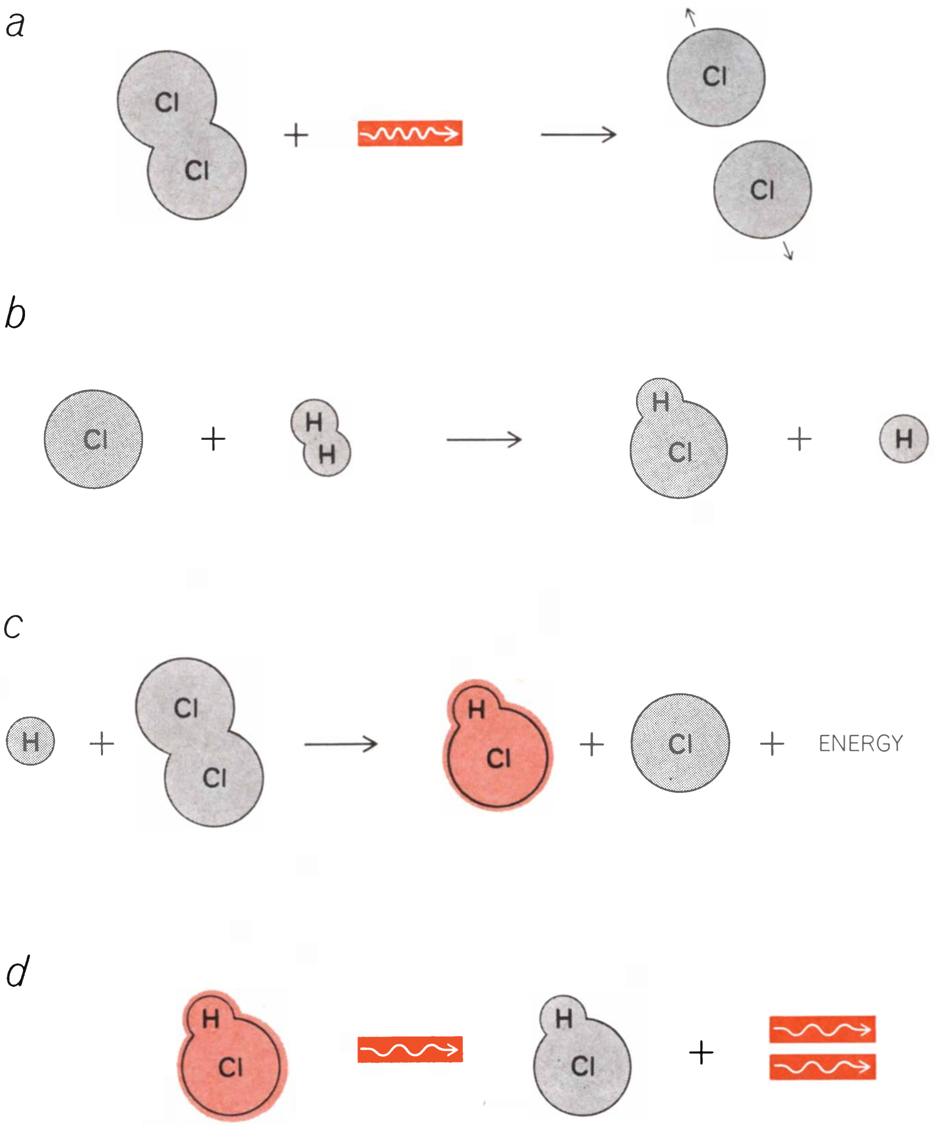
Lasers based on vibrational excitation suffer an additional disadvantage because of the fact that each excited vibrational state has a variety of rotationally excited sublevels. These sublevels are generally occupied in accordance

TYPE	ENERGY LEVEL	EXCITATION	MECHANISM
ELECTRONIC	100,000 TO 200,000 CALORIES PER MOLE	VISIBLE OR ULTRAVIOLET LIGHT	
VIBRATIONAL	500 TO 10,000 CALORIES PER MOLE	INFRARED LIGHT	
ROTATIONAL	.1 TO 100 CALORIES PER MOLE	MICROWAVE LIGHT	
TRANSLATIONAL	ANYTHING ABOVE 0	HEAT	

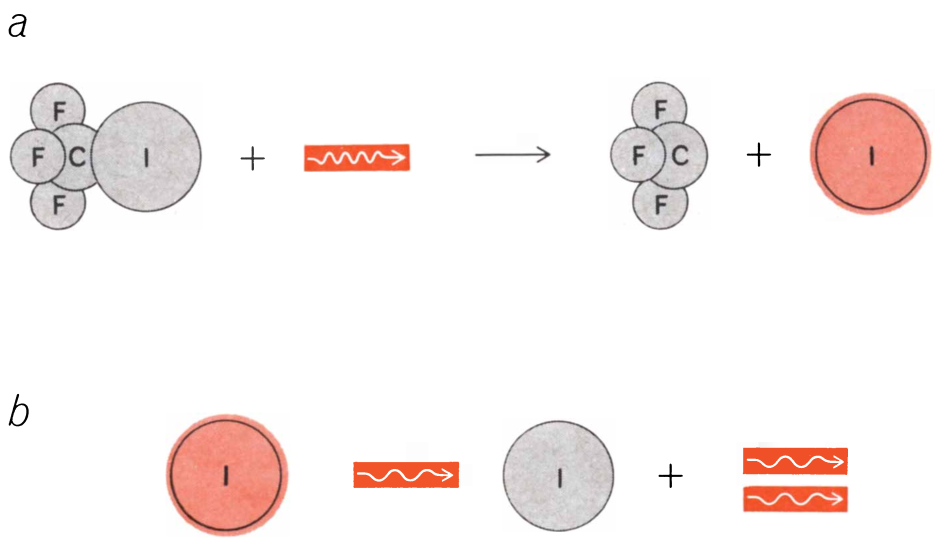
EXCITATION OF MOLECULES as a result of pumping takes four forms, each of which is related to the amount of energy required to achieve the excitation. The energy is expressed here in terms of calories per mole; a mole represents a standard number of molecules. Electronic excitation requires the highest input of energy, equivalent to that in ultraviolet or visible light. The other forms of molecular excitation require less energy.



CHEMICAL PUMPING is based on the energy released in the making and breaking of chemical bonds. For example (*a*), atom *A* might combine with a molecule consisting of atoms *B* and *C* to produce an intermediate and transient molecule (*color*) possessing extra energy. This molecule could separate into two molecular fragments (*b*); either might be excited and could be stimulated to drop to a lower energy level (*c*), emitting a photon.



REACTIONS between hydrogen and chlorine in an explosion provide pumping for a chemical laser. A trigger of light (*a*) separates a chlorine molecule into two chlorine atoms; one of them (*b*) combines with a hydrogen molecule to yield a hydrogen chloride molecule and a free hydrogen atom, which reacts as shown at *c* to produce an excited hydrogen chloride molecule (*color*) that thereupon (*d*) emits a photon of infrared radiation.



IODINE LASER derives its pumping from the dissociation by light of a molecule consisting of a carbon atom, three fluorine atoms and an iodine atom (CF_3I). In rupture of the carbon-iodine bond an excited iodine atom (*color*) is born and can release a photon (*b*).

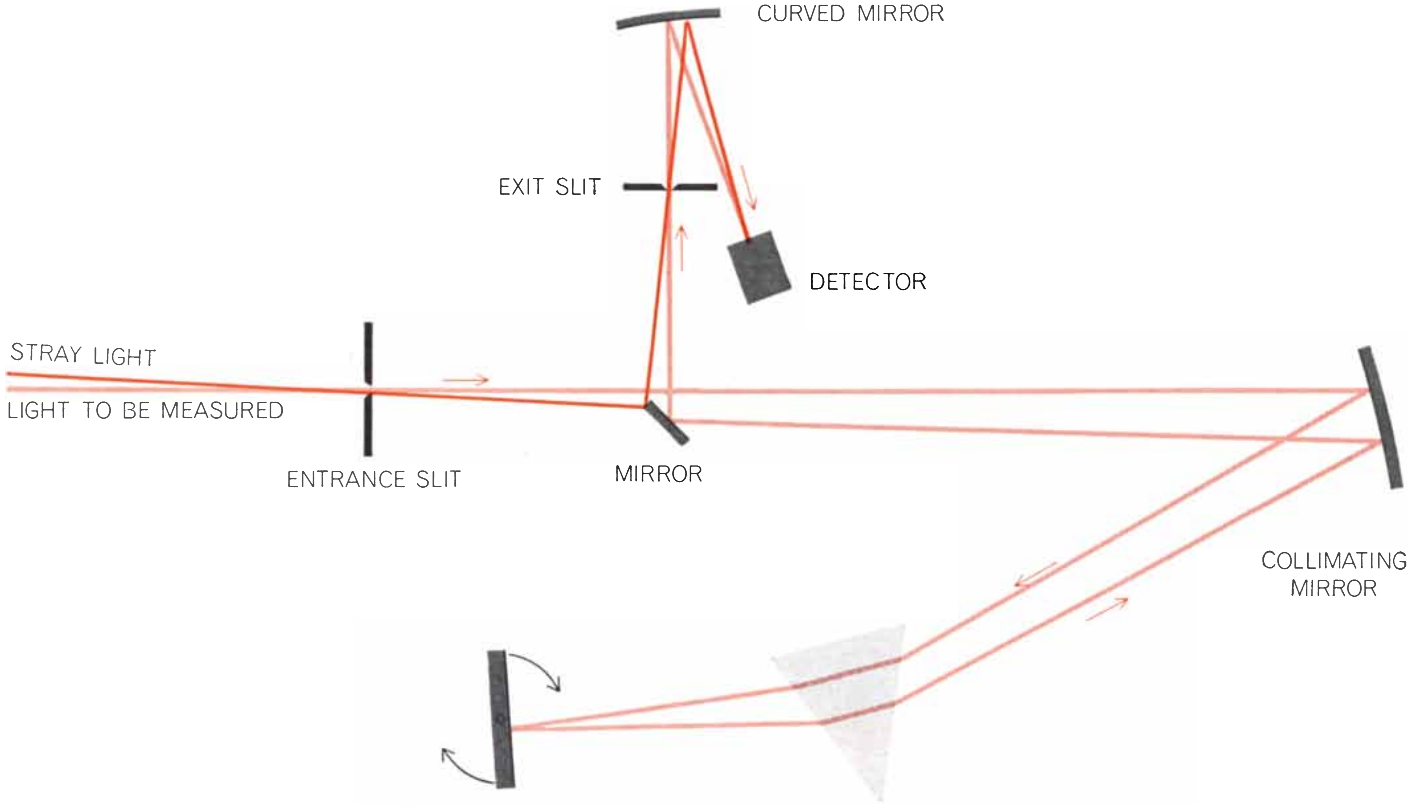
with the surrounding temperature, and they tend to dilute the possible occupancy of any particular level from which laser action is sought. Such dilution reduces the potential gain of the laser action.

A final limitation of chemical lasers is not intrinsic but has to do with the state of knowledge. There are very few chemical reactions for which the distribution of energy is known in sufficient detail to allow a prediction of whether or not laser action will occur. This limitation, however, is precisely the reason chemical lasers are of such great interest to a chemist. When laser action is achieved in a chemical reaction, the chemist gains new information about the distribution of energy at the time of reaction—about what is usually called the microscopic distribution of energy. Chemical lasers contribute a new weapon to a sparsely equipped arsenal for learning this crucial information. Chemists need to know the microscopic distribution of energy at the time of reaction in order to understand fully the dynamics of chemical reactions.

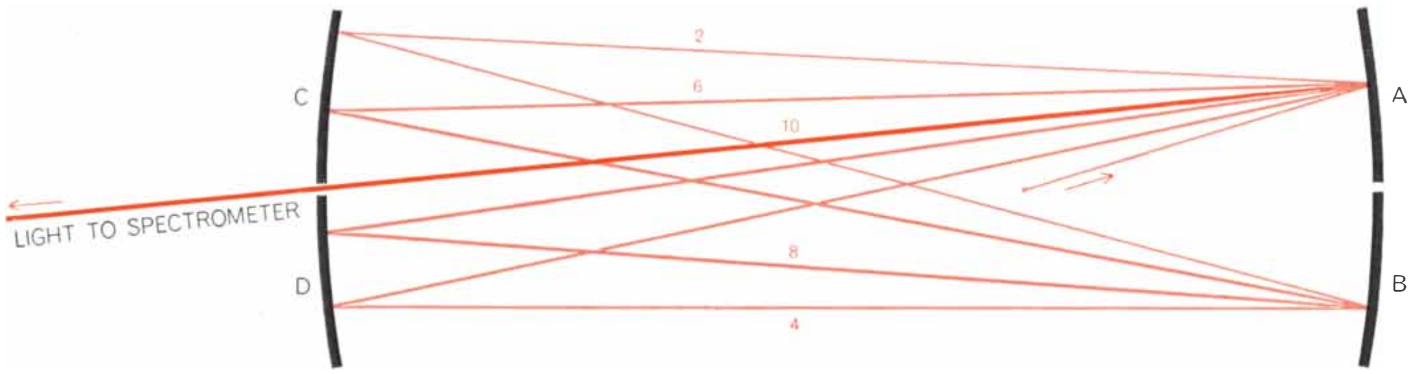
Considerations of this nature brought about the widespread interest in chemical lasers and led to our own experiments. As is so often the case, our success in these experiments grew out of some special conditions. As is also often the case, these special conditions involved a portion of particular capability, a portion of persistence, a portion of creativity and a portion of luck.

The portion of particular capability was furnished by a rapid-scan infrared spectrometer constructed by Kenneth C. Herr, then a graduate student in our laboratory. This instrument was designed for studies of the chemical species produced transiently by flash photolysis: chemical decomposition caused by an intense burst of light. Herr's spectrometer scans in approximately 200 microseconds the portion of the infrared region of the spectrum that is characterized by wavelengths of from one to 15 microns. On its first successful operation it was faster by two orders of magnitude than any earlier instrument capable of scanning this region.

As the potentiality of this instrument became apparent, Kasper, who was also a graduate student at the time, began investigating infrared fluorescence that occurred shortly after flash-initiated decompositions. Our intention was to examine the distribution of energy among chemical-reaction products at their birth and to follow the subsequent equilibration of energy. Kasper designed a



RAPID-SCAN SPECTROMETER provided the first indication that stimulated emission was occurring in molecules excited by chemical reactions. It was designed to scan infrared radiations produced by flash photolysis: chemical decompositions resulting from an intense burst of light. Stray emissions (*dark color*) appearing among the expected emissions (*light color*) proved to be highly intense near-infrared radiation deflected from the edges of a mirror and caused by stimulated emissions among excited molecular fragments.

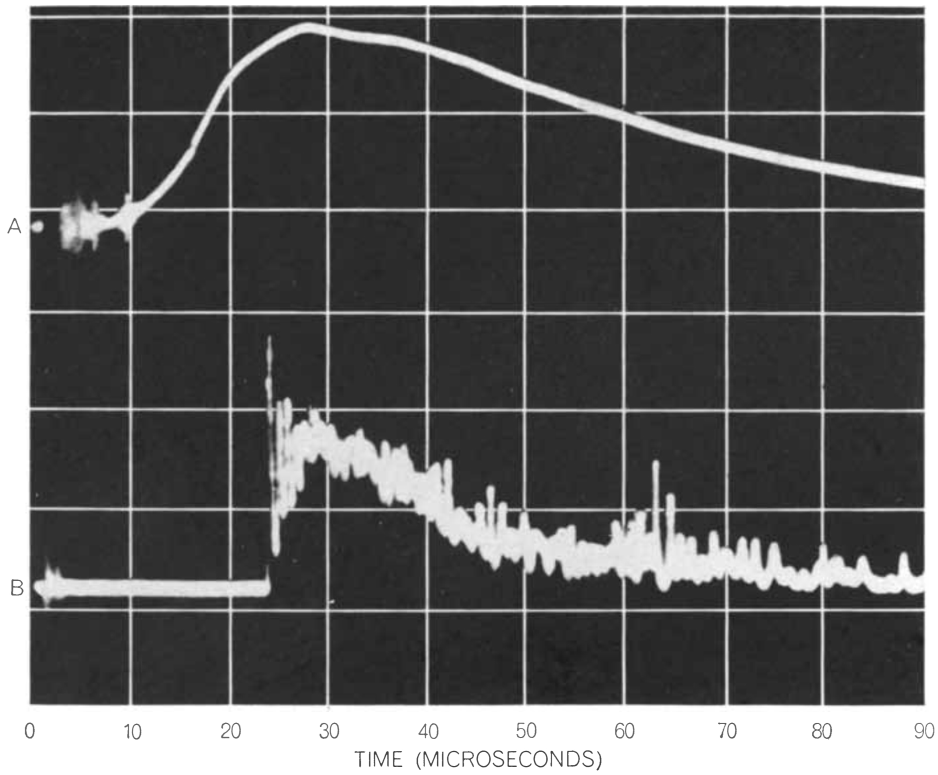


MULTIPLE-REFLECTION CELL acted as an optical cavity. Four mirrors (*A*, *B*, *C* and *D*) that could be focused independently reflected light back and forth; some of the traversals are numbered. With this arrangement there would be an increasing gain in intensity per traversal if stimulated emission were occurring and a decreasing gain if it were not. Stimulated emission was observed.

multiple-reflection Raman cell—a stainless steel cylinder about a foot in diameter and a meter long with two independently focusable halves of spherical mirrors at each end [*see lower illustration above*]. This arrangement provided an effective path length exceeding 40 meters for the travel of light (or other radiation) and made possible the efficient collection of light from a diffuse emitting gas.

Kasper began his studies by initiating explosions in hydrogen-chlorine (HCl) mixtures with flashes. This energy-level system was selected in direct response to promising work at the University of Toronto by J. C. Polanyi and his coworkers, who had observed and systematically elucidated infrared fluorescence in reactions between hydrogen and chlorine and had thought the HCl system might provide a basis for a chemical laser. Kasper observed emissions of infrared radiation, but it was confusing because it occurred at unpredictable frequencies and times, which should not have been the case with the stimulated emissions expected from the HCl system. For a time we thought that stimulated emissions might be occurring in carbon dioxide impurities in the system. The system was finally shelved, after many experiments, when it was found that periodic shock waves in the multiple-reflection experimental cell were causing some of the fluctuations in intensity.

We then turned to the idea of substituting such halogens as fluorine and iodine for the hydrogen atoms in organic compounds in the expectation that the halogen-substituted compounds would provide likely energy-level systems for infrared fluorescence. One of the first molecules we selected was trifluoro-



INTENSE EMISSION from excited iodine atoms produced these traces on an oscilloscope. Line *A* records the flash that set off the photodissociation reaction in which iodine atoms were separated from molecules; line *B* shows the stimulated emission that resulted.

methiodide (CF_3I). The intent was to search for vibrational excitation in the CF_3 fragment produced by photolysis. We expected this excitation to be left as the electronically excited CF_3I molecule underwent rupture of the carbon-iodine bond.

In this system, as in the HCl system, emission was observed after flash photolysis, but once again it was not reproducible in terms of frequency or time. The only certain thing at this point was that Kasper's work was in a frustrating phase. The time for persistence, creativity and luck (if we were to have any) had arrived.

Kasper provided the persistence and creativity by continuing his attack on the CF_3I problem. During a crucial week he recognized that his spurious and nonreproducible signals were not in the infrared region that he was scanning. He found that instead they originated with intense bursts of near-infrared radiation. The pulses of radiation were so intense that energy scattered from the edges of the spectrometer's mirrors would reach the detector no matter what the position of the spectrometer's rotating mirror. (This mirror was designed to restrict the light reaching the detector to a narrow frequency range.) Hence the pulses were observed at various locations in the spectrum [*see upper illustration on preceding page*]. Kasper measured the frequency of the intense bursts and found that the emitter was not CF_3, as we had sought and expected, but the iodine atom! The reaction was producing this atom preferentially in a state of electronic excitation. This intense excitation of an atom that we had not expected to be excited was our portion of luck.

By increasing the length of the light path in the multiple-reflection cell we ascertained that the emission was amplified in a way that identified it as stimulated emission. This emission displayed laser threshold behavior in spite of the unconventional geometry of the optical cavity, which was the multiple-reflection cell. The energy levels were provided by iodine atoms; the pumping, by the dynamics of bond rupture in the electronically excited CF_3I.

Here, then, was the discovery of the first photodissociation laser: laser action achieved by the breaking of a molecular bond following the absorption of light by the system. It can be argued that this is a somewhat loose definition of a chemical laser because the reaction has to be initiated by absorption of light and is not self-sustaining. In spite of this legitimate semantic distinction there is strong chemical interest in the photodissociation laser because the population inversion is brought about by the distribution of energy that accompanies the rupture of chemical bonds.

The clarification of the confusing behavior of the CF_3I system gave meaning to all the similar spurious signals that had been recorded in the studies of HCl explosions. Kasper returned to the HCl system and was able to establish quickly that here again the emission was stimulated emission. In this case the photolysis acts only as a trigger. The pumping occurs during the chemical reactions of the ensuing explosion. Accordingly the HCl laser satisfies a more rigorous definition of a chemical laser.

The first part of the cycle begins when a chlorine atom reacts with a hydrogen molecule to produce a hydrogen chloride molecule (HCl) and a free hydrogen atom. The free hydrogen atom is available to engage in the reaction that constitutes the second part of the cycle: the hydrogen atom and a chlorine molecule (Cl_2) react to produce an excited hydrogen chloride molecule and a free chlorine atom, which is thus available to allow a repetition of the first part of the cycle [*see top illustration on page 36*]. This reaction releases a large amount of energy, a portion of which is left in vibrational excitation of the HCl product. Another portion is in the form of rotational motions; the remainder goes directly into translational motion. (There is not enough energy to produce electronic excitation.) We estimate that about 15 percent of the energy goes into the vibrational excitation that is so crucial for laser action.

After establishing that these two forms of emission were stimulated emissions, we investigated them in an optical cavity of more conventional geometry [*see illustration on page 33*]. This cavity consisted of a quartz tube fitted with quartz end windows tilted at a carefully calculated angle that minimizes reflection losses in the cavity. Reflection is provided by two spherical mirrors 86.5 centimeters apart. Front-surfaced gold mirrors are used to provide high reflectivity in the infrared. About 6 percent of the radiation in the cavity is deflected to the outside by a flat piece of quartz and focused on a fast-response detector. For photodissociation experiments we place a flash tube alongside the laser tube and, to concentrate the flash further, wrap an aluminum reflector around the two tubes.

One of the interesting discoveries made with this apparatus is that the intensity of the iodine laser emission can be very high. Under certain circumstances one can obtain power at the kilowatt level. This level of power implies that there is a high gain of energy in the system. We were able to demonstrate such a gain experimentally: the laser emission could still be obtained with only five centimeters of the length of the tube exposed to the flash and with a filter inside the optical cavity that absorbed 71 percent of the energy! These findings indicate that in a single trip down the tube one photon entering the tube at one end can give rise to 10 billion photons at the other end. This is one of the highest gains ever reported for any gas laser.

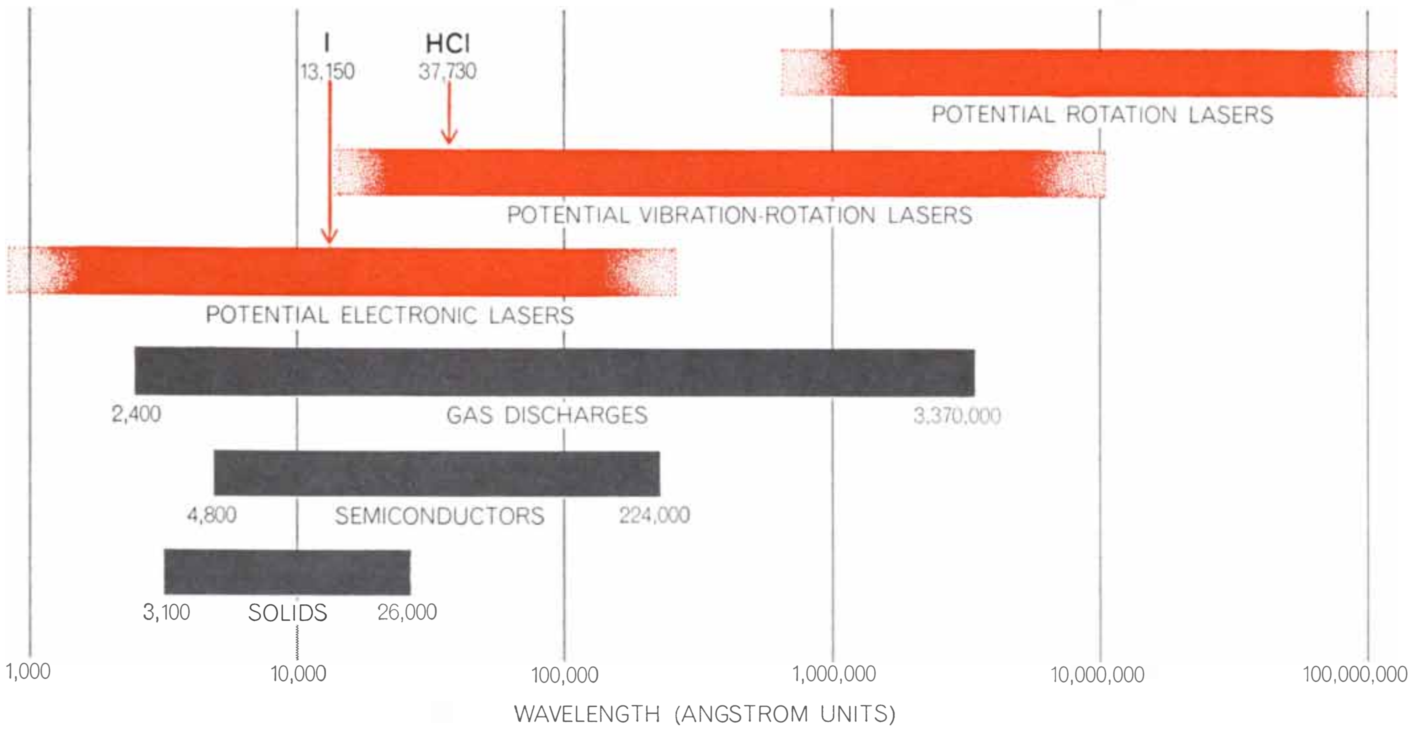
With our chemical lasers we have been able to investigate a number of intriguing questions in chemistry. I have already mentioned the value of the laser in yielding data about the microscopic distribution of energy in chemical reactions. Another investigation has provided information about why the laser emission of iodine terminates so suddenly. It turns out that the temperature rises so rapidly that new chemical reactions become important. We have also been interested to find that a number of organic iodides besides CF_3I produce laser emission and even more interested to find that some do not. These exceptions present particularly challenging problems to the chemist.

What of the future? I think it reasonable to expect that chemically activated vibration-rotation lasers will someday be numerous. Many chemical reactions occur with changes of bond lengths, and such reactions will almost surely leave the products in vibrationally excited states. On the other side of the ledger, it must be noted that the conversion of vibrational energy into rotation and translation occurs more rapidly as the size of the molecules involved increases. Therefore most vibration-rotation lasers will have to be based on gaseous molecules with only two to five atoms. We can also expect that such lasers will be difficult to operate in the far infrared, using rotational excitation. The very rapid change of rotational energy into translational energy will be quite an obstacle. Electronic excitation of reaction fragments resulting in laser emission seems more likely to be fruitful, even in the far infrared, than pure rotation lasers.

The search for a chemical laser that will operate continuously remains a challenge. One would think that flames, in which excited molecules are known to exist, could provide a basis for such a laser. Yet careful studies of this question, such as those conducted by R. Bleekrode and W. C. Nieuwpoort at the Philips Research Laboratories in the Netherlands, have so far been unsuccessful. Here too my colleagues and I lean toward the expectation that, as more chemists enter this interesting area, the problems will become clearer and success will eventually be attained.

The extremely large gain achieved by the iodine-atom laser gives promise that high power levels may be one of the special virtues of chemical lasers. It should be noted, however, that the gain and power of the HCl laser are relatively low. This laser does not even approach the limiting power once calculated by Polanyi, who showed that a vibration laser with chemical pumping could in principle achieve an output as high as 100 billion watts. Polanyi foresaw, however, that dilution of occupancy by the many rotational states would prevent achievement of such astronomical power levels, and this problem has proved to be significant. As investigators of chemical lasers proceed to heavier molecules, where the rotational levels are closer together, the dilution will be even greater.

For these reasons I cannot hold out such prospects as an astronaut mixing two liquids to turn on the laser headlights of his spacecraft. A more realistic prospect for the chemical laser is that it will furnish a tool, equivalent to a new chemical microscope, that will focus on the distribution of energy in elementary reactions, revealing the exact energetic state of the product species as they are born during a reaction. In this role the laser will somewhat relieve, although only momentarily, the chemist's insatiable desire to know more about how chemical reactions occur.



AREA OF SPECTRUM spanned by existing lasers (*gray*) ranges from 2,400 angstrom units in the ultraviolet region to 3,370,000 angstroms in the far infrared. Two chemical lasers (*colored arrows*) have been operated; other chemical lasers might extend into the microwave region (*right*). Frequencies range from 100,000 waves per centimeter at far left to one wave per centimeter at far right.

Chromosome Analysis by Computer

Now that certain human disorders have been linked with chromosome abnormalities, it is desirable to examine large numbers of cells for such abnormalities. A computer regime has been devised for the purpose

by Robert S. Ledley and Frank H. Ruddle

In recent years a number of human disorders have been found to be related to abnormalities in the chromosomes, the bodies in the living cell that contain the genetic material. Accordingly many medical institutions have undertaken programs of examining in the microscope the chromosomes of samples of tissue taken from numerous patients. Such programs have been limited by the fact that the examination of chromosomes takes time and calls for individuals who have been trained in recognizing chromosomal abnormalities. An obvious way to circumvent this limitation is to devise some kind of machine that can examine the chromosomes automatically, although of course it is less obvious how the machine would work. Such a machine, the central component of which is an electronic computer, has now been assembled and successfully operated.

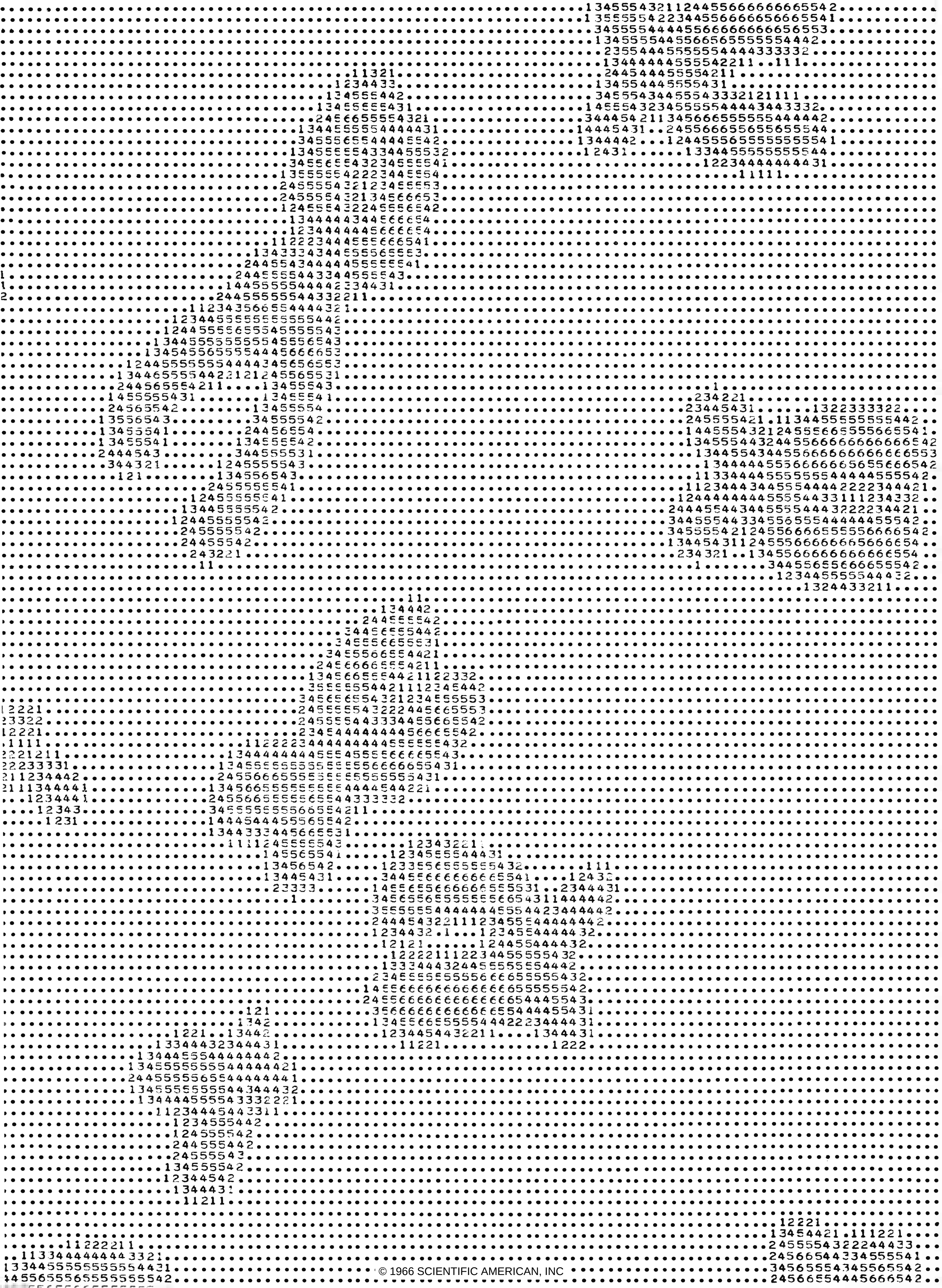
Human somatic cells (as distinguished from sperm or egg cells) normally contain 46 chromosomes. The chromosomes can most conveniently be examined in the white cells of the blood, which are readily available in a blood sample. (Mature red blood cells contain no chromosomes.) After the white cells have been segregated, however, they must be kept alive in tissue culture and induced to undergo mitosis, or to divide; it is only during mitosis that chromosomes and their abnormalities are clearly visible. Treating the cells with the drug colchicine halts mitosis exactly at metaphase—the stage of somatic-cell division in which each chromosome has divided into two mirror-image halves lying side by side and connected at one point called the centromere. The cell preparation is now treated with a dilute salt solution, which causes the cells to swell and the chromosomes to move apart. Finally the cells are fixed and stained, so that the chromosomes can be observed and photographed through the microscope [*see upper illustration on page 42*].

For purposes of analysis a photomicrograph must be made and enlarged; then the chromosome images are cut out and arranged on a white card in what is called an idiogram. The chromosomes are matched into 22 pairs of homologous, or related, chromosomes, plus the two sex chromosomes. (One member of each pair and one sex chromosome is descended from each parent at the fertilization of the egg.) The pairs are arranged in a standardized order based on size, shape and the ratio of the length of the "arms" on each side of the centromere [*see lower illustration on page 42*]. Only when the cells are thus arranged can abnormalities be readily identified. Even when the abnormality is as gross as the presence of extra chromosomes the idiogram is needed to detect with which normal pair the extra chromosome is associated. Some of the disorders that have been linked with chromosomal abnormalities are Down's syndrome (mongolism), chronic myeloid leukemia, Klinefelter's syndrome (a congenital disorder of males involving infertility) and Turner's syndrome (a congenital disorder of females involving infertility). Also detectable by such analysis is chromosome damage caused by certain substances or by ionizing radiation; accordingly chromosome analysis can play an important role in the screening of foods and drugs and in the evaluation of radiation hazards.

The construction and examination of the idiogram—both of which are time-consuming and somewhat subjective procedures—are eliminated by the automatic regime we shall describe. This means of analysis still requires the collection of blood samples, of course, and the preparation of cells for photomicrography, but the photomicrographs need not be enlarged and the manual analysis need not be made. Instead a series of photomicrographs on a roll of film are "read" directly into the memory unit of a computer by a scanning device called FIDAC (Film Input to Digital Automatic Computer). The computer is programmed to recognize and classify the objects under consideration by doing the same things an investigator would: counting the total number of chromosomes and measuring their lengths, areas and other morphological features. The FIDAC procedure reduces the time required to study the human complement of 46 chromosomes to about 20 seconds; this is some 500 times faster than analysis by visual means.

When a roll of photographic film is ready for examination, it is placed in the film-transport unit of the FIDAC instrument and the "Start" button of the computer is pushed. The computer system—FIDACSYS, a combination of several basic programs for recognizing and analyzing patterns—signals FIDAC to consider the first frame. The instrument scans the photomicrograph and within .3 second

IMAGES OF CHROMOSOMES appear as grid of numerals in computer print-out that provides a rudimentary picture of a photomicrograph. Details of the micrograph were conveyed to memory unit of the computer by a scanning device called FIDAC. Numerals from 0 to 6 on a gray scale describe the darkness of corresponding points on micrograph, made during phase of cell division at which a chromosome consists of two strands (chromatids) connected in one area (the centromere). Dots correspond to the background.



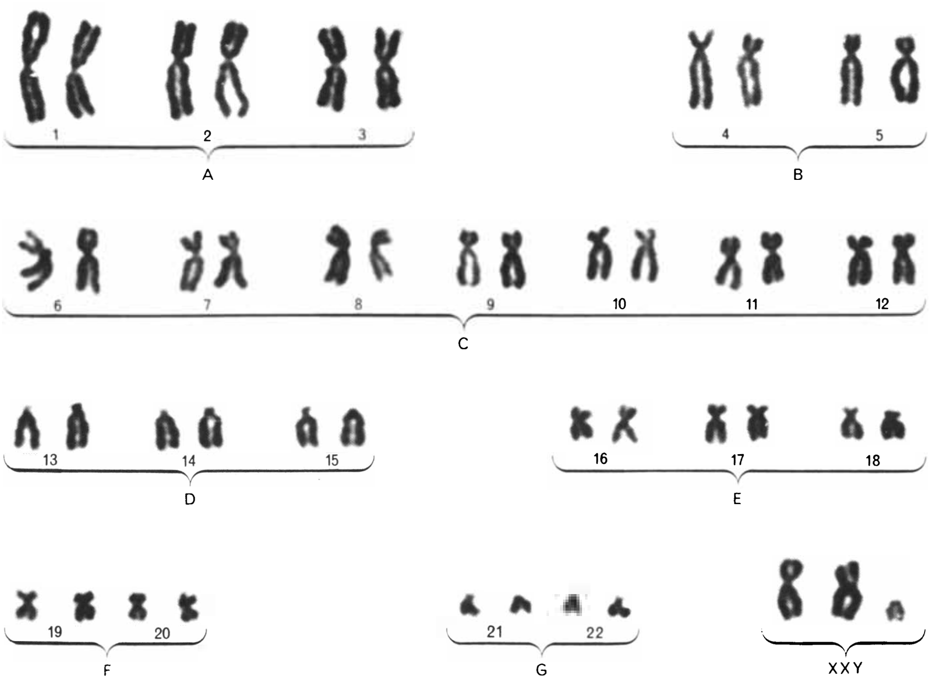
transmits a digital image of it into the magnetic-core memory unit of the computer. In this digitalized image the photomicrograph is represented by a rectangular grid of numbers that correspond to the densities of points in a similar grid on the photomicrograph. The numbers on this "gray scale" run from 0 to 6; the number 7 is reserved to denote boundaries during processing. If at this stage the contents of the memory are printed out, they form a rudimentary image of the objects in the photomicrograph [*see illustration on preceding page*].

No significant information is lost in translating the pictorial data into numerical data. The resolution of a good optical microscope at a magnification of 1,000 is .2 micron, that is, .2 micron is the narrowest spacing that can be distinguished between two lines. The FIDAC instrument can sample three picture points within a span of .2 micron on the specimen; in other words, its resolution is comparable to that of the microscope. The instrument has another feature worth mentioning: because it transmits directly ("on line") into the computer's memory, information that would ordinarily be rerecorded onto intermediate magnetic storage tapes can remain instead on the original roll of photomicrographic film for reprocessing whenever it is desired. A 100-foot roll of this 16-millimeter film, containing 4,000 photomicrographs, can fit into a can smaller than four inches in diameter. Recording that much information on magnetic tapes would require more than 50 reels, making a stack more than four feet high.

When the processing of a frame has been completed, the computer program signals FIDAC to advance the film and consider the next frame. If any frame is blank—that is, either 98 percent black or 98 percent white—the program signals FIDAC to move to the next frame. In this way blank frames or leader can be skipped automatically. If the frame is not blank, the computer program establishes a value on the gray scale as a cutoff level between those values that represent points inside the chromosomes and those that represent the background. The task of recognizing patterns in the frames as chromosomes is accomplished by first sweeping a programmable "bug," or detecting pointer, in a horizontal raster pattern to find points with a gray value greater than the cutoff level. The bug then traces around the boundary of each object, and every number in the original digital representation of the boundary that has a value just above the cutoff level is replaced by 7. The silhouette that is formed is now automatically examined to determine if it has the most obvious feature of a chromosome: arms originating at a centromere. If the silhouette does not meet this criterion, it is eliminated from further analysis.

When all the chromosomes in a frame have been silhouetted, the bug will have reached the lower right-hand corner of the frame. At this point the machine evaluates the contents of the frame. The chromosomes are counted and their total length is computed, so that the length of individual chromosomes can be considered as a fraction of the total

PHOTOMICROGRAPH OF CHROMOSOMES from the white blood cell of a man reveals an abnormal total of 47 (one too many). It is impossible to determine which one is in excess until the chromosomes are reassembled into a standard classification called an idiogram.



IDIOGRAM of a complement of human chromosomes reveals an abnormality. Chromosomes matched according to size, area and ratio of the lengths of the "arms" on each side of the centromere were put into sequence by Herbert A. Lubs, Jr., of Yale University. The three sex chromosomes at right of bottom row (normal men have one *X* and one *Y* sex chromosome) provide evidence of Klinefelter's syndrome, a disorder of males involving infertility.

length of the chromosomes in the frame. Homologous chromosomes are matched according to area, length and arm-length ratio, and the pairs are classified according to the standardized sequence of the idiogram. When the analysis of a frame is finished, the FIDAC instrument is instructed to move to the next frame and the process is repeated. After a predetermined number of frames have been processed the statistics of all the photomicrographs on the roll of film are automatically collated and analyzed.

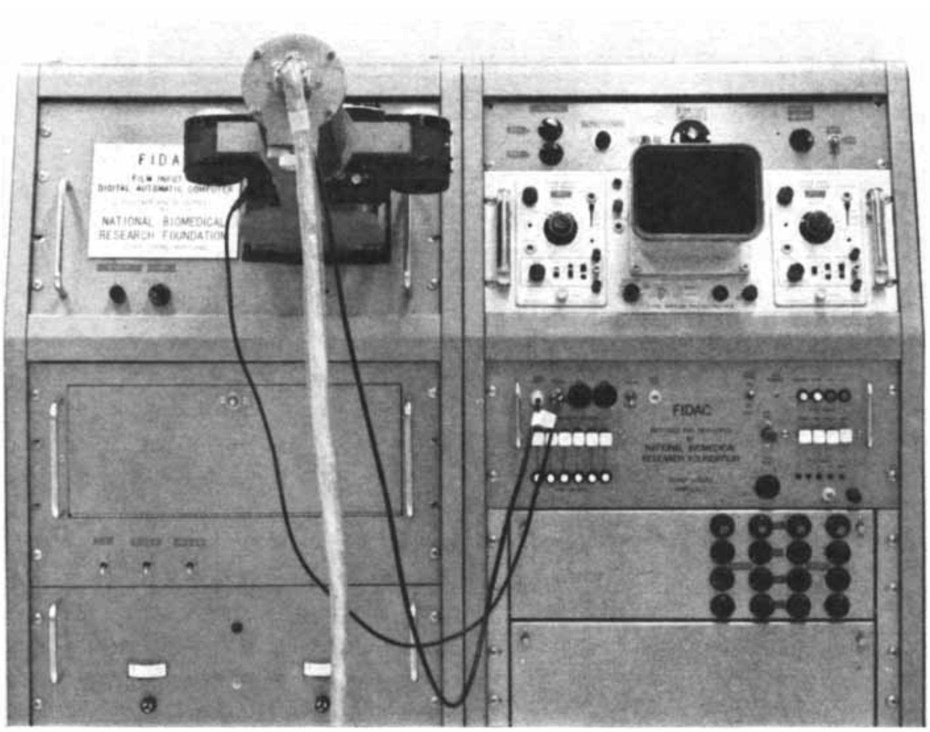
Let us consider more closely the essential step in this procedure: the recognition and analysis of individual chromosomes. The location of anything encountered by the bug—the boundary of an object, for example—can be given in a Cartesian-coordinate system mapping the entire frame. Thus when the bug first meets an object, its point of contact can be located on a grid in terms of horizontal and vertical positions denoted by X and Y coordinates. The bug now proceeds along the boundary of the object in a clockwise direction, and points on the boundary are delineated in the same notation. When a certain number of boundary points have been traversed, they are said to constitute a segment. The bug continues to mark boundary points and segments until it returns to the original point of contact; it is now ready to search for a "next object."

The computer program characterizes the individual segments in terms of their direction and curvature. This involves several measurements. First the center point of a segment is ascertained. The arc of the segment reached by moving clockwise from the center point is called the leading half; the arc reached by moving counterclockwise, the trailing half. A vector arrow is drawn in each half; the length of the segment is chosen as a distance short enough so that the angle between the leading and the trailing vector will be an approximation of the segment's curvature. The arrow that is the vector sum of the leading and trailing vectors is approximately the tangent to the segment at its center point and so provides a measure of the direction of the segment.

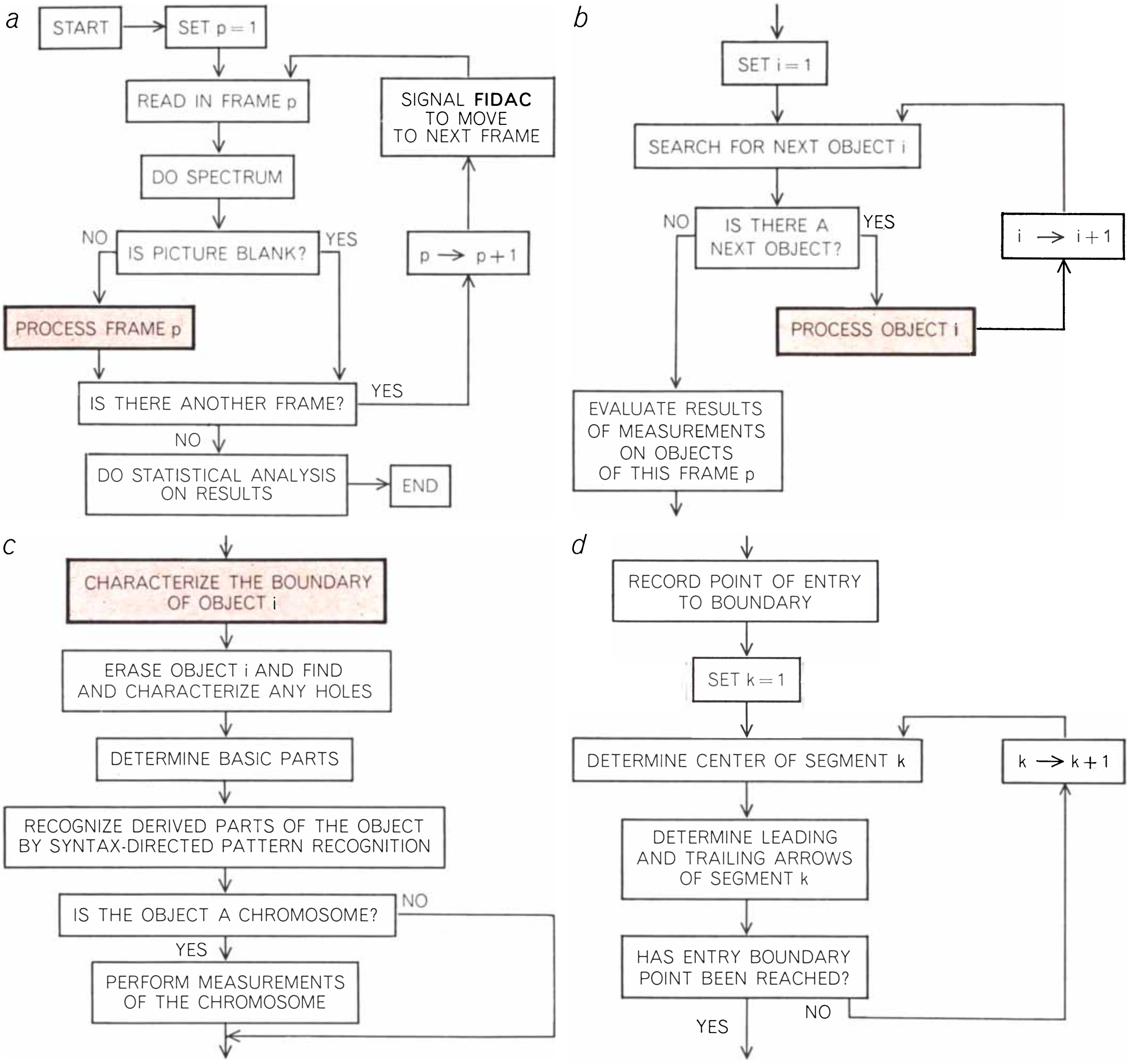
In determining the curvature of the segments the FIDAC system uses a small vocabulary of 13 terms to describe degrees of curvature. For purposes of explanation let us consider a vocabulary of four terms: a fairly straight segment is called Type O; a clockwise curve, Type E; a slight counterclockwise curve, Type V, and a pronounced counterclockwise curve, Type Y. By combining such terms the complete outline of a chromosome can be described.

The program by which the computer "builds up" the shape of a chromosome from combinations of curve types is relatively simple in conception. One arm of a chromosome, for example, might have Type O curves on its sides and a Type E curve at its end; between this arm and another on the same chromosome there would be a Type Y curve. The programmer's role is to set forth,

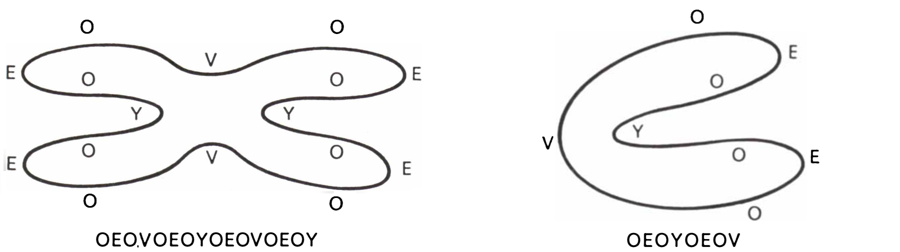
COMPUTER AND SCANNING DEVICE used by the authors are located at the Goddard Space Flight Center outside Washington, D.C. The IBM 7094 computer (*foreground*) receives descriptions of photomicrographs of chromosomes from the FIDAC scanner (*background*), on the basis of which it counts, analyzes and collates data on the chromosomes.



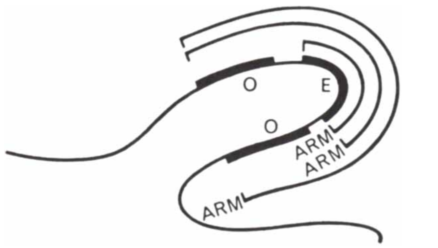
FIDAC INSTRUMENT is named for its function: "Film Input to Digital Automatic Computer." A roll of film containing a great many photomicrographs of chromosomes is put into the film transport unit at top left (*behind the cylindrical photomultiplier*). A detailed description of each micrograph is transmitted by FIDAC to the memory unit of the computer. A video amplifier displays the micrograph being scanned on the small screen at top right.



STEPS PERFORMED BY COMPUTER in examining photomicrographs of chromosomes are presented on four levels of detail. The overall procedure (*a*) entails advancing the roll of photomicrographic film, instructing FIDAC to "read" the image of a frame into the computer's memory unit, computing the spectrum of the image, processing the frame if it is not blank, again advancing the film and finally, when the roll is finished, collating data pertaining to all the photomicrographs that have been inspected. The key step in the sequence is the processing of a frame (*b*), which involves a search for individual objects. The boundary of each object is considered (*c*) in terms of the segments that comprise it. The curvature and directionality of each segment are analyzed (*d*) and the segments are defined as "curve types." Certain sequences of curve types are recognized by the program as arms or other parts of chromosomes. (This is called "syntax-directed pattern recognition.") An object composed of such parts is thus identified as a chromosome.



SEGMENTS on boundary of a chromosome are defined as types of curve. *O* is a fairly straight segment; *E*, a clockwise curve; *V*, a slight counterclockwise curve; *Y*, a sharp counterclockwise curve. Different sequences of curve types represent a four-armed submedian chromosome (*left*) and a teleocentric chromosome (*right*) in the computer program.

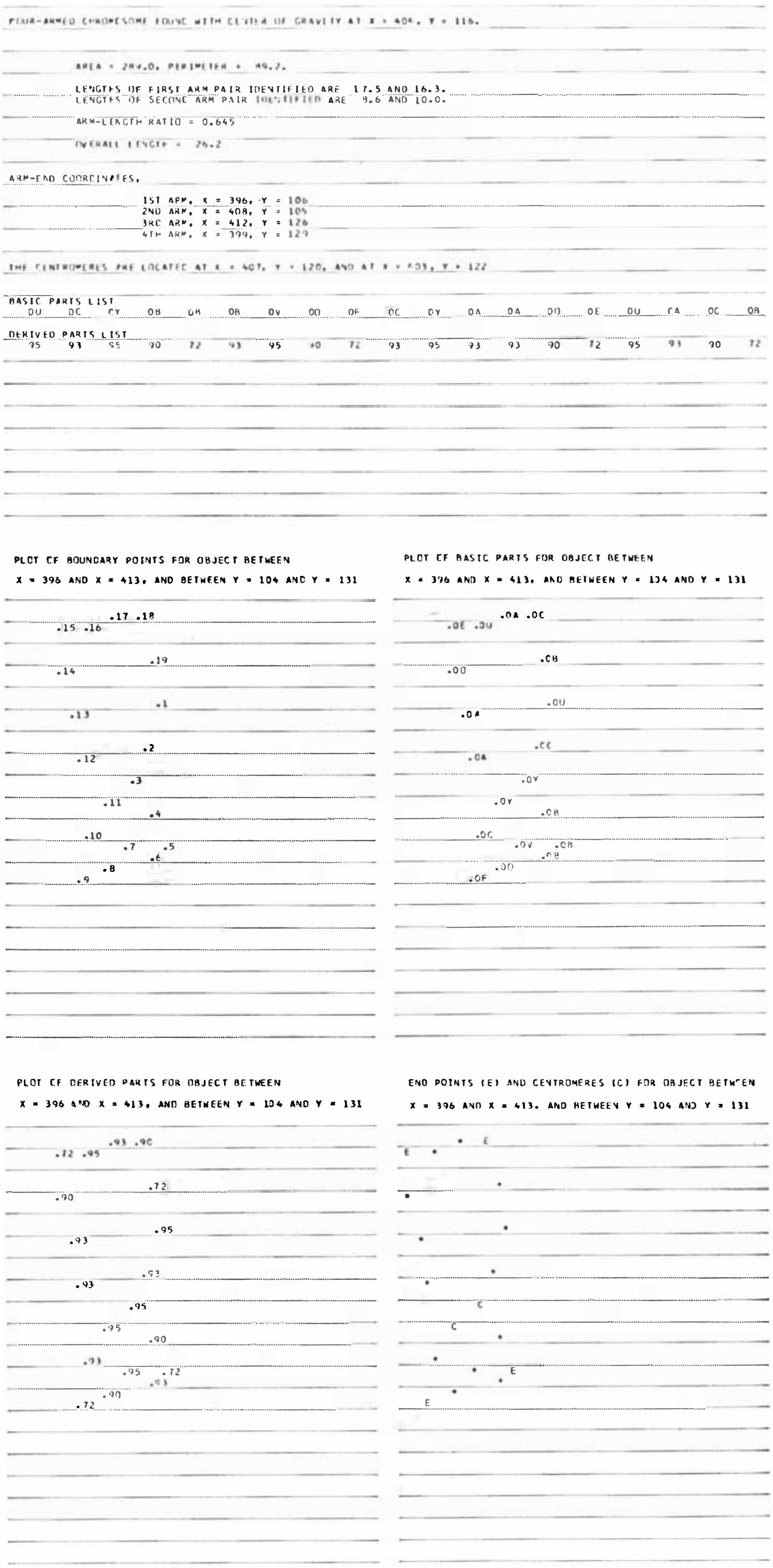


ARM IS IDENTIFIED in stages by program. Type *E* curve is tentatively called an arm (*notation outside brackets*). Scan showing it between *O* types confirms this fact.

in the notation of symbolic logic, a recursive definition (one that can be used repetitively in the program) by which a "derived part" such as an arm can be recognized from its component curves [*see bottom illustrations on opposite page*]. The process is then taken up by an element of FIDACSYS called the mobilizer, which is analogous to the translator program for a computer language. The mobilizer operates on a list of terms describing the parts of a particular object; by using a general syntactical description of various kinds of chromosome it determines whether or not an object is a chromosome and, if so, what type of chromosome it is. This technique, called syntax-directed pattern recognition, was developed by one of the authors (Ledley) at the National Biomedical Research Foundation in Silver Spring, Md.

The results of each step in the analytic process can be printed out by the computer. First come data describing the coordinates of the chromosome's center of gravity, its area and its perimeter. The lengths of the arms are given and the arm-length ratio is computed by comparing the average length of the two long arms to the overall length of the chromosome [*see illustration at right*]. Next come the coordinates locating the centers of the boundary segments and designations describing the curvature of these "basic parts." FIDACSYS then prints out the derived parts, giving coordinates for the positions of the arms and the centromere. In the print-outs the code letter *E* is placed at points representing the ends of the arms, and the letter *C* at the points marking the centromere. On the basis of all these data an automatic plotting device makes a tracing of all the chromosomes in the original photomicrograph. The plotter also numbers the chromosomes and draws a line to indicate their centromeres [*see illustration on next page*].

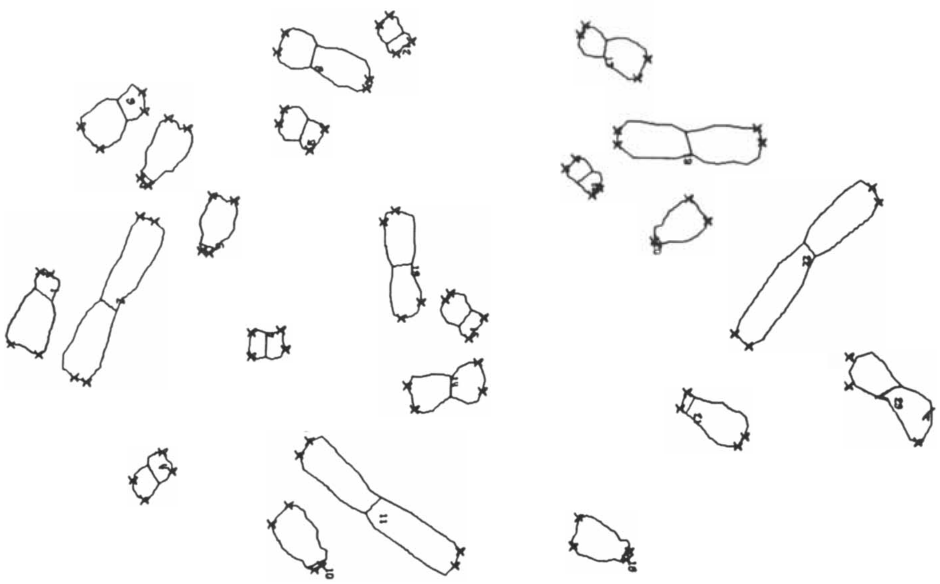
There is still another way in which a computer programmed by FIDACSYS translates numerical data back into graphic form: the final print-out consists of a schematic idiogram of the complement of chromosomes under inspection. To evaluate the accuracy of chromosome analysis by computer we must ask: How does the automatic idiogram compare with one based on visual observation and measurement? Assessments made by the authors indicate that the figures for areas and arm lengths worked out by computer are sufficiently precise. There is reason to

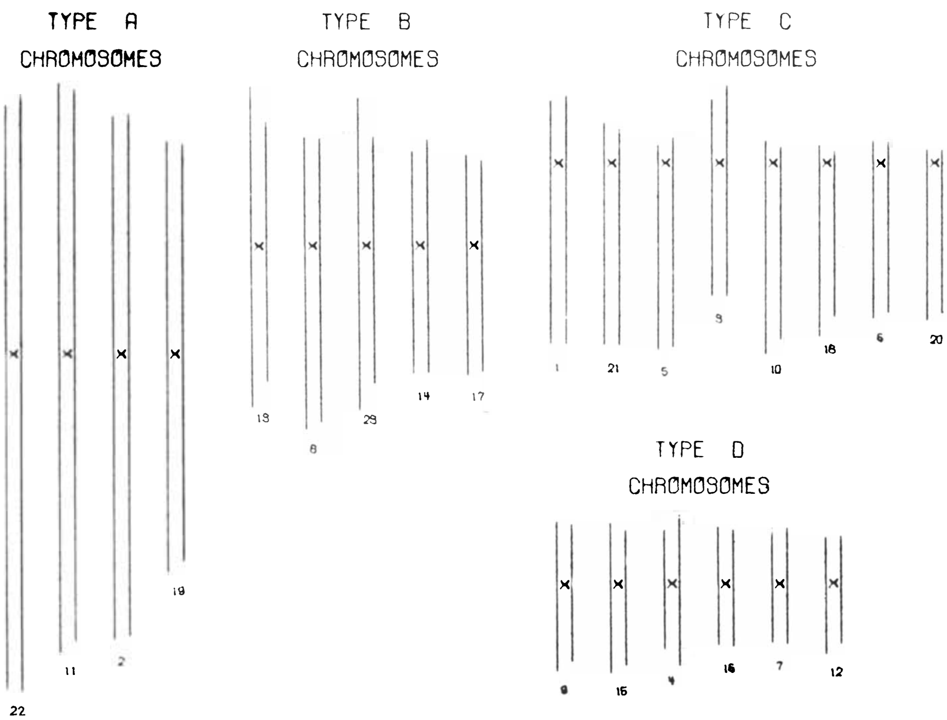


INTERMEDIATE PRINT-OUTS from computer examining chromosomes by syntax-directed pattern recognition are assembled. At top are data giving location and size of chromosome and its arm-length ratio; in middle, plots of boundary points and segments ("Basic parts"); at bottom, plots with labels for ends of arms and centromere ("Derived parts").

CHROMOSOME ANALYSIS SUMMARY

FR NO	CH NO	T	CENTER GRAVITY	PERI METER	OVRALL LENGTH	2 LONG LENGTHS	2 SHORT LENGTHS	LENGTH RATIO	AREA	LONG AREA	SHORT AREA	AREA RATIO
1	1	C	328, 37	100.3	34.7	26.2,26.5	7.9, 8.6	.761	499.	390.	105.	.788
1	2	A	321, 70	183.6	73.3	38.5,37.9	34.9,35.2	.522	1013.	512.	489.	.512
1	3	C	245, 69	89.5	28.8	19.2,19.5	8.6,10.3	.673	434.	303.	128.	.703
1	4	D	416, 87	59.7	18.9	8.4,10.9	8.1,10.3	.511	219.	110.	110.	.501
1	5	C	259, 90	81.2	29.0	24.9,24.7	3.8, 4.5	.856	378.	357.	35.	.910
1	6	C	288,113	68.5	24.4	19.5,19.0	5.3, 5.0	.788	295.	235.	56.	.808
1	7	D	338,134	53.5	16.1	8.6, 8.6	7.3, 7.8	.533	171.	93.	76.	.549
1	8	B	220,156	112.3	40.5	24.7,23.8	16.4,16.1	.598	572.	324.	242.	.572
1	9	D	248,146	64.5	20.1	12.0,10.8	8.9, 8.5	.568	240.	143.	100.	.589
1	10	C	441,151	80.7	28.2	21.0,19.4	8.2, 7.8	.716	397.	293.	97.	.750
1	11	A	427,183	199.7	78.7	42.3,40.9	37.5,36.7	.529	1114.	591.	499.	.542
1	12	D	208,164	49.5	15.6	8.7, 7.5	7.6, 7.4	.520	153.	79.	72.	.521
1	13	B	304,190	117.6	41.0	25.2,21.5	20.0,15.3	.570	531.	295.	237.	.555
1	14	B	356,208	99.2	32.1	18.5,18.7	12.7,14.2	.580	451.	246.	205.	.545
1	15	D	326,215	63.6	19.8	11.9,11.0	9.1, 7.5	.580	219.	128.	87.	.596
1	16	D	265,264	51.7	16.5	8.7, 9.2	7.9, 7.1	.544	154.	81.	69.	.540
1	17	B	214,275	90.9	30.5	19.1,18.7	12.0,11.2	.619	382.	253.	125.	.669
1	18	C	442,274	76.5	24.7	21.0,18.5	5.3, 4.6	.799	351.	277.	64.	.813
1	19	A	250,307	161.0	59.7	32.4,32.0	28.0,26.9	.540	895.	450.	426.	.514
1	20	C	285,305	71.6	23.9	23.2,21.6	1.5, 1.5	.937	301.	297.	7.	.977
1	21	C	366,318	90.9	30.2	22.0,22.4	8.9, 7.1	.735	382.	310.	69.	.818
1	22	A	303,356	203.2	83.0	45.4,46.0	36.5,38.2	.550	1139.	592.	550.	.518
1	23	B	356,394	120.5	39.3	23.5,19.9	20.5,14.7	.552	596.	318.	262.	.548





THREE DESCRIPTIONS of the complement of chromosomes of a Chinese hamster were printed by machine. At top are data describing the morphology of each of the animal's 23 chromosomes. In middle is a tracing of the chromosomes, made by an automatic plotting device in which chromosomes are numbered, ends of arms marked and centromeres represented by a line. At bottom is an idiogram of the chromosomes arranged by computer.

hope that analysis by computer will eventually uncover small but important chromosomal abnormalities that have not been discerned by eye. It is known, for example, that one of the chromosomes in the cells of individuals with chronic myeloid leukemia lacks only a small portion of one arm; it is quite likely that other small deletions or additions have been overlooked by investigators and will be revealed by means of the computer.

It can be said with some assurance that the procedure we have described will soon be sufficiently refined and tested for clinical use by physicians who want to examine the chromosomes of a significant number of people. The method will also be available for screening new drugs and biologicals (such as vaccines) for possible chromosomal effects. Moreover, it will now be possible to conduct large-scale studies in such matters as the effects of radiation and aging on chromosomes. The main limitations of the procedure—limits on the speed of the scan and on the number of points that are sampled per picture—are imposed not by the FIDAC device or the basic technique of syntax-directed pattern recognition but by the cycle time and capacity of the memory of the International Business Machines 7094 computer we have been using in our investigations. Newer machines, such as the IBM 360-series computers, will have a larger memory and greater speed, allowing an even faster and more accurate procedure.

It is also safe to predict that methods of automatic analysis closely akin to those described in this article will be employed by biologists and research physicians for tasks other than the study of human chromosomes. There are many branches of biology in which pictorial data have been collected in quantities so large that systematic analysis has heretofore seemed impractical. Examples of such material are sequences of pictures made through the microscope that show the myriad dendritic extensions of nerve cells; electron micrographs of muscle fibers or virus particles; autoradiographs showing the uptake of a tracer element, and X-ray pictures of bone revealing the distribution of calcium. Pictures from these and other categories of material, which describe the structural characteristics of cells in terms of lengths, areas, volumes and densities, can be translated into numerical information. Like photomicrographs of chromosomes, they readily lend themselves to study by computer.

Kodak advertises:

pictures for 3-dimensional printing . . . fast, emotion-free flareups on film. . . a bargain for atomic absorption spectroscopy . . . a shortened wait for x-rays and the possible consequences

One way to be vivid in print

The camera swathed in black as it photographs a young couple by a rail fence implies a more ponderous approach to photography than you had thought necessary in this day and age. There is a reason. The camera is quite an unusual one that makes 3-dimensional photographs for reproduction through a printing press in Chicago. The printing press also has unusual features. First it prints with ink and then it prints with a hydrocarbon resin of our manufacture. The four colors of ink and the surprinted optical system have to be aligned with the cruelest kind of precision.

The extent of success achieved in this and in other less physical and more fiscal matters has just been submitted to the scrutiny of our more than 150,000 shareowners, who find the rail fence sticking out at them from the cover of our Annual Report for 1965. Without purchasing our stock, it is possible by writing Eastman Kodak Company, Public Relations Department, Rochester, N. Y. 14650, to acquire this flexible, naked-eye-type stereoscopic color photograph for possible inspiration toward some commercial or instructional scheme.

Inquiries of a business or technical nature should be directed to our associate in this development, Visual Panographics, Inc., 488 Madison Avenue, New York City 10022. It's nothing for the home darkroom.

For the solar patrol

A line of KODAK RAR Films was launched some 18 months ago. RAR happens to be the initials of the phrase "rapid access recording." RAR Films can be processed in solutions as hot as 130°F. From this follows a train of consequences. The hotter a chemical reaction, the quicker the results. The quicker exposed film turns into usable images, the shorter the length of film in process at a time. The less film to be contained in the processing equipment, the smaller the equipment. The smaller a piece of capital equipment, the less imposing. The less imposing, the fewer the people attracted to tend it. The fewer tenders, the less the cost. The less the cost, the more justifiable to strive for the benefits in view. The train at this point enters the tunnel of value judgments, which is ventilated by gusts of emotion.

Emotional response is not wanted from images recorded on the various RAR Films. All are used for capturing data in analog or digital form. One of our newest films of this type is designated "SO-375." It has been emotionally received by one team that tried it out and promptly proclaimed it the greatest thing that ever came down the pike. The team is employed by a very large company that is interested in sunspots.

On February 23, 1956, the sun flared up with more than 10^{32} ergs of electromagnetic and corpuscular emission ranging from 10^{-8} cm to 3×10^3 cm in wavelength and 1 Kev to 15 Bev in kinetic energy. Such outbursts could conceivably affect the comfort and safety of extraterrestrial travel as well as the dependability of terrestrial communications. The International Quiet Sun Year has ended. The 11-year sunspot cycle is on the upswing, as are those travel plans. Along with those plans go plans to keep an eye on sunspots. If a world-wide sunspot patrol can help understand and predict flares, it appears justifiable. Solar markings show up best by Hα light. A 0.5 Å band width is about right. With much more band-pass than that the continuum from the photosphere takes over. Shifting the band 0.5 Å redward or violetward also proves astrophysically illuminating. But 0.5 Å is a pretty thin slice of spectral energy, even for photographing the sun. The previous film favorite for solar markings was beginning to get a little strained for both speed and granularity as improvements in filters narrowed the band-pass and improvements in solar knowledge enhanced interest in the sun's own fine granularity. The new "SO-375" takes up the burden. Its rapid-access feature may prove useful when reliance is placed on world-girdling chains of sunwatching stations to send out flare alerts in seconds. More valuable than its speed, it seems, are its high contrast and the high density attainable. Maybe it *is* the greatest thing that ever came down the pike.

Information about "SO-375" is obtainable from Eastman Kodak Company, Special Applications, Rochester, N. Y. 14650.

A revelation to the keepers of the flame

Devotees of the triumphantly booming cult of atomic absorption spectroscopy need *1-Pyrrolidinecarbodithioic Acid Ammonium Salt* but call it "APDC," or "APDTC," or even spell it out as ammonium pyrrolidine dithiocarbamate. Our well-meaning efforts at consistency of nomenclature for all EASTMAN Organic Chemicals seem to have succeeded in concealing that as EASTMAN 9279 it is available in superior quality at a bargain price of $6.60 for 25 grams or $23.65 for 100 grams from Distillation Products Industries, Rochester, N. Y. 14603 (Division of Eastman Kodak Company). It is reported to extract nearly 30 different metals from dilute aqueous into more concentrated ketonic solution for feeding into the flames now being widely lit in the name of analytical economy.

Since there is a minimum order of $10, you might check for other EASTMAN *Organic Chemicals that need replenishing.*

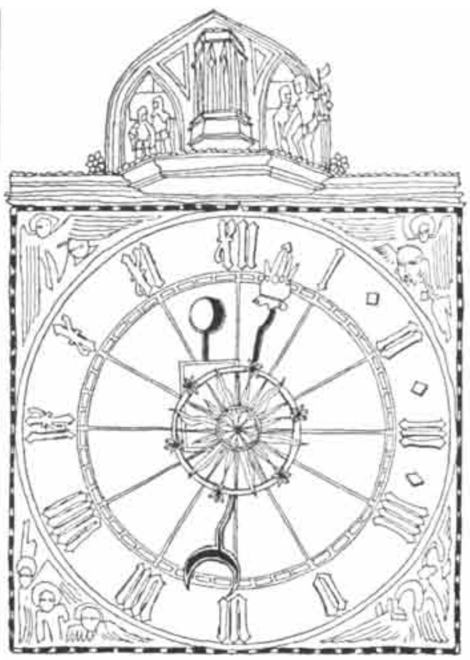
Prices subject to change without notice.

A quick look inside

We are introducing to hospitals and radiologists—physicians who counsel other physicians through diagnosis by x-rays—a processing system which delivers a finished dry radiograph in 90 seconds. In order to make the system work with due regard for current informed opinion on the minimizing of radiation dosage, it has been necessary to develop along with the processor its own brand of film and of chemicals that work unseen inside. There our part ends.

We, along with the rest of the lay world, are free to wonder, however. Ever-growing throngs of human beings deserve and demand the best in health services from a force of physicians and technicians that is unable to expand at the same rate as the demand. Everybody knows all about "waiting for the x-rays." Not everybody knows that a few years ago we cut the minimum waiting time to seven minutes. Now that we have cut it to 90 seconds, the information that the radiologist has trained himself for long years to see in the radiograph can be available in a small fraction of the average total time needed to perform a surgical or other medical procedure. Can this new factor lead, apart from faster throughput, to desirable changes in the procedures themselves? Ask the doctor.

On second thought, better not. He's too busy.



Smoking and Women

The effect of smoking is about the same on women as on men but apparently somewhat less severe. The death rate for women who smoke cigarettes is higher in all age groups from 35 to 84 than it is for nonsmokers, but the mortality ratio (the death rate for smokers divided by the rate for nonsmokers) is less than the ratio for men in all age groups and for almost every disease associated with smoking. These findings are reported by E. Cuyler Hammond of the American Cancer Society in Monograph 19 of the National Cancer Institute, a memorial to the late Harold F. Dorn of the National Institutes of Health. The data come from the society's prospective study of more than a million men and women, who were followed for nearly four years for this report.

Among both male and female smokers total death rates increased with the number of cigarettes smoked each day, the degree of inhaling and the number of years of smoking. The increase associated with each of these variables was less for women than for men. Women as a group, however, start smoking so much later than men, smoke so many fewer cigarettes a day and inhale so much less that it was impossible to compare male and female cigarette smokers who were alike in all three variables.

In women as in men, death rates were much higher among cigarette smokers than among nonsmokers for emphysema; cancer of the lung, mouth, upper respiratory tract, esophagus and pancreas; aortic aneurysm and cirrhosis of the liver. In the case of coronary heart disease and stroke the effect of smoking was most marked in both men and women between the ages of 45 and 54. The mortality ratio was 2.81 in men of this age group for coronary heart disease and 2.00 in women. For stroke the pattern was reversed: the ratio was 2.11 in women and 1.50 in men.

The new study confirmed previous data on the association between cigarette smoking and cancer of the lung in men and showed a similar association in women. The lung cancer mortality ratio for male cigarette smokers from 35 to 84 was 9.20. (There were 12 deaths per 100,000 persons per year among men who never smoked regularly and 111 deaths among cigarette smokers.) The lung cancer mortality ratio was 2.20 for women from 40 to 74 with a history of cigarette smoking. As in the case of men, the ratio varied substantially with the amount and kind of smoking. It was only 1.06 for women who smoked 19 or fewer cigarettes a day, for example, and 4.76 for those who smoked 20 or more; it was 1.78 for those who inhaled slightly or not at all and 3.70 for moderate or deep inhalers.

Telescopes in Orbit

The National Aeronautics and Space Administration is being urged to place in orbit before 1975 two manned reflecting telescopes with an aperture of from 40 to 80 inches, and to launch five to 10 years thereafter a very large reflector with an effective aperture of at least 120 inches. The recommendation is contained in a report made recently by the Space Science Board of the National Academy of Sciences.

The Space Science Board suggests that all the proposed telescopes be equipped to detect radiation between the wavelengths of 800 angstrom units in the far-ultraviolet part of the spectrum to one millimeter in the infrared. The board considered three possible locations for the telescopes: a low orbit (400 kilometers or less), a high orbit (30,000 kilometers or more) and on the moon. The moon has important drawbacks, including high cost and the engineering problems presented by the flexure of the telescope mirror under the influence of gravity. The chief drawback of the low orbit is the occultation of celestial objects by the earth, which would complicate the programming of the telescope and might reduce the net observing time by half. The high orbit satisfies most criteria better than the other two locations, but it may present a radiation hazard to personnel during solar flares. At least 10 hours would be needed to return an operator to the earth from the high orbit. Moreover, the cost of placing a telescope in such an orbit and sending men to operate and maintain it would be high and "could be a conclusive argument for the low orbit."

The Space Science Board coupled its proposals with a strong recommendation for increased support of ground-based astronomy. The board noted that "space astronomy cannot sustain a healthy growth unless ground-based astronomy is also expanding at a somewhat comparable rate."

Pandora's Box

Two physicians at the Harvard Medical School have challenged the validity of an argument put forward with increasing frequency in recent months to justify the use of "nonlethal" gases by U.S. forces in Vietnam. In an extensive review of the medical effects of modern chemical and biological weapons, published in *The New England Journal of Medicine,* Victor W. Sidel and Robert M. Goldwyn assert that there are two principal objections to the contention of certain military spokesmen that such weapons are more humane than other types of weapon:

"This position assumes that once Pandora's box of chemical and biologic weapons is opened, only the most benign will come forth. Most of the agents now available either are benign and relatively ineffective or are lethal, permanently crippling and therefore quite effective. From the types of weapons that have been stockpiled for which instructions for offensive tactical use have been issued, it appears more likely that military commanders will select the most effective and therefore the most lethal.

"Even if a 'humane weapon' is developed, its 'humanity' will require the delivery, as in the laboratory, of a precisely measured dose to a standard victim. Both these requisites have thus far been impossible to attain in the field. Chemical and biologic weapons are notoriously uneven in their dispersal and therefore in the amount absorbed by each recipient; to ensure that every person receives an incapacitating dose, some will have to receive an overdose. Furthermore, the young, the elderly and the infirm will be the particularly susceptible victims."

Sidel and Goldwyn state that physicians have a special responsibility to concern themselves with the "grave ethical considerations" presented by the increasing development and stockpiling of these weapons, both because of their "specialized knowledge about chemical and biologic agents" and because of their "fixed commitment to the health of individuals, singly and collectively." Among the general features of chemical and biological weapons that they believe should be considered are the facts that these weapons are likely to be used against noncombatant populations, that their medical, social and ecological effects cannot be completely predicted and that they can easily be manufactured by countries with limited industrial potential. Sidel and Goldwyn conclude, on the basis of these general features and the information contained in their review of the current status of chemical and biological warfare, that "physicians can do very little about the effects of such agents once they are used. As in other areas of medicine, the major emphasis must be prevention."

X-ray Galaxies

The first two sources of X radiation outside our galaxy have been discovered in data obtained a year ago by means of rocket-borne X-ray detectors. The new sources have been identified by their discoverers, Edward T. Byram, Talbot A. Chubb and Herbert Friedman of the U.S. Naval Research Laboratory, as coinciding with two of the most powerful radio-emitting galaxies, designated Cygnus A and M 87. The X radiation from both galaxies appears to be from 10 to 100 times stronger than the energy they emit in the form of light and radio waves.

Because the earth's atmosphere is essentially opaque to X rays from space, X-ray astronomers must find some means to place their instruments above most of the atmosphere. In the experiments carried out over the past few years by the group from the Naval Research Laboratory this has been accomplished by means of Aerobee rockets fired from the White Sands Proving Ground in New Mexico (see "X-ray Astronomy," by Herbert Friedman; SCIENTIFIC AMERICAN, June, 1964).

The new X-ray source observed in the direction of Cygnus A was not detected on an earlier rocket flight in 1964 because it was overpowered by a nearby X-ray emitter designated Cygnus XR-1, which was identified at the time as the second-brightest X-ray source in the sky. Between the 1964 and 1965 flights Cygnus XR-1 dropped to a quarter of its original brightness, making the discovery of the Cygnus A source possible. Cygnus XR-1 is thus the first clear example of a variable X-ray source.

Improved detectors aboard the more recent rocket have doubled the number of known celestial X-ray sources, which now total about 25. One of the sources discovered in 1964 and designated Cassiopeia A has been identified as the remnant of a supernova within our galaxy. Of the dozen or so discrete sources discovered on previous flights, only one—the Crab nebula—had been identified with a visible object.

A background of unresolved X radiation exists in all directions above the horizon. Its distribution was found to be "lumpy" rather than smooth, indicating that it is composed of a multitude of discrete sources of comparatively low brightness. Friedman and his colleagues estimate that as many as 10,000 of these sources might eventually be identified as X-ray galaxies.

Enhanced Separation

A new principle for separating fluid mixtures has been developed by Richard H. Wilhelm of the department of chemical engineering at Princeton University. Called parametric pumping, it employs oscillations in temperature to push to limiting conditions the chemical separation that can be achieved when a solution is brought in contact with particles of an adsorptive material. The new process is now being compared in cost and efficiency with such conventional processes as distillation and solvent extraction.

A simple embodiment of the new process can be described as follows. An adsorbent, which can consist of particles of an ion-exchange resin, is placed in a column. At each end of the column is a reservoir whose contents can be displaced and pushed through the column by a piston. One reservoir contains a heating element, the other a cooling element; accordingly before each passage through the column the solution is either heated or cooled. As the solution is passed repeatedly through the column on a carefully regulated time schedule the fluid reaching one reservoir (usually the heated one) becomes progressively enriched in one or more of the solutes until a limiting concentration is reached. Without the alternate heating and cooling there would be no change in the composition of the solution after the first pass through the column.

This process can be modified in many ways. For example, in an industrial installation the fluid mixture would probably be passed through a cascade of columns instead of being passed back and forth through a single column. Wilhelm has been assisted in his experiments by Alan Rice and Alan Bendelius.

A Human Protein Synthesized

The first synthesis of a human protein has been reported by a group of workers at the Brookhaven National Laboratory. The protein is insulin; the workers are Panayotis G. Katsoyannis, Andrew M. Tometsko, Clyde Zalut, James Z. Ginos and Manohar A. Tilak. Human insulin is the third protein to be made artificially. The others are sheep insulin, synthesized two years ago by Katsoyannis and his co-workers at the University of Pittsburgh, and beef insulin, made by a group of Chinese chemists.

An insulin molecule is composed of two amino acid chains. The *A* chain has 21 amino acids and the *B* chain 30. In this respect human, sheep and beef insulin are the same; they differ somewhat in the amino acids they contain. The Brookhaven investigators, describing their work in two communications published in the *Journal of the American Chemical Society*, report in the first the synthesis of the *B* chain of human insulin. In the second they report the synthesis of the *A* chain "and its combination, either with the natural bovine *B* chain or with the synthetic human *B* chain, to generate insulin activity" when tested in mice. The authors express the hope that, although "the overall yield of the all-synthetic human insulin produced was approximately 2 percent of theory," new techniques they have developed for recombining *A* and *B* chains will make possible "considerably higher" yields.

Even if higher yields can be obtained, it is not expected that synthetic human insulin will supplant natural insulin from animals in the treatment of diabetes. For the foreseeable future the supply of animal insulin seems adequate for this purpose. On the other hand, reasonable quantities of human insulin will make it possible to conduct new experiments on the role of insulin in human physiology. For example, it should be possible to elucidate the role of various parts of the insulin molecule by omitting or changing them in the process of synthesis.

Oldest New World Community

Archaeological evidence that as many as 20 families of Paleo-Indian hunters of the American Southwest lived together in a community of semipermanent dwellings in about 8000 B.C. has recently been presented by Frank Hibben of the University of New Mexico. This date is some 4,500 years before the earliest formal village settlements—those of farmer-fishermen along the west coast of South America—arose in the New World (see "Early Man in Peru," by Edward P. Lanning; SCIENTIFIC AMERICAN, October, 1965). The estimated age of the New Mexico community, which stretches along the shore of a now vanished lake near Albuquerque, is based on the presence of numerous Folsom projectile points at the site; these delicately flaked and hollowed flint points are found elsewhere in association with a species of bison that died out 10,000 to 15,000 years ago.

The Albuquerque site, known as Rio Rancho, has yielded more than 8,000 points, scrapers, gravers and other stone tools. Hibben states that it "already... has been more productive of Folsom artifacts than any other [site] previously known." A score of circular "lodge floors" 12 to 15 feet in diameter, which remind Hibben of the floors of tepees used by the Plains Indians before the introduction of the horse, have yielded an abundance of charcoal from which precise carbon-14 dates for the site should be obtained.

Until recent years sizable semipermanent communities of Paleolithic hunters were almost unknown in the Old World and were totally unsuspected in the New World. The terrain at Rio Rancho favored the communal driving and slaughter of bison. In Old World Paleolithic sites that are roughly comparable—those of the 16-mile Kostenki complex along the Don River in the U.S.S.R.—the food animal was the mammoth. In both instances conditions of plenty evidently fostered the growth of larger human groups.

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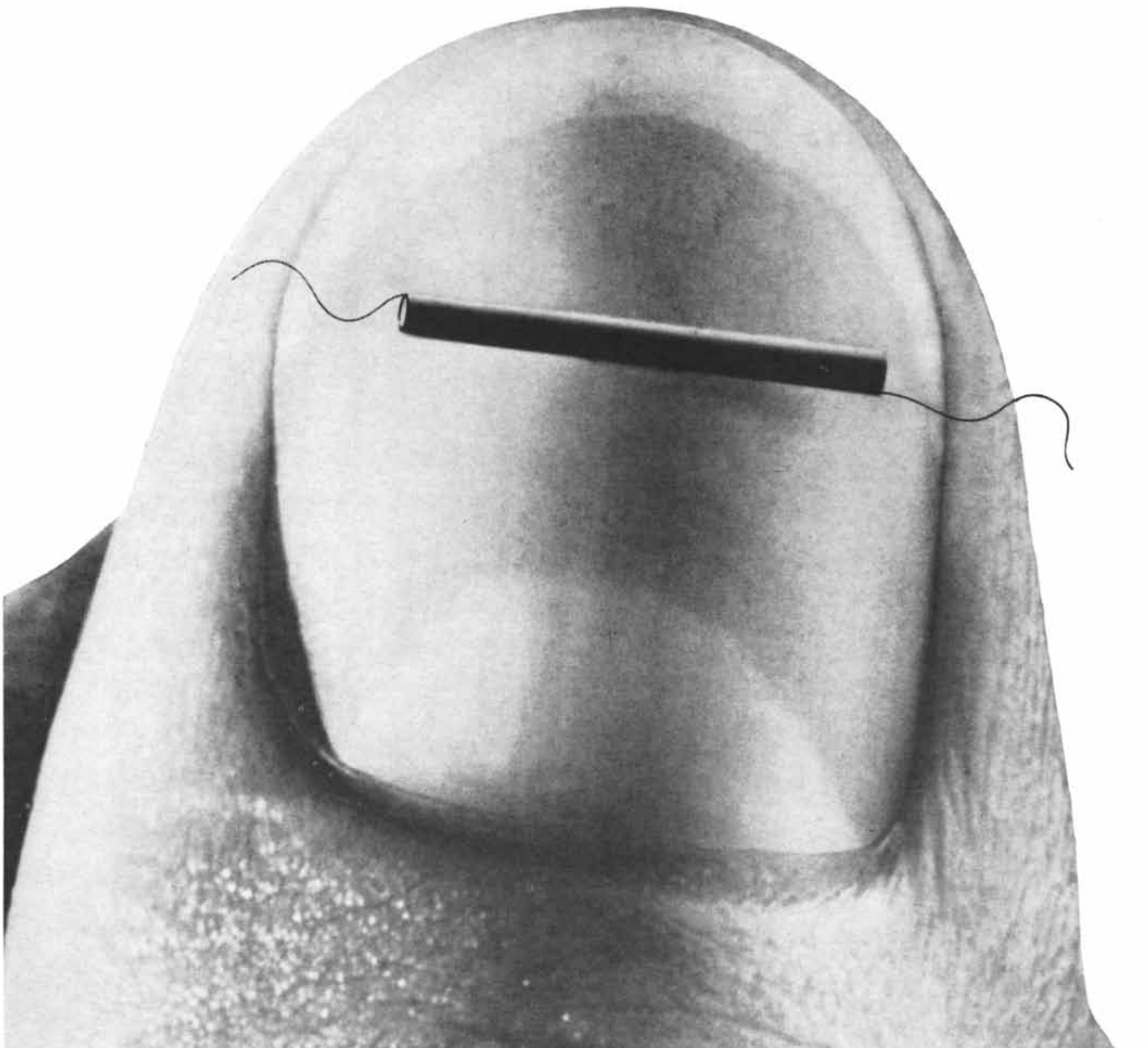

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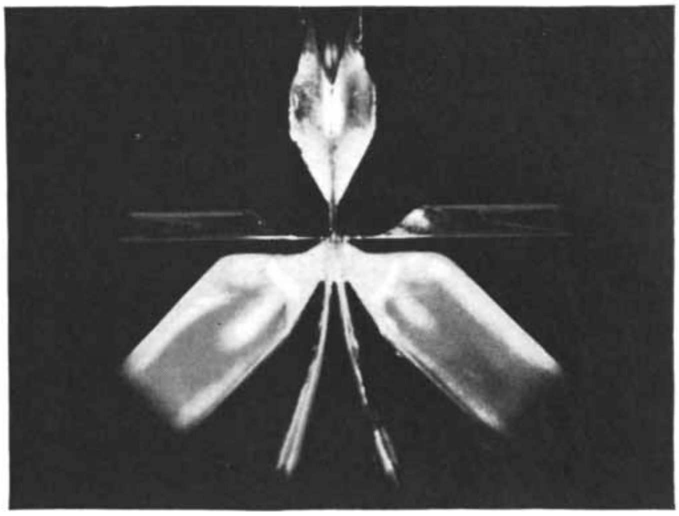

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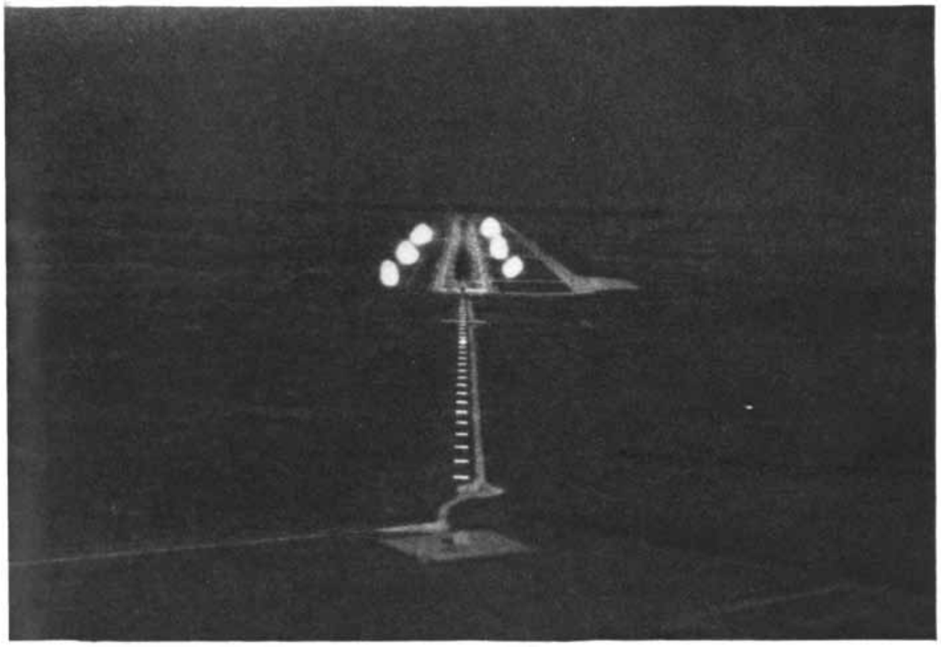

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The Photographs from Mariner IV

How they were made and what they show is reviewed. The second of three articles on the remarkably successful Mariner mission

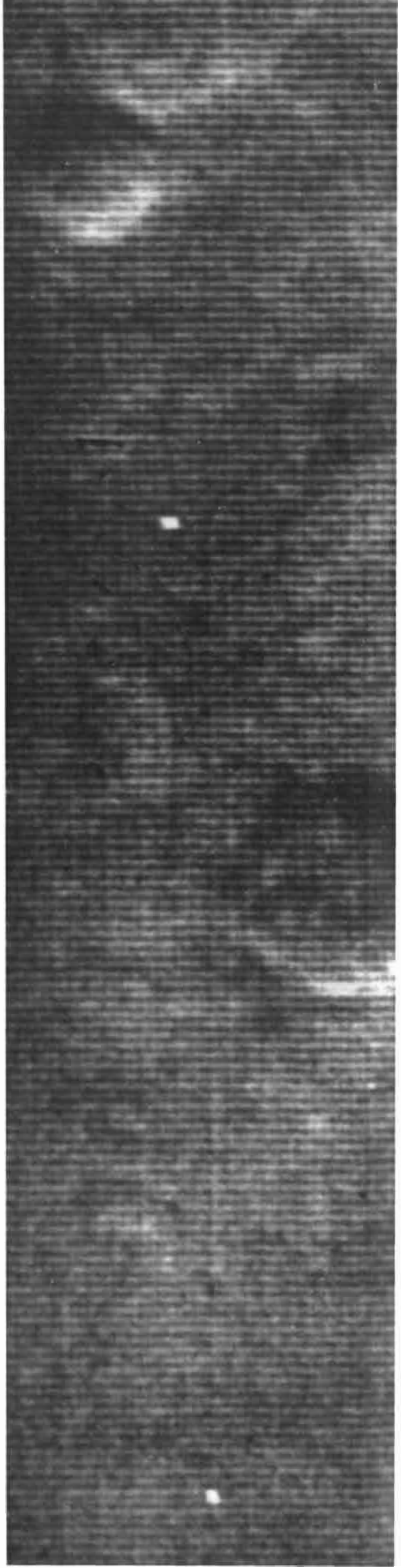
by Robert B. Leighton

It seems likely that in the 350 years since the telescope was invented more time has been devoted to viewing and photographing Mars than to any other planet. The reason is that Mars is the only planet (apart from the earth) on which it is possible to perceive permanent surface markings. Last July 14 the spacecraft *Mariner IV* made 22 photographs of Mars that represented an improvement in optical resolution over earlier photographs comparable to that which Galileo's telescopic observations of the moon represented over what had previously been visible with the unaided eye.

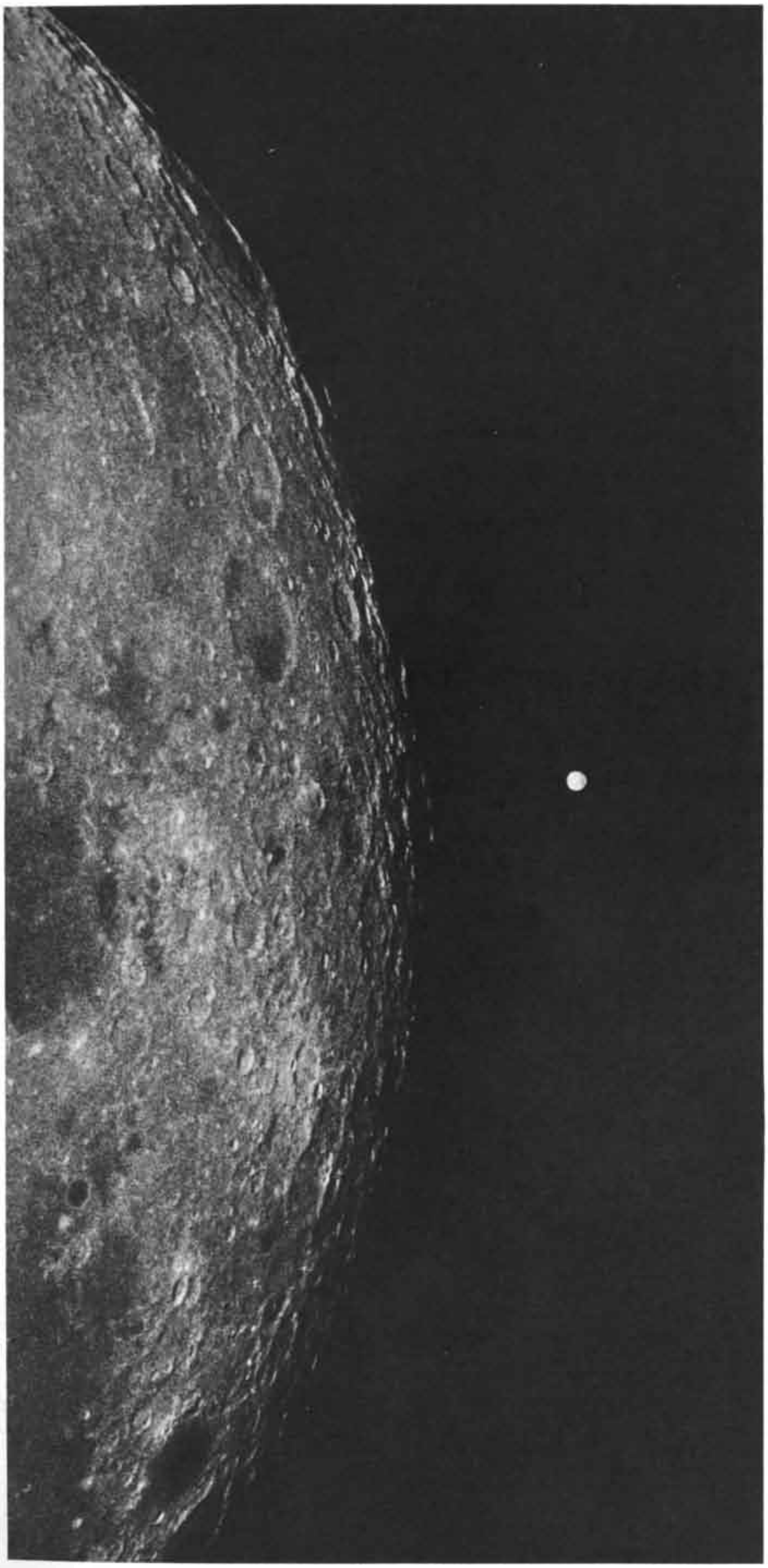
At the 15-to-17-year intervals when Mars makes a particularly close approach to the earth (a distance of some 35 million miles), its disk is about a 70th the diameter of the moon as it is seen from the earth, or about half the size of a typical lunar crater [*see illustration on page 56*]. Within the compass of this tiny area three centuries of astronomers have given specific names to dozens of surface features. The most prominent of all, first shown in a drawing made by Christian Huygens in 1659, is Syrtis Major, which in shape and location somewhat resembles the terrestrial subcontinent of India. Syrtis Major actually projects into the northern hemisphere of Mars, but according to astronomical custom photographs of Mars are usually printed with the Martian south pole at the top; hence Syrtis Major appears to point down [*see illustration on page 57*].

The most widely discussed features of Mars are of course the "canals"—those straight-line markings that are firmly vouched for by many leading observers of the planet, and just as firmly doubted by others. Because fine detail on Mars is continuously shifted in and out of focus by thermal inhomogeneities in the earth's atmosphere, the canals have been particularly difficult to capture on photographic plates. Nevertheless, photographs do provide some evidence for their existence.

Concerning other features of Mars there is no dispute. Photographs show clearly that something resembling an ice cap forms first on one pole, then on the other, as the inclination of the planet's axis to the plane of its orbit around the sun produces summer and winter seasons. The polar cap slowly disappears with the coming of the Martian spring. Because the atmosphere of Mars is exceedingly thin (as has been verified by the occultation experiment performed by *Mariner IV*), it is somewhat difficult to believe that it contains enough water vapor to give rise to a polar cap with such whiteness and such a slow rate of



CRATERED FACE OF MARS is revealed in the now famous Picture No. 11 taken by *Mariner IV* from a distance of 7,800 miles on July 14, 1965. The large crater that fills most of the picture is about 75 miles in diameter. The clearly defined small crater on its rim is about three miles across. The center of the picture is at 32 degrees South latitude, 197 degrees East longitude. The sun is shining on the surface from the north, which is at the top. The picture was taken through a green filter. Other *Mariner IV* pictures of Mars begin on page 61.



APPARENT SIZE of the moon and Mars indicates the difficulty of observing surface features on Mars from the earth. When this picture was made in December, 1911, at the Lowell Observatory, Mars was 50 million miles away. At times it comes to within 35 million miles.

retreat. It has been suggested, however, that the polar caps may consist not of frozen water but of frozen carbon dioxide, an alternative that seems much more in keeping with what is known about the composition of the Martian atmosphere.

With the changing seasons there are also apparent changes in the coloration of dark regions such as Syrtis Major. The observed color is reported to range from yellowish brown to blue-green. Infrared photography and other tests demonstrate conclusively that the blue-green color is not due to the presence of chlorophyll. The color change may represent a purely inorganic phenomenon, for example a change associated with alterations in the degree of hydration of certain minerals. Finally, in addition to the "canals," polar caps and color changes, there are clearly discernible disturbances in the Martian atmosphere that appear to be clouds and dust storms. After such disturbances there are often pronounced changes in the visibility of the planet's surface features, and over the years certain features change in shape and color.

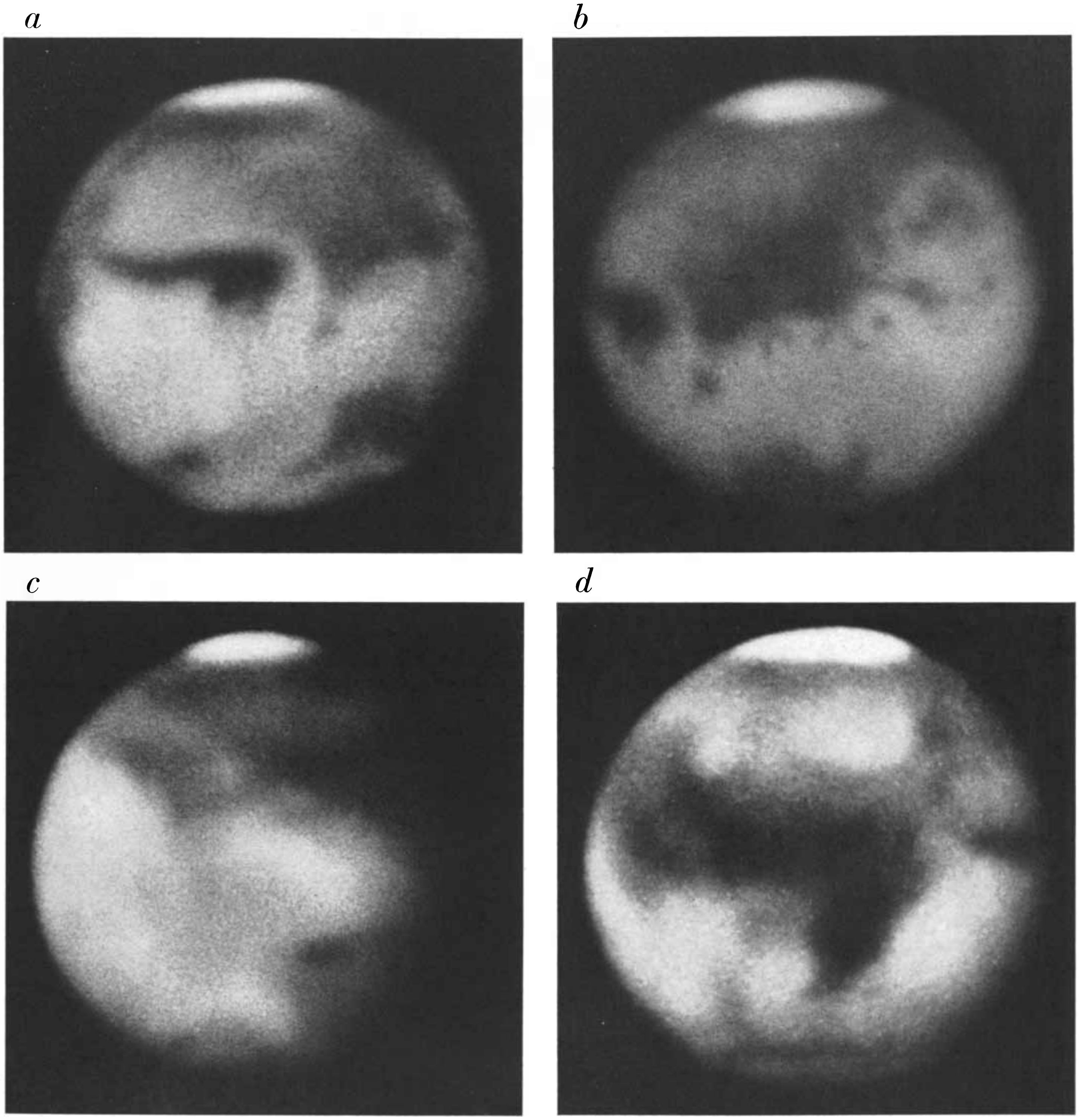
The Origins of the Program

My own interest in Mars dates back about a dozen years, when I devised a simple technique that I hoped would stabilize the image of a planet while it was being photographed. During the summer of 1956, when Mars made its last close approach to the earth, I took hundreds of color pictures of the planet on 16-millimeter film, using my stabilizing technique in conjunction with the 60-inch reflecting telescope on Mount Wilson. As luck would have it, a large dust storm developed midway through the most favorable picture-taking period and partly frustrated not only my efforts but also those of astronomers at other observatories.

A few years later, when the National Aeronautics and Space Administration, working through the Jet Propulsion Laboratory of the California Institute of Technology, began to plan spacecraft that could carry out missions to the nearby planets, it was natural for some of us at Cal Tech to consider the possibility of taking closeup pictures of Mars. Accordingly Bruce C. Murray, Robert P. Sharp and I proposed to NASA that Mars be photographed by a television camera placed aboard a spacecraft.

The proposal was accepted in 1962, and we were invited to develop our ideas in collaboration with the technical staff of the Jet Propulsion Laboratory. J. Denton Allen's electronic group and Richard K. Sloan, who served as project scientist, played major roles in bringing the television system into existence. The spacecraft then being designed for a mission to Mars at the next favorable opportunity—1965—was known as Mariner B. This was to be a spacecraft weighing from 1,200 to 1,500 pounds launched by an Atlas/Centaur vehicle. When the liquid-hydrogen-fueled Centaur ran into delays, the mission was recast to make use of an Atlas/Agena launch vehicle, which could send only about a third as much weight to the vicinity of Mars. The craft for this mission, designated Mariner C, ultimately became the successful *Mariner IV* [see "The Voyage of Mariner IV," by J. N. James; SCIENTIFIC AMERICAN, March].

For the heavier Mariner B we had planned to use two television cameras, one to provide 20 close-ups and the oth-

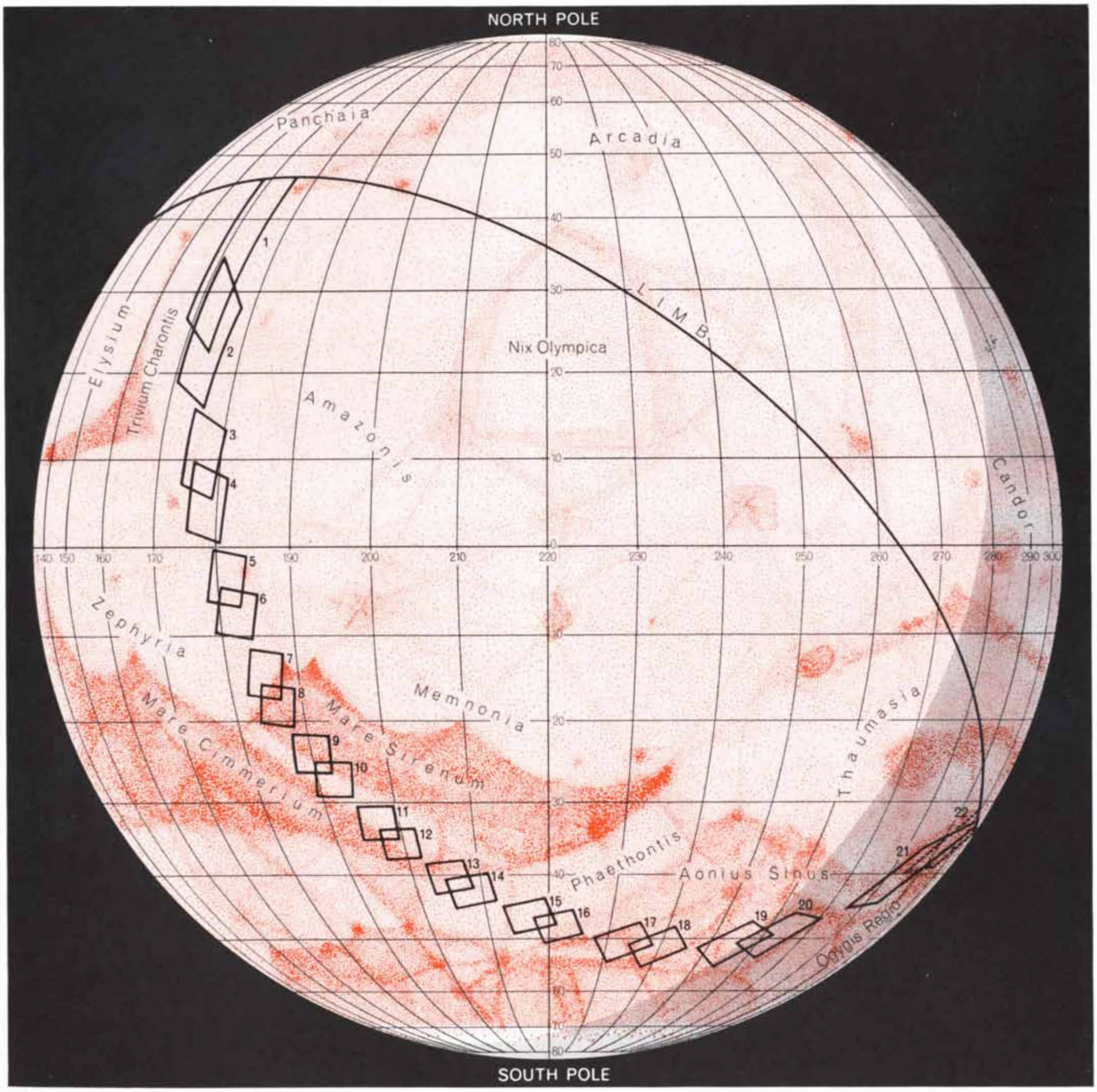


FOUR VIEWS OF MARS are representative of the best that can be made from the earth. All were taken at the Lowell Observatory. Picture *a* was made in 1954 when Mars was 40 million miles away; the other three were taken during the close approach of 1939, when the planet came to within 36 million miles of earth. The four views show how the planet, rotating to the left, presents different aspects to earth-based observers. The four views are centered on the following degrees of East longitude: picture *a*, 4 degrees; picture *b*, 47 degrees; picture *c*, 187 degrees; picture *d*, 283 degrees. The prominent feature Syrtis Major, which resembles the subcontinent of India, is clearly visible in picture *d*. The *Mariner IV* photographs trace a vertical path close to the center line of picture *c*, beginning to the left of the dark region at the lower right (Trivium Charontis) and traveling upward (southward) into the dark regions at upper left (Mare Cimmerium and Mare Sirenum). These and other regions are identified in the map of the scan path on the next page.

er to provide 20 views in two colors (red and green) of the entire disk of the planet. The closeup pictures were to have had a resolution of one kilometer and the full-disk pictures a resolution of five kilometers. This resolution was to have been achieved by using a television system that recorded 160,000 (400 by 400) picture elements per frame. The whole system of two cameras would have weighed about 50 pounds.

When the television system had to be redesigned for Mariner C, we were limited to about 30 pounds, including the tape recorder needed for data storage. Because this reduced the data-storage space to about 10 percent of the space originally available, we were obliged to settle for one camera and a television system that recorded only 40,000 (200 by 200) picture elements per frame. The camera selected had a focal length intermediate between the focal lengths of the two cameras originally planned and could resolve surface features of one or two kilometers. The specific focal length selected, 12 inches, was determined by the fact that it was assumed for planning purposes that the distance between the spacecraft and Mars when the pictures were being taken would be between 12,000 and 15,000 kilometers (7,500 and 9,300 miles).

The other characteristics of the camera system followed from the resolution desired, the focal length and the sensi-



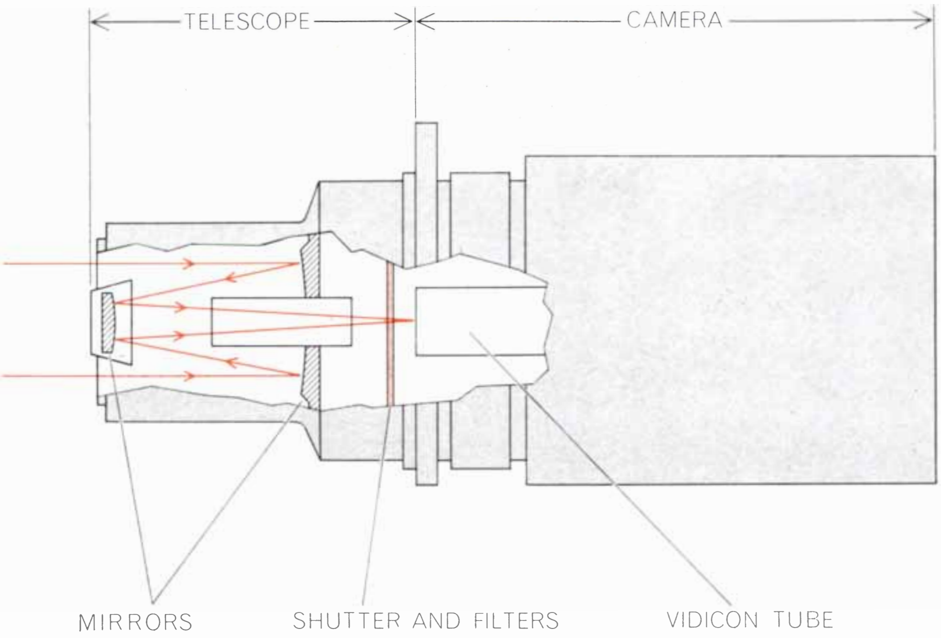
REGIONS PHOTOGRAPHED by *Mariner IV* are plotted on a pictorial representation of Mars that shows some of the prominent surface features reported by astronomers over three centuries. The map, centered on 220 degrees East longitude, is based on one prepared by the Army Map Service. Picture No. 1 caught the limb, or edge, of the planet as *Mariner IV* observed it from a position about 8,000 miles below the plane of Mars's orbit, at a slant range of 10,500 miles. As the spacecraft swept under the planet, the television scan path progressed toward the southeast and in Picture No. 19 moved across the terminator (the light-dark boundary). The last three pictures were taken in complete darkness. The coordinates of the last picture have not yet been well established.

tivity of the Vidicon television picture tube. The shutter speed had to be held to a fifth of a second or less in order to limit blurring of the image caused by the spacecraft's motion of four or five kilometers per second with respect to Mars. The light sensitivity of the television picture tube then established that the aperture had to be about an eighth of the focal length, giving a focal ratio of $f/8$. To obtain the optical system we needed within the prescribed limits of weight and size—and with optical components that had proved themselves in space flight—we selected a reflecting telescope of the Cassegrain type with an aperture of 1.5 inches [*see top illustration at right*]. The development of the entire television system was handled by engineers of the Jet Propulsion Laboratory.

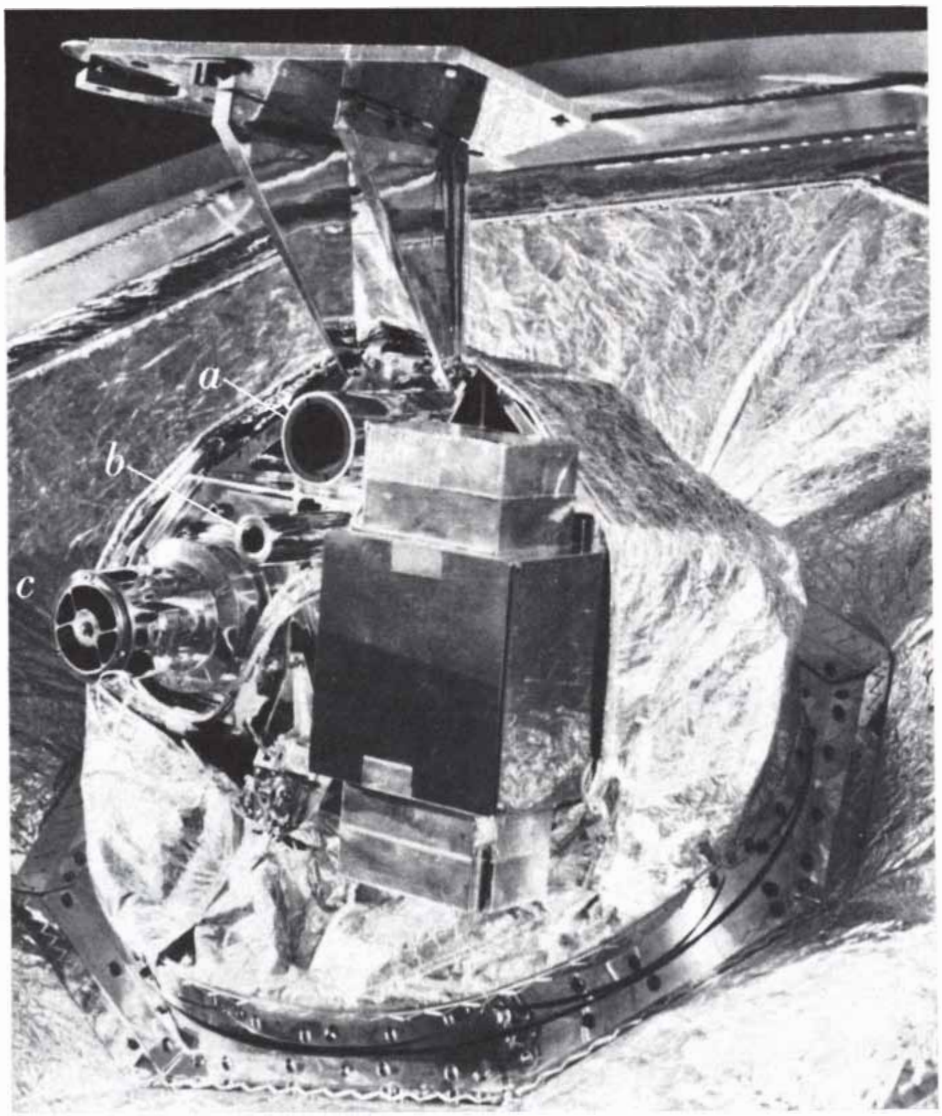
To transmit the pictorial data back to the earth various signaling schemes were considered. One sophisticated scheme involved data compression, in which only a change of intensity from one picture element to the next would be transmitted. We also had to decide whether to transmit the signal in analogue or digital form. (Ordinary television signals are transmitted in analogue form.)

Experience had shown that the best way to send a weak radio signal through space in the presence of background noise is to use a signaling method known as pulse-code modulation. In this signal-coding method the output of an electrical device, whether it be a thermometer or a television camera, is coded into a sequence of "bits," or binary digits made up of 0's and 1's, that represent a particular level of intensity. Accordingly the output of the *Mariner IV* television camera was translated into a six-bit code that identified the brightness of each picture element on a scale that had 64 steps from full black to full white. The 64 steps of the sequence ran from 0 to 63. A sequence of six 1's represented full black, or no light at all; a sequence of six 0's represented full white, or maximum light. To encode the information contained in 40,000 picture elements therefore required 240,000 binary digits. These were transmitted back to the earth at the rate of 8⅓ bits a second. The total transmission time for a single picture should have been eight hours; in actuality 8⅓ hours were required because a small amount of extra information, such as that required for synchronization, had to be sent with each picture.

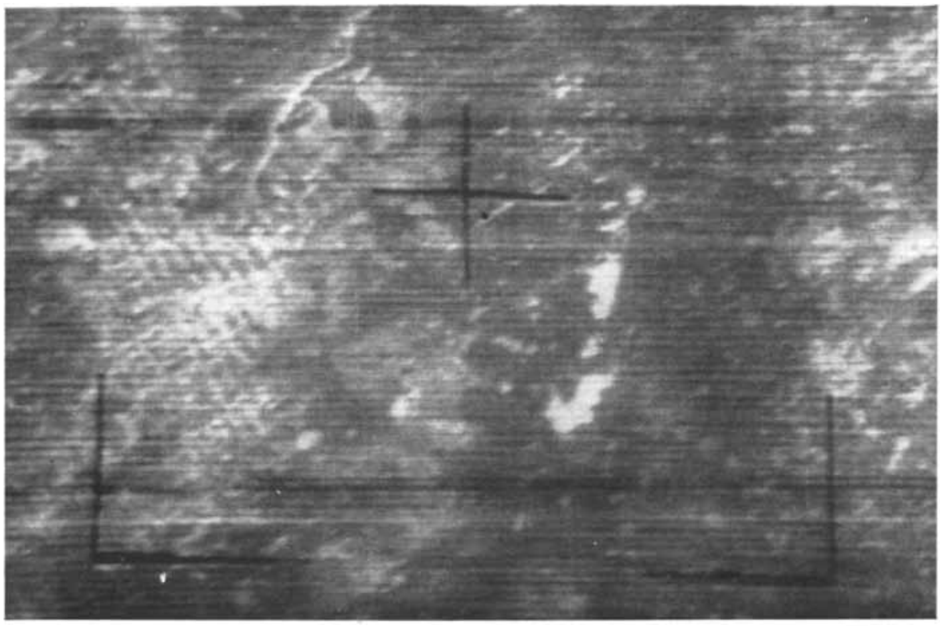
In an effort to obtain information about the surface coloration of Mars, we



TELEVISION CAMERA on *Mariner IV* consisted of a reflecting telescope of 12-inch focal length and a focal ratio of $f/8$. The image produced on the face of the Vidicon tube was .22 inch square. The image was converted into a television picture of 200 lines that contained 200 picture elements per line. The camera and electronics weighed approximately 30 pounds.



TELEVISION-SCAN PLATFORM carried wide-angle (*a*) and narrow-angle (*b*) sensors that picked up the sunlight reflected from Mars, which was used to aim the television camera (*c*).



IS THERE LIFE ON EARTH? This view of earth was taken by the narrow-angle camera of a Tiros satellite, which could resolve features of about .2 kilometer compared with about one or two kilometers for the camera of *Mariner IV*. Made after a fresh snowfall in April, 1961, the Tiros picture shows a checkerboard pattern produced by a timbering operation in the Canadian Province of Ontario. Had this not been known, the pattern would have remained a mystery. An examination of thousands of pictures made by weather satellites turned up only this and one other that showed presumptive evidence of human activity on the surface of the earth. (Contrails of jet aircraft, however, show up frequently.) The other showed faint traces of a new highway in Tennessee. The two pictures appear in a study by Steven D. Kilston of Harvard College, Robert R. Drummond of the National Aeronautics and Space Administration and Carl Sagan of the Smithsonian Astrophysical Observatory.

designed the television system to take overlapping pairs of pictures, with one member of each pair being taken through a green filter and the other through a red filter. A wheel carrying four filters, alternately red and green, was arranged to rotate 90 degrees after each exposure, thus producing a sequence of pictures alternately red and green. To have recorded all these pictures, however, would have used up all the data-storage capacity long before the television scan path had crossed the planet. To stretch out the sequence and yet have some pairs of overlapping colored pictures, every third picture was omitted from the stored sequence. Hence the overlapping pairs of pictures followed the sequence green-red, red-green, green-red and so on.

Although the system was provided with automatic gain control to adjust for changes in the brightness of the Martian surface, the gain adjustment could function only after the first picture had been recorded on the face of the Vidicon tube and had been scanned electronically. Furthermore, in order to keep the gain control simple and not run the risk of a large error in correction between pictures, the gain correction was made only on the basis of the green image and then was limited to a gain change, up or down, of only one step, representing a factor of three. This meant that we had to estimate the exposure rather accurately for the first picture or several of our precious pictures might be wasted before the gain-control system could make the corrections.

Even after we had gone through the calculations several times we could not feel satisfied until the system had been tested on some real object, illuminated by the sun itself, outside the laboratory. The moon seemed an ideal subject; its reflectivity, compared with that of Mars, is known with considerable certainty. Accordingly we attached the *Mariner IV* camera-and-television system to the 60-inch telescope on Mount Wilson and checked its operation as we scanned a less than full moon from its bright side across the terminator to the dark side. The test not only confirmed our calculations but also increased our confidence in the operation of the whole system.

The Path of the Photographs

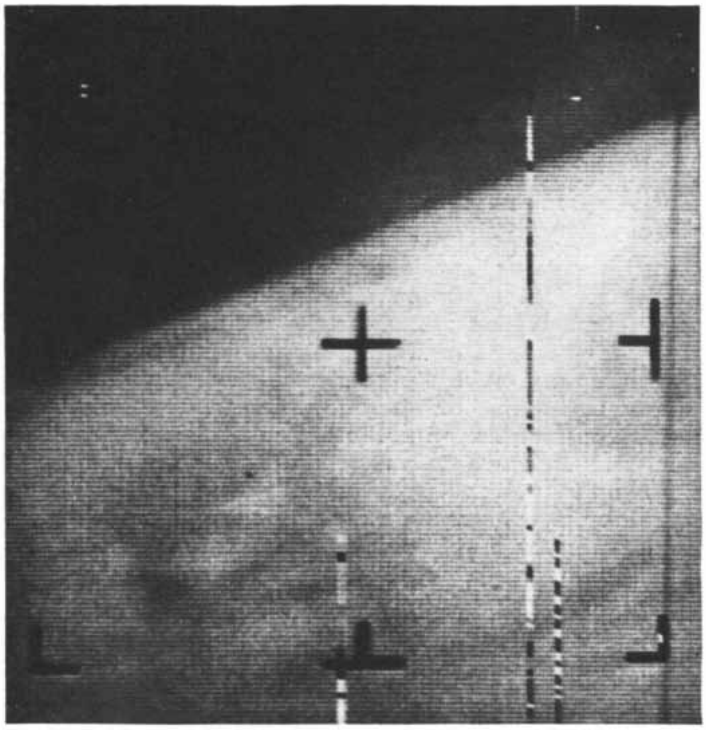
Meanwhile we had also discussed among ourselves and with trajectory experts at the Jet Propulsion Laboratory the question of what regions of Mars to photograph. We knew that if everything functioned perfectly we would at best be able to photograph about 1 percent of the planet's entire surface. We concluded that the best scan paths were those that crossed the largest number of light and dark regions. Naturally we were also anxious to photograph regions in which canal-like markings had most consistently been reported. Finally, we wanted the camera to view the side of the planet including Syrtis Major in at least some of its pictures.

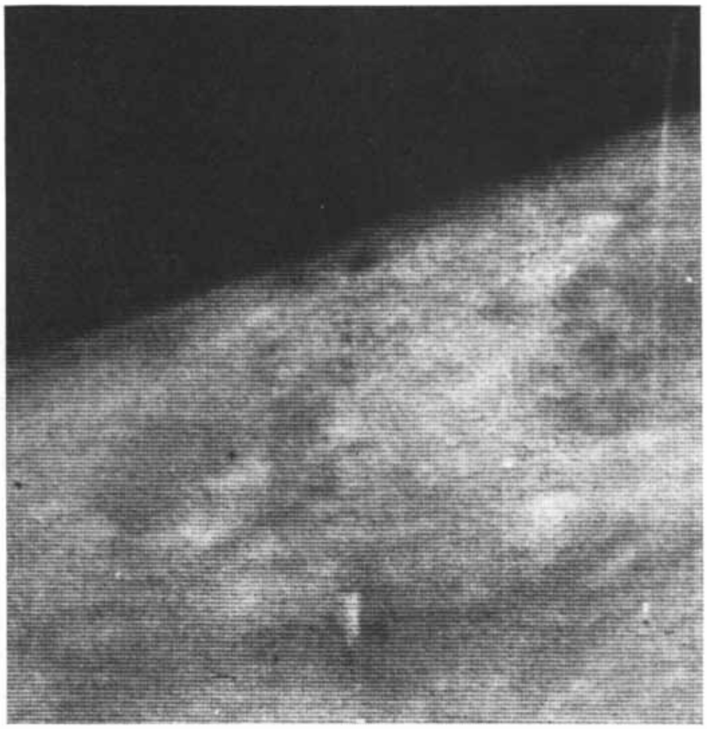
The needs of the television experiment were not the only ones, however, that had to be considered in selecting *Mariner IV*'s flight path. For example, the spacecraft could not be allowed to pass in the shadow of Mars or it would lose its fix on the sun; it could not pass above Mars or it would lose its fix on Canopus, the star that would be used to control the orientation of *Mariner IV* around its roll axis. In addition, the flight path had to carry the spacecraft behind Mars so that its radio would be blacked out in the occultation experiment that would provide information about the density of the Martian atmosphere.

One final requirement, however, placed such a restriction on the flight path that in the end it proved impossible to have the camera pointing anywhere near Syrtis Major. This was the requirement that California be facing Mars at the time of encounter, so that the powerful transmitter at the Goldstone tracking station near Barstow, Calif., would be in a position to send last-minute commands to the spacecraft if that proved necessary. The desired time of encounter was to be achieved by making an appropriate adjustment in the spacecraft's trajectory at the time of the mid-course maneuver, which actually took place on the eighth day of flight. The maneuver could adjust the encounter time to any desired value over a period of several days, but because the earth and Mars rotate on their axes at nearly the same rate, it was impossible to delay or accelerate the encounter sufficiently during the favorable 1965 launch period for Syrtis Major to be facing *Mariner IV*'s camera at the same time that Goldstone was facing Mars.

The Photographs Are Made

The story of the launching and flight of *Mariner IV*, after the structural failure of the shroud of *Mariner III*, was told in last month's issue of *Scientific American* by J. N. James. To recapitulate briefly, *Mariner IV* was launched on November 28, 1964. On the 78th day of flight a command was given to remove



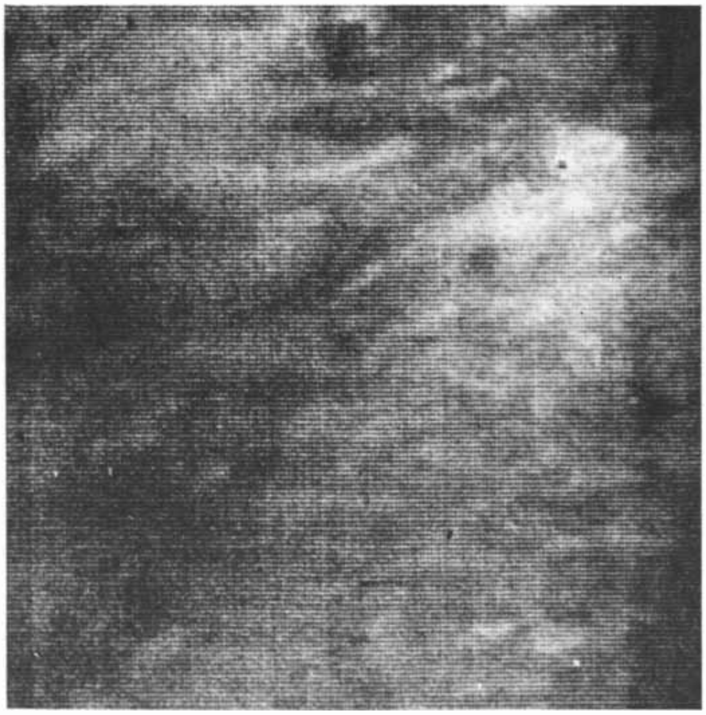


MARINER PICTURE NO. 1, taken through a red filter, is shown after two stages of computer processing. In this and subsequent pictures north is at top. The second processing (*right*) enhanced the contrast by a factor of two. Because the sun is only 25 degrees from the zenith there are no strong shadows to bring out detail. The distance along the limb of the planet is about 410 miles.

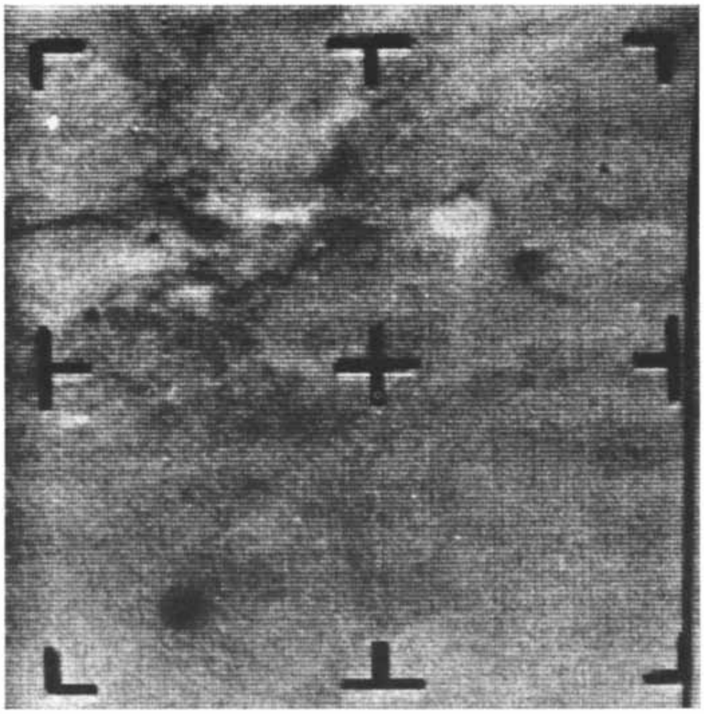
the lens cover from the television camera to avoid the possibility that an attempt to remove it just before encounter, as originally planned, might cause last-minute problems that could not quickly be corrected. (One fear was that moving the lens cover might jar loose dust particles that would gleam like stars in the sunlight and disorient the Canopus-sensor.)

At the same time that the lens cover was removed the scanning platform that carried the camera was tested and left in a position that was correctly aimed at Mars, on the basis of the computed flight path. The concern here was that the platform bearings might "freeze" in the course of the seven-and-a-half-month flight through the high vacuum of space and not move on command when sensing devices responded to light reflected from Mars.

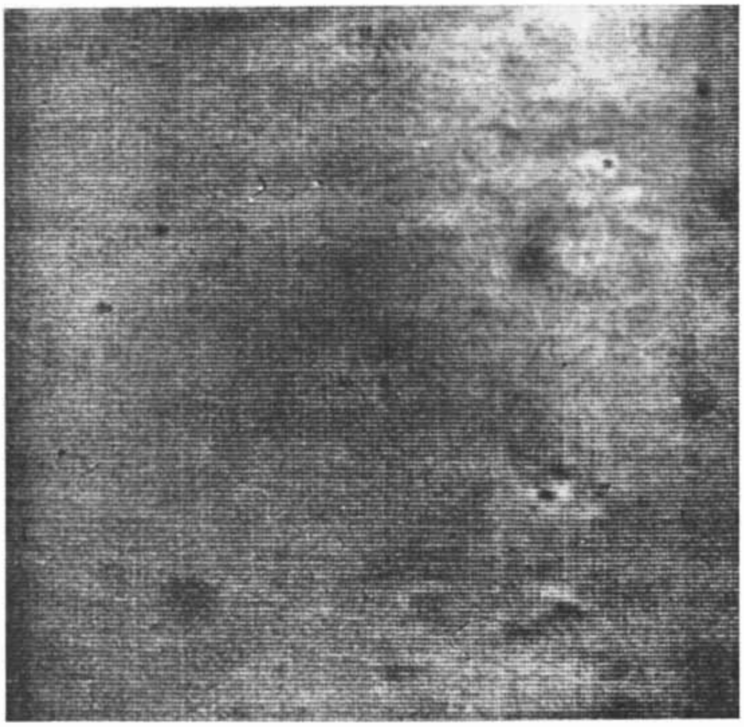
On July 14, 1965, on the 228th day of flight, when *Mariner IV* was about

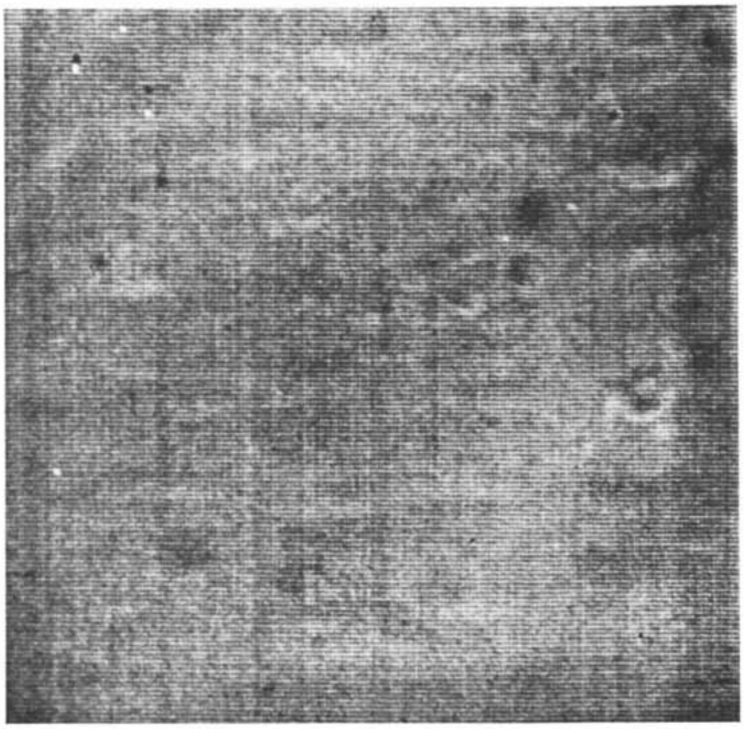


PICTURE NO. 2, taken through a green filter, shows even fewer features than Picture No. 1. The sun is 20 degrees from the zenith. The upper left corner of the picture overlaps the lower right corner of the first picture. The picture is enhanced by a factor of two.



PICTURE NO. 3, also taken through a green filter, was the first to show good surface detail. The sun is 14 degrees from the zenith; the enhancement factor is five. The area shown in the picture measures 220 miles from east to west and 310 miles from north to south.

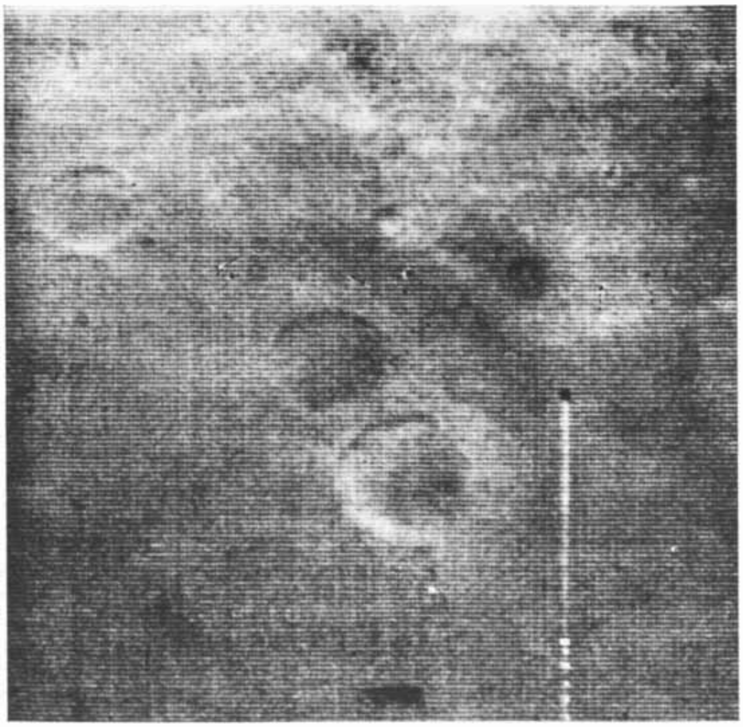


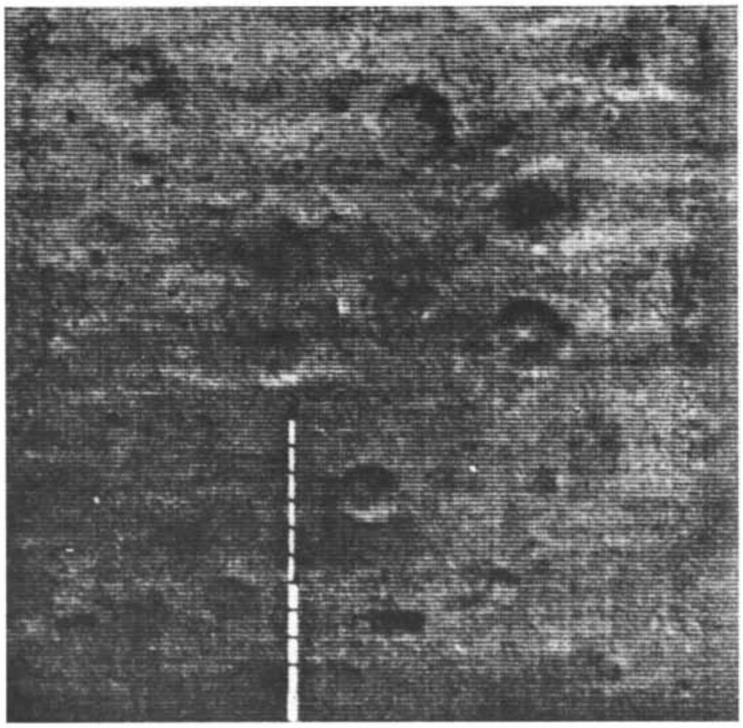


PICTURES NO. 4 THROUGH NO. 7 carry the television sequence from the northern hemisphere of Mars into the southern hemisphere. The sun remains within 29 degrees of the zenith, providing little shadow relief. The filter sequence is red, red, green, green; the enhancement factor is two. The first circular features that can definitely be identified as craters show up in Picture No. 5, a region

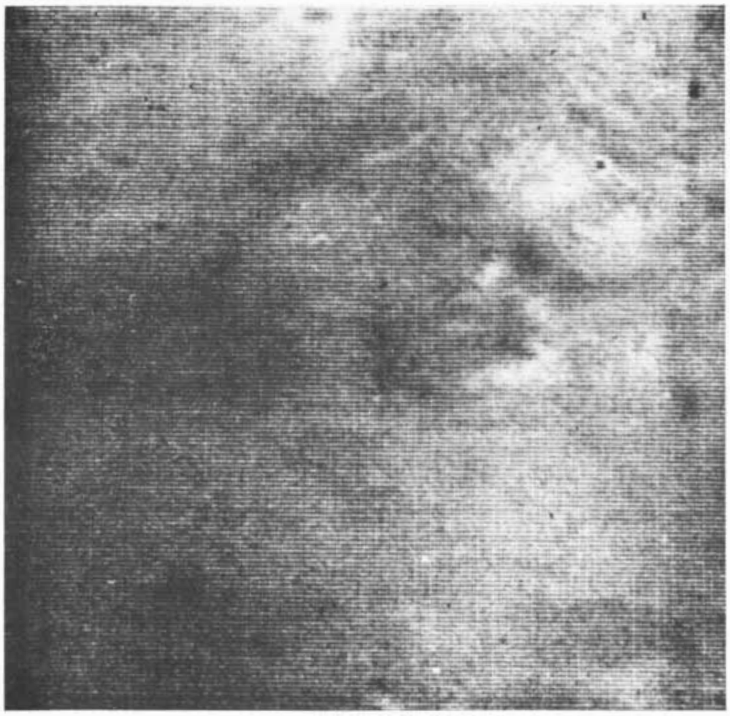
20,000 miles from Mars, a command from the earth switched on the Mars-acquisition system that was linked to the scanning platform. The platform responded. Simultaneously the television system was switched on and began warming up preparatory to the actual picture-taking. The shutter began operating and the Vidicon's electron beam scanned the blank "pictures" of space, but according to plan none of these pictures was recorded.

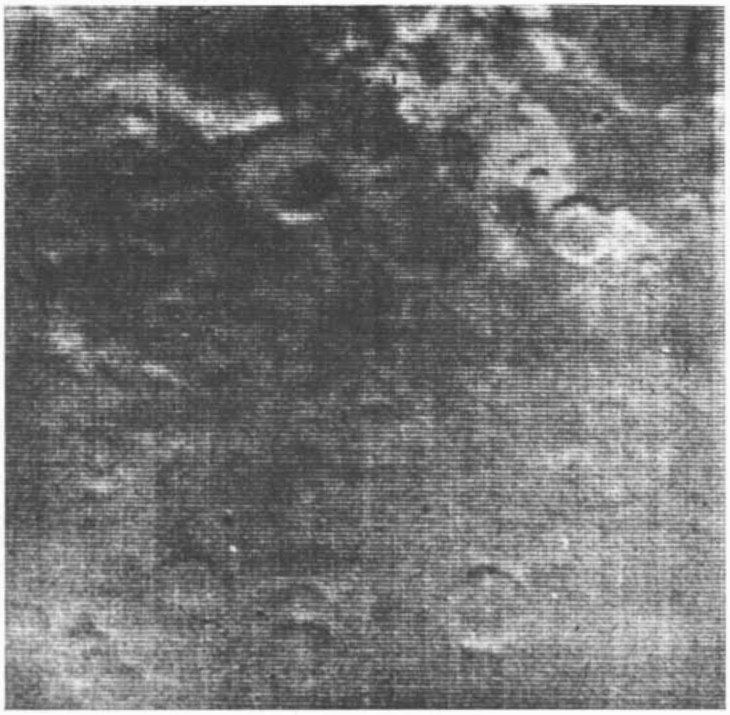
The actual recording of pictures could have been initiated in any of three ways: by the narrow-angle planet-sensor, which responded to sunlight reflected from Mars; by a sufficient brightening of the television images, indicating a bright object in the picture, or by direct command from the earth. In case both of the built-in systems failed, a precisely timed command sent from the earth 12 minutes earlier would order the picture-taking and -recording to





PICTURES NO. 8 THROUGH NO. 11 show steadily increasing contrast as the angle of the sun from zenith increases from 32 degrees to 47 degrees. It is now midafternoon on Mars. The filter sequence is red, red, green, green; the enhancement factors are two, four, two, and four. The slant range decreases steadily from 8,300 miles to 7,800 miles. In Picture No. 11 the area covered is 170

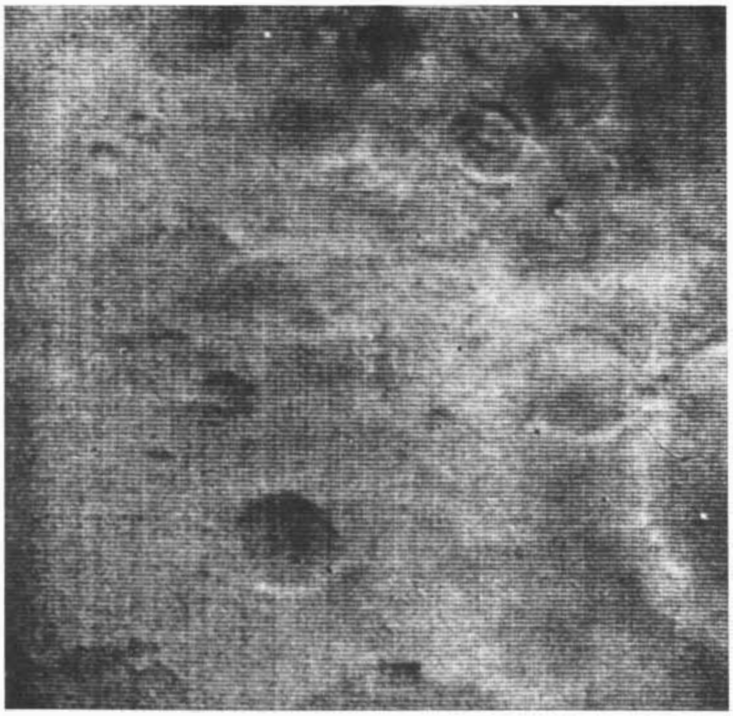


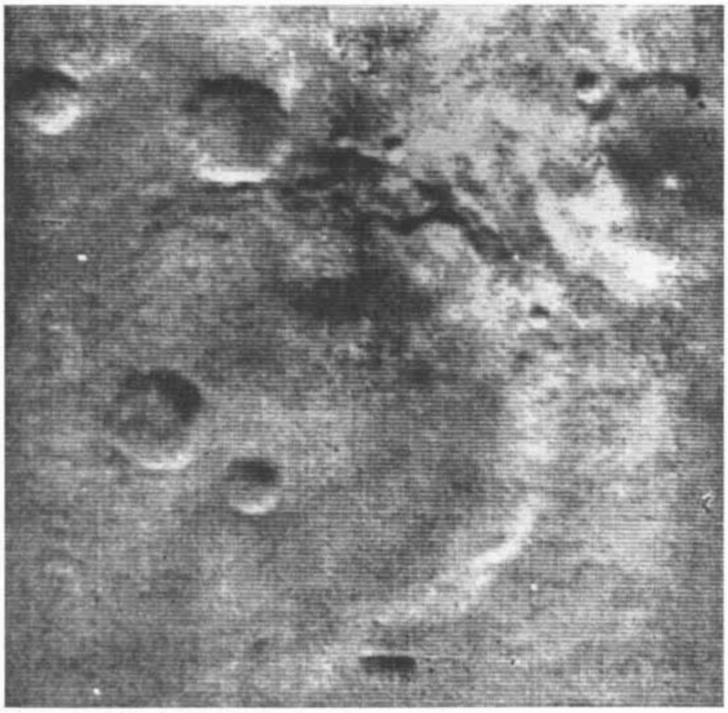


just south of the Martian equator. Taken at a slant range of 8,900 miles, the picture covers an area 190 miles from east to west and 220 miles from north to south. A few faint craters can be seen in Picture No. 6. In Picture No. 7, however, the crater-strewn surface has become unmistakably moonlike. The area covered is 180 miles on each side and was taken from a slant range of 8,400 miles.

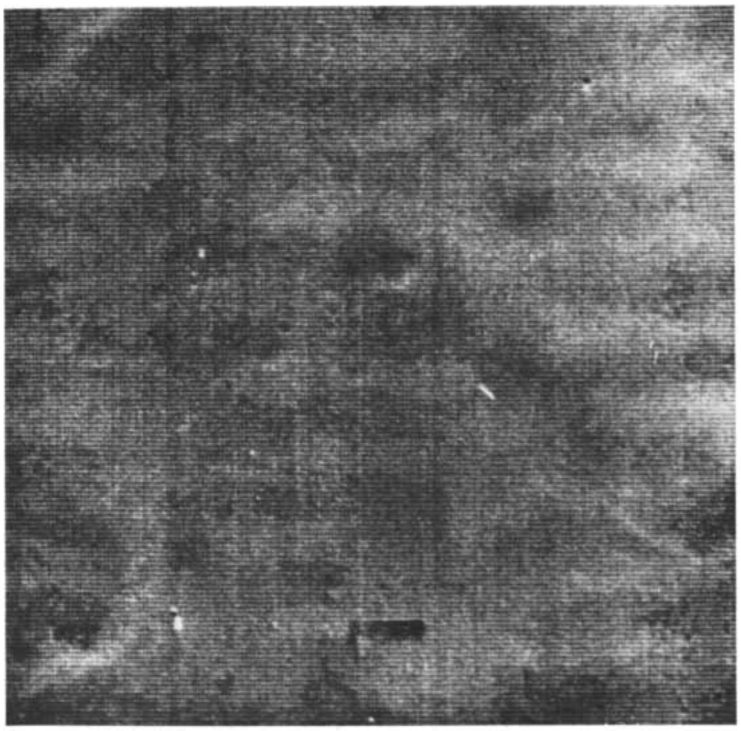
begin when *Mariner IV* came to within 10,000 miles of Mars. In actuality the narrow-angle planet-sensor is believed to have triggered the sequence. The direct command from the earth arrived about two minutes later. Because the spacecraft was then about 130 million miles from the earth, the signal telling us that the first picture had been taken did not reach Goldstone until 12 minutes later. By then the 10th picture had already been taken. Had anything appeared abnormal at that time, a corrective command from the earth, even if made immediately, would barely have reached *Mariner IV* before the planet had passed from view. We finally received word that 22 pictures had been taken in a 26-minute period, but we still had no information about their content—or about whether any images had been recorded at all.

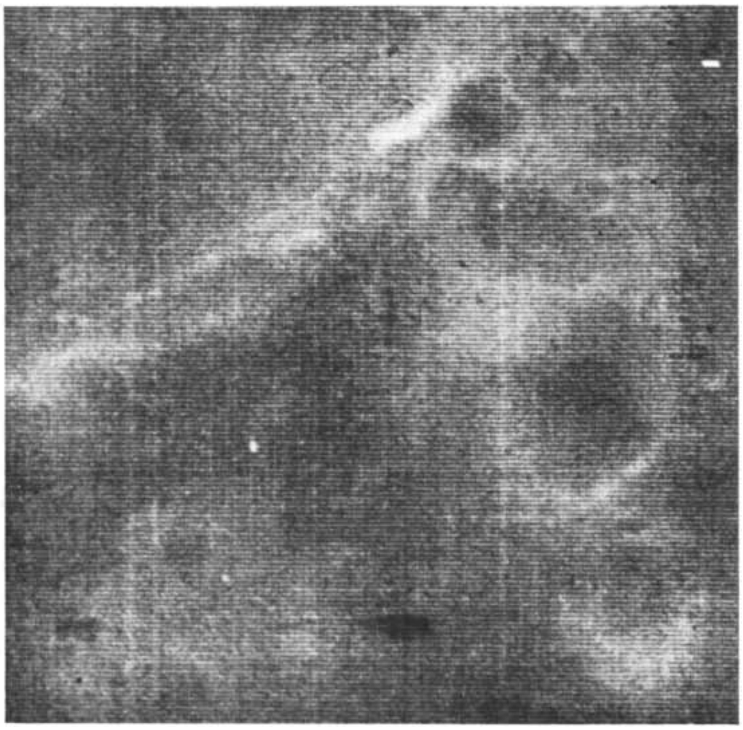
The project staff was somewhat disturbed by a signal indicating that the





miles from east to west and 150 miles from north to south. The bright dashes in Picture No. 8 and No. 9 are defects produced by the television system. The bright areas in the upper right of Picture No. 11 are the result of the enhancement process and not frost. Frost may be present, however, in some of the later pictures. (An enlargement of Picture No. 11 is reproduced on pages 54 and 55.)

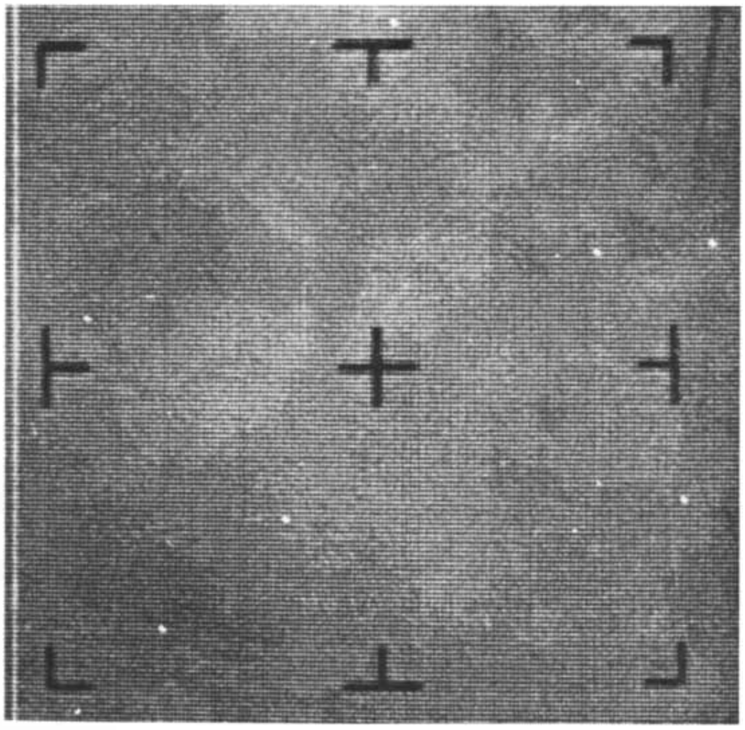


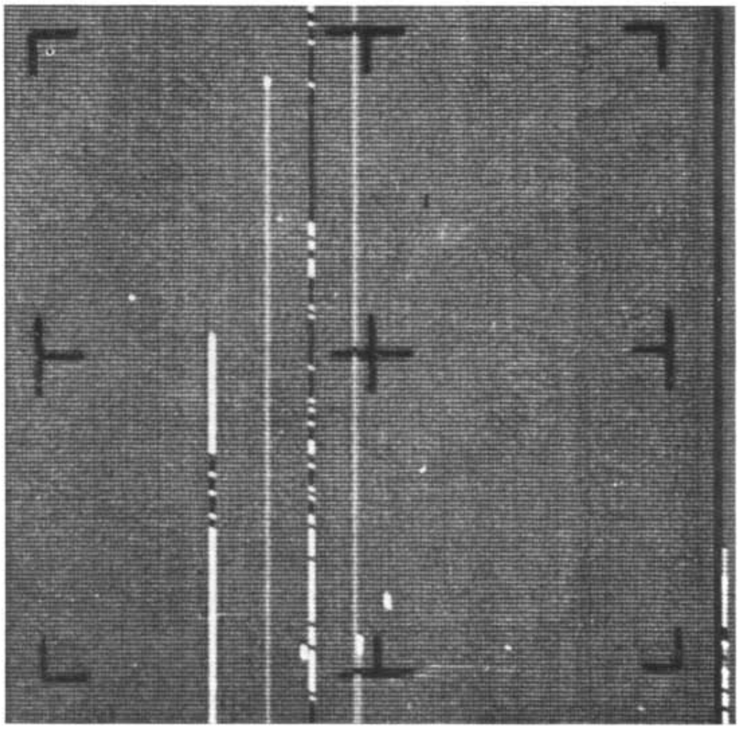


PICTURES NO. 12 THROUGH NO. 15 were taken deeper and deeper in the southern hemisphere, with the last of the four being centered on 46 degrees South latitude. The filter sequence is red, red, green, green; the enhancement factors are four, four, two, two. When *Mariner IV* reached Mars, it was late midwinter in the Martian southern hemisphere. Frost can be expected in the late afternoon,

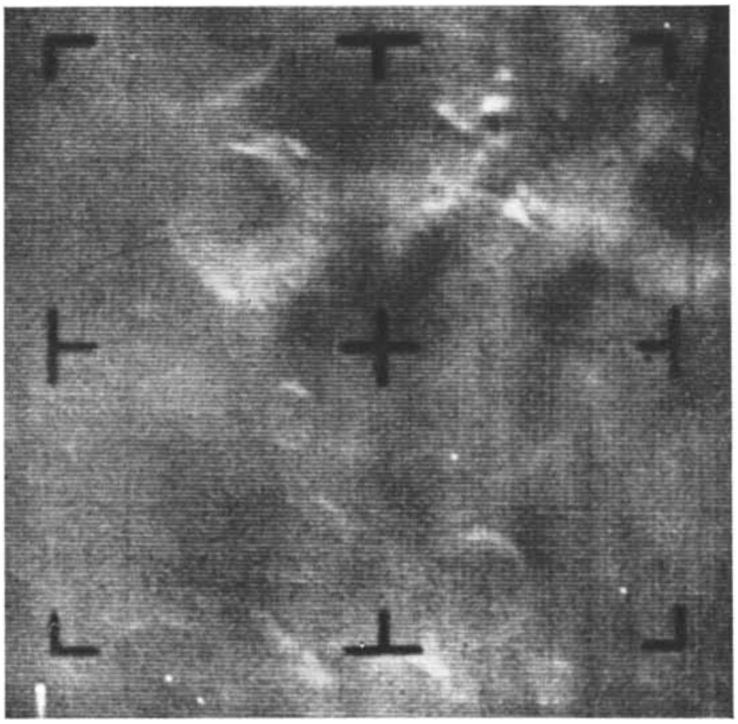
end of the first track of the 330-foot loop of tape had been reached after the fifth picture had been taken and that the tape had then begun recording on its second (and last) track. This seemed to imply a serious malfunction—for example, that only five pictures were recorded altogether, or that five pictures were recorded on the first track and that 10 or 11 more were recorded on the second track.

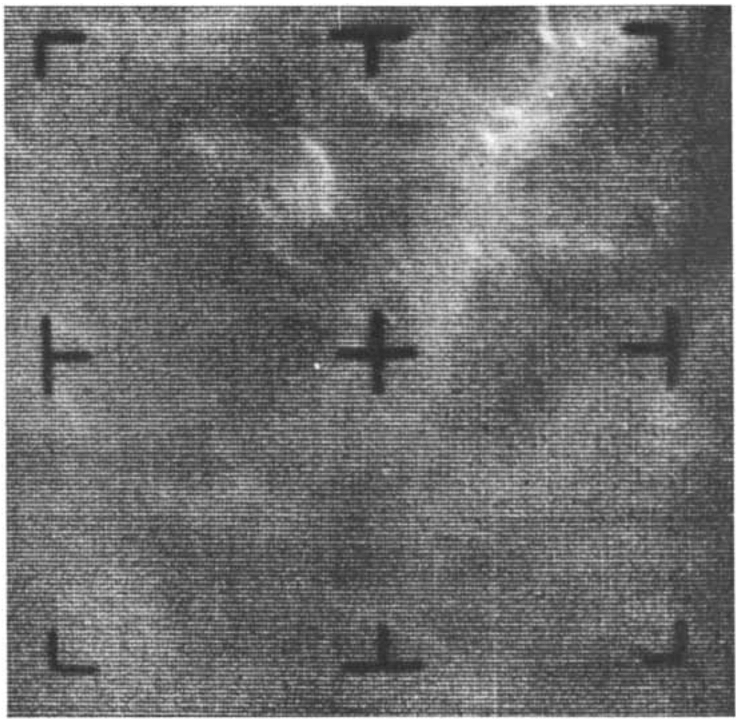
Eighteen minutes after the end of the picture-taking *Mariner IV* passed within 6,118 miles of the surface of the planet. An hour and 18 minutes later it went behind Mars, where its radio was blacked out for 54 minutes, and three hours and 20 minutes later, as the earth turned, *Mariner IV*'s radio beam no longer reached the Goldstone station. We would have to wait until Mars—and *Mariner*—rose next morning over the Johannesburg tracking station in South Africa to receive the playback of the





PICTURES NO. 16 THROUGH NO. 19 are the last to show any discernible detail. It is now late evening on Mars; the sun angle from zenith is 69, 76, 80 and 88 degrees. The filter sequence is red, red, green, green; the enhancement factors are two, zero, four, four. Picture No. 17 is in raw form, just as received. The terminator can barely be made out in Picture No. 19, slanting from upper right to



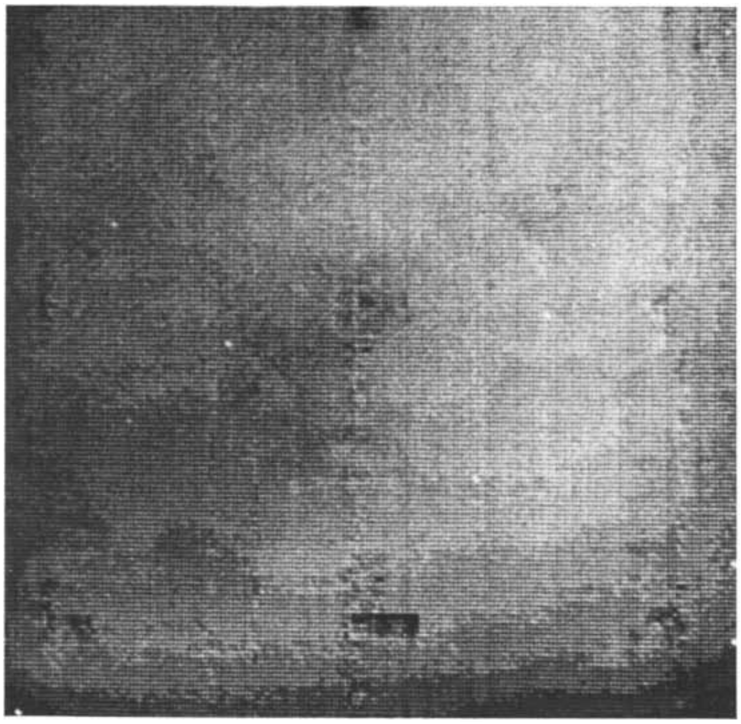


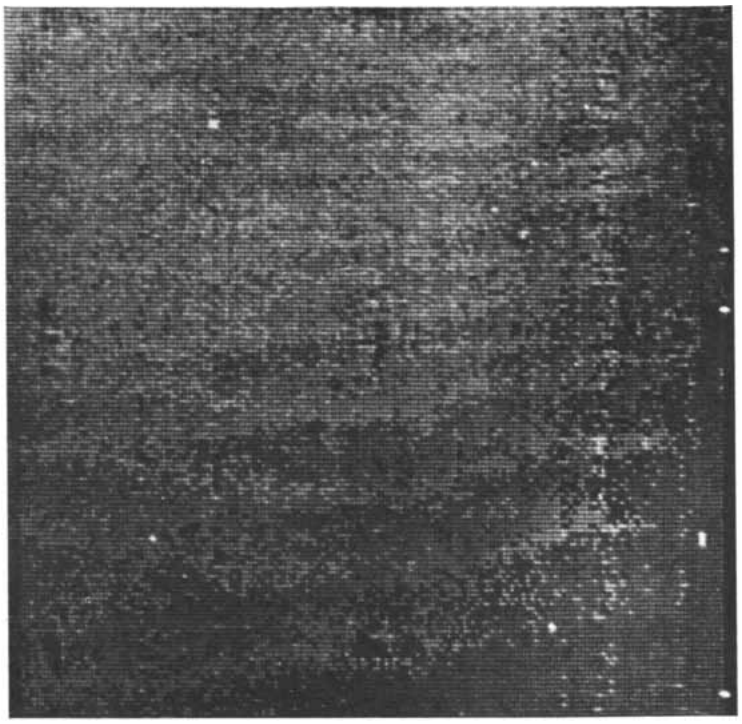
which is when these pictures were taken. The bright points of light in the upper-right quarter of Picture No. 14 may be frost-covered peaks. The craters in Picture No. 15 may also be ringed with frost. The slant range decreased from 7,700 miles to 7,500 miles while these four pictures were being taken. The angle of the sun from zenith increased steadily from 50 degrees to 66 degrees.

first picture, and to learn whether our mission had been a success or a failure.

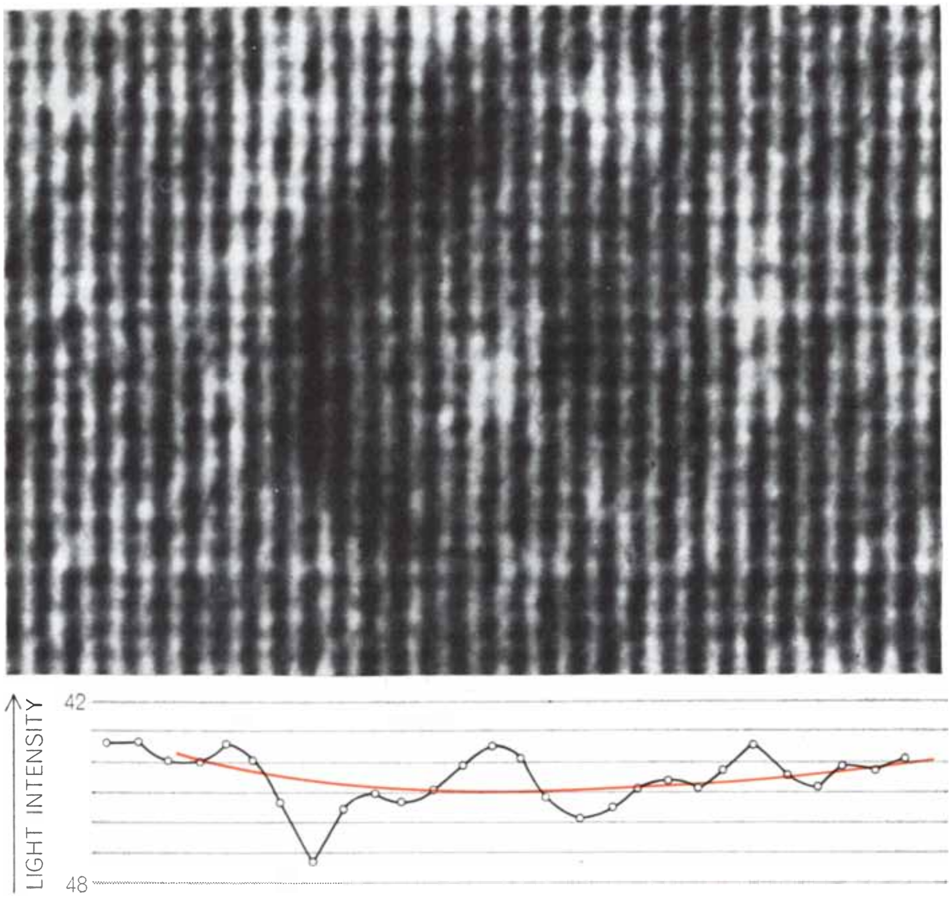
Ten hours and 59 minutes after the last picture had been taken the slow playback began. As the signal was received at Johannesburg it was relayed, bit by bit, to the Jet Propulsion Laboratory in Pasadena. At first all the numbers were 63's, because all pictures were black for a few lines along the top edge and down the left side. After an hour or so it was noted that the numbers were no longer 63's and, more important, that they were different from the numbers that had been left on the tape after the final tests at the launch site. So we knew at last that *some* information from Mars itself had been received.

Even then, however, we remained puzzled for several minutes, because all the six-bit sequences were very much the same and indicated a light intensity about a fourth of the maximum





lower left. The quality of the photographs deteriorated more rapidly after Picture No. 15 than had been anticipated. Evidently the level of surface illumination on Mars dropped faster than could be compensated for by the automatic gain-control mechanism on the television camera. The entire series of *Mariner IV* pictures is still being subjected to improvement by computer techniques.



CRATER ANALYSIS is performed by plotting the light values of successive picture elements that cut across the diameter of a crater. The crater shown enlarged here is from Picture No. 9. The light-intensity curve (*below*) traces the light and dark values on the 64-step intensity scale assigned to each picture element. The curve can be used to compute the slope and depth of the crater. The central peak is like those often seen in lunar craters.

possible value. If the camera had been looking at the sky next to the limb, or edge, of the planet, the light intensity (we thought) should have been low or close to zero. If the camera had been looking at the planet, we had hoped to see more variation in the numbers. Finally, however, the signal jumped suddenly nearly to maximum intensity and we felt sure we were recording the sunbathed planet itself.

As the signals arrived they were recorded on magnetic tape to provide a permanent record, and they were also typed out simultaneously as a sequence of 0's and 1's on paper tape that resembled adding-machine tape. Many people were clustered around the machines producing these tapes. It was an exciting experience to realize that we were actually receiving knowledge from a man-made machine almost 150 million miles away. Of course we were seeing only a sequence of bare numbers. What would the picture look like? Eight hours seemed an eternity to wait.

Then someone conceived the idea of cutting the tape from one of the printers into short lengths, each containing a series of 200 numbers representing the light intensity of one line of the picture. These sections of tape could be stapled together, one next to the other, to build up a two-dimensional picture of the numbers. To make the picture "readable," each element was filled in with one of five different colors of crayon, depending on the light level indicated by its numerical code. Each color of crayon was applied by a different person. In this way the first closeup picture of Mars emerged line by line in the form of a hand-colored mosaic. Within the day it was framed and presented to William H. Pickering, director of the Jet Propulsion Laboratory.

The Photographs Are Reproduced

Meanwhile the tape-recorded version of Picture No. 1 was fed into a television-like picture tube and photographed, to produce a picture in a more familiar form. Because the sun would be striking the Martian surface almost vertically in the first few pictures, we knew there would be no strong shadows to bring out surface details. Nonetheless, we were all, I think, somewhat shocked by the almost total absence of surface features in the first few pictures when they were viewed just as they arrived, without enhancement of any kind. In fact, we were not sure that the few surface features visible were real until we saw, on close inspection, that certain markings in the first picture coincided with similar markings in the overlapping second picture.

The first unmistakable craters turned up in Picture No. 7 and continued to appear prominently through No. 14. Beginning with No. 15 the light level dropped faster than the automatic gain control could adjust, in part because a light level that was acceptable for a green-filter picture was not adequate for the subsequent red-filter picture. There may also be significant atmospheric obscuration in pictures No. 16 through No. 18. The camera crossed the terminator to the dark side of Mars in Picture No. 19, and from then on no surface details can be seen.

The television scan path started on the limb of Mars at about 47 degrees North latitude, swept southward across the equator to about 53 degrees South latitude, then curved northward again and moved off the planet at about 30 degrees South latitude [*see illustration on page 58*]. As it turned out, the path crossed a region in which maps of Mars show only a few canal-like markings, and we have not yet been able to discern any such markings with certainty. It appears that the camera just failed to catch the edge of an interesting feature called Trivium Charontis, which has the shape of a long, thin triangle. This region is significant because it has been observed to change considerably during the past few years, and because it is close to the "desert" area Elysium. Earlier in 1965 persistent white clouds had been seen in the Elysium area, and it is also known to be a strong reflector of radar signals.

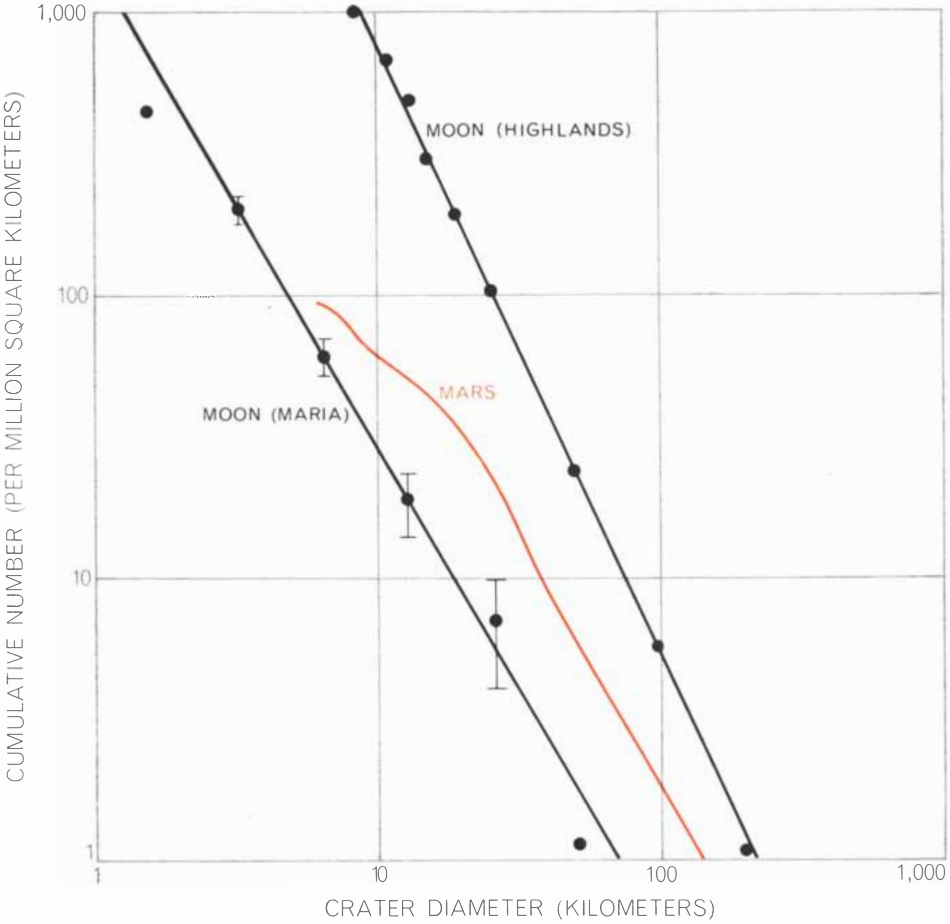
After the 22 pictures had been recorded once, a process that took a little more than eight days, *Mariner IV* was ordered to transmit the entire set a second time. We were anxious to see how closely a replay would duplicate the initial values for the 40,000 picture elements in each picture. Any discrepancies between the two playbacks would indicate the number of errors that had occurred in transmission and would also tell us where they had occurred in each picture. We were gratified to find that the second transmission differed from the first in only about 20 elements of the 40,000 in each picture, making an average of 10 errors per picture in each transmission. This was far fewer than we had dared hope to achieve, and represents a truly remarkable level of performance for such a complex system.

To those of us involved in the project the major surprise in the pictures was the large number of craters; more than 70 of all sizes are clearly distinguishable. We realize now that we should not have been so surprised. Both Ernst J. Öpik of the Armagh Observatory in Northern Ireland and Clyde W. Tombaugh of New Mexico State University, and probably others as well, had predicted that closeup pictures of Mars would reveal a cratered surface. In *The Astronomical Journal* for October, 1950, Tombaugh proposed that the "round 'oases' are [the] sites of impact craters caused by the collisions of small asteroids," and he also predicted that "the lack of water erosion on Mars would permit the surface to retain a visible record of major events that happened during the planet's entire separate existence, similar to the moon."

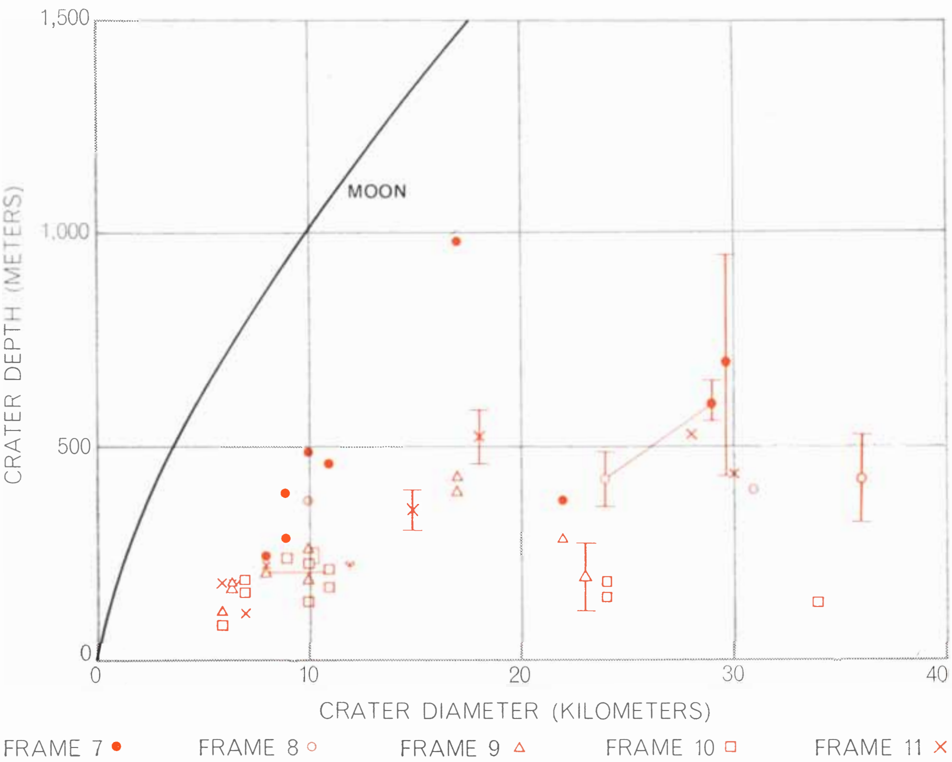
After examining the *Mariner IV* pictures (and without knowing of Öpik's and Tombaugh's predictions) my colleague Murray pointed out that they apparently depicted an extremely ancient surface. We guessed that the surface might be as much as two billion to five billion years old. We meant by this that features of that age would still be visible. In contrast, surface features on the earth are eroded and effaced in a few tens of millions of years. Our estimate of the age of the Martian surface has since been challenged by other investigators, who believe the pictures would show even more craters if some had not been removed by erosion. In our opinion the matter cannot be settled until more of the Martian surface has been photographed and until more is known about the relative rates of impact of asteroid-sized bodies on the moon and Mars.

The Meaning of the Photographs

On the basis of the sample provided by *Mariner IV* one can say that the number of large craters per unit area on the Martian surface and their size distribution resemble closely the size and distribution of craters on the highlands of the moon [*see top illustration at right*]. The Martian craters have rims that rise about 100 meters above the surrounding surface and depths that extend several hundred meters below the rims. The crater walls slope at angles up to about 10 degrees. If *Mariner IV*'s sample of photographs is representative, there must be more than 10,-



MARS AND MOON CRATERS show great similarity in density, size and distribution. Two curves are shown for the moon because the highlands are more heavily cratered than the maria, or "seas." Estimated number of craters per million square kilometers on Mars falls roughly midway between the number found in the two kinds of lunar topography. Chief anomaly of Martian craters is a falling off in the number below 10 kilometers in diameter.



DEPTH V. DIAMETER COMPARISON suggests that Martian craters are significantly more shallow than freshly formed lunar craters (*smooth curve*). This is to be expected if the Martian craters have been subjected to erosion, but it could also be an artifact of the fogging of the pictures. Where the same crater appears in two different pictures and appears to have two different sizes the two values are connected by a straight line.

000 craters on the surface of Mars.

Judging by the *Mariner IV* sample Mars seems to have fewer craters of 10 kilometers in diameter and smaller than would be expected if their distribution in size were similar to that on the moon. Moreover, there seems to be a tendency for the small craters to appear on the rims of large craters. This suggests that there may be something special about the composition or texture of the crater rims that resists the forces that tend to erode small craters when they are formed elsewhere on the Martian surface.

In some of the pictures taken deep in the Martian southern hemisphere one can see areas that seem to have a light covering of frost. One can also see that many of the craters, instead of being circular, are flattened along a portion of their circumference. This phenomenon, also observed in lunar craters, is believed to result from structural faults below the surface. In at least one picture (No. 11) a pronounced line, quite straight, intersects a crater and continues across the rim. This too might be caused by a fault. So far we have not been able to complete the computer processing needed to draw any conclusions from the paired red and green pictures, or to prepare them in a form suitable for combining their overlapping areas into a color picture.

A mystery of considerable interest is presented by the high light levels recorded near the limb of the planet in the first picture. Where we had expected to find a black sky the sky was more than half as bright as the planet! The other pictures also show evidence of "fogging," as if the Martian atmosphere were enormously brighter and more extended than anyone had expected.

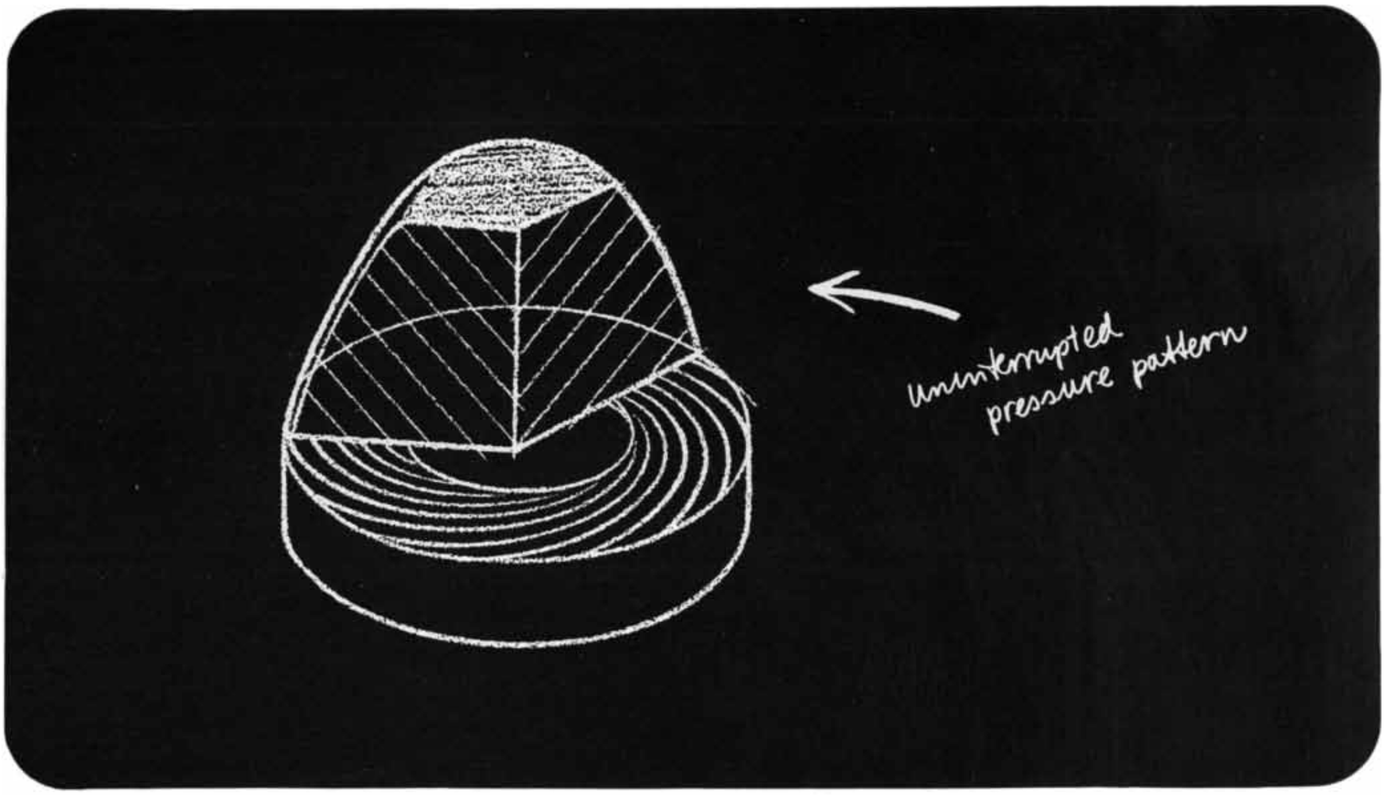
Our first thought was that the fogging represented some kind of defect in the optical system. We wondered, for example, if the surface of the telescope mirror could have been pitted by the impact of meteoritic dust, but this seems to be ruled out by the fact that the meteorite detector, fully exposed outside the spacecraft, received only a few hundred hits. We have also considered the possibility that volatile substances from the foam cushions used to protect the Vidicon tube might have whitened the black inside surface of the telescope tube and created internal reflections. We found, however, that we could not duplicate the fogging even by inserting white cardboard baffles in place of the black ones in the optical system.

Finally, we considered the possibility that the nickel compound that provides the top coat on the telescope mirror before it receives final polishing might have blistered after long exposure to the vacuum of space. We simulated blisters by putting drops of glue on a mirror but were still unable to duplicate the fogging seen in the *Mariner IV* pictures. We have tentatively decided that the cause of the fogging is really on Mars. Recent models of the Martian atmosphere seem to suggest that tiny crystals of frozen carbon dioxide are present at all times, even at great heights. Whatever the cause of the fogging in July, 1965, it must have extended to at least 100 kilometers above the surface of the planet and therefore it may be distinguishable from the earth with careful observation.

Life on Mars?

There was never any expectation that these photographs, with their coarse one-kilometer resolution, would settle the question of whether or not life exists on Mars. We and others (notably Carl Sagan of the Smithsonian Astrophysical Observatory) have examined many pictures of the earth taken by the Tiros and Nimbus weather satellites, whose narrow-angle cameras provide somewhat better resolution than the *Mariner IV* camera, and can find only one or two examples of a picture that shows a human work of engineering [*see illustration on page 60*]. And this is even when one knows what to look for. Still more surprising, the Tiros and Nimbus pictures fail to provide any evidence of vegetation, or seasonal changes in the earth's ground cover, except for snow and floods. It is certainly true that Mars looks inhospitable to life as we know it, but the question of whether there is life on the planet remains open.

After an experiment such as *Mariner IV*'s is concluded one always has second thoughts. For example, it might have been better to photograph a different area, or to use a camera system that provided a wider field of view. It would have been desirable, of course, to have sent Mariner B with its two cameras. One would like to see the entire disk of Mars with, say, five-kilometer resolution. Still, there will be opportunities to make other photographs in the future. We feel satisfied that the first closeup views of Mars, made possible by the ingenuity and hard work of hundreds of people, have shown the importance of an exploratory approach to the study of our planetary neighbors, and that they will be remembered as among the outstanding photographs of the early space age.



Spiral Bearings and their possible utilization

Wherever, in this dynamic world, a mass moves in relation to another with which it is in contact - there is the need for a bearing. And when masses become heavier, speeds higher, contact surfaces smaller, there is the need for bearing research and technology.

We believe we have designed and calculated improvements that are both significant and practical. (Described in Philips Research Reports supplements - No. 2 1964.)

We can now make, for example, a wear-resistant thrust bearing able to take a load of 900 grams rotating at 60.000 rpm. without incurring a power consumption of more than 2.8 watts. We do this with a one millimetre conical spiral-groove bearing, oil lubricated within which a pressure of about 135 atm. is generated. The bearing is simple: shallow, spiral-grooves on a tapered spindle, fitting in a conical cup. How do these spiral-grooves bearings work?

As in other self-acting bearings, pressure arises from two effects. The first is the pumping action: the fluid will be pumped - in this particular type - towards the centre. Secondly, due to leakage: the piled-up viscous medium in the centre leaks back towards places of ambients pressure.

Over and beyond other bearings the spiral bearing builds up an uninterrupted pressure pattern. The practical value? First off; as a self acting gas thrust bearing, no other equals it at the present time. And in oil-lubricated bearings we are testing flat spiral bearings, carrying loads of several tons. Spiral bearings can be of every required shape: flat, round, cylindrical, conical.

A finding of great practical value, because it opens a wide range of applications, was that when grease is used as intermediate agent spiral-groove bearings are self-acting full-film lubricated bearings. In our special designs they too can take up high axial, radial loads. During the service life of the bearing, there is no lubrication problem; there is no leakage problem; the bearing can be used in all positions in space. It is silent in operation. Spiral bearings can support large thrust loads; they cause little friction, negligible wear and no trouble with fatigue. They can replace other bearings simply because they are cheaper. Also, under extreme conditions, they can perform satisfactorily where others can not.

Condensed from a lecture
by Dr. Ir. E.A. Muijderman
Mechanical Research Group
Philips Research Laboratories
Eindhoven, The Netherlands.

The Philips Research Laboratories carry out research in many fields of fundamental science. Among these: Acoustics, Chemistry, Cryogenics, Perception, Plasma, Material testing, Nuclear physics, Solid state physics, Telecommunications, Colour Television.

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This system enabled Mount Holyoke College to issue cards with color-keyed backgrounds to the entire faculty, staff, and student body in a couple of days during registration. They got cards like the freckled Miss Duffy's.

There are three parts to the system: the camera (that's it at bottom), a laminator, and a die cutter. And operation is so simple that the people who work it can be recruited from the typing pool or student body (as they were at Mount Holyoke). Here's how it works:

An individual's vital statistics are typed on a data processing card. The card goes into the camera and the subject steps in front. Then, in a single exposure, the camera records both the subject's face and the data card (the card can then go into a central processing system). Incidentally, this makes on-the-spot identifications as tamperproof as any yet devised. Because picture and data are incorporated in a single photograph (which is then laminated in plastic) they can't be separated without detection.

After making the exposure, you pull out the film packet, wait 60 seconds, peel it apart and insert it into the laminator. In a simple, two-step process the card is laminated and trimmed. The individual pockets his card and he's through.

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The Polaroid Identification System

PRE-COLUMBIAN HAMMERED WORK ranged from simple to elaborate. The Peruvian ceremonial knife (*left*) has a blade of gold and silver segments, probably joined by the hammer-welding technique. It was probably made between A.D. 1200 and 1400. The Peruvian cutout jaguar figure (*top right*) is typical of the earliest-known New World work in gold, dating from about 500 B.C.; the design was raised by working from the reverse side with a blunt tool. The human head, raised on a sheet of copper by the same technique, is from the Spiro site in Oklahoma and is about 500 years old. Metalwork north of Mexico was rarely more complex than this.

Early Metallurgy in the New World

In 4000 B.C. the people of the Great Lakes region were hammering tools out of native copper. By the time of Columbus the gold work of cultures from Peru to Mexico rivaled the best in the Old World

by Dudley T. Easby, Jr.

The practice of metallurgy in the New World before the time of Columbus is one of the most fascinating and, on occasion, infuriatingly enigmatic subjects in the history of technology. Early accounts by European eyewitnesses are rare. One outstanding exception is the description of "lost wax" casting in ancient Mexico recorded by the Franciscan friar Bernardino de Sahagún in the Florentine Codex, but even that account suffered from inept translations until 1959. A 16th-century Spanish chronicler, Pedro Cieza de León, gave a brief description of the *huaira,* or wind furnace, used in the Andes when the Spaniards first arrived in that region, and there are historical references to primitive methods of mining, such as placer mining for alluvial gold and platinum, shallow shaft mining and the strip mining of surface outcrops. A few references to metalcraftsmen, their favored position in society, their deities and ceremonies, and some vague allusions to metalworking centers also are known, but practically nothing has been preserved concerning technology. How, for example, were New World metalworkers able to make articulated metal figures and produce objects that were half silver and half gold? The tale persists that the egotistical Benvenuto Cellini spent months trying to ascertain how an ancient Mexican craftsman had fashioned a silver fish with gold scales and finally conceded that he was baffled.

Occasionally a crumb of contemporary technical information will turn up in an unlikely place. In an anonymous report to the president of the Council of the Indies in 1519 it is stated that a large gold solar disk presented to Cortes by Montezuma had been "worked, as when they work over pitch." This is obviously a description of the repoussé technique of decoration, in which a raised design is formed on a metal sheet by resting the sheet on pitch or leather and impressing a design from the back with a blunt tool. A similar reference to working sheet-gold masks "over pitch" is contained in one account of Columbus' second voyage.

Large-scale metal workshops are known to have flourished at Chan Chan in Peru, and others—called *patios de Indios*—are reported to have existed in Colombia. Azcapotzalco, near the Aztec capital of Mexico, was a great metalworking center, and there undoubtedly were other centers in those Mexican towns that are known from surviving records to have paid tribute to the Aztecs in the form of gold artifacts. Of none of these, however, is there any archaeological evidence; indeed, in the New World it is the exception rather than the rule that objects made of precious metal were discovered in the course of controlled excavations. Among the notable exceptions are the finds made at Monte Albán and Zaachila in Mexico, at Coclé in Panama and at Batan Grande and Lambayeque in Peru. The fact remains that most of the gold and silver objects in public and private collections today have been retrieved by means of clandestine grave-robbing. Their archaeological origins are without documentation, and frequently their place of origin and age may be debatable.

Much information can nonetheless be gleaned from the artifacts themselves. Visual examination, for example, will reveal tool marks that at times even show whether the artisan was right-handed or left-handed. The appearance of a casting will indicate whether the original model was "faced" with an emulsion of powdered carbon in order to give the casting greater sharpness, and it will also indicate how the mold was vented to ensure a better flow of the molten metal. X-ray studies will disclose internal structures and hidden defects. Chemical and spectrographic analyses reveal the composition of the ancient alloys, from which their physical properties can be deduced. Examination of polished and etched sections of metal with the metallurgical microscope often reveals what steps were taken in the process of manufacture. In brief, laboratory investigation yields a surprising amount of information about the materials and techniques employed by these ancient craftsmen.

The earliest-known metal artifacts in the New World are those of the "Old Copper" culture that flourished in the upper Great Lakes region of North America beginning about 4000 B.C. The tools and weapons of this culture have been found in northern Michigan and Wisconsin and in southern Ontario; stratigraphic, geological and paleontological evidence, as well as carbon-14 dating, suggest that they were made during the course of the next 2,000 years, which was a warm, low-water period. The raw material was "native" copper, that is, copper occurring in nature as a relatively pure metal rather than copper that had to be extracted from an ore by smelting.

The Old Copper craftsmen probably looked on the metal as a new kind of stone that differed from flint in not needing to be chipped or ground to give it form. Native copper is sufficiently soft and malleable to be shaped by hammering. In common with other nonferrous metals, copper has an additional property of which the Old Copper artisans apparently took no advantage: it becomes increasingly hard the more it is hammered, until finally it is too hard

ANTHROPOMORPHIC FIGURE occupies the center of a bronze disk cast in South America by the "lost wax" method about the end of the first millennium A.D. Unearthed near Cobres, a pre-Columbian copper mining and smelting center in northwestern Argentina, the disk is six inches high. A pair of curly-tailed mammals are represented beside the figure's shoulders; the figure's feet rest on the beaks of a pair of birds portrayed upside down.

and brittle to be worked further. This phenomenon, known as work-hardening or strain-hardening, results from the breakdown of the metal's microscopic grains. Work-hardening can be reversed, and the metal softened to allow further working, by annealing, that is, heating the object to some temperature below the melting point. Annealing causes the work-distorted grains to recrystallize, forming new grains. Under the microscope parallel bands called annealing twins can often be seen in the new grains. Such bands may also appear in metal that has been forged while hot. Annealing twins have been detected in Old Copper implements, which has caused speculation whether these implements were cold-worked and then annealed or hot-worked.

The implements of the Old Copper culture include knives, chisels, axes, harpoon heads, awls and projectile points. The shapes of these artifacts were derived for the most part from prototypes made of stone, bone, horn or shell, although sockets in projectile points and the rolling of conical points represent innovations made possible by the plasticity of the metal.

The apogee of fine copper work in the region north of Mexico was reached long after the Old Copper culture had vanished. This high point was achieved by the craftsmen of the Hopewell culture. The most notable examples of their work come from Mound City and nearby sites in Ohio and were made sometime around A.D. 200. The Hopewell artisans did not know how to cast or solder, but they showed remarkable skill in hammering, in repoussé decoration, in cutting intricate designs out of sheet metal, in crimping, in riveting and in hammer-welding copper and silver or copper and meteoric iron to produce bimetallic objects. In hammer-welding the two pieces of metal were placed together and joined by repeated blows.

As for the other metals used north of Mexico, gold—the decorative metal par excellence in the Old World and in much of the New—apparently was restricted largely to Florida, where a few ornaments fashioned from sheet gold have been found. Thin flakes of gold, probably the remains of sheathing, have been reported on some Hopewell copper ornaments, and rudely shaped and perforated gold beads were reportedly found at the Etowah mound site in Georgia. Far to the north the Eskimos of the Dorset and Thule cultures in eastern arctic North America hammered and ground meteoric iron to make knives, which they often set in handles of walrus ivory.

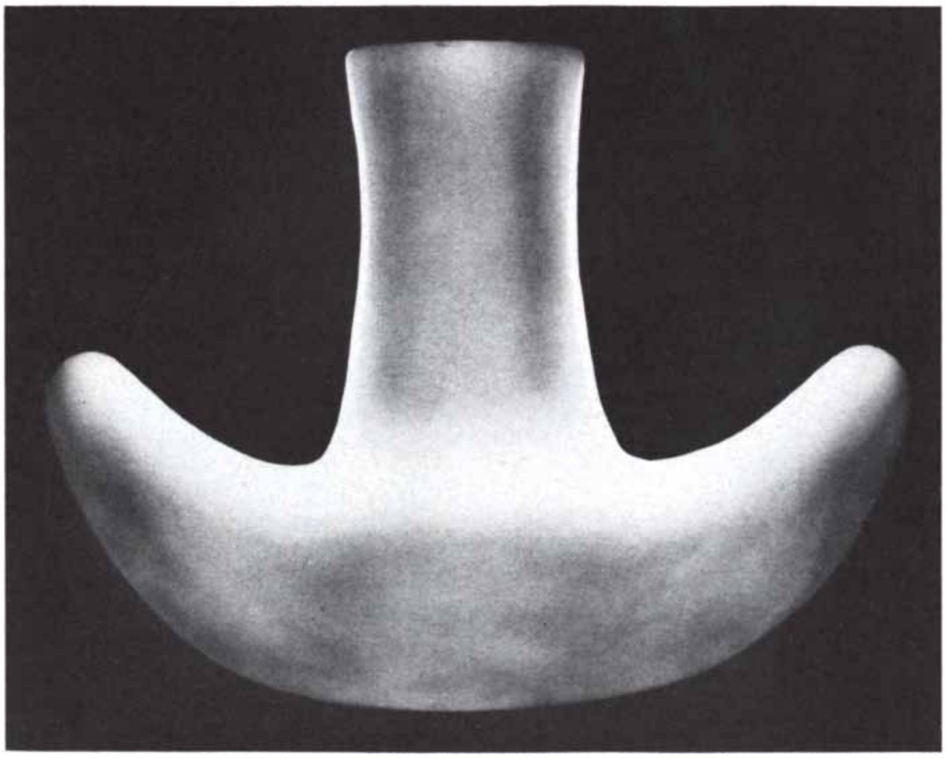
In South America the oldest evidence of the use of metal, dating back to at least 2,000 years before the Spanish Conquest in 1532, has been found in northern Peru. Here, as in the Great Lakes area, the first metal to be used was in the native state. In Peru, however, the metal was not copper but gold. The earliest objects were ornaments cut out of sheet gold and given repoussé decoration in the Chavin style [*see illustration on page 72*]. This is a stage of development that was not attained in North America until Hopewell times.

Later metalworkers in the Andes were by no means limited to native metals in their choice of raw materials. Their efficient *huairas*—cylindrical furnaces of terra-cotta about three feet high with a series of openings along the sides—were capable of smelting a variety of ores. A charge of crushed ore and charcoal was placed inside the furnace and ignited. At the base of each opening along the wall of the cylinder was a small terra-cotta platform; piles of charcoal were kept burning on these platforms during the smelting process, sending a current of hot air and carbon monoxide through the furnace. Oxide and carbonate ores were reduced by the charcoal, the oxygen being driven off as carbon dioxide. The molten metal settled and was drained off through a tap at the base of the cylinder. These furnaces were usually placed on hillsides, where the prevailing winds provided a forced draft. There is evidence that in both Peru and Mexico copper was extracted from oxide and carbonate ores by this kind of charcoal reduction and from sulfide ores by a combination of roasting and charcoal reduction. Metallic tin was also smelted from cassiterite, and lead from galena. In spite of the rudimentary methods used, the metals recovered were surprisingly pure.

The tradition of making ornaments out of sheet gold continued in Peru down to the time of the Incas. Other techniques were also employed in this region. They included a method of "raising" beakers, cups and other vessels from flat disks of sheet metal by hammering them over a series of anvils and annealing them when necessary. (This is the same technique that was employed at the Mesopotamian site of Ur in the third millennium B.C.; it is still used by many handcraftsmen.) Large numbers of identical beads were formed by pressing thin sheets of gold or silver over carved replicas or into carved matrices of wood, stone or even metal. Artisans on the northern coast of Peru in the period from A.D. 200 to 700 occasionally decorated their masterpieces with elaborate mosaic inlays using as many as four different materials [*see illustration on the cover of this issue*]. In the same general area during Chimú times (A.D. 1200 to 1400) decorative techniques included painting with the red mercury ore cinnabar, encrusting with turquoise, and dividing the surface of a metal object with small partitions and then filling the spaces with cinnabar (a method resembling the cloisonné work of the Old World).

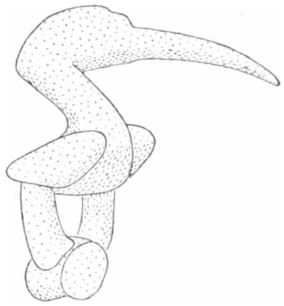
A further advance in technology—casting—probably first occurred in Colombia shortly before the birth of Christ. Decorative pins in the Calima style are topped with effigy figures that were cast by the lost-wax process, to which we shall return. Casting did not arise in Peru, however, until some-

AXE-BLADE CASTING as practiced in Mexico is depicted in Bernardino de Sahagún's study of pre-Columbian technology. Copper was brought to melting temperature with a blowpipe; the molten metal ran out of a furnace tap into a stone mold. On the ground is a finished axe blank; this will be given its final form by hammering (*see illustration below*).



X-RAY PHOTOGRAPH of a copper axe blade from western Mexico reveals that the hammering process with which the blade was finally shaped has left it thickest (*lightest areas*) where blade and shank meet. Narrow raised flanges along both edges of the shank were also produced by hammering. Copper axe blades were a New World medium of exchange.

1



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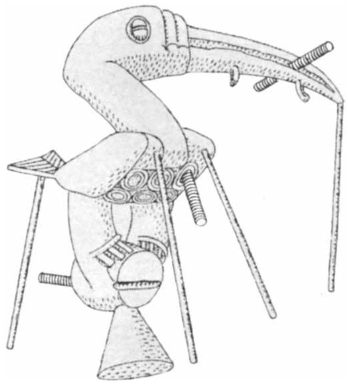


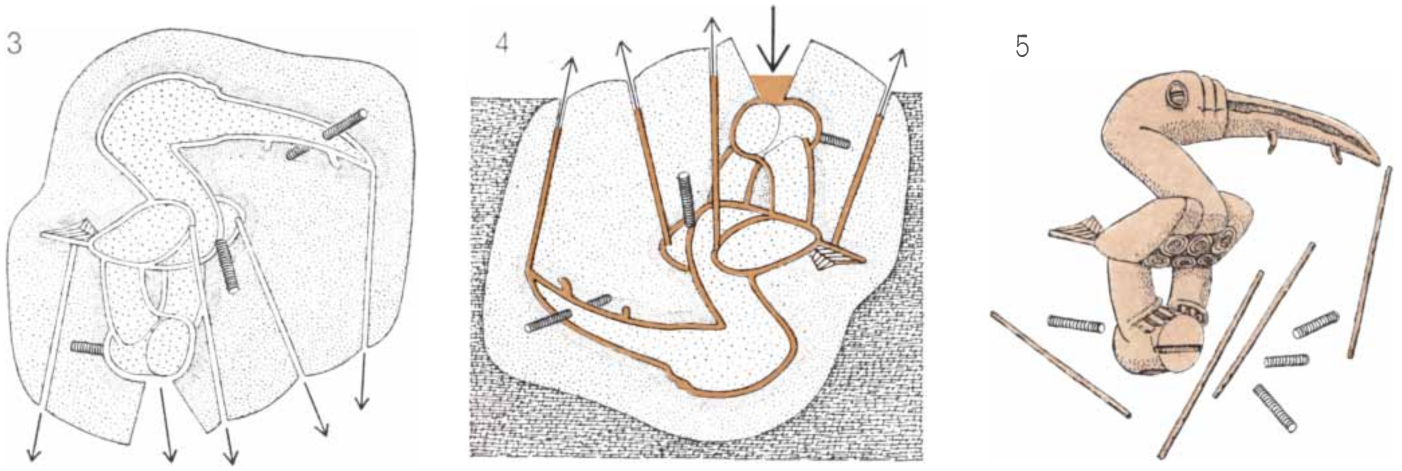
STEPS IN LOST-WAX CASTING are reconstructed, using a golden bird from Colombia that once formed the head of a staff (*photograph at far left*) as a hypothetical example. The first step is production of a core, made of clay and charcoal, that closely resembles the final figure (*1*). The core is then covered with a wax coating the thickness of which determines the thickness of metal in the casting. The metalworker models all the fine detail that he desires in this wax coating; he then adds wooden pegs to hold the core in place

time after the birth of Christ; the technique reached full flower there between A.D. 1200 and the arrival of the conquistadors.

Although most Peruvian metalwork was made to be worn as personal adornment or carried in ceremonies, copper weapons and tools also appeared when casting was introduced. Casting in copper is generally regarded as difficult, but impurities the early workers could not eliminate made a kind of alloy and thus facilitated the process. By the time the Spaniards had arrived Inca craftsmen were turning out weapons and tools of bronze. Analyses of these bronze artifacts indicate some appreciation and understanding of the effect of differing percentages of tin on such physical properties of the alloy as hardness and mold-filling ability.

Bronze objects have also been found in Bolivia, Chile and Argentina. Indeed, the first bronze in the New World was probably made about A.D. 700 in Bolivia, an area still famous for its tin deposits. In northwestern Argentina a few remarkable bronze castings have been discovered not far from Cobres, where early in this century a French scientific mission unearthed a pre-Columbian copper mining and smelting operation [*see illustration on page 74*].

EFFIGIES OF BIRDS, produced by the lost-wax method, demonstrate both the technical skill and the artistic capability of New World metalworkers. The copper bell (*left*) bears the image of a turkey; 2¼ inches in diameter, it is one of a large cache of bells discovered in a cave in Honduras. Both the owl and the eagle heads are hollow gold castings little more than an inch wide. They are in the Mixtec style of western Mexico, where the art of lost-wax casting reached its highest state of development in the New World.



within the mold, wax rods to provide air vents and a wax cone to provide the casting funnel (*2*). The model is then invested in a mold of clay and charcoal that is dried and heated (*3*) so that the wax melts and runs out of the mold. The hot mold is then inverted (*4*) and the molten metal poured in through the funnel. When cold, the mold is broken away, the core supports and surplus metal are removed and the core is broken up and extracted through the various holes in the casting that were made by the core supports (*5*).

The pre-Columbian craftsmen of Ecuador have aroused the admiration of modern metallurgists by their manufacture of almost microscopic beads from an alloy of gold and platinum. Platinum has a very high melting point—more than 3,000 degrees Fahrenheit—but Ecuadorean smiths overcame the problem by mixing grains of platinum with gold dust. They repeatedly heated and hammered the mixture until the combination of temperature and pressure blended the two metals into a homogeneous mass without ever actually melting the platinum. The discovery of bits of this alloy in various stages of manufacture enabled the Danish metallurgist Paul Bergsøe to reconstruct the ancient practice, which is really an application of a basic principle of modern powder metallurgy, the sintering of refractory metals.

EFFIGY OF REPTILE, from the Coclé site in Panama, is a typical coreless lost-wax casting. The model was fashioned wholly of wax; as a result the cast figure is solid gold.

Although more an economic than a metallurgical matter, metallic money appeared in Ecuador and northern Peru about A.D. 1000 or slightly earlier. It consisted of small copper axe blades, too thin for any practical purpose, that were used as a medium of exchange. This concept of copper axe-money was transmitted, probably by maritime contacts, to western Mexico, where hoards of such axes numbering in the hundreds have been found in the state of Oaxaca.

In Colombia, Panama and Costa Rica gold was the principal metal, but a gold-copper alloy known as *tumbaga* was also widely used. Some ancient craftsman discovered that when an object made of this alloy was heated in the open air, a thin layer of copper oxide formed on the surface. If the heated object was then quenched in an acid bath of plant juices, some of the copper and copper oxide on the surface was dissolved; each time the process was repeated the proportion of gold at the surface increased.

In this process, known today as "pickling," the gold comes from the object itself; nothing is added, as it is in gold-plating. The extent to which true plating was practiced in the New World remains to be established. Gold foil was often applied as sheathing, and Bergsøe has shown that fusion-gilding, in which a molten gold-copper alloy is applied to preheated copper by flowing, was used on some Ecuadorean objects. Recent metallographic studies by the New York metallurgist Sidney B. Tuwiner have shown that metal disks from Vicús in Peru are sandwiches made up of copper between layers of gold applied by this same fusion-gilding process, which is a first cousin to the Old World technique known as Sheffield plating.

The outstanding achievement of the metalworkers of Colombia, Panama and Costa Rica was the perfection of lost-wax casting. In this process the artisan began by making an exact wax model of the object he wished to cast in metal, much as a sculptor works in clay. The wax, still called *cera de Campeche* in Mexico, came from the stingless bees of the rain forest; it was mixed with copal gum or some other resin to give it firmness and workability. Adding little pellets and threads of wax to his model as decorative details, the artisan next affixed a cone of wax, which later served as a funnel-shaped pouring channel for the molten metal, to the model's base. If the model had a complex form, with undercutting or other recesses where air might be trapped in the course of pouring the metal, wax rods were joined to these parts; the rods became air vents when the wax was burned out.

When the wax model was complete, it was usually faced with an emulsion of powdered charcoal in water to ensure a smooth surface and a clean, sharp casting. The Aztecs called this emulsion *teculatl*, literally "charcoal water"; its equivalent in modern precision casting

GOLD FIGURINE of a seated woman with flowers in her hands was made by the lost-wax method in Colombia. It was cast in separate sections that were soldered together.

CLOSER VIEW of the figurine's shoulder reveals a circular plug of gold that fills a hole in the casting. This seeming flaw marks the point where a peg supported the core of the figurine during the casting process (*see top illustration on preceding two pages*).

is a mold wash made of water glass (sodium or potassium silicate) and graphite. Rough surfaces on the back of some Panamanian, Costa Rican and Mexican cast pieces and on both front and back of Chibcha votive figures from Colombia show that these areas were not faced.

The next step was to cover the model with an outer shell made of a mixture of moist clay and crushed charcoal. This, of course, had to be done without covering the pouring funnel or the tips of the wax rods that would form air vents. After the outer shell had dried, the entire assembly was fired. This strengthened the mold, burned out the wax and left a cavity of the same shape and volume as the now-lost wax model. The mold was then brought to red heat to facilitate the flow of molten metal, placed with the pouring channel uppermost, and the molten metal was poured in. When the metal had solidified, the mold was broken away, revealing a duplicate in metal of the wax original. The excess metal in the pouring channel (called a "casting button") and the rods that had formed in the air vents were cut off and the cuts were burnished down. The finished object was then given a final polish.

If the casting was to be hollow rather than solid, the process differed in two respects. The starting point was the preparation of a porous core made of clay and crushed charcoal. When the core had dried, it was carved to shape and covered with a layer of wax, the details of the model being completed as before. The thickness of the wax coating determined the thickness of the metal in the finished casting. Before the model was faced and covered by the outer shell of the mold the core had to be anchored to keep it from slipping out of place later when the wax was melted out. This was done by piercing the wax model at inconspicuous places with compact wooden pegs or cactus thorns that penetrated the core and projected above the surface of the wax. The projecting ends were embedded in the outer shell when it was applied and formed little bridges between the mold and the core, anchoring the core in place. These core supports of course left small holes in the finished casting. In some lost-wax castings from Colombia and Panama these tiny holes have been expertly plugged with the same metal or alloy used for the casting [*see bottom illustration at left*].

Both in Peru and in Mexico bimetallic objects made by multiple casting have been found. In this process a metal with a lower melting point, such as silver, is cast around a metal with a higher melting point, such as gold. A modern industrial counterpart is the "cladding" of one metal with another that has a lower melting point.

Lost-wax casting in the New World reached its highest development in the Oaxaca area of Mexico, where during the 15th and 16th centuries A.D. Mixtec master craftsmen produced little hollow castings that are unrivaled for delicacy, realism and precision. A favorite Mixtec decorative device was a fine cast filigree; the model for this cast wire presumably was made by extruding long strands of wax thread much as toothpaste is squeezed from a tube. A similar extrusion technique is still used in India. Drawn wire (as opposed to cast or rolled wire) has not been found in the New World so far.

Soldering, fairly common both in Peru and in Colombia, apparently was never fully mastered in Mexico. The solder customarily used for small work was a finely pulverized copper oxide or copper carbonate mixed with some organic binder. The mixture was applied to the metal parts to be joined and then reduced to metallic copper on the spot by means of flame and a blowpipe. According to the late Herbert Maryon of the British Museum, the same process was used by the Etruscans.

For a time it was believed that casting metal in molds might have been mastered by the Hohokam culture of Arizona in the period between A.D. 900 and 1100. This belief was based on a find of 28 cast copper bells at the Snaketown site. Large numbers of similar bells, however, have since been found in the states of Nayarit and Michoacan in western Mexico. In both the Snaketown and the western Mexico bells the copper had been extracted by the smelting of sulfide ores, and it is now generally accepted that the Hohokam bells were imported from this area of Mexico.

The question arises: Whence came the knowledge and skill of these talented New World metalworkers? It is not hard to imagine that the Old Copper people learned their techniques empirically, but what about the wide range of metallurgical practices and techniques employed later in other regions? Undoubtedly the craftsmen of Panama, Costa Rica and Mexico were the recipients of practices developed in and spread from the Andean

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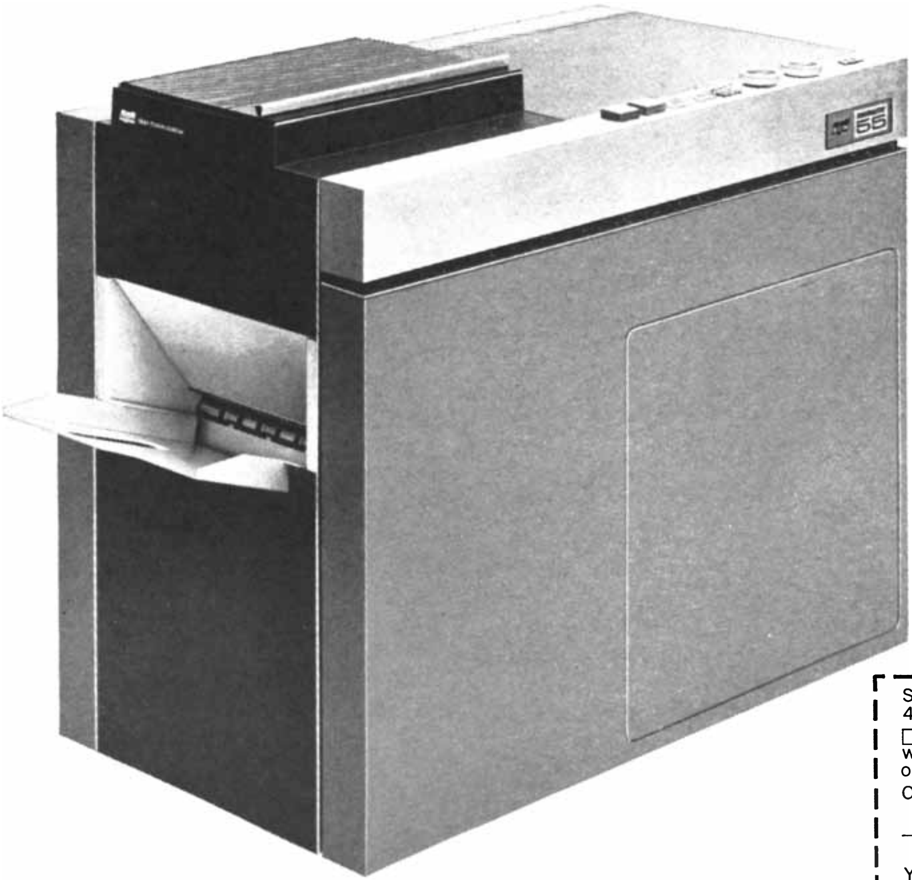

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Unique aerospace fuel cell introduces a new louvered thermal control system

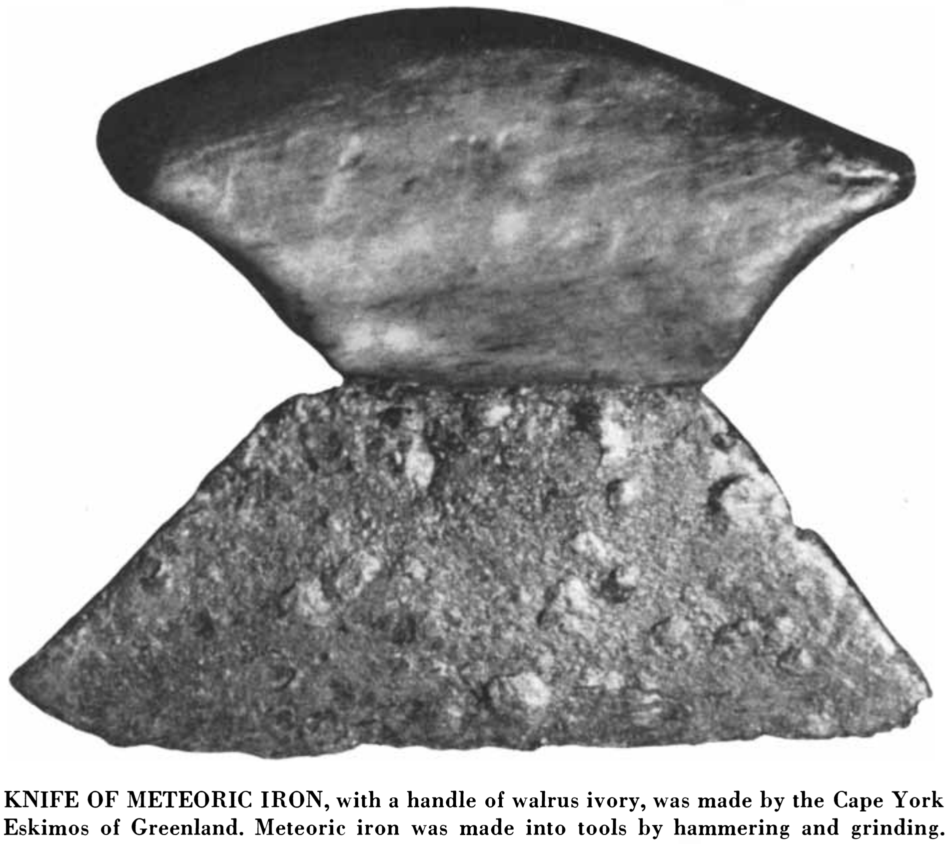
lightweight, modular design provides highly flexible power systems for unmanned satellites

Each of these shuttered aerospace fuel-cell modules weighs just 30 pounds and occupies less than a half cubic foot; yet each can deliver 200 watts at 26 volts dc. These modules are designed to operate between 22.0 and 29.5 volts dc.

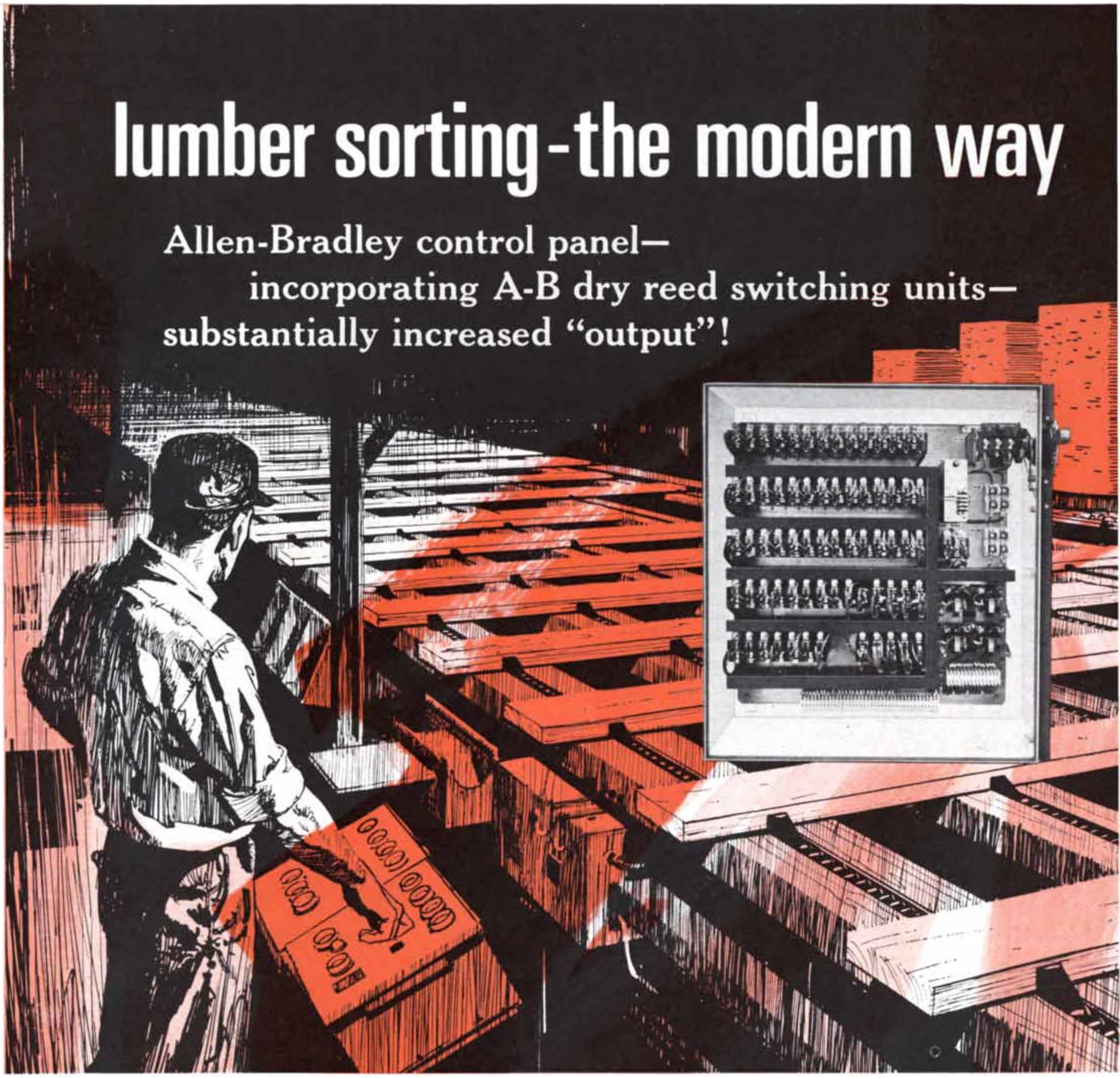
Developed by Allis-Chalmers for the Air Force, these 200 watt aerospace modules feature a weight-saving thermal control system, utilizing self-actuated shutters. They regulate module emissivity to meet the requirements of any environment from 20°F to 160°F: operating parameters readily achieved by simply selecting a radiation shield of suitable reflectivity.

The building block concept permits ideal answers to many different space-power requirements. Space and weight are trimmed because no coolant, region of South America, but how did these older skills evolve? In the traditional "parallelist" view there is no reason to assume, even in the absence of evidence for the local beginnings and evolution of such skills, that the ancient Indians were incapable of independently discovering them. Opposed to this view is the "diffusionist" position that the metallurgical processes are so complex that they must have been imported from across the Pacific. At present there is no concrete and persuasive evidence to support either contention.

EARLIEST METALWORKERS in the New World produced knives, projectile points and other kinds of tool from nearly pure native copper found in the Great Lakes area of North America. Artisans of the "Old Copper" culture, which flourished between 4000 and 2000 B.C., shaped their products primarily by hammering. Their manufacture of rolled points (*left*) and sockets (*center*) shows their appreciation of the plasticity of the new raw material.



KNIFE OF METEORIC IRON, with a handle of walrus ivory, was made by the Cape York Eskimos of Greenland. Meteoric iron was made into tools by hammering and grinding. Although the metal is far from abundant, it was used wherever chance made it available.



Here's a lumber sorting operation where Allen-Bradley dry reed switching solved a serious problem. It provides not only the required high speed switching for rapid sorting but also the required reliability to insure continuous operation. The unavoidable operating conditions —extreme dust with wide temperature variations—can be ignored in reed switching.

The reason for the success of this installation is self-evident. To begin with, each individual dry reed contact in the Allen-Bradley system is hermetically sealed within an inert gas filled glass tube—contact contamination cannot occur. Consequently, the A-B reed devices will provide hundreds of millions of faultless operations.

Allen-Bradley dry reed switching is in the millisecond range. Unlike solid state devices, it is insensitive to "transients" or wide temperature variations. Also, A-B dry reed switching consists of simple relay circuits, with which electricians are well acquainted.

All Allen-Bradley units are of rugged modular construction, uniform in height and depth and arranged for panel mounting. Terminals—all accessible from the front and individually identified—simplify wiring and circuit tracing.

Allen-Bradley dry reed switching units are available in a variety of types, as described at the right, to make possible complete design flexibility. Allen-Bradley engineers will be pleased to work with you on the application of these dry reed switching units. Please let us hear from you. Allen-Bradley Co., 1204 South Third Street, Milwaukee, Wisconsin 53204. In Canada: Allen-Bradley Canada Ltd. Export Office: 630 Third Ave., N.Y., N.Y., U.S.A. 10017.

Allen-Bradley has available a complete line of dry reed switching units

BULLETIN 1610
Dry Reed Relays
All A-B dry reed switching units are similar in appearance and construction. Enclosures are identical in height and depth—only the width varies. The dry reed relays consist of individual hermetically sealed contacts, either N.O., N.C., or various combinations of both. A single coil surrounds all the switches in the relay. The steel enclosure completes the magnetic circuit and shields the switches from external fields. Available in four basic enclosure sizes. Standard coil voltages 24 v and 125 v dc.

BULLETIN 1610L
Magnetically Latched Dry Reed Relays
Latching contacts have permanent magnet bias not strong enough to operate the contacts, but strong enough to hold them in position once they have been operated even if coil power is removed. Relays have coils with separate "latch" and "unlatch" windings. Available with 2, 4, 6, and 8 poles.

Bulletin 1610

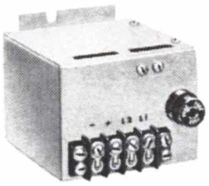
BULLETIN 1612L
Shift Register Units
These are self-contained shift register stages consisting of magnetically latched storage and transfer relays. A dual coil surrounds the magnetically biased dry reed switches. Two isolated contacts are available for signal outputs. Can be furnished with various contact arrangements.

BULLETIN 1614L
Flip-Flop Units
Consist of prewired magnetically latched input and output relays. Output relays have four contacts. Units can be assembled to perform counting functions: binary, binary coded decimal, and decimal counters. No power is required to maintain steady state condition.

BULLETIN 1618
Diode Units
Are assemblies of hermetically sealed high quality silicon diodes conveniently enclosed. The units are internally wired in three ways: separate terminals for each diode, pairs of diodes with a common anode terminal or with a common cathode terminal. Number of diodes: 7 or 13; pairs of diodes: 5 or 9.

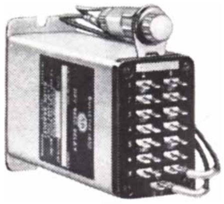
BULLETIN 1616
Logic Units
Contain double-wound coils with the windings in opposition. Each winding will cause contact operation when energized alone. Various logic functions can be performed: nor, and exclusive-or, inclusive-or, and comparator. A variety of output contact combinations can be furnished.

Allen-Bradley has many other components and accessories to round out the complete dry reed switching line, such as:



BULLETIN 1690
Power Supply
It furnishes filtered direct current for proper operation of the high speed dry reed devices.

BULLETIN 1691
Resistor-Capacity Network
Provides arc suppression for contact protection when switching inductive loads.



Compact clip-on pilot light units are also available. Readily visible, lights are easy to mount by slipping bracket into a recess at the top of the terminal block.

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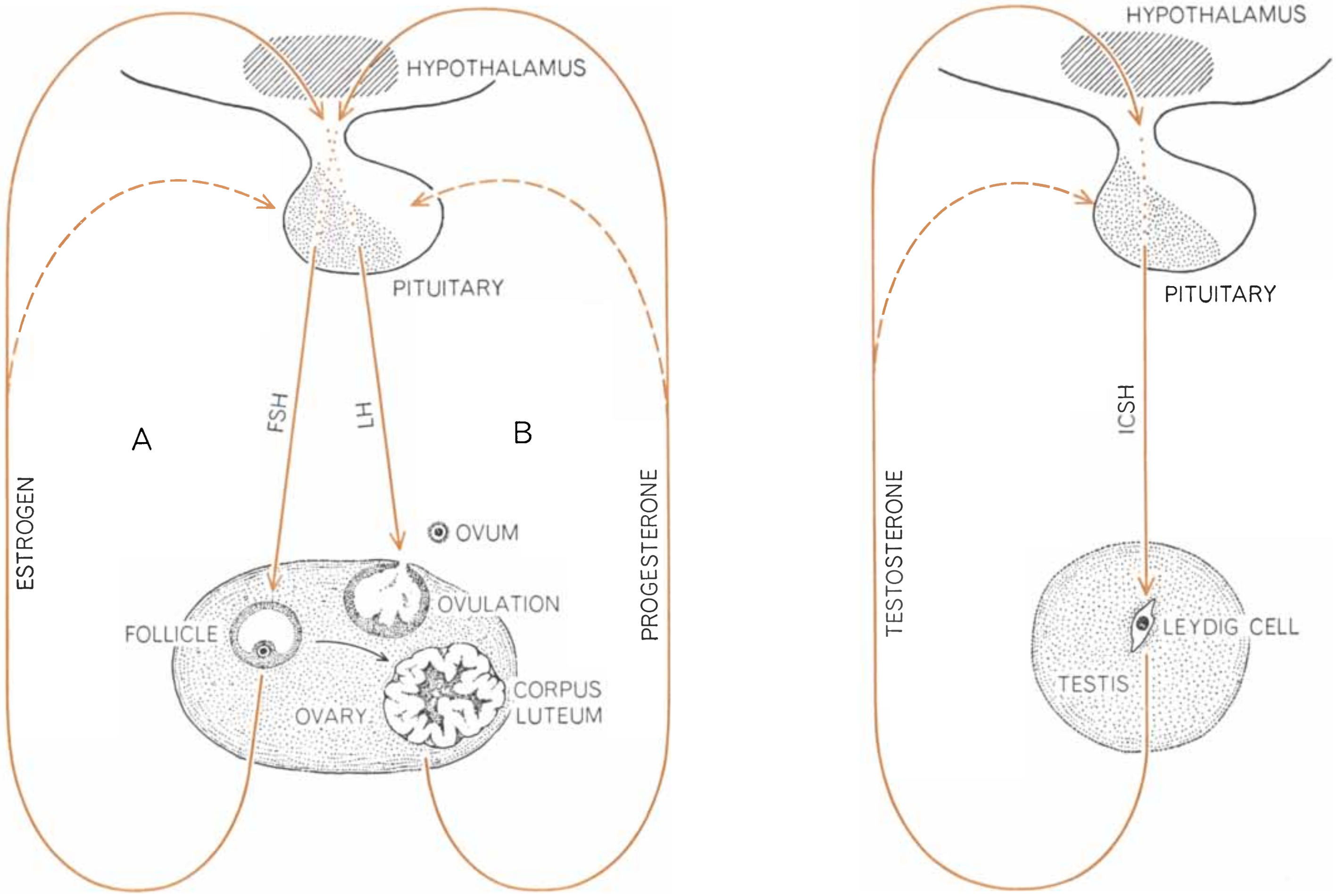
SEX DIFFERENCES IN THE BRAIN

There is increasing evidence that mammalian behavior patterns are basically female and that male patterns are induced by the action of the sex hormone testosterone on the brain of the newborn animal

by Seymour Levine

What makes a male mammal male and a female mammal female? We might sum up the answer in the word heredity, but this would evade the question. How is the genetic information translated into the differentiation of the sexes, as expressed in their physiology and behavior? Again we might summarize the answer in a single word: hormones. Recent investigations have revealed, however, that sexual differentiation in mammals cannot be explained solely in terms of hormones. There is now considerable evidence that the brain is also involved. According to this evidence there are distinct differences between the male brain and the female brain in a mammal, differences that determine not only sexual activity but also certain other forms of behavior.

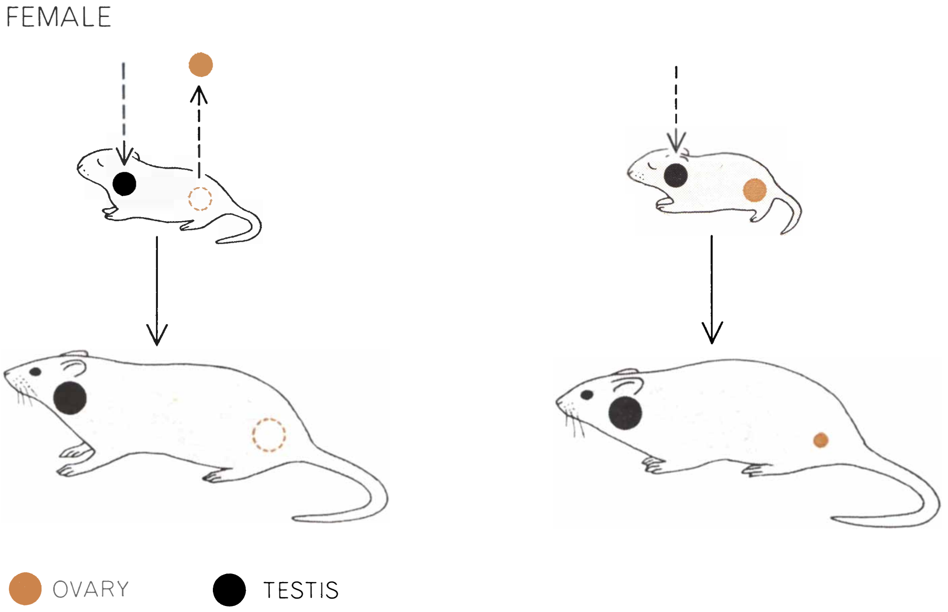


INTERPLAY OF SEX HORMONES differs in the female mammal (*left*) and the male (*right*). In the cyclic female system the pituitary initially releases a follicle-stimulating hormone (FSH) that makes the ovary produce estrogen (*colored arrows at A*): the estrogen then acts on the hypothalamus of the brain to inhibit the further release of FSH by the pituitary and to stimulate the release of a luteinizing hormone (LH) instead. This hormone both triggers ovulation and makes the ovary produce a second hormone, progesterone (*colored arrows at B*). On reaching the hypothalamus the latter hormone inhibits further pituitary release of LH, thereby completing the cycle. In the noncyclic male system the pituitary continually releases an interstitial-cell-stimulating hormone (ICSH) that makes the testes produce testosterone; the latter hormone acts on the hypothalamus to stimulate further release of ICSH by the pituitary. Broken arrows represent the earlier theory that the sex hormones from ovaries and testes stimulated the pituitary directly.

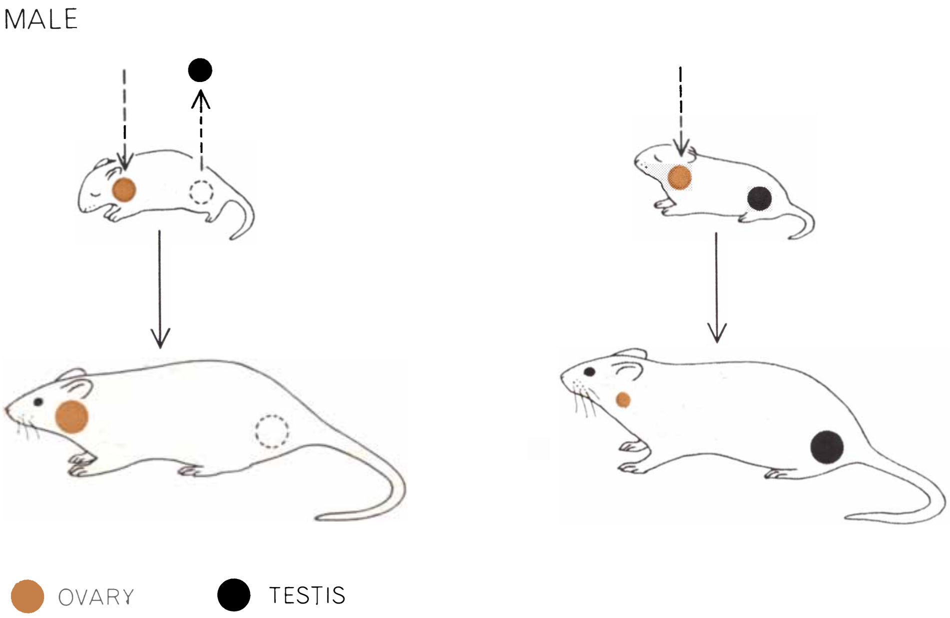
Let us begin by examining one of the principal distinctions between males and females. In most species of mammals the female has a cyclic pattern of ovulation. The human female ovulates about every 28 days; the guinea pig, about every 15 days; the rat, every four to five days. The process is dominated by hormones of the pituitary gland. In cyclic fashion the anterior (front) part of the pituitary delivers to the ovary a follicle-stimulating hormone (FSH), which promotes the growth of Graafian follicles, and a luteinizing hormone (LH), which induces the formation of corpora lutea and triggers ovulation. The formation of corpora lutea is clear evidence that ovulation has occurred. The ovary in turn responds to FSH by releasing the female sex hormone estrogen and to LH by releasing the female sex hormone progesterone [*see illustration on opposite page*].

The male mammal shows no such cycle. Its testes continually receive from the pituitary the same hormone (LH) that stimulates formation of corpora lutea in the female's ovary; in the male, however, this hormone is known as the interstitial-cell-stimulating hormone (ICSH) because it causes the interstitial cells of the testes to secrete testosterone. Thus the patterns of pituitary effects on the sex organs are distinctly different in the two sexes: cyclic in the female, noncyclic in the male.

What might account for this difference? When the interaction of the pituitary and sex organs was discovered, it was natural to suppose that the sex hormones regulated the pituitary's secretions. In the female the pituitary hormones controlled the process that led to ovulation; the consequent output of estrogen and progesterone by the ovary caused the pituitary to cut down production of its stimulating hormones, and the cycle might therefore be described as a negative-feedback system.



REVERSAL OF SEX in young female rats was achieved experimentally by Carroll A. Pfeiffer of the Yale University School of Medicine 30 years ago in proof of the action of the male sex hormone testosterone. When the ovaries of a young female (*at top left in color*) were removed and testes were implanted, the animal in effect became male (*gray*) and showed no estrus at maturity. Even when a female's ovaries were left intact (*top right*), the output of testosterone from the implant prevented normal functioning of the ovaries.



LACK OF TESTOSTERONE permitted a similar reversal of sex among young male rats in the Pfeiffer experiment. When the rat's testes were removed and an ovary was then implanted (*top left*), the ovary continued to function and the animal in effect became female (*color*). When an ovary was implanted in a normal male, however (*top right*), the male's output of testosterone kept the ovary from functioning and the rat remained male (*gray*).

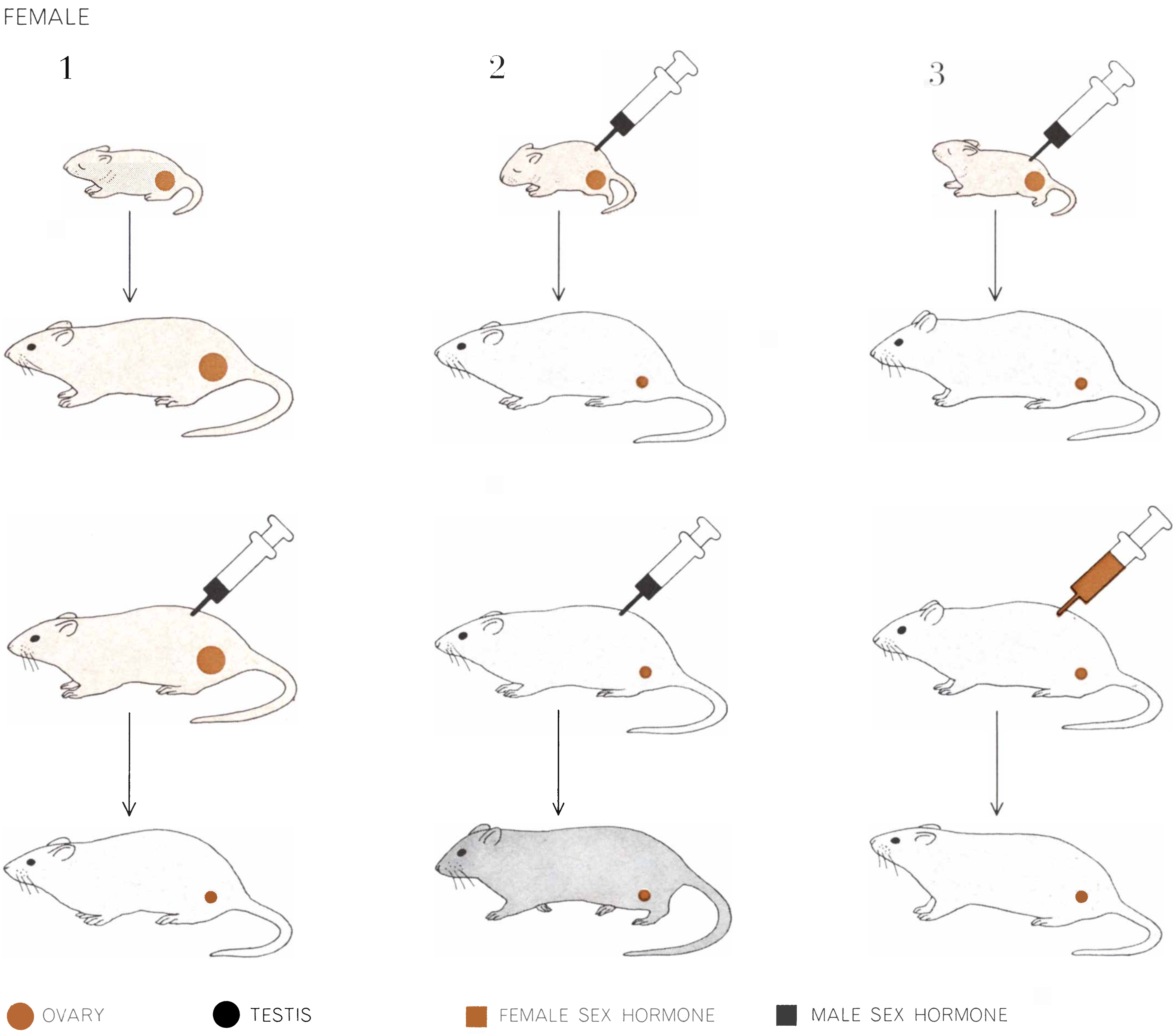
Thirty years ago the endocrinologist Carroll A. Pfeiffer, then working at the Yale University School of Medicine, reported a series of studies unequivocally demonstrating that the process of sexual differentiation occurred very early in the course of a mammal's development. In these studies he undertook to exchange the sex organs in the formative period of early life. In newborn male rats he removed the testes and replaced them with transplanted ovaries; in newborn females he replaced the ovaries with testes; other animals in his experiments were provided with both organs—testes and ovaries. The main findings that emerged were these: Males with ovaries in place of testes showed the female capacity for producing corpora lutea in the ovarian tissues. Those that possessed testes as well as ovaries failed to form any corpora lutea in the implanted ovaries. Of the females that had testes implanted, many failed to show estrous cycles or any formation of corpora lutea in their ovaries if the ovaries were left intact.

From these results Pfeiffer deduced that, since the controlling factor seemed to be the presence or absence of testosterone, in the newborn rat testosterone acted to induce a permanent sexual differentiation of the pituitary. If testosterone was present during this critical early period, it would cause the pituitary to produce stimulating secretions thereafter in the noncyclic, male mode; if testosterone was absent, the pituitary would behave throughout life as if it belonged to a female.

Pfeiffer's hypothesis that the pituitary itself was sexually differentiated did not stand up, however. Direct evidence on this question was produced in the 1950's by Geoffrey W. Harris of the University of Oxford and investigators working with him at the Institute of Psychiatry in London. Harris and Dora Jacobsohn found that when the pituitary gland of a male rat was transplanted under the hypothalamus of a female, her reproductive functions and behavior remained entirely female and normal. The same absence of change was noted when pituitaries from female rats were implanted in males. Meanwhile the late F. H. A. Marshall of the University of Cambridge was able to demonstrate that a close relation exists between the external environment and reproduction. In many species of mammals the female cycle of ovulation is affected by light, diet, temperature and emotional stress. Moreover, electrical stimulation of the hypothalamus could induce ovulation, and lesions of the hypothalamus could block ovulation.

Reviewing Pfeiffer's findings and the other experimental evidence, Harris and another investigator, the late William C. Young of the University of Kansas, suggested that it was the brain (not the pituitary, as Pfeiffer had proposed) that was subject to differentiation by the action of hormones. According to this view, the brain of a mammal was essentially female until a certain stage of development (which in the rat came within a short time after birth). If testosterone was absent at this stage, the brain would remain female; if testosterone was present, the brain would develop male characteristics.

Under Harris' leadership the author and other investigators working in the department of neuroendocrinology at the Institute of Psychiatry started a systematic and extensive program of experiments to test this hypothesis. The



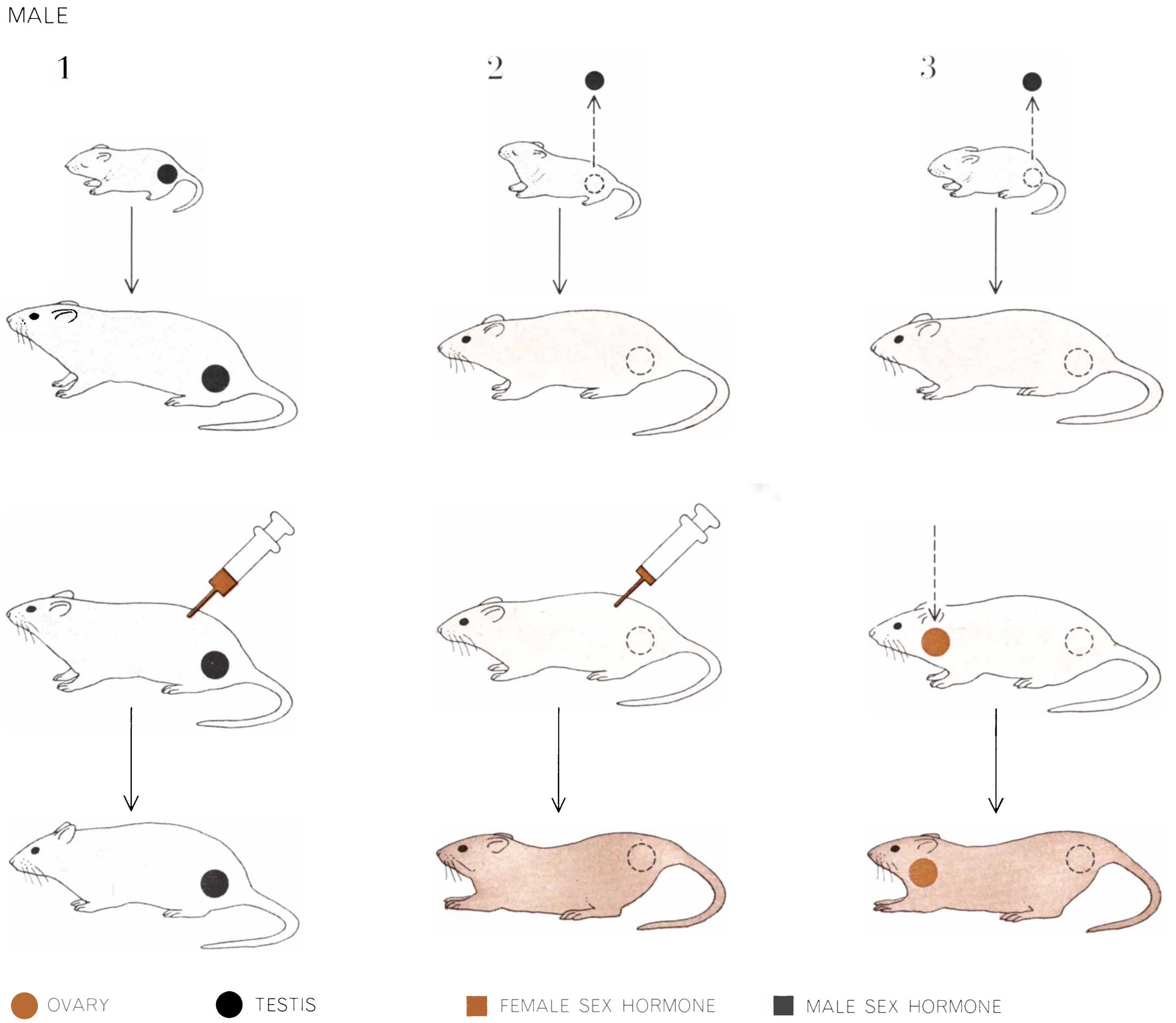
MASCULINIZED FEMALE RATS were produced by injections of testosterone (*black syringe*) at birth. In Column 1 a normal female (*color*) is injected with male hormone when mature; the animal exhibits some male sexual behavior (*gray*). In Column 2 the female is injected with male hormone in infancy; when reinjected at maturity, it exhibits full male sexual behavior. In Column 3, in spite of an injection of female hormone (*colored syringe*) at maturity, the masculinized female fails to exhibit female sexual behavior.

program has been continued at the Stanford University School of Medicine. We worked mainly with rats, and the basic procedure entailed alteration of the newborn animal's normal exposure to sex hormones within the first four days after birth. Instead of transplanting organs we simply injected the hormone whose effects we wished to test; it was already known that a single injection of testosterone (in the form of the long-acting compound testosterone propionate) in a newborn female rat could produce the same effects as the implantation of male testes.

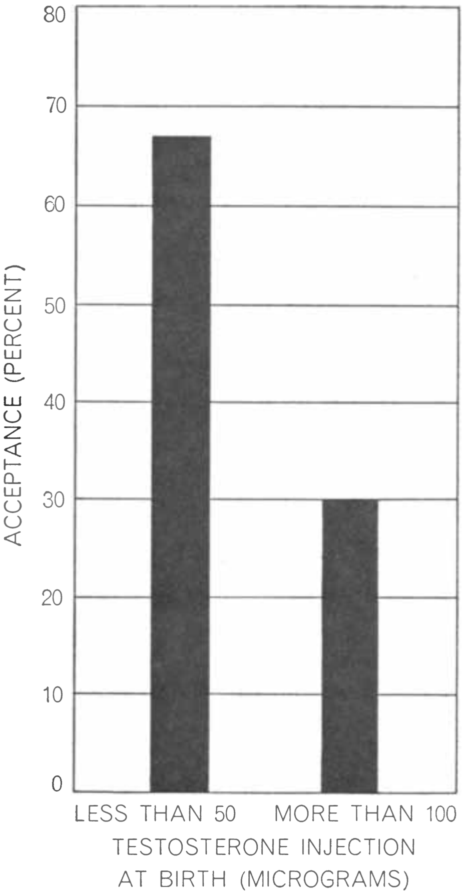
We found that females injected with testosterone in this critical early period did not develop the normal female pattern of physiology when they became adults. Their ovaries were dwarfed and they failed to produce corpora lutea or show the usual cycle of ovulation. On the other hand, males that were castrated (and thus deprived of testosterone) within the first days after birth did show signs of female physiology; when ovaries were implanted in them as adults, they developed corpora lutea. It was clear that a permanent control over the activity of the pituitary in the rat was established by the absence or presence of testosterone in the critical first few days after birth. In the absence of testosterone a pattern of cyclic release of FSH and LH by the pituitary was formed; if testosterone was present, it abolished the cycle.

Essentially the same effect has been demonstrated in guinea pigs and monkeys, but the critical period for these longer-gestating mammals occurs before birth. A series of injections of testosterone in the fetal stage of a female guinea pig or monkey produces permanent masculinizing effects such as we have observed in the female rat.

What are the effects of the early administration of testosterone on the rat's sexual behavior? In this area, as in physiology, there are measurable



FEMINIZED MALE RATS were produced by injections of estrogen and progesterone or by ovary implants only when the males had been castrated at birth and thereby deprived of testosterone during the critical first days of life. In Column 1 a normal male (*gray*) is unaffected by the injection of female hormones (*colored syringe*) at maturity. In Column 2 a castrated male is similarly injected; it then assumes the female's permissive sexual posture. In Column 3 the same behavior is produced by implanting an ovary.



SEXUAL BEHAVIOR of female rats was substantially modified by the injection of male hormone at birth. Although dosed with female hormones at maturity, females that had received 100 micrograms or more of testosterone at birth were less than half as responsive to male sexual advances as rats that had received little or no male hormone.

criteria for male and female behavior. The male goes through a complex pattern of behavior that begins with mounting of the female and proceeds through several stages to the final ejaculation. The female's display of sexual receptivity is marked by a "lordosis response" (which consists of arching the back and elevating the pelvis) when she is mounted by the male. Now, in most subprimate mammals, including the rat, the female's sexual behavior depends entirely on the hormones circulating in her bloodstream. Removal of the ovaries (and hence the elimination of estrogen and progesterone) will completely suppress her normal female sexual behavior, and conversely injections of estrogen and progesterone will restore it. Hence it was no surprise to find that the testosterone treatment of newborn female rats, which disrupted their normal secretion of sex hormones, affected their sexual behavior. The effects were marked, however, by several unusual features.

These masculinized females not only lost the usual female sexual receptivity, including the normal lordosis response to a male, but also failed to show the normal response even when they were given large replacement injections of estrogen and progesterone. Moreover, they showed male behavior that went beyond any previously observed. Male sex behavior is not uncommon even in normal female animals; they can often be observed going through the motions of mounting. A normal adult female rat, if injected with testosterone, will sometimes go so far as to mimic some components of the male's act of copulation. Some of our female rats that had been testosteronized at birth went further, however. Although such females lack any semblance of male genitalia, when they were given a new dose of testosterone as adults, they performed the entire male sexual ritual, including the motions that accompany ejaculation.

The male rats in our experiments showed a similarly striking change of sexual behavior as a result of hormonal alteration at birth. Normally it is extremely difficult to elicit female sexual behavior in an adult male merely by injecting him with female hormones. When, however, newborn male rats were castrated, so that they lacked testosterone at the critical stage of development occurring in the few days after birth, it was found that injection of very small doses of estrogen and progesterone in these males as adults caused them to display sexual behavior precisely like that of normal females. Clearly the change in these animals involved the central nervous system; the system's response to female hormones, as reflected in the animal's behavior, had been altered.

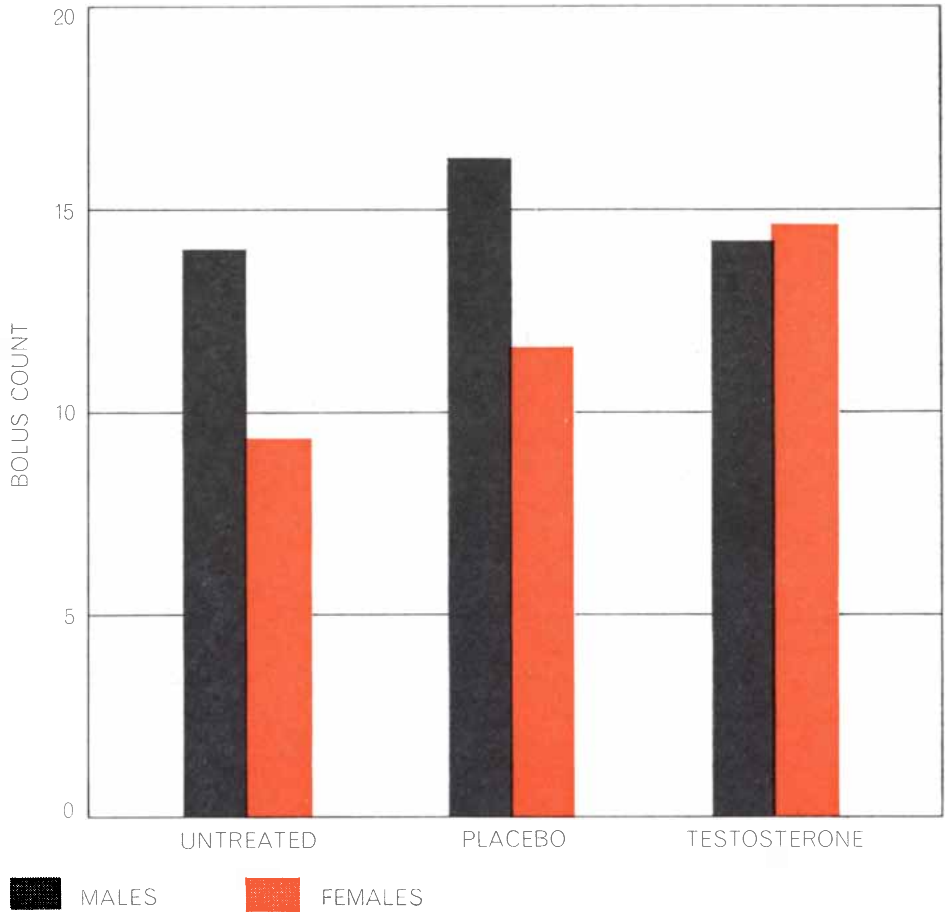
Thus all the experiments, both on males and on females, left little doubt that testosterone could determine the sexual differentiation of the brain in the first few days after birth. In some manner testosterone produced a profound and permanent change in the sensitivity of the brain to sex hormones. In the female it made the brain tissue much more sensitive to testosterone and insensitive to estrogen and progesterone, so that the animal did not display normal female behavior in response to these female hormones. In the male the absence of testosterone at the critical period caused the animal to be sensitive to estrogen and progesterone. To put it another way, the absence of testosterone at the differentiation stage would leave both males and females sensitive to the female hormones and capable of displaying female behavior; the presence of testosterone, on the other hand, would desensitize females as well as males, so that both sexes failed to display feminine behavior when they were challenged with female hormones.

That the sex hormones can act directly on the brain was clearly demonstrated in experiments by Harris and Richard Michael. They implanted a synthetic estrogen (stilbestrol) into the hypothalamus of female cats and found that the implant evoked full female sexual behavior although the cats did not show the usual physiological signs of estrus. In similar experiments with males Julian M. Davidson of Stanford University showed that implants of testosterone in the brain of a castrated male rat would elicit male sexual behavior, although again there was no sign of effects on the anatomy of the male reproductive system.

If the brain differentiates into male and female types, may not the difference be reflected in fields of behavior other than the sexual? A few experiments looking into this question have been conducted; they suggest that other forms of behavior can indeed be influenced by hormonal treatment during the critical period of sexual differentiation.

One of these studies involved a difference between male and female behavior that Curt P. Richter of the Johns Hopkins School of Medicine observed many years ago. He used an activity wheel that measured the amount of voluntary running activity an animal would perform each day. The activity of females, he found, went in cycles, rising to a peak at the time of ovulation; males, on the other hand, performed more uniformly from day to day. Harris recently applied this activity test to male rats that had been castrated shortly after birth and then implanted with an ovary as adults. They showed a cyclic pattern of running activity corresponding to the cycle of ovulation (covering four to five days) of the female rat.

Another test employed the open-field apparatus with which we have gauged animals' behavior in response to various emotion-evoking stimuli [see "Stimulation in Infancy," by Seymour Levine; SCIENTIFIC AMERICAN, May, 1960]. In this apparatus females tend to be more exploratory and to defecate less often than males. We found that female rats to which testosterone had been ad-



EXPLORATORY BEHAVIOR, more extensive among female rats than among males, was modified when the females were injected with male hormones at birth. The bar chart shows the frequency of defecation, which is inversely proportional to exploration, in three minutes' exposure in an open-field apparatus. When the females had not been injected at birth (*left and center*), their count was significantly lower than the males'. Females that had been masculinized (*right*), however, defecated at a rate insignificantly different from the males'.

ministered at birth displayed the male pattern of defecation behavior instead of the female pattern [*see illustration above*].

Analyzing the play of young monkeys before they reach sexual maturity, Young and his co-workers found that the juvenile male's behavior is distinctly different from the female's: the male is more inclined to rough-and-tumble play, more aggressive and more given to threatening facial expressions. Again experiments showed that injections of testosterone during the critical differentiation period (before birth in the monkey's case) caused females to display the male type of behavior in play.

Obviously the findings so far are only first steps in what promises to be an important new field of investigation. They invite a full exploration of the extent to which behavior, nonsexual as well as sexual, can be masculinized by testosterone treatment or feminized by castration at the critical stage of sexual differentiation. It presents a new biological mystery: If testosterone at the critical period does indeed produce sexual differentiation in the brain, by what mechanism does it do so? The studies on animals may well have clinical implications for human beings with respect to the problem of homosexuality. Human homosexual behavior undoubtedly involves many psychological factors that do not apply to the lower animals, but it may also depend in a fundamental sense on what the hormonal makeup of the individual happens to be during the development of the nervous system.

There are other questions of broader interest. Do the hormones of the thyroid gland, the adrenal cortex and other organs of the endocrine system exert differentiating effects on the developing brain? To what extent may the various hormones acting on the brain during infancy shape the future behavior of an individual? The artificially masculinized female rat and the feminized male have opened a wide field for speculation and research.

Basic Research at Honeywell
Research Center
Hopkins, Minnesota

Deformation and Fracture of Bone

The high sensitivity micro strain measuring technique of the metallurgist has been applied to the study of the mechanical properties of bone. The findings indicate some unexpected characteristics of bone.

Conventional studies of the mechanical properties of bone have been made for many years on stress-strain curves to fracture for a wide range of biochemical variables. These low-sensitivity measurements, however, have not permitted correlation of mechanical behavior with the atomic and defect structure of bone.

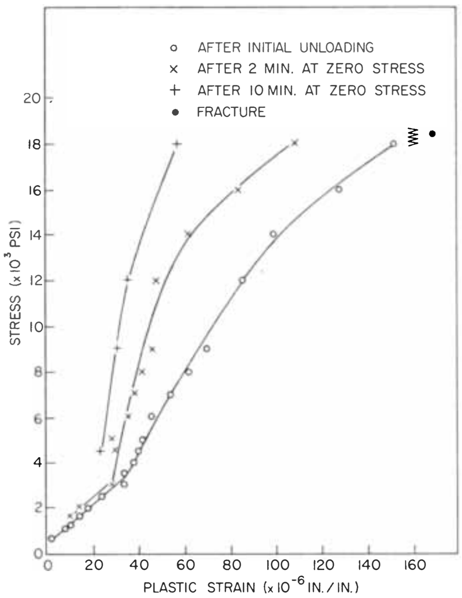


FIGURE 1.

Last year Honeywell's research metallurgists were asked to check inconsistencies in the performance of ivory in a particular application. Using a high sensitivity micro strain technique they had developed for aerospace materials, they determined that plastic deformation can be detected in ivory at the surprisingly low stress level of 180 psi. This and other unexpected findings caused them to broaden their research to include bone and to undertake a two-part investigation of the deformation and fracture of bone.

First, the micro strain technique was used to measure the initiation and extent of plastic yielding in bone. Second, fracture characteristics were determined under impact and tensile loading and as a function of temperature.

Two types of specimens – tensile and impact – were prepared from the outer periphery of compact bone of the femur of a cow.

Using a load unload technique, a series of increasing tensile stresses was applied to the tensile specimens at a strain rate of 3.3×10^{-4} sec. $^{-1}$. The total strain (elastic and plastic) at stress and the residual plastic strain after unloading were measured for each stress level. From these measurements the microscopic yield stress (the stress required to produce the first detectable plastic strain of 2×10^{-6} in./in.) and the subsequent variation of plastic strain with stress were determined.

Fig. 1 shows that the onset of plastic yielding was detected at the low level of approximately 600 psi. As the stress was increased above this level the amount of plastic strain progressively increased. This plastic strain was not all permanent strain since a large anelastic contraction was noted, as the graph shows.

Impact tests were conducted in a modified Charpy impact machine and specimens were struck at their midpoint with a hammer delivering 5.1 in. lb. of energy. The energy absorbed during impact was measured at temperatures from —196° to 900°C.

Fig. 2 plots results obtained for each unnotched longitudinal and transverse specimen with the energy absorbed during fracture shown as a function of test temperature.

Note that transverse specimens showed two marked differences from longitudinal specimens. First, the values of energies absorbed were significantly smaller for the transverse. Secondly, only a small peak in energy absorbed was noted at 0°C.

A series of longitudinal tensile specimens were also strained to fracture at a rate of 3.3×10^{-4} sec. $^{-1}$ at temperatures ranging from −196° to 200°C. Results showed that the tensile fracture stress exhibits a similar temperature dependance to that of the longitudinal impact specimens.

These findings demonstrate that up to a stress near to the fracture point, bone does not deform in an elastic manner as has previously been thought. Instead plastic yielding was detected at the low applied stress of 600 psi.

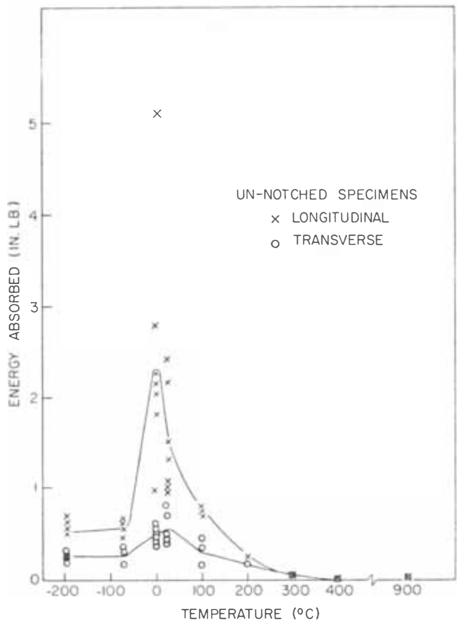


FIGURE 2.

Also significant was the large contraction which occurred with time after unloading. This indicates that the dominant deformation mode of bone must be anelastic and reversible.

The temperature dependance of the fracture characteristics was marked. Further work demonstrated that between −196° and 200°C. these temperature characteristics are related to reversible changes in atomic structure or the deformation mode.

The way bone deforms is obviously much more complicated than previously thought. Having defined deformation and fracture in bone, Honeywell scientists now seek to understand their underlying mechanism. Beyond the medical implications, it is hoped that interdisciplinary work such as this will yield unique results that will aid our understanding of other materials.

If you are engaged in related work and wish to learn more of Honeywell's study of the mechanical properties of bone, you are invited to correspond with Dr. William Bonfield and Dr. C. H. Li, Honeywell Research Center, Hopkins, Minnesota. If you are interested in a career in basic research at Honeywell, please write to Dr. John Dempsey, Vice President, Research, at this same address.

Honeywell

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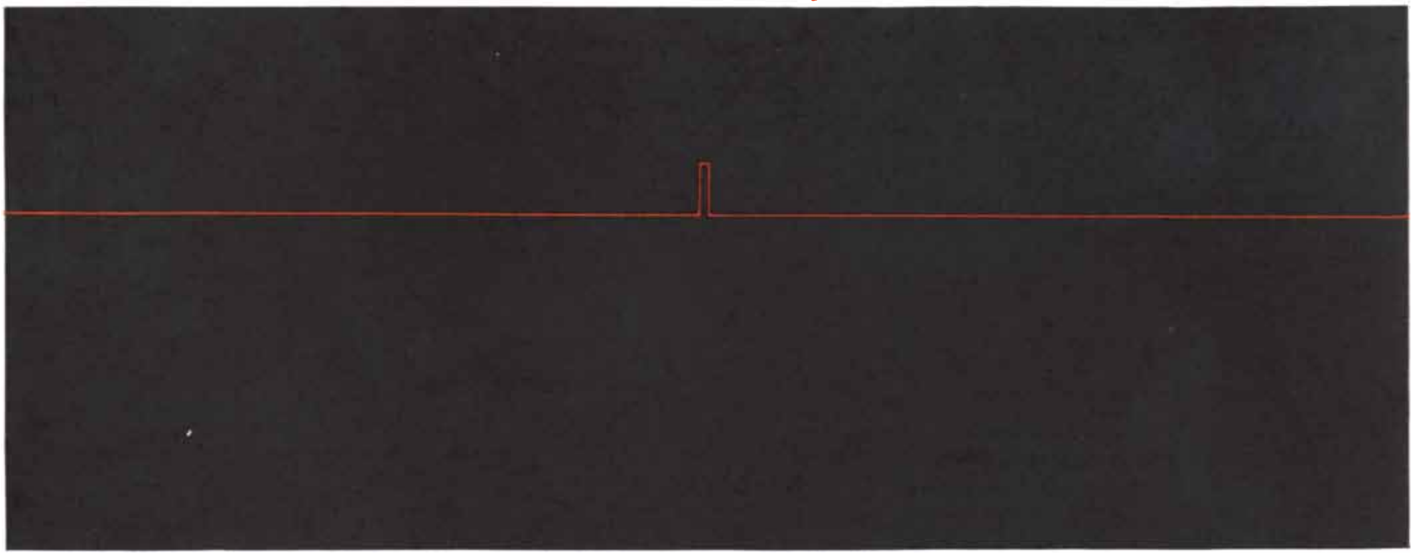

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THE MUONIUM ATOM

This recently discovered atom consists of only two elementary particles: a positive muon and an electron. A study of its energy levels has yielded precise new information that pertains to all electromagnetic interactions

by Vernon W. Hughes

This article concerns an extraordinary new atom, called the muonium atom, that was first observed by my colleagues and me in an experiment performed six years ago. The muonium atom consists of only two elementary particles of matter: a positive muon (abbreviated μ^+) and an electron (e^-). In many respects the muonium atom resembles the simplest ordinary atom, the atom of hydrogen, which consists of a proton (p^+) and an electron. In fact, muonium can be considered a lighter isotope of hydrogen. In both atoms the nucleus is a comparatively heavy positively charged particle (either a proton or a muon) that is surrounded by a much lighter negatively charged particle (an electron). The ratio of the masses of the electron, the muon and the proton is respectively one to 207 to 1,836.

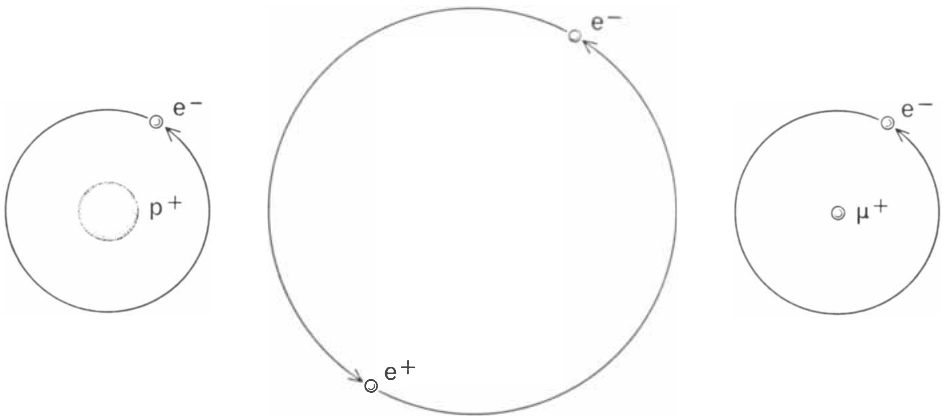
The muonium atom also bears some resemblance to the positronium atom, which was discovered by workers at the Massachusetts Institute of Technology more than a decade ago [see "The Ultimate Atom," by H. C. Corben and S. De Benedetti; SCIENTIFIC AMERICAN, December, 1954]. The positronium atom consists of an electron and a positron, or positively charged electron (e^+). A major difference between muonium and positronium is that the positive muon is much more massive than the electron, whereas the positron is equal in mass to the electron. In addition, the electron and the positron have the relation of particle and antiparticle and hence can annihilate each other to produce electromagnetic radiation in the form of gamma rays. The electron and the positive muon, on the other hand, are not particle and antiparticle and do not annihilate each other.

One of the main reasons why the muonium atom has attracted so much attention since its discovery is that the muon itself is such a mysterious particle. Discovered in 1936, the muon was for a time mistakenly considered the middle-weight particle, called the meson, that transmits the strong nuclear force. The peculiar fact about the muon is that in all its interactions with other particles and fields it behaves exactly like a heavy electron. This is the only clear instance in which a difference in mass between two particles cannot be explained in terms of the different interactions that the two particles undergo. Accordingly the muon contradicts a generally useful hypothesis on how to understand the mass spectrum of the elementary particles.

Since muonium is the simplest system involving both the muon and the electron, its study can perhaps provide a clue toward an understanding of the unique relationship of these two particles. Our studies of muonium, carried out over the past few years, have generally served to confirm the view that in its electromagnetic interactions the muon behaves like a heavy electron. Moreover, the results of these studies have provided precise new information that pertains to all electromagnetic interactions.

The second reason for the special interest in muonium has to do with the fact that it is an isotope of hydrogen. There is a wide range of atomic interactions and chemical reactions involving muonium that can be studied and compared with existing data for hydrogen itself.

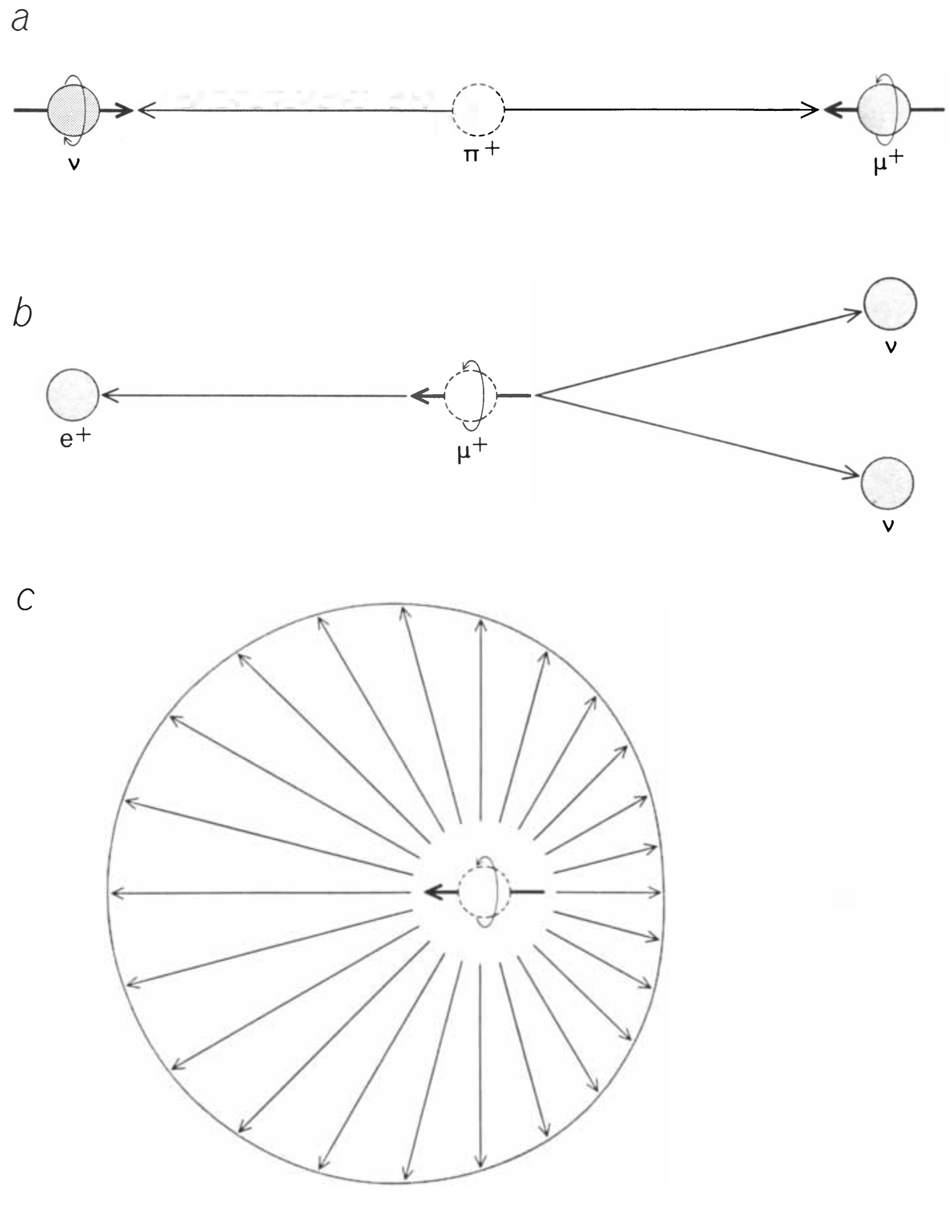
The energy levels of muonium are expected to be similar to those of hydrogen. Thus in the ground state, or lowest energy state, of muonium the electron is bound to the positive muon with an energy of 13.5 electron volts, which is very nearly the energy of the



THREE SIMPLEST ATOMS are each made up of only two elementary particles. The simplest ordinary atom, hydrogen (*left*), consists of a proton (p^+) and an electron (e^-). The positronium atom (*center*), discovered in 1953, consists of an electron and its antiparticle, the positron, or positively charged electron (e^+). The muonium atom (*right*), discovered by the author and his colleagues in 1960, consists of an electron and a positive muon (μ^+). The ratio of the masses of the electron, the muon and the proton is respectively one to 207 to 1,836. Relative sizes of the orbits of the three atoms are drawn to scale; particles are not.

ground state of hydrogen. On a very fine scale the ground state of muonium is actually split into two close states, called hyperfine energy levels, that arise from the magnetic interaction of the electron and the positive muon. Like most elementary particles, the electron and the muon can be visualized as tiny bar magnets that spin and so have a magnetic moment directed along their axis of spin, as well as an internal angular momentum. The energy involved in the interaction of the electron spin magnetic moment with the muon spin magnetic moment has one value when the two particles spin in the same direction and another value when they spin in opposite directions, and this causes the splitting of the hyperfine energy levels. In the presence of a static magnetic field, the two hyperfine levels of muonium are further split into four levels, owing to the magnetic interactions of the external magnetic field with the magnetic moments of the electron and the muon [*see bottom illustration on page 96*].

Since the magnetic moment of the muon is 3.18 times the magnetic moment of the proton, the interval between the two hyperfine energy levels for muonium in the absence of a magnetic field should be about 4,463 megacycles per second, compared with 1,420 megacycles per second for hydrogen. One of the major results of our experiments has been a highly precise measurement of this hyperfine-structure interval for muonium.

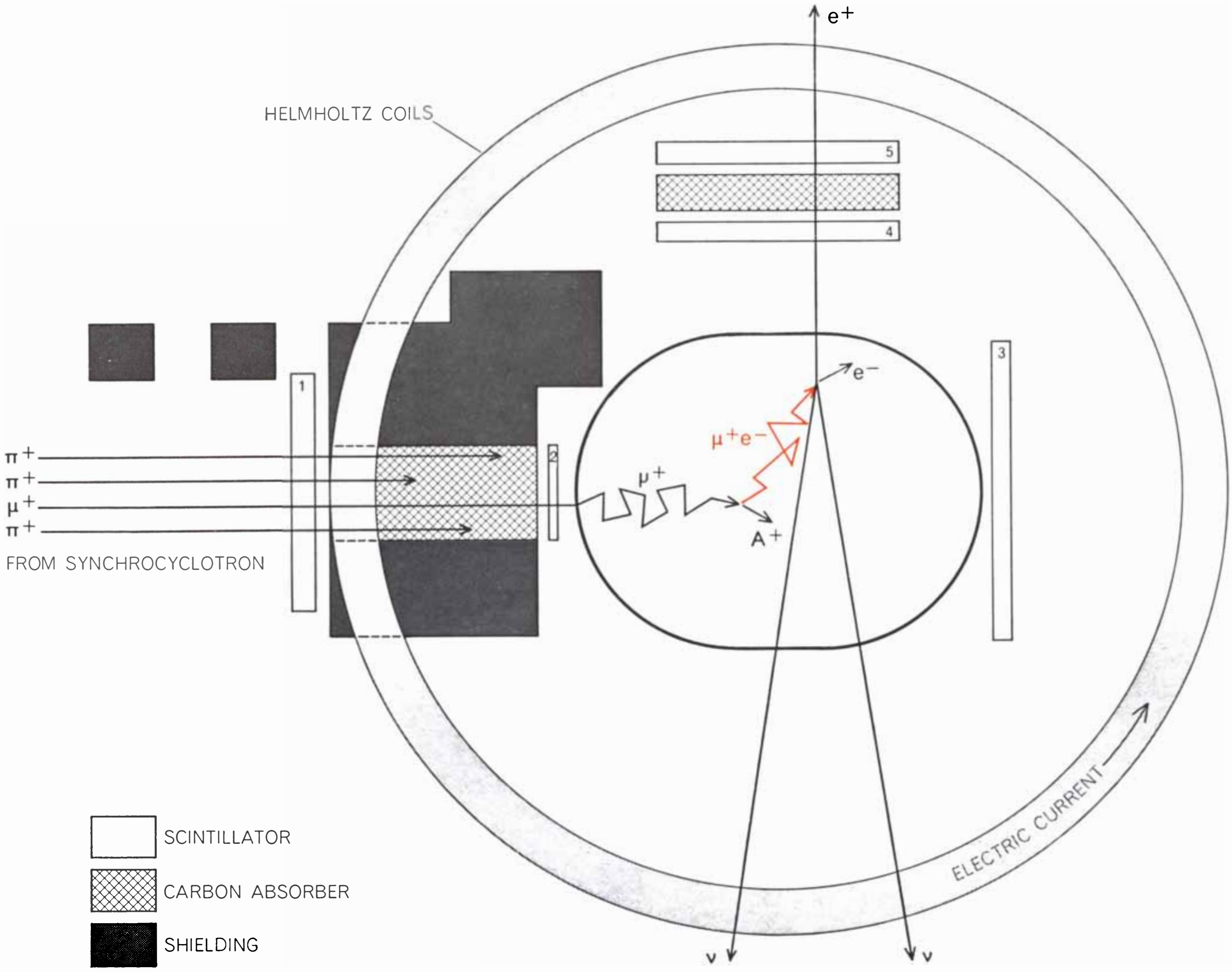


NONCONSERVATION OF PARITY, or mirror symmetry, in the weak interactions involving the production and decay of a muon is characteristically revealed in a correlation between the linear momentum, or direction of motion, of the muon and the internal angular momentum, or direction of spin, of the muon. When a positive pion (π^+) decays to produce a positive muon and a neutrino (ν), the muon has its spin vector (*heavy arrow*) and associated magnetic moment directed opposite to its linear momentum (*top*). When the positive muon subsequently decays into a positron and two neutrinos, the positron is emitted preferentially in the direction of the muon spin (*middle*). The probability of the positron's being emitted in a given direction is proportional to the lengths of the arrows at bottom.

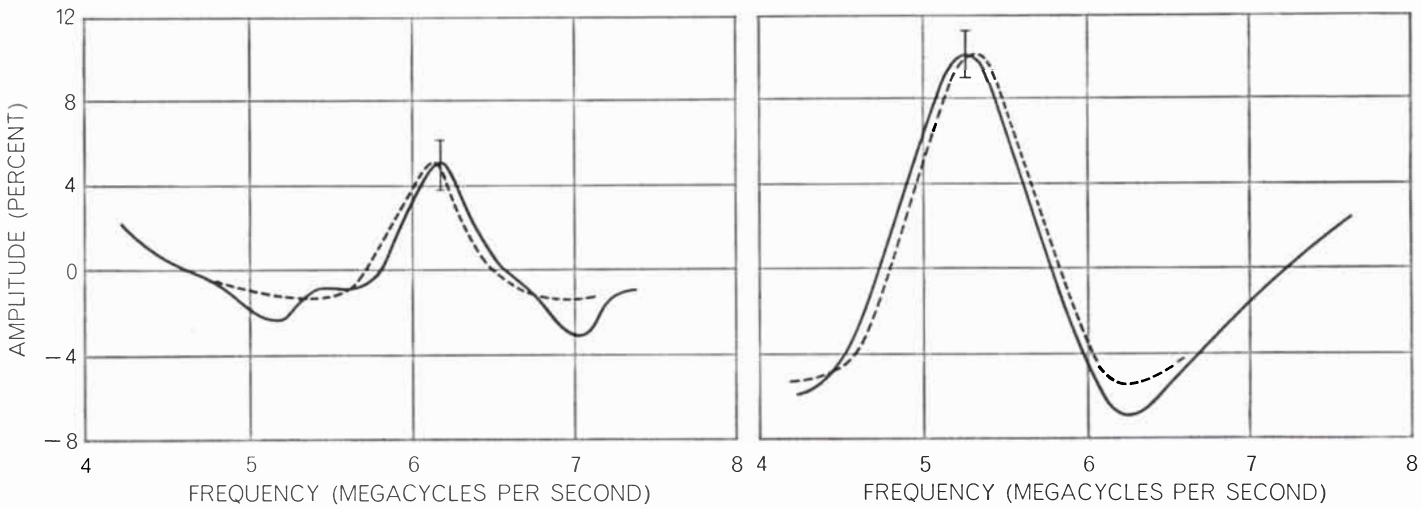
Muonium is an unstable atom with a mean lifetime of 2.2 microseconds (millionths of a second). It is unstable because the muon itself is unstable and decays (in 2.2 microseconds) into a positron and two neutrinos (ν) by the process known as weak interaction. The positrons produced by this interaction have various energies extending up to 52 million electron volts. When the positive muon in a muonium atom decays, then, the muonium atom is converted into four free, or unbound, particles: an electron, a positron and two neutrinos [*see top illustration on opposite page*]. Although the mode of decay of muonium is different from that of positronium, the brevity of its lifetime and the energetic nature of its decay products are similar to the corresponding properties of positronium. As a result some of the experimental techniques used to study muonium are similar to those used in the earlier positronium experiments.

The discovery of muonium became possible only when it was discovered that, in the weak interactions involving the production and decay of the muon, "parity" was not conserved [see "The Overthrow of Parity," by Philip Morrison; SCIENTIFIC AMERICAN, April, 1957]. Essentially the principle of the conservation of parity states that for most physical systems there is no absolute distinction between right and left—that a real object or event is a precise counterpart of its mirror image. In the weak interactions, however, it was discovered that there is a preferential handedness, or lack of mirror symmetry, that is characteristically revealed in a correlation between the linear momentum, or direction of motion, of a particle and its internal angular momentum, or direction of spin.

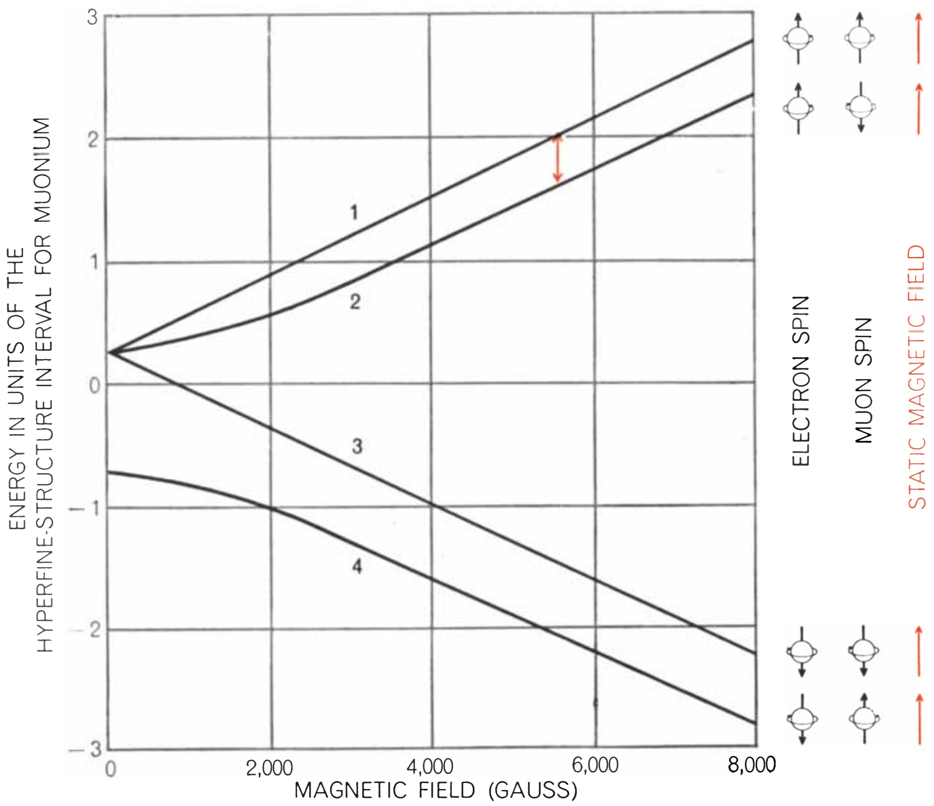
The nonconservation of parity in the production of a muon is demonstrated by the fact that when a positive pion (π^+) decays to produce a positive muon and a neutrino, the muon has its spin (and associated magnetic moment) directed opposite to its linear momentum [*see illustration at left*]. When the positive muon subsequently decays into a positron and two neutrinos, the positron is emitted preferentially in the direction of the muon spin magnetic mo-



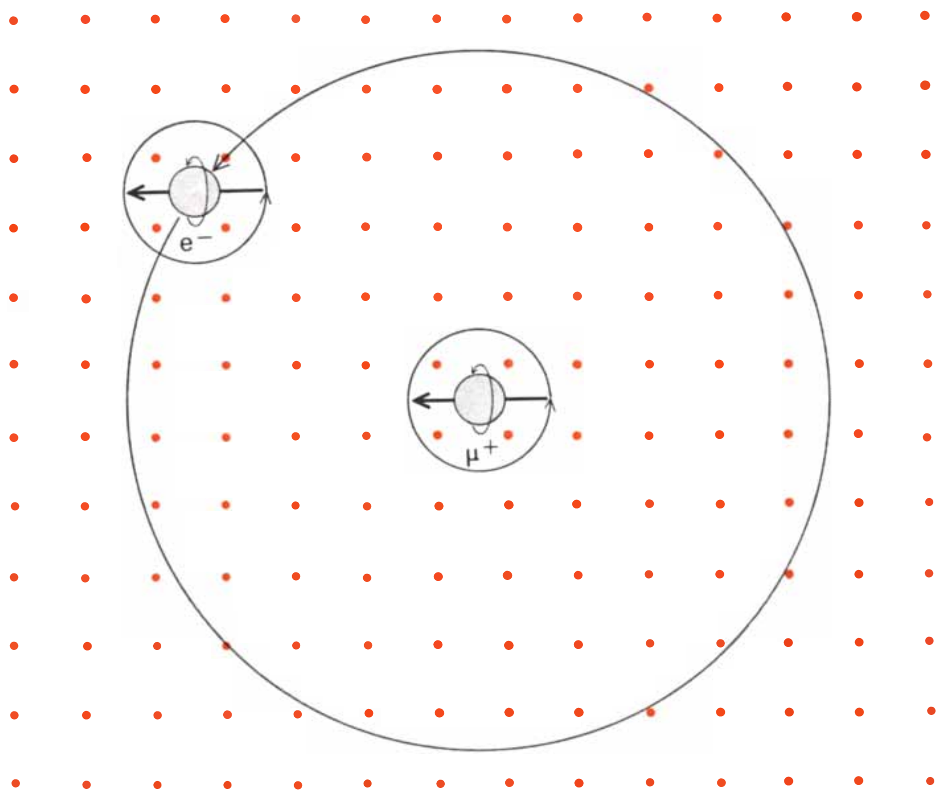
MUONIUM WAS DISCOVERED using the experimental apparatus depicted here. A beam of pions and muons from the Columbia University synchrocyclotron (*left*) strikes a block of carbon, which absorbs the pions, allowing only the muons to enter a tank of argon gas (*center*). The muons, which enter the tank with energies up to a million electron volts, lose their energy in ionizing collisions with argon atoms until they reach an energy of about 100 electron volts, at which point it becomes probable for a muon to capture an electron from an argon atom to form a stable muonium atom (μ^+e^-) and a positive argon ion (A^+). The muonium atom then quickly slows down to "thermal" speeds in collisions with argon atoms, whereupon the muon decays, emitting a positron and two neutrinos. When a muon enters and stops in the gas target, this is recorded by coincident pulses in scintillation Counter 1 and Counter 2 but no pulse in Counter 3. Counter 4 and Counter 5 detect the decay positron, and its time of arrival with respect to the time of arrival of the incoming muon is measured. The coils produce a static magnetic field perpendicular to the plane of the illustration.



TYPICAL RESULTS of the first successful muonium experiments are shown in these graphs, in which the solid curves give the analysis of the data for the amplitude of a component of the positron time distribution against the frequency of that component; the broken curves are expected on theoretical grounds. The graphs represent the data for two different strengths of the magnetic field.



SYNCHRONOUS PRECESSION, or rotation, of the spin axes (and associated magnetic moments) of the particles in a muonium atom occurs when a magnetic field (*colored dots*) is applied at right angles to the magnetic moments. (In this case magnetic field is also at right angles to the plane of the illustration.) The frequency of the precession is proportional to the strength of the field. In the case of muonium this frequency is detectable, because of the preferential emission of positrons in the direction of the muon spin magnetic moment.



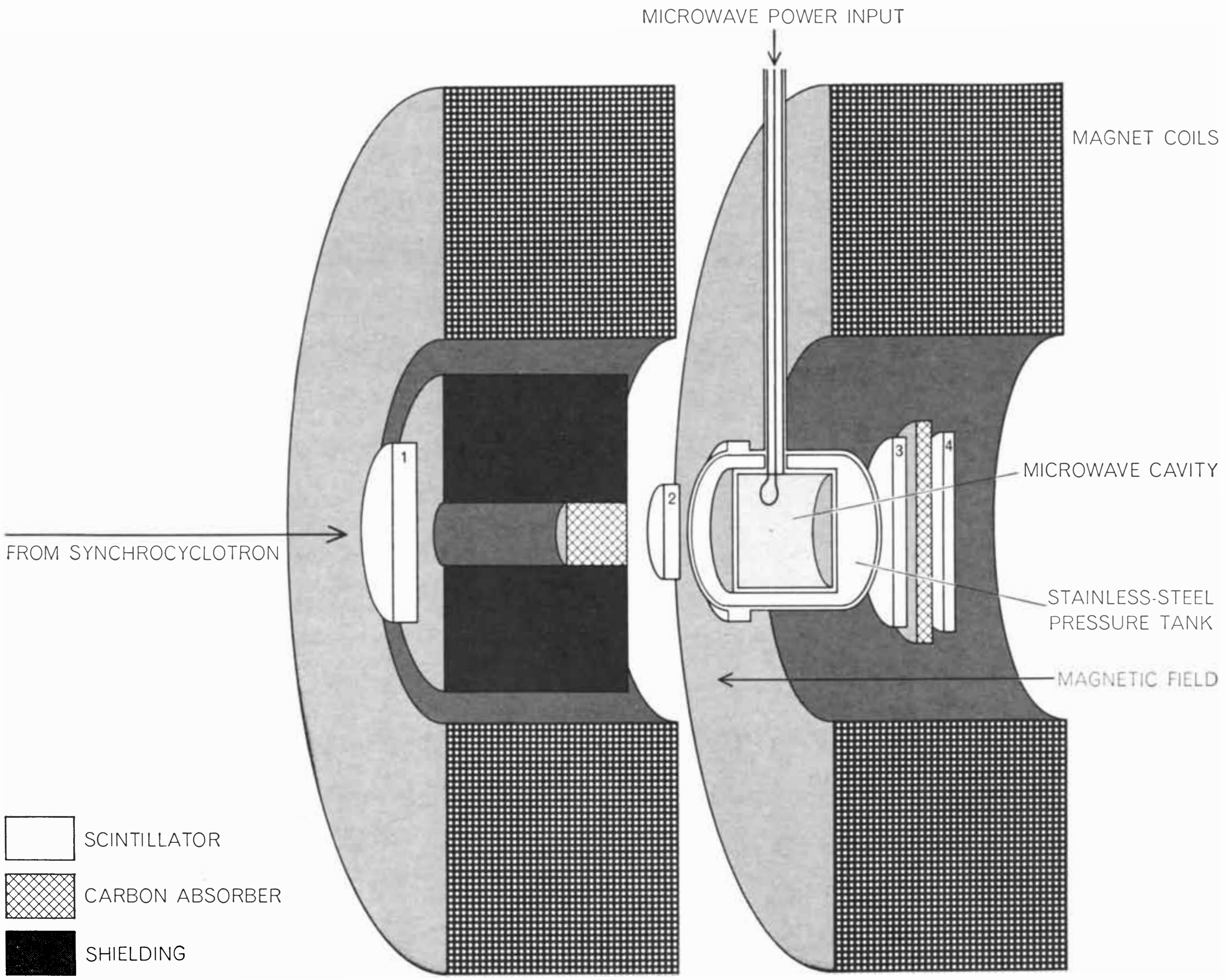
FOUR HYPERFINE ENERGY LEVELS of the ground state of muonium correspond to four different orientations of the spins of the muon and the electron with respect to the direction of the external magnetic field (*right*). The interval between the first two hyperfine energy levels at zero magnetic field has been computed to be about 4,463 megacycles per second for muonium. The transition indicated by the two-headed colored arrow was measured by the author's group to provide a highly precise new value for this interval.

ment. The availability of such "polarized" muons, or muons with their spins predominantly in one direction, and a means for detecting this direction (positron emission) were exploited in the discovery of muonium.

Conceptually the search for muonium was simple. A muonium atom was to be formed in a collision between a positive muon and a chemically inert atom, such as the argon atom (A), in which the muon captures an electron from the argon atom, creating a positive argon ion (A^+). Since the muons are polarized, the number of hyperfine energy levels of muonium that can be formed initially are restricted to those in which the direction of the muon spin magnetic moment is the same as that of the incoming muon. In a strong static magnetic field that is parallel to the direction of the initial muon spin magnetic moment, only two hyperfine energy levels will be formed: one corresponding to the case in which the muon spin and the electron spin are in the same direction and the other corresponding to the case in which the muon spin and the electron spin are in opposite directions. In a very weak magnetic field three hyperfine energy states will be formed; in only one of these states (the one in which the muon spin and the electron spin are in the same direction) does the muonium atom have a net magnetic moment.

Our experiment to discover muonium was based on the fact that the spin axis (and associated magnetic moment) of an atom slowly precesses, or rotates, around the lines of force in a perpendicularly applied magnetic field, with a frequency that is proportional to the strength of the field. In the case of muonium this precession frequency should be detectable because of the preferential emission of positrons along the direction of the muon spin magnetic moment. The characteristic precession frequency for muonium can be readily calculated from the known properties of the muon and the electron; hence such an observation would provide a test for the existence of muonium.

The experiment was performed at the Nevis Laboratories of Columbia University with a synchrocyclotron that produces protons with energies up to 380 million electron volts. Participating in the experiment were D. W. McColm, K. Ziock and myself, all of Yale University, and R. Prepost of Columbia. The protons strike a target inside the synchrocyclotron and produce positive pions, some of which then decay into



EXPERIMENTAL APPARATUS for measuring the hyperfine-structure interval of the ground state of muonium is similar in some respects to the apparatus in which muonium was discovered (*see top illustration on page 95*). To achieve a maximum transition signal, a strong static magnetic field of about 5,000 gauss (*colored arrow*) is set up by a pair of large solenoid coils. An additional time-varying microwave field is applied inside the microwave cavity at right angles to the static field. The transition of the muonium atoms from one hyperfine energy state to another is induced when this microwave field is in resonance with the frequency of the transition. The transition is observed by a change in the rate of positron emission in a given direction (*see illustrations on next page*).

positive muons. The mixed beam of pions and muons then passes through a block of carbon, which absorbs the pions, allowing only the muons to enter the tank of argon gas. The muons, which enter the tank with energies up to a million electron volts, lose their energy in ionizing collisions with argon atoms until they reach an energy of about 100 electron volts, at which point it becomes probable for a muon to capture an electron from an argon atom to form a stable muonium atom in its ground state. The muonium atom then quickly slows down to "thermal" speeds (about a million centimeters per second, the equivalent of a twenty-fifth of an electron volt) in collisions with the argon atoms, whereupon it decays, emitting the telltale positron.

Because of the results of our experiments, this description of the way in which the positive muons lose energy in the argon gas to form muonium atoms is now believed to be true. At the time, however, many other possible explanations for the slowing down of the muons could be imagined that would not result in the formation of stable atoms of muonium.

One of these explanations was that the positive muon would simply lose energy in collisions with argon atoms until it had less than two electron volts of energy, which is the minimum energy required for a muon to capture an electron from argon to form muonium. Another explanation was that the muonium atom would be formed but would immediately break up in a collision with an argon atom. We also thought that the positive muon and the argon atom might combine to form a molecular ion. Quantitative estimates, even to within a factor of 10, of these various processes are very difficult to make. As it turned out, happily for our experiments, the process that resulted in the formation of a stable muonium atom was the dominant one.

We were also concerned about the chemical stability of muonium. It is well known that hydrogen is highly reactive, and muonium, being an isotope of hydrogen, should be equally reactive. With the inert gas argon there would be no chemical reaction, but theoretical estimates suggested that small amounts of impurities, such as oxygen or water vapor, in quantities as small as several parts per million parts of argon might lead to atomic interactions or chemical reactions disastrous to the formation of stable muonium. Some of our early experiments, and probably some experiments of other workers, failed because of these chemical effects caused by impurities. Eventually we took great care to obtain pure argon gas. This involved the continuous recirculation of the argon over hot titanium, which removes most of the impurities from the gas. Such a system should keep the impurity content of the argon to less than about one part per million. In view of our later studies of muonium chemistry, this precaution was crucial to the success of our first muonium experiments.

In these experiments the muons enter the gas with their direction of spin opposite to their direction of motion. In a weak magnetic field only the first of the three hyperfine states formed will have a magnetic moment. The value of the magnetic moment of this state will be equal to the magnetic moment of the electron minus that of the muon and hence will be approximately equal to the electron's magnetic moment, which is 207 times the muon's. (Unlike the muon, the electron has its magnetic moment and angular momentum vector pointing in opposite directions.)

The coils shown in the illustration at the top of page 95 produce a static magnetic field perpendicular to the plane of the illustration and to the initial direction of the muon spin. In this perpendicular field the spins of the electron and the muon, which are parallel in the first hyperfine state, will precess together in the plane of the page [*see top illustration on page 96*]. The direction of the muon spin can be detected at any time because, as I have mentioned, the positron produced in muon decay is emitted preferentially in the direction of the muon spin.

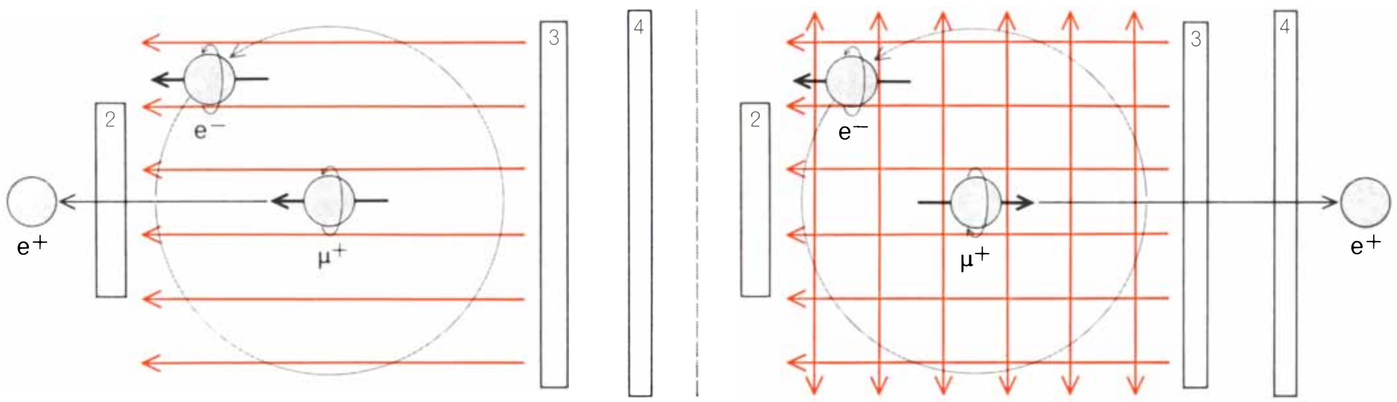
The actual observation of the characteristic muonium precession frequency is achieved by recording pulses from five radiation counters set up to detect the passage of the incoming muons and the decay products of the muonium atom. When a muon enters the gas target and stops, this is recorded by coincident pulses in Counter 1 and Counter 2, but no pulse occurs in Counter 3. Counter 4 and Counter 5 detect the decay positron, and its time of arrival with respect to the time of the incoming muon is measured. In the absence of any muon precession the positron counts will be distributed in time according to a smooth curve of decrease. If the muon is precessing in the magnetic field, however, the curve will oscillate at the precession frequency, because the positron is most likely to be detected when the muon spin points toward Counter 4 and Counter 5.

Some typical results of the muonium precession experiments are shown in the graphs at the bottom of page 95. The solid curves give an analysis of the data for the frequency component of the positron time distribution. The broken curves are expected on theoretical grounds at the characteristic precession frequency of muonium. As is evident, the two curves are in close agreement. This observation provides unambiguous proof of the formation of polarized muonium in the tank. The observation of the precession frequency of muonium also constituted the first unambiguous proof that the spin angular momentum of the muon is equal to that of the electron, since if the muon spin had had some other value, the muonium precession frequency would be different.

To appreciate the extreme sensitivity of this experiment, it will be helpful to consider that seldom during the experiment is more than one muonium atom present. Indeed, on the average one muonium atom is present for only about a thousandth of the time—in spite of the fact that with the muon-beam intensities available we can form about 1,000 muonium atoms per second! This results from the fact that the mean lifetime of a muon is only 2.2 microseconds. Fortunately the positrons emitted when the muons decay are quite energetic, and the experiment can be carried out with radiation counters capable of recording the passage of a single charged particle.

In order to test all the subtle electromagnetic properties and interactions of the muon and the electron, a precise knowledge of the hyperfine-structure interval is necessary. The discovery of muonium paved the way for an experiment to measure this interval with high precision. The experiment was performed at the Nevis Laboratories from 1962 to 1965 by a group from Yale consisting of J. M. Bailey, W. E. Cleland, M. Eckhause, R. M. Mobley, J. E. Rothberg, Prepost, Ziock and myself.

The principle of the experiment is a classic spectroscopic approach to the study of energy-level difference. A transition of the muonium atoms from one hyperfine energy state to another can be induced by means of an external electromagnetic field that varies in resonance with the frequency of the transition; these frequencies are in the microwave region of the electromagnetic spectrum.

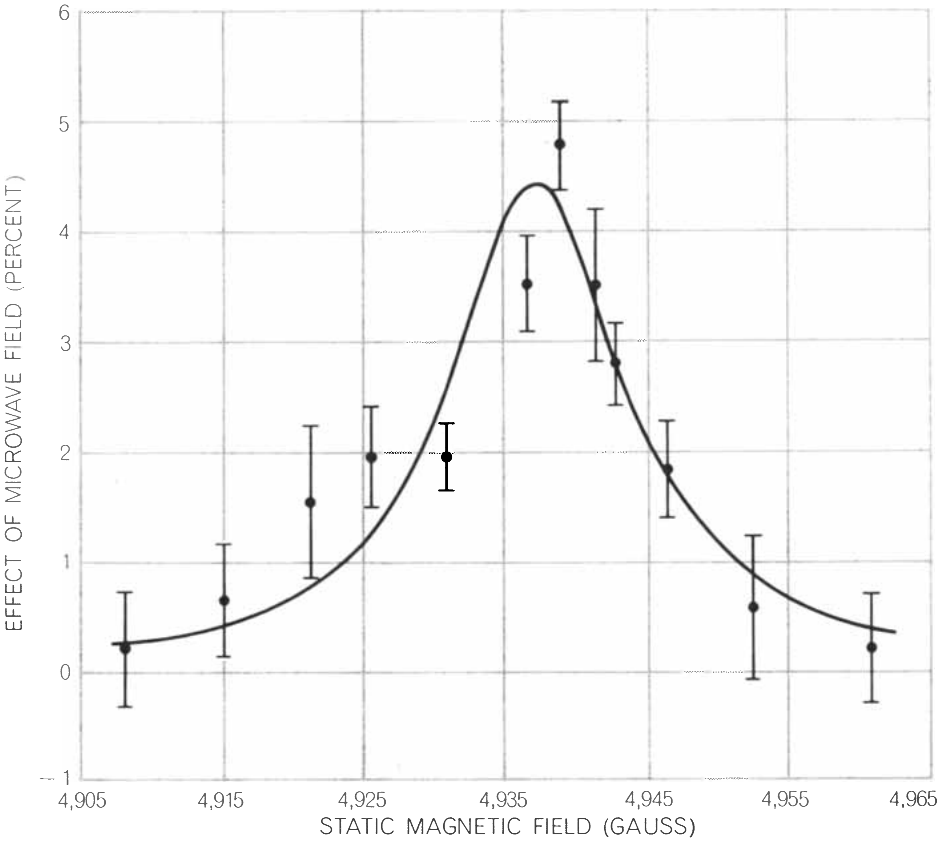


DECAY POSITRONS ARE EMITTED preferentially in the direction of Counter 2 in the first stage (*left*) of the experiment depicted on the preceding page, since, owing to the polarization of the incoming muons, the muonium atoms will be formed initially in the first hyperfine energy state but not in the second. The only field in this stage is the strong static magnetic field in the same direction as the spin vectors of the muon and the electron. If microwave power is applied at right angles to the direction of the static field (*right*), and if a transition is thereby induced between the two energy states, the muon spin direction will be reversed and the decay positrons will be emitted preferentially in the direction of Counter 3 and Counter 4. The muonium atom is of course greatly enlarged.

The transition is then observed through the change in some property of the atoms that accompanies the change in energy state. In the case of muonium this property is the rate of positron emission in a given direction.

For technical reasons having to do in part with achieving the maximum signal accompanying a transition, a strong static magnetic field of about 5,000 gauss is employed in this experiment. The two states involved in the experiment are the one in which the muon spin is in the same direction as the electron spin and the static magnetic field and the one in which the muon spin is in the opposite direction.

As we have seen, the energy difference between these two states is caused both by the interaction of the muon spin magnetic moment with the electron spin magnetic moment and by the interactions of the muon and electron magnetic moments with the external magnetic field. Since the magnetic moments of the electron and the muon are known from other experiments, and since the external magnetic field can be measured, a measurement of the energy difference between these two states would provide a determination of the hyperfine-structure interval.



RESONANCE CURVE for the microwave-induced transition between the first two hyperfine energy levels of muonium is shown here. The ratio of the number of decay positrons to the number of muons stopped in the gas is measured as a function of the magnetic field for the two conditions of microwave-power-on and microwave-power-off. Ratio of these two quantities minus one is the ordinate of the graph. Vertical bars indicate statistical errors.

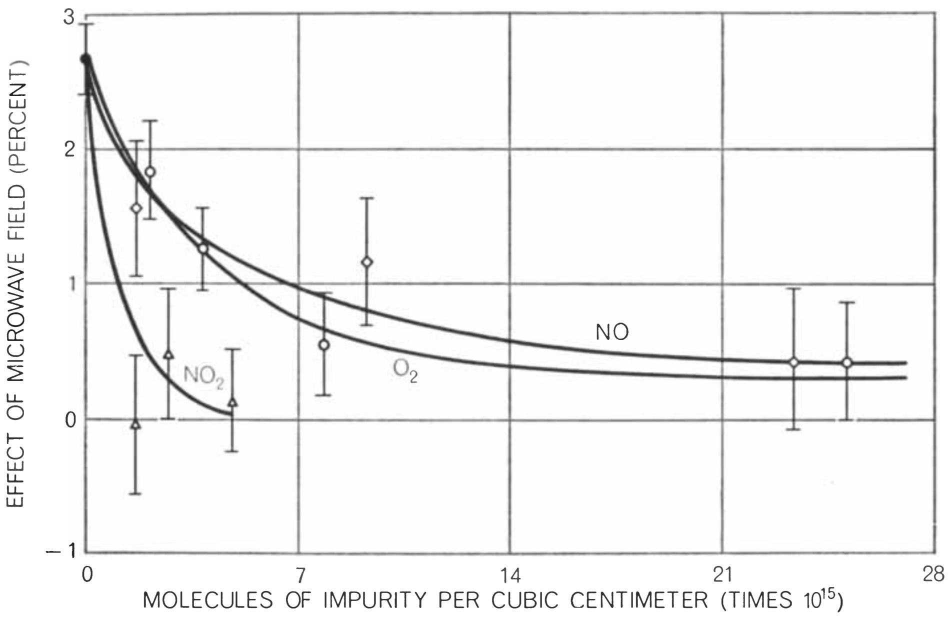
The experiment relies again on the availability of polarized muons and the possibility of detecting their spin direction by the emission of positrons [*see illustration on page* 97]. Because of the polarization of the incoming muons, muonium atoms will be formed initially in the first state but not in the second. If no transition of state is induced, the positrons will be emitted preferentially in the direction of Counter 2 [*see illustration at bottom left on opposite page*]. On the other hand, if microwave power of the resonant frequency is applied in the microwave cavity and a transition between the two energy states is thereby induced, the muon spin direction will be reversed and the decay positrons will be emitted in the direction of Counter 3 and Counter 4 [*see illustration at bottom right on opposite page*].

The ratio of the number of decay positrons to the number of muons stopped in the gas is measured as a function of the magnetic field for the two conditions of microwave-power-on and microwave-power-off. The ratio of these two quantities minus one is the ordinate of the graph on this page, which shows a characteristic resonance curve. Since the experiment was intended to achieve a very high precision in the determination of the hyperfine-structure constant, the greatest care was taken to achieve a static magnetic field that was both constant and homogeneous, a microwave field with constant frequency and amplitude, an electronic counting system with high stability, and finally as much data as possible. Over a period of two and a half years data were taken at the Nevis synchrocyclotron for a total of about three months' running time. All these data were analyzed in arriving at our final result for the hyperfine-structure interval of muonium: 4,463.15 ± .06 megacycles per second. The uncertainty in this figure of ±13 parts per million was determined by the counting method associated with the limited number of muonium atoms studied (about 100 million in this experiment). With a higher-intensity source of muons, such as some of the new accelerators now being designed will provide, a more precise determination of this hyperfine-structure interval should be possible.

Assuming that the muon is a heavy electron, the theoretical value for the hyperfine-structure interval of muonium can be calculated according to the modern quantum theory of the electron formulated by P. A. M. Dirac in 1928. This theoretical value is 4,463.15 ± .10 megacycles per second. Here the uncertainty of ±22 parts per million arises primarily out of an uncertain knowledge of the fundamental "fine-structure constant," a quantity that characterizes the strength of all electromagnetic interactions and appears in the theoretical formula for the hyperfine-structure interval of muonium.

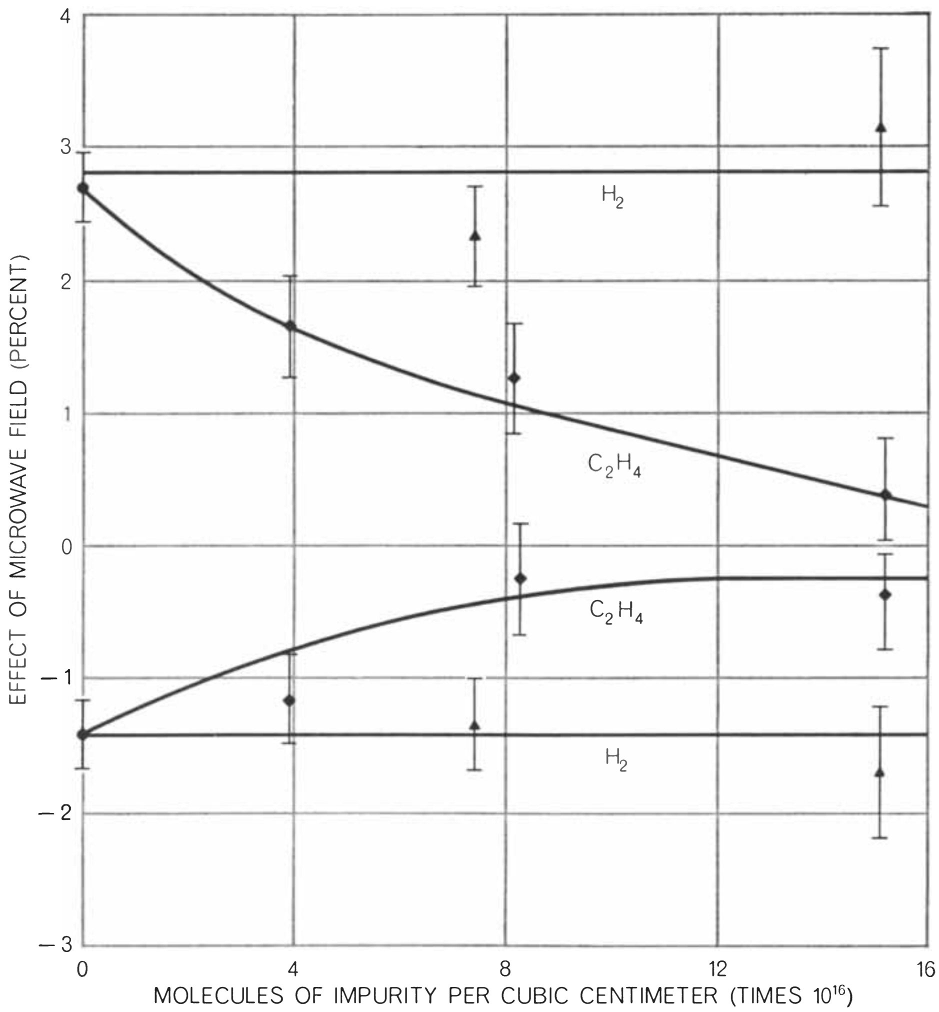
The agreement between the theoretical and the experimental values for the hyperfine-structure interval is excellent, and hence it confirms that in its interaction with the electron the muon behaves exactly like a heavy electron. Moreover, since the experimental value for this interval is known as precisely as the value for the fine-structure constant, the experimental value of the interval can be combined with the theoretical formula for the interval to determine a new and independent value for this fundamental constant. The new value for the fine-structure constant is 137.0388 ± 9 parts per million, which is in agreement with the previously determined value; by combining the two values a more precise estimate of the fine-structure constant can be obtained.

I have mentioned that muonium, as



● A
○ O_2
◇ NO
△ NO_2

MUONIUM RESONANCE SIGNAL is quenched, or reduced, by the addition of impurities to the argon. This quenching is caused by collisions that remove muonium from one of the states involved in the resonance transition. The three impurities are molecular oxygen (O_2), nitric oxide (NO) and nitrogen dioxide (NO_2).



● A
▲ H_2
◆ C_2H_4

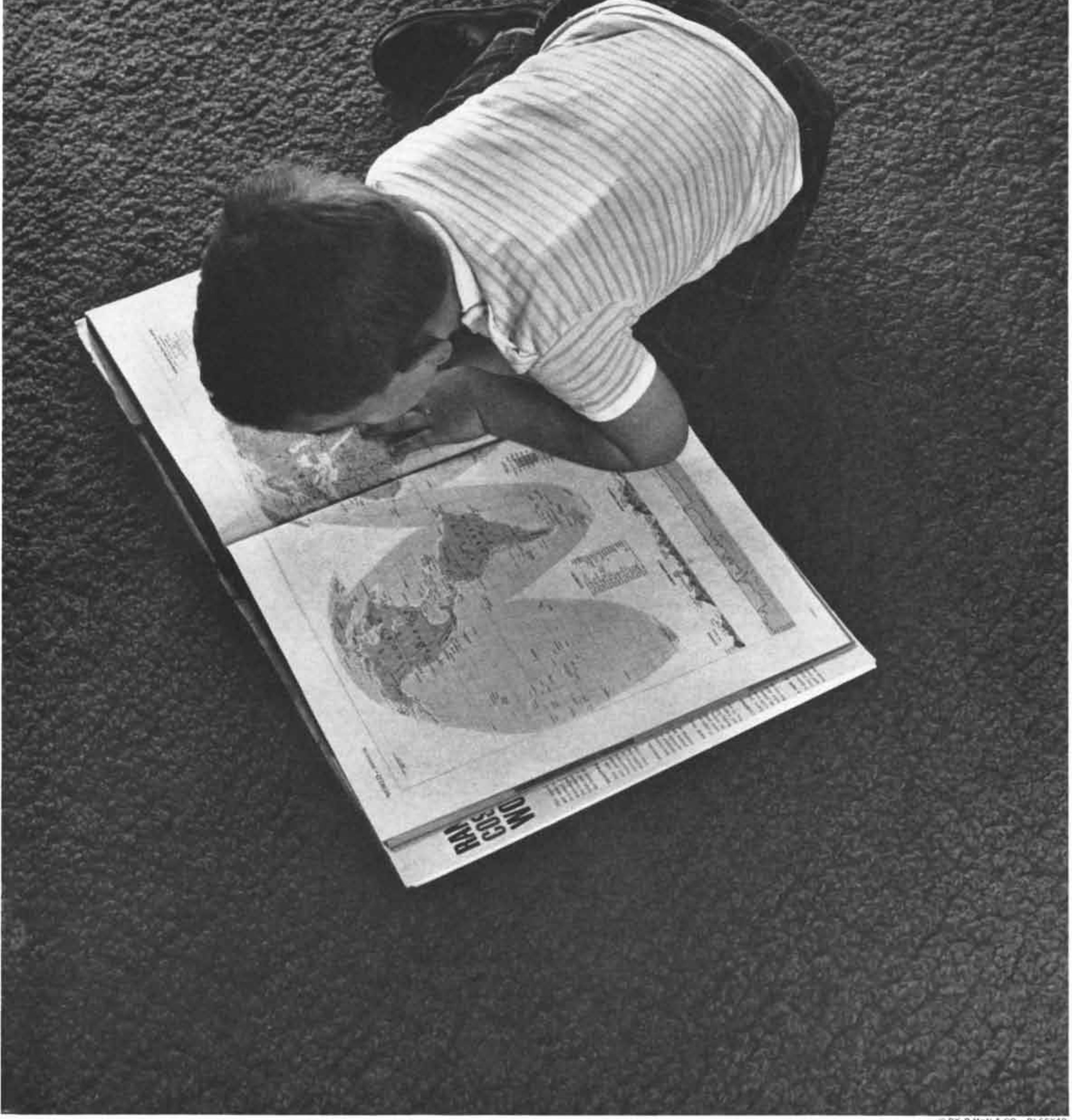
QUENCHING of muonium resonance signal by molecular hydrogen (H_2) and ethylene (C_2H_4) is compared. Muonium does not interact with hydrogen and hence no quenching occurs. The quenching produced by ethylene is believed to be caused by a real chemical reaction of muonium with this molecule. Positron signals were recorded by Counter 3 and Counter 4 (*top*) and by Counter 2 (*bottom*).

an isotope of hydrogen, can be expected to interact strongly with other atoms and to form chemical compounds. In order to study the interactions of muonium with atoms or molecules more reactive than argon, such atoms or molecules were introduced into the argon as impurities. These impurities were observed to decrease the size of the muonium resonance signal; it is clear that any reaction that removes muonium from one of the states involved in the resonance transition will cause a reduction in the signal. Data for the various impurities are shown in the graphs at the left.

As the graphs show, the reactions of muonium with molecular oxygen (O_2), nitric oxide (NO) and nitrogen dioxide (NO_2) are strongest. All these molecules are paramagnetic, which is to say that they have at least one electron whose spin is not "paired," or canceled out, by the spin of another electron; such an electron is freer than a paired electron to interact with an unpaired electron in another atom or molecule. (In the case of molecular oxygen several electrons are unpaired.) We believe that in a collision between a muonium atom and one of these molecules an electron is exchanged between the muonium and the molecule and vice versa. Such an electron-spin exchange reaction will remove the muonium atom from one of its resonant states and hence reduce the resonance signal. The weaker reaction of muonium with ethylene (C_2H_4), which has no unpaired electron, is believed to be a real chemical reaction that results in the formation of a compound of ethylene and muonium.

Muonium does not interact with molecular hydrogen (H_2), which is not paramagnetic and so cannot exchange an electron with the muonium atom. A real chemical reaction between muonium and hydrogen to form a molecule of muonium hydride (MH) is forbidden by the law of conservation of energy, because the energy of vibration contained in the muonium-hydride molecule that would be formed by such a reaction is considerably greater than that of the hydrogen molecule.

It is worth noting that in a number of cases, as a consequence of our work, the reactions of muonium have become better known than the corresponding reactions of hydrogen. This is the result of the great power of the method for studying muonium, which enables us to observe the behavior of a single muonium atom. A rich field of muonium chemistry is now open for exploration.



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Antibiotics and the Genetic Code

The meaning of the code that directs the synthesis of proteins can be changed by the action of streptomycin and related drugs. They cause "misreading" by altering the structure of ribosomes

by Luigi Gorini

A cell is characterized by the metabolic activities that occur within its boundaries. These activities proceed along chemical pathways involving numerous steps, each catalyzed by a different enzyme. The cell's characteristics are therefore maintained by its enzymes, and the conservation of these characteristics in a hereditary line of cells depends on their ability to synthesize the same set of enzymes in successive generations. Enzymes are proteins; their catalytic specificity is determined by their structure and that structure is encoded in the genetic material of the cell. It has become common knowledge that the transmission of genetic information from one generation to another is subject to mutations, or occasional errors, and that these mutations are the basis of biological evolution. Until recently, however, the possibility that errors might occur in the transfer of information within the cell, from the genetic material to the protein, was overlooked.

As molecular biologists and geneticists have learned more about the mechanism of this transfer they have wondered if it too might not be subject to error. It is. Not only can mutations affect the transfer mechanism, as one might have expected; in our laboratory at the Harvard Medical School we have discovered that the genetic information encoded within a cell is sometimes ambiguous and can be misunderstood. The ambiguity results from unexpected complex variations in the structure of the cell components known as ribosomes. And the misunderstanding can be prompted by antibiotics such as streptomycin in a manner that explains at least in part how such antibiotics kill cells.

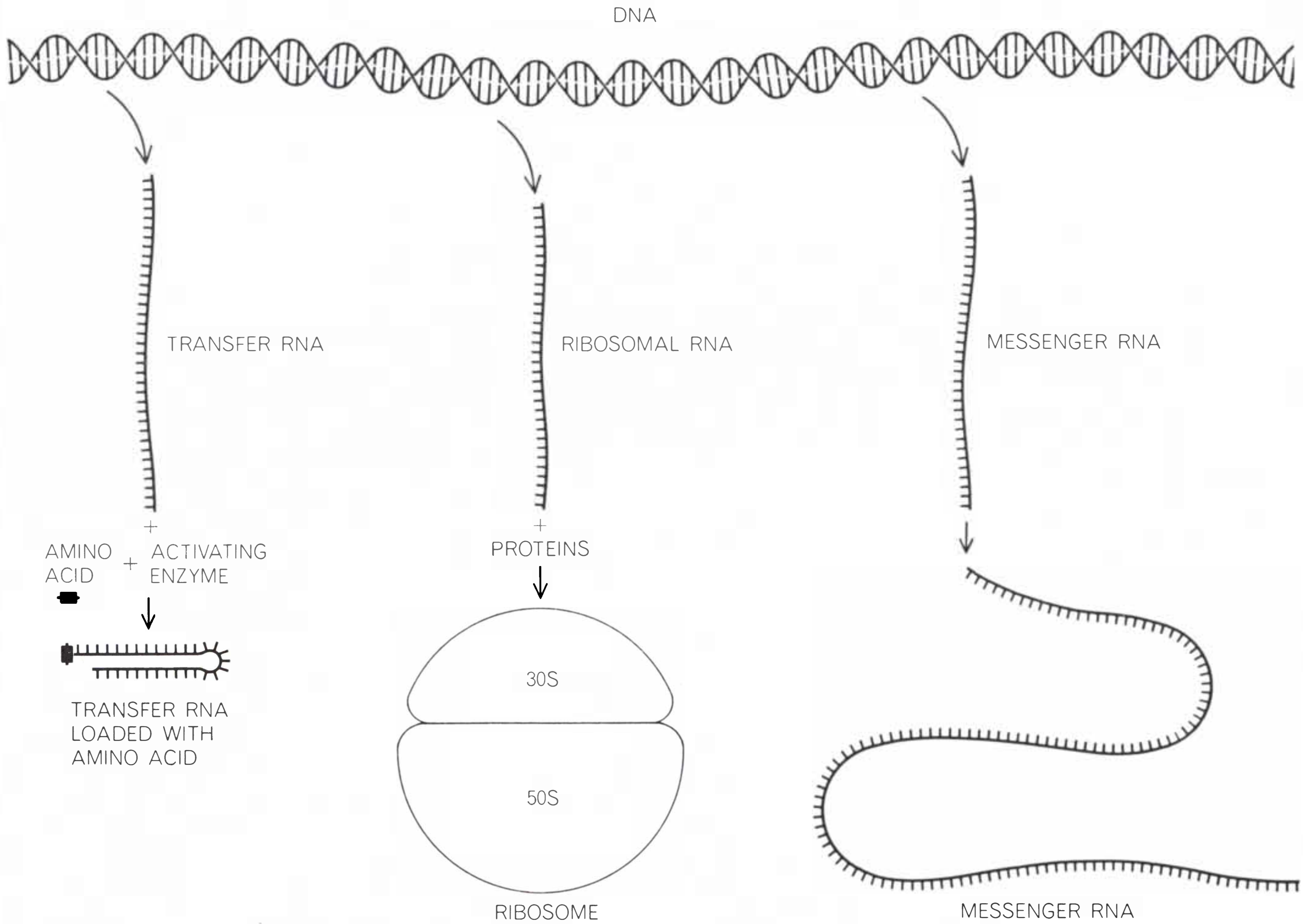
Our work can best be understood in the context of much that has gone before, and so I must briefly review some of that history. In science a line of investigation may often be based on a postulate that in time proves not to have been correct but that nevertheless has great suggestive value. That is, the postulate serves as a starting point for valuable discoveries, with the result that a solid structure of knowledge may be erected in spite of an original oversimplification. So it has been with the celebrated "one gene, one enzyme" postulate put forward in 1941 by George W. Beadle and Edward L. Tatum at Stanford University. Their assumption that each gene defines the structure of one and only one protein ignored the possibility that a gene might make slightly different proteins at different times, but it nevertheless opened the door to biochemical genetics. It did so by providing experimenters with a set of principles: A mutant deficient in a specific enzyme must have a defect in the gene controlling the synthesis of that enzyme; if several metabolic products are lacking as the result of a single mutation, a single enzyme must be responsible and so the products must have a single precursor; a substance that allows the growth of a mutant with a defective enzyme must be the product of a step subsequent to that enzyme's action or of a reaction bypassing the missing enzyme.

By isolating and studying defective mutants and applying these few principles, investigators learned a great deal about the enzyme-catalyzed reactions that build up and break down small molecules in the cell. The principles were close enough to being correct to work well at that level. Their limited validity became apparent, however, as new information made it possible to look behind conventional enzymatic reactions and study the synthesis of the enzymes themselves. The synthesis of enzymes utilizes novel reactions that are directed by the template molecules deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) and that involve the translation of a code.

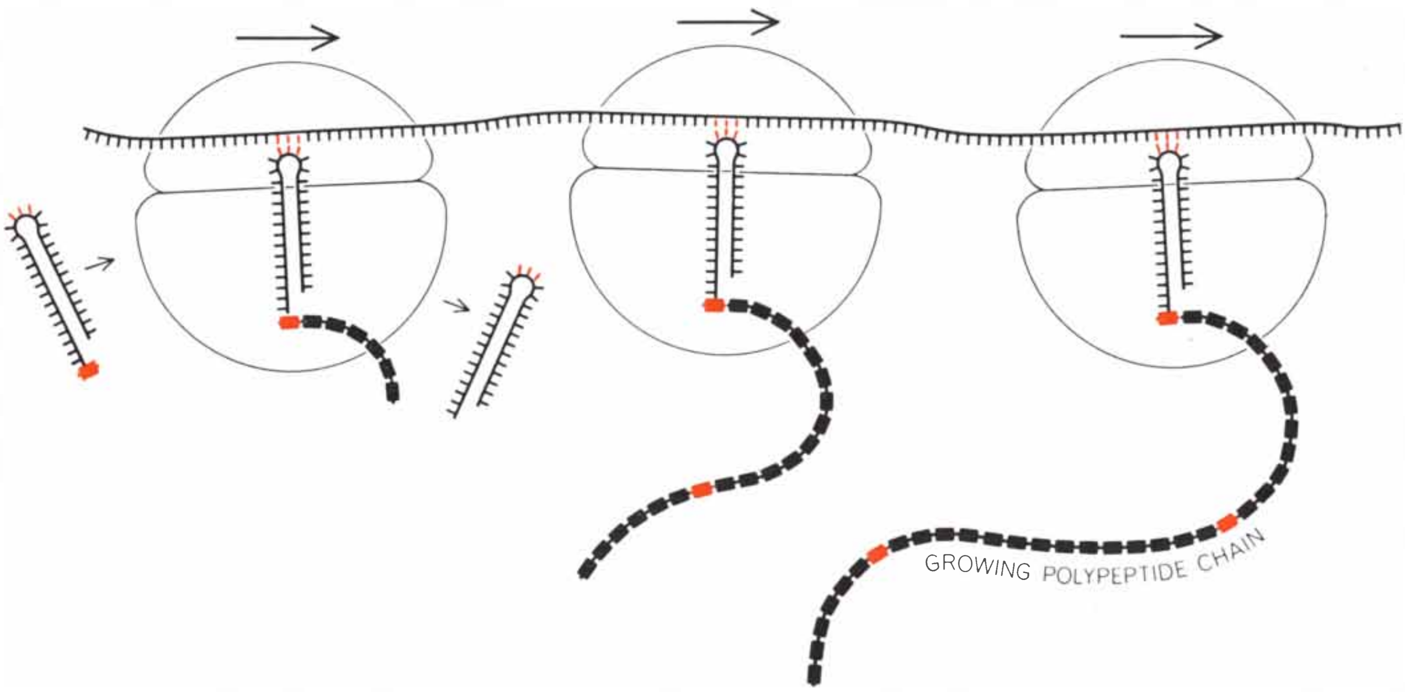
Proteins are made up of one or more peptide chains, which are in turn linear arrays of linked subunits: the 20 amino acids. It is the sequence in which these amino acids are linked into structures several hundred units long that determines the coiling and folding, and hence the specific characteristics, of each protein. The synthesis of a protein involves the selection, from the pool of amino acids in the cell, of the proper amino acids and their linkage in the proper sequence. This is accomplished in several steps [*see illustrations on opposite page*].

The first step involves the transcription of the inherited instructions in a structural gene—a segment of DNA—into a template molecule of RNA. This "messenger RNA" is the basic link between a gene and its enzyme. Like other kinds of RNA, it is a polynucleotide chain: a strand made up of the nucleotide bases adenine, cytosine, guanine and uracil. The sequence of these bases follows that of the corresponding DNA bases and constitutes the code that establishes the order in which amino acids are assembled to form the protein. The codon, or code word, for each amino acid is a group of three "letters": a nucleotide triplet [see "The Genetic Code: II," by Marshall W. Nirenberg; SCIENTIFIC AMERICAN, March, 1963].

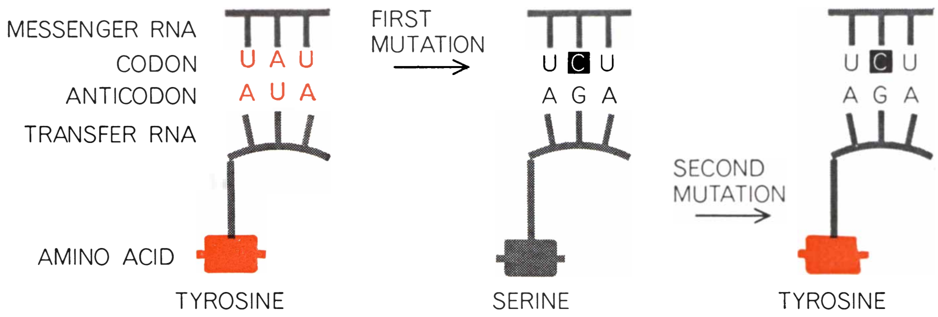
The second, or translation, step is to "plug in" the right amino acid at each codon of the messenger RNA



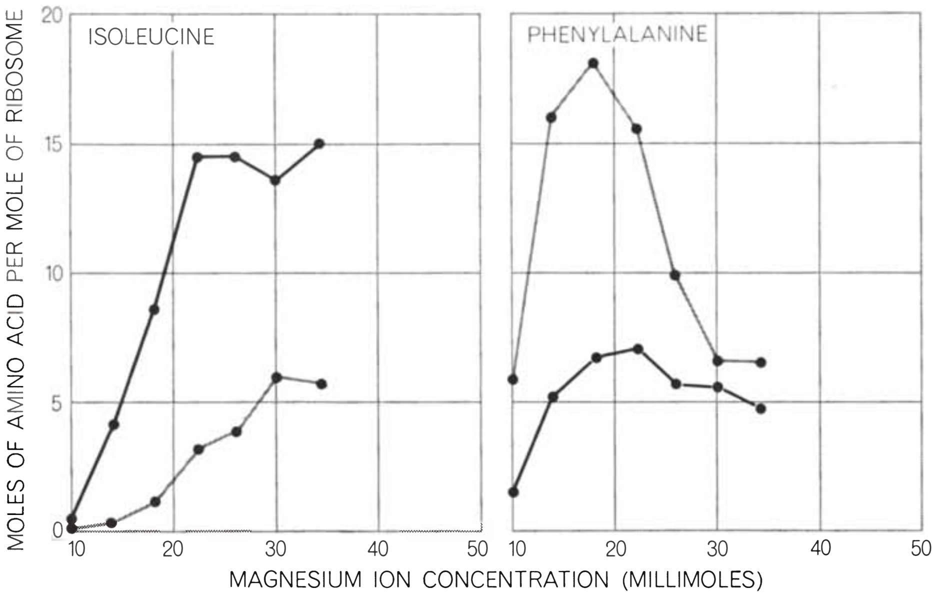
PROTEIN SYNTHESIS involves transcription of deoxyribonucleic acid (*DNA*) into several kinds of ribonucleic acid (*RNA*). Messenger RNA is a sequence of three-base codons, or code words, indicating the amino acid sequence of a protein. Each molecule of transfer RNA is loaded with a specific amino acid through the action of an activating enzyme. Ribosomal RNA and ribosomal proteins combine to constitute ribosomes, the components that are the sites of protein synthesis. The ribosomes have two subunits.



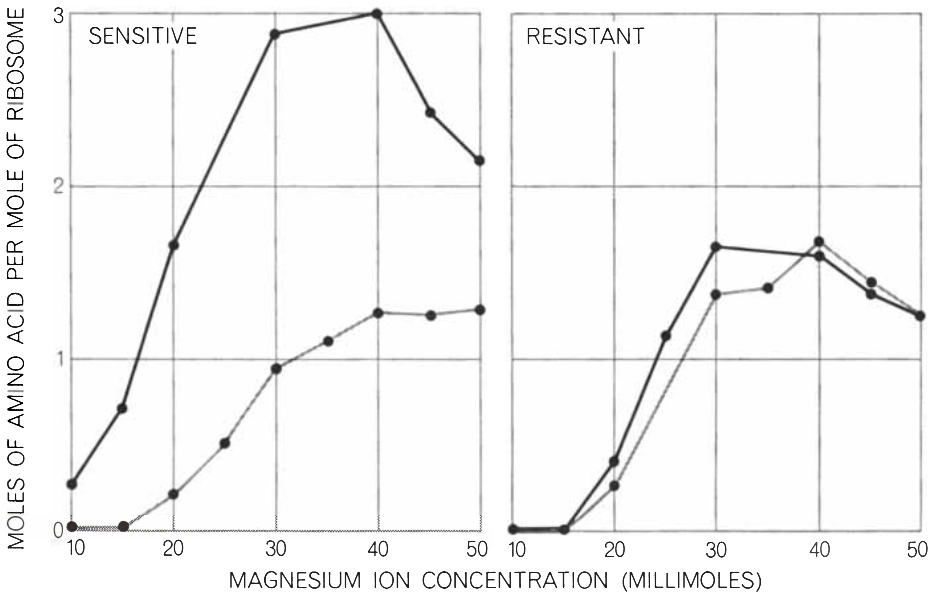
TRANSLATION of genetic instructions from RNA into protein involves the assembly of amino acids into a peptide chain in the sequence coded for by the codons of the messenger RNA. Transfer RNA loaded with an amino acid is thought to "recognize" the codon for that amino acid, perhaps through the binding to the codon of an anticodon of three complementary bases on transfer RNA.



SUPPRESSION of a mutation can occur through the agency of a second mutation affecting transfer RNA or an activating enzyme. The triplet UAU normally codes for tyrosine, for example, perhaps by binding the anticodon AUA on tyrosine transfer RNA according to base-pairing rules (*left*). Mutated to UCU, it would encode serine (*middle*). Another mutation might insert correct amino acid again, perhaps by loading it on serine transfer RNA (*right*).



MISREADING is induced in a preparation containing ribosomes from streptomycin-sensitive cells and polyuridylic acid (UUU). The amino acid incorporated in the absence of streptomycin (*gray curves*) is primarily phenylalanine. When streptomycin is added (*black*), incorporation of phenylalanine is inhibited and incorporation of isoleucine is stimulated.



MORE ISOLEUCINE is incorporated in the presence of streptomycin (*black curves*) than in its absence (*gray*) in this system only if the ribosomes in the system are from streptomycin-sensitive cells (*left*). The incorporation varies with magnesium-ion concentration.

template. This is accomplished by a set of enzymes and specialized molecules of "transfer RNA." Each enzyme is able to "recognize," or interact with, one of the amino acids. Each transfer RNA molecule has two specificities: it can interact with one of the enzymes and so become "loaded" with the corresponding amino acid, and it can interact with the codon in the messenger RNA that designates that amino acid. In doing so it inserts the amino acid in the proper position in the developing peptide chain. The site on the messenger that accomplishes this recognition is thought to be an "anticodon" of three bases that fit the three bases of the codon according to the rules of base-pairing: adenine pairs with uracil and guanine with cytosine. That is to say, an adenine-guanine-cytosine (AGC) codon would pair with a uracil-cytosine-guanine (UCG) anticodon. Now, in a code utilizing four letters, 64 triplets are possible, but there are only 20 amino acids to be coded for. The fact is that the code is "degenerate": most amino acids are indicated by several synonymous codons. In each case one of these synonyms seems to appear more frequently than the others—to be the "preferred" codon, in effect.

The translation step takes place in the ribosomes: ultramicroscopic particles made up of nucleic acid and protein. Each ribosome has a large and a small subunit designated (on the basis of their rates of sedimentation in a centrifuge) 50S and 30S. During protein synthesis the messenger RNA is apparently attached to the 30S subunit, the growing protein to the 50S subunit and the transfer RNA to both. The protein-synthesizing system seems to consist of groups of several ribosomes, or polyribosomes, traveling along a messenger RNA strand, each carrying an elongating peptide chain [see "Polyribosomes," by Alexander Rich; Scientific American, December, 1963]. The assumption has been that the ribosomes serve as inert jigs to hold the various reactants of the translation process in position with respect to one another.

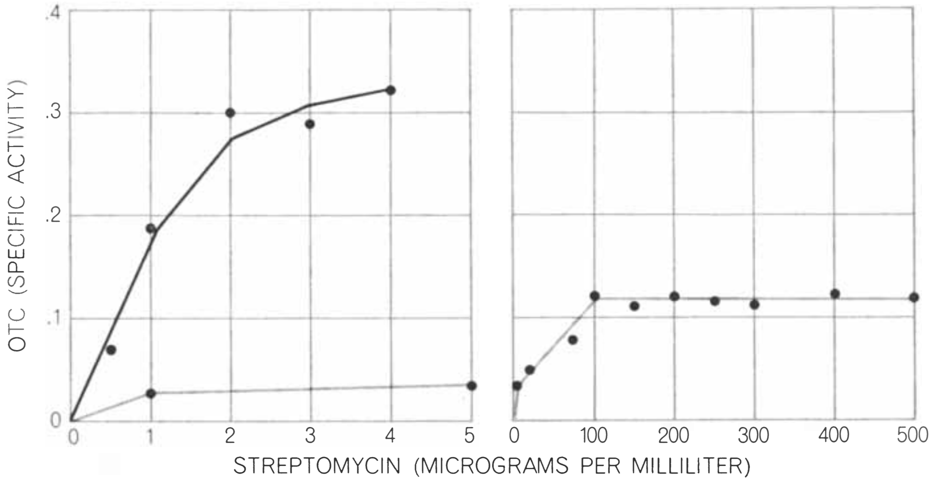
Among the mutational events that might account for a defective mutant the most obvious (and the only one predicted by the one-gene, one-enzyme postulate) is one that occurs in the gene controlling the structure of a messenger RNA. Clearly a mutation that changes even one codon could either alter the message or deprive it of any sense at all and thus result in an altered or missing protein. As for the converse event, the "reversion" of a defective mutant to its parental characteristics, that would presumably be due to an analogous situation: the occurrence of a second mutation, with a "backward" effect, in the defective gene for the same messenger RNA.

Quite frequently, however, one finds a revertant in which the second mutation can be shown to occur in a gene different from that of the defective messenger RNA. Somehow this second mutation suppresses the effect of the original one; it enables the mutant cell to produce an active enzyme even though the gene for that enzyme is producing a defective messenger RNA. Such "suppressor" mutations have been known for more than 40 years. Barring a few cases for which conventional explanations could be found, however, they remained puzzling anomalies, quite in conflict with the one-gene, one-enzyme postulate.

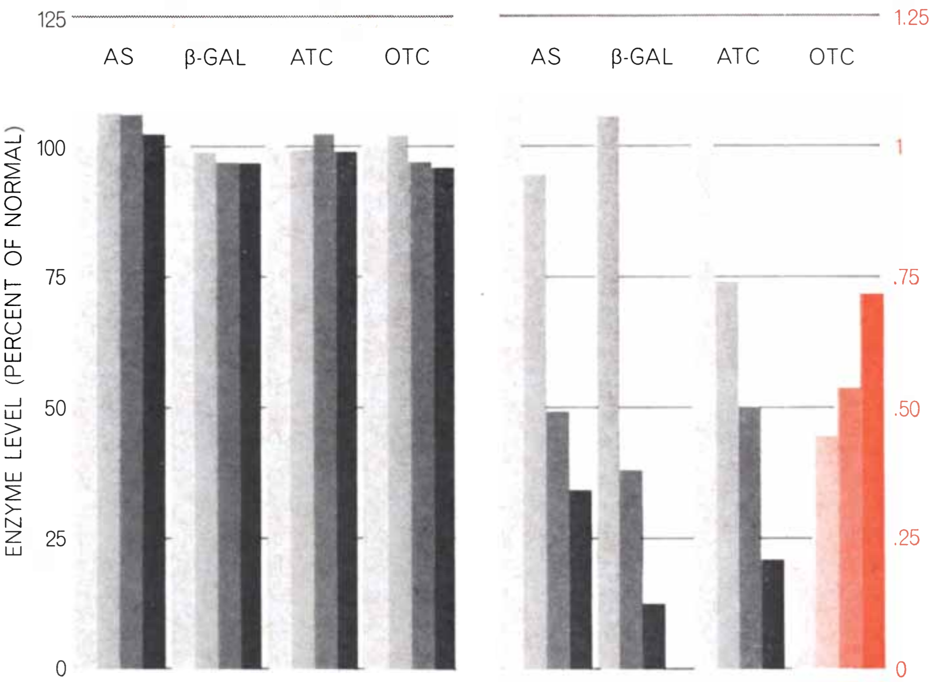
In 1960, on the basis of the new knowledge of the steps in protein synthesis, Charles A. Yanofsky of Stanford University suggested that suppressor genes might be genes that control the structure of activating enzymes or of transfer RNA. A mutation altering the specificity of one of these tools of translation could result in the plugging in of an amino acid other than the one designated by the messenger RNA, and this substitution could reinstate the original structure of the affected enzyme. Such suppressor mutations have since been found. In them an incorrect messenger RNA is "read" by a transfer RNA carrying an amino acid other than the one coded for, and the net result of the double error is the synthesis of a correct protein. Since any given mutation in the tools of translation will suppress any messenger RNA mutations that stand to benefit by the given amino acid substitution, the one-gene, one-enzyme rule is violated: a single mutation can simultaneously produce changes in several proteins quite unrelated in their metabolic function.

In 1961, before much was known about translation errors, we isolated a peculiar mutant in our laboratory. We were working with a strain of the intestinal bacterium *Escherichia coli* that was unable to manufacture a necessary growth factor, the amino acid arginine. In the course of an experiment we "plated" some streptomycin-resistant mutants of these defective cells (which ordinarily could not grow unless arginine was supplied in their medium) on a medium containing streptomycin but no arginine. We expected no growth, but to our surprise we found that some of the resistant mutants no longer required arginine; streptomycin fulfilled their requirement. The requirement was due to a defective enzyme, ornithine transcarbamylase (OTC), and the peculiar thing was that OTC activity, which was lacking in cells grown in arginine, was present in cells grown in streptomycin. This meant that the antibiotic was not simply providing a chemical bypass that made arginine synthesis possible without OTC. Various experiments eliminated several other conventional explanations involving the control of enzyme synthesis. We were left with the possibility that streptomycin was acting at the level of protein synthesis, somehow counteracting the effect of a mutation in a structural gene. The idea seemed too radical to pursue. We reported the finding, consigned the mutant to the category of the "funny mutants" one occasionally encounters and cannot explain, and paid no more attention to it.

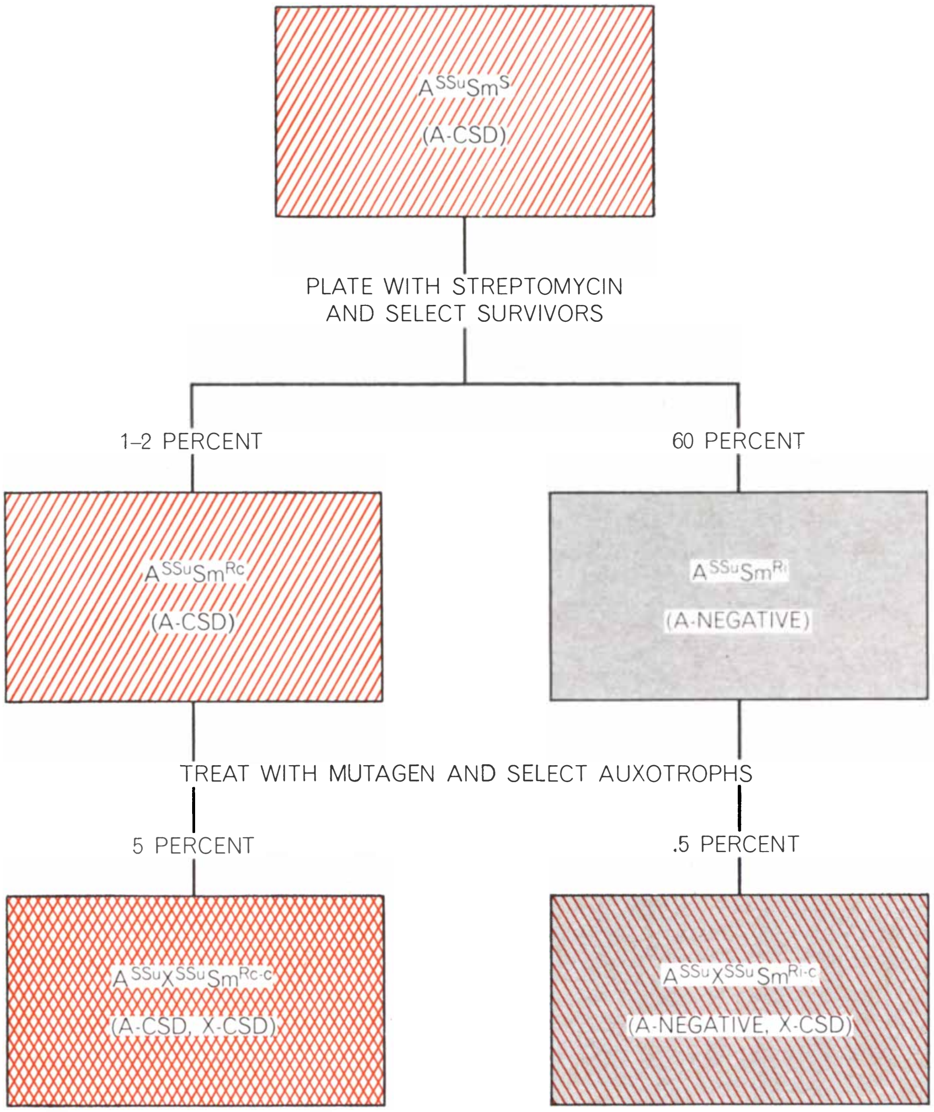
It was only two years later, after the annual symposium on genetics held in



STREPTOMYCIN SUPPRESSION of a mutation affecting the synthesis of an enzyme (*OTC*) occurs at much lower concentrations in streptomycin-sensitive cells (*black curve*) than in resistant cells (*gray curves*). The concentration must be kept sublethal with sensitive cells. The curve for resistant cells has been shown on an expanded scale at the right.



ERRORS are imposed in good enzymes as the error in OTC is suppressed. When the misreading level is too high, "oversuppression" may occur. In a streptomycin-resistant parent strain (*left*) synthesis of four enzymes is unaffected as the streptomycin concentration increases (*successively darker bars*) from zero to five, eight and 12 micrograms per milliliter. In an "oversuppressible" derivative of the conditionally streptomycin-dependent mutant (*right*) the drug increases the OTC level but decreases the level of the other three enzymes.



GENETIC EXPERIMENT begins with a strain that has an arginine defect suppressible by streptomycin (A^{SSu}) and is sensitive to streptomycin (Sm^{S}). Its behavior is conditionally streptomycin-dependent as to arginine (*A-CSD*). Plated on streptomycin medium, it yields three mutants (*middle row*): 1 or 2 percent drug-resistant and "competent" for suppression of the defect (Sm^{Rc}), about 60 percent resistant and "incompetent" (Sm^{Ri}) and about 40 percent dependent on the drug (*not shown*). A second crop of mutants (*bottom row*) includes some with a new drug-suppressible defect (X^{SSu}). A few of the cells that were incompetent for the suppression of the first defect are competent for the suppression of the new one.

Cold Spring Harbor, N.Y., at which there was much discussion of mutations in the genetic-code-reading mechanism, that I became aware of the parallel between streptomycin's effect in our funny mutant and the mechanism being proposed for suppressor mutations. I wondered if streptomycin could interfere with the accuracy of the reading machinery in such a way that the incorrect reading of an incorrect messenger RNA could result in the production of a correct protein.

To support such a hypothesis it was absolutely necessary to show that streptomycin was not merely counteracting the effect of an enzyme specifically involved in arginine synthesis—that the correction induced by streptomycin was associated not with particular metabolic pathways but with particular kinds of mutation, regardless of the structural gene in which they might occur. The crucial experiment was performed by Eva Kataja, a graduate student. She treated a streptomycin-resistant strain of *E. coli* with a mutagen, isolated all the auxotrophs, or cells ordinarily requiring a growth factor, and screened them for the ability to multiply without the growth factor in the presence of streptomycin. She found that from 2 to 5 percent of the auxotrophs requiring different amino acids that were unrelated as to their synthesis were actually "conditional" auxotrophs: their need for the growth factor was conditional on the absence of streptomycin. We designated this new class of mutants "conditionally streptomycin-dependent."

The name has proved not broad enough, because this kind of suppression has now been reported by a number of laboratories to be prompted by other antibiotics and to involve various kinds of mutation other than auxotrophy, including the inability of certain mutant bacterial viruses to grow in a given strain of bacteria. We also find mutants that are in effect "conditionally streptomycin-resistant" in that streptomycin makes them dependent on, rather than independent of, some growth requirement; in this case streptomycin is apparently "impressing" an error rather than suppressing one. All these examples illustrate the same basic finding: Whatever its genetic inheritance (genotype), a cell's characteristics (phenotype) may vary under the influence of certain comparatively small molecules that change the meaning of the genetic code. The idea that the information encoded in DNA may not be inviolate had already been accepted, but it was assumed that the code could be interfered with only by a mutation in the tools of translation. Here we have examples of phenotypic interference with translation, brought about by small molecules present in the cell or in its surroundings.

At the time of our original experiment the relative infrequency of the conditionally streptomycin-dependent mutants among auxotrophs obtained from a single parent indicated that the reading inaccuracy induced by the antibiotic was profitable only to a restricted class of defects in the structural genes. It appeared, moreover, that the mutation to streptomycin resistance did not always result in cells that were "competent" for streptomycin-induced suppression of auxotrophy. That indicated a linkage between the suppressibility phenomenon and the particular mutation to streptomycin resistance. We suggested, therefore, that suppressibility might be dependent on the structure of the ribosome, because it was already known that the mutation from "wild type" streptomycin-sensitive cells to streptomycin-resistant cells involves a change in the structure of the ribosome. Charles R. Spotts and Roger Y. Stanier of the University of California at Berkeley had predicted as much in 1961, and Julian E. Davies of the Harvard Medical School and Joel G. Flaks of the University of Pennsylvania School of Medicine had each proved it in 1963.

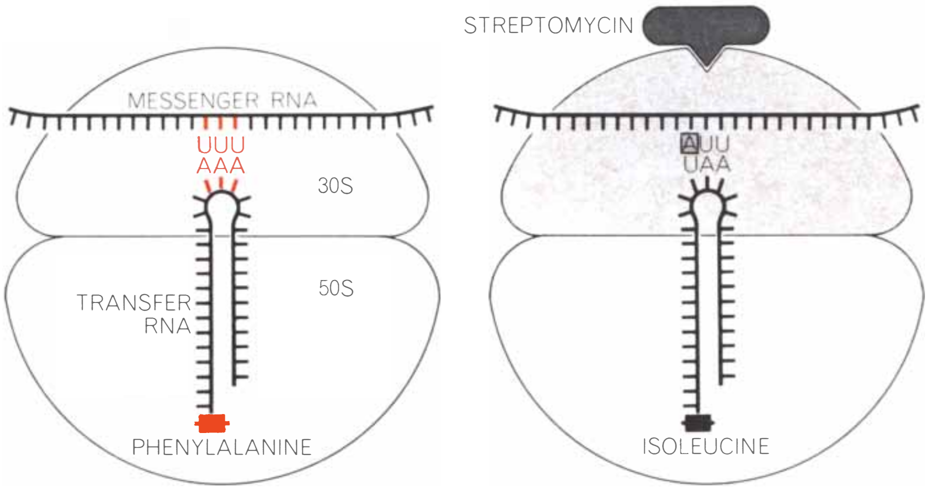
They had done so by experimenting with the cell-free amino-acid-incorporating system perfected by Marshall W.

Nirenberg and J. Heinrich Matthaei of the National Institutes of Health in 1961 and since utilized for most of the research on the genetic code. In a system containing purified ribosomes, transfer RNA and enzymes from *E. coli* together with amino acids and a synthetic polynucleotide as an artificial messenger RNA, only the amino acids encoded by the polynucleotide are incorporated in peptide chains. A "homopolymer" such as polyuridylic acid (UUU) codes for phenylalanine, for example. Confirming and broadening previous reports, Davies and Flaks found that if streptomycin was added to a cell-free system containing polyuridylic acid and phenylalanine, it prevented the incorporation of the amino acid unless the ribosomes—and specifically the 30S subunit—had been extracted from streptomycin-resistant cells. Apparently streptomycin acted by somehow "poisoning" the 30S ribosomal subunit.

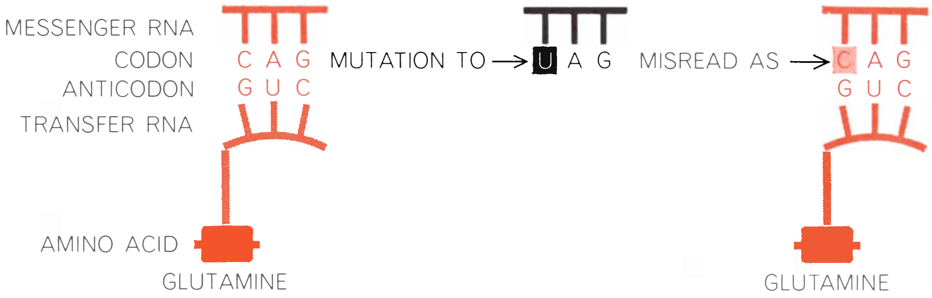
The behavior of the conditionally streptomycin-dependent mutants suggested, however, that streptomycin was altering code translation rather than simply inhibiting it. Davies, Walter Gilbert and I confirmed this prediction with an experiment in which we put all the amino acids, rather than just the one that should properly be incorporated, into a synthetic-nucleotide preparation with ribosomes, transfer RNA and enzymes from streptomycin-sensitive cells. We found that streptomycin not only inhibited incorporation of the correct polypeptide but also caused incorporation of incorrect ones. With polyuridylic acid as the messenger, for example, streptomycin decreased the incorporation of phenylalanine and also caused the misincorporation of substantial amounts of isoleucine, serine, tyrosine and leucine—amino acids for which UUU is not the correct codon. This misreading did not occur when the cell components came from streptomycin-resistant cells. By interchanging the components we established that the streptomycin misreading depended on the source of the 30S subunit of the ribosome only; the origin of the 50S subunit, the transfer RNA and the activating enzymes did not matter, so apparently these components were unaffected by the antibiotic.

It became evident that streptomycin, by altering the configuration of the 30S subunit (the subunit that attaches to the messenger RNA), disturbs the reading of the RNA code, and therefore that the ribosome controls the accuracy of codon-anticodon binding and that misreading is the result of misrecognition between codon and anticodon. Nirenberg and his colleagues S. Pestka and R. Marshall tested the effect of streptomycin on the binding of amino-acid-loaded transfer RNA to ribosomes and got essentially the same results as we did studying incorporation. By examining this intermediate step in the translation process they confirmed that it is at the recognition stage and through ribosomal intervention that streptomycin-induced misreadings occur. Finally David Old and I analyzed the amino acid composition of the growing polypeptide attached to the ribosome. With polyuridylic acid as the messenger RNA and with no streptomycin, the peptide is a chain of phenylalanine. With streptomycin added, the polypeptide contains about 40 percent isoleucine.

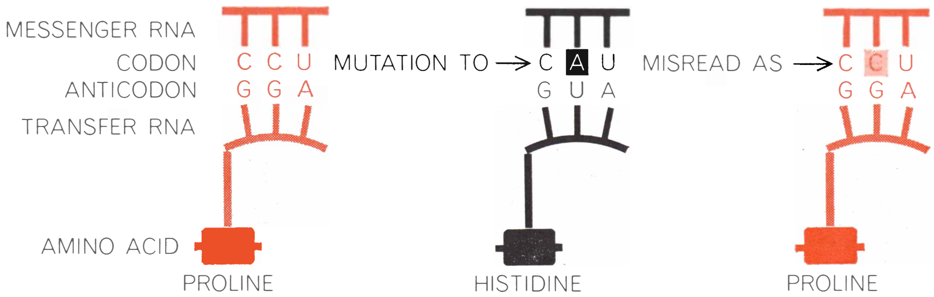
To be sure, various ways of producing misreading in cell-free preparations are known. Misreading can be induced



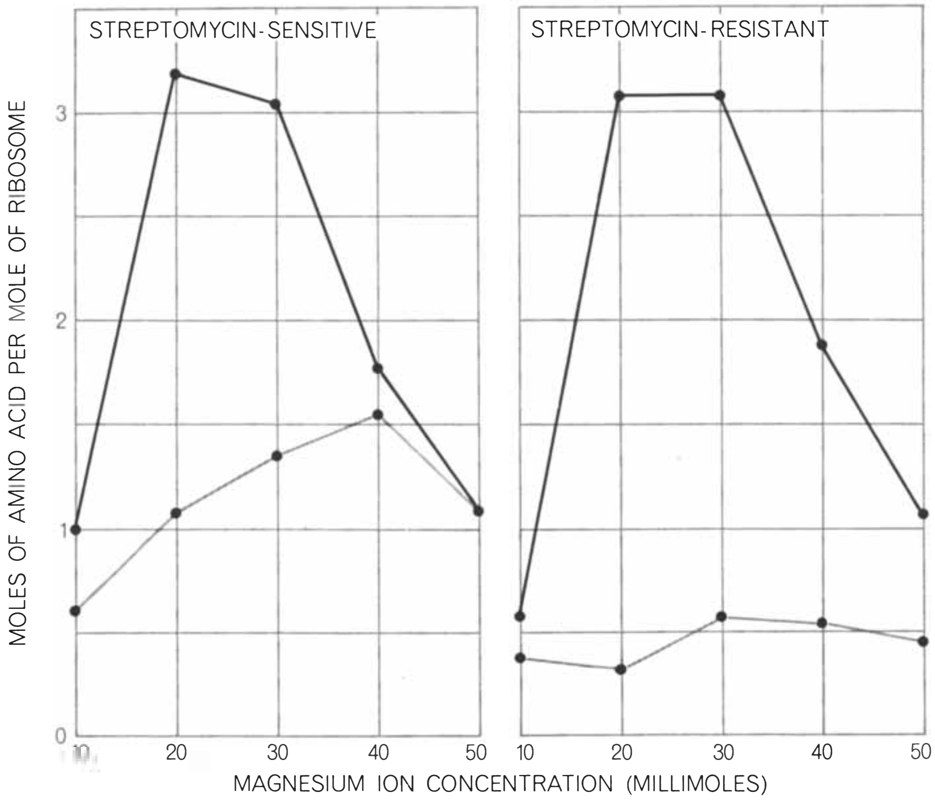
ACTION OF STREPTOMYCIN can be conceived of as an alteration, perhaps some kind of distortion, of the 30S subunit of the ribosome such that the codon is "read" incorrectly, binds the wrong transfer RNA and thus incorporates into the peptide chain an amino acid other than the one it coded for. This highly schematic diagram shows how a UUU codon should incorporate phenylalanine (*left*). Altered by a streptomycin molecule (*right*), the ribosome causes the UUU to be read as if it were AUU, and thus to incorporate isoleucine.



"NONSENSE" mutant is one in which the correct codon (*left*) is mutated to one that encodes no amino acid (*middle*), so no protein can be formed. Streptomycin might suppress the error by causing the nonsense codon to be misread as if it were the correct one (*right*).



"MISSENSE" MUTANT is one in which the codon (*left*) is mutated to one incorporating a different amino acid (*middle*), making an inactive or perhaps unstable enzyme. Streptomycin-induced misreading might cause incorporation of the correct amino acid (*right*).



NEOMYCIN, a related antibiotic, stimulates the misincorporation of serine in a polyuridylic acid preparation whether the ribosomes are from streptomycin-sensitive or resistant cells (*black curves*). In contrast, streptomycin (*gray curves*) has no effect on ribosomes from resistant cells (*right*); incorporation is the same as it is in the absence of the drug.

by changing the concentration of positive ions, the acidity or the temperature, or by adding certain organic solvents. The effects of these changes may be laboratory artifacts, however, quite without biological significance. In the case of the streptomycin effect it has been possible to throw a bridge between misreading in cell-free preparations on one hand and suppression in living mutant cells on the other.

At first there was some conflict between the two. Whereas the conditionally streptomycin-dependent cells had been streptomycin-resistant, ribosomes from resistant cells were not subject to misreading in our cell-free preparations. In those preparations it was ribosomes from drug-sensitive cells that seemed subject to misreading, but we had not tested the sensitive cells in vivo because we assumed that the streptomycin would kill them. We subsequently found that it is indeed possible to isolate conditionally streptomycin-dependent mutants among auxotrophs obtained from wild-type, sensitive strains, provided that streptomycin is added to the medium at a very low concentration. Sensitive cells respond readily to these small amounts of streptomycin. Resistant cells, however, respond sluggishly and require much more of the streptomycin in order to synthesize the enzyme in which they are defective [*see top illustration on page 105*]. This weak response in resistant conditionally streptomycin-dependent cells suggested that our failure to find even a little misreading with resistant ribosomes in the cell-free preparations was due to the low efficiency of our biochemical system. Sure enough, when we developed a highly purified system, we found that even some streptomycin-resistant ribosomes were subject to misreading.

All these experiments pointed to a picture of the ribosome as a cell component with a very complex function. The structure and function of ribosomes can be investigated by isolating and examining ribosomal mutants in much the same way that other mutants have been followed in genetic experiments to unravel the structure of enzymes. In this task one can select for altered ribosomes by taking advantage of the fact that streptomycin and other "aminoglycoside" antibiotics related to it cause changes in ribosome structure. So far it is clear that two classes of streptomycin-resistant cell can be isolated from a strain bearing a defect that can be suppressed by streptomycin. One is "competent" for the suppression and the other "incompetent." A graduate student in our laboratory, Lee Breckenridge, succeeded in isolating a second crop of conditionally streptomycin-dependent mutants from competent and incompetent parents and found that a mutant that is incompetent for one defect may be competent for another. This confirms our impression that there is a relation between a specific change in ribosome structure and the defect that can be corrected. This is equivalent to saying that as a result of mutation or of the presence of streptomycin or related drugs a ribosome can assume different conformations that are specific for different types of misreading.

Other findings support this conclusion. For one thing, the pattern of misreading induced in a cell-free system by streptomycin and related drugs such as kanamycin and neomycin varies with the drug. Moreover, in experiments with living cells certain auxotrophs are suppressed by one drug and not by another. Even in the absence of inducing drugs, variations in ribosome structure play a role in the accuracy of translation. There seems to be a steady low level of misreading, and that level varies with specific ribosomal mutations. It has also been noted that a single mutation from drug-sensitive to resistant—which means a change in ribosome structure—is often accompanied by the appearance of other defects, such as auxotrophy, that suggest errors in translation.

All of this means that ambiguity of translation is inherent in the process of protein synthesis; the genetic script transcribed into messenger RNA is not read in only one way. A cell is capable of a certain frequency of misreading, and drugs or other agents in the environment can increase this frequency by acting on the ribosomes.

The misreading caused by streptomycin is not random; it makes polyuridylic acid, for example, code for only a few incorrect amino acids. The results of experiments conducted in Nirenberg's laboratory and by Davies in our laboratory make it possible tentatively to define a simple pattern for these misreadings and to obtain some insight into the way in which antibiotics cause them and thus into the mechanism of translation. According to the available data and the code "dictionary" compiled to date, it is possible to suggest that streptomycin distorts the configuration of the ribosome in a way that affects the reading of only one base of a triplet at a time. It follows that the codon is read as if it were one of the triplets "connected" to it, that is, differing from it by only one base substitution. The ambiguity, as is evident in cell-free preparations, is still more selective in that the misreadings we find do not include all the possible connected codons but only some of them. This selectivity largely accounts for the relative infrequency of conditionally streptomycin-dependent mutants among all the auxotrophs derived from a given parent.

Another reason for this infrequency could be that a streptomycin-induced misreading can often lead to the incorporation of the same amino acid encoded by the messenger RNA, because connected codons are often synonymous. This might explain why a large fraction of the conditionally streptomycin-dependent auxotrophs we find are really "leaky," or incomplete, auxotrophs stimulated by streptomycin rather than strictly dependent on it: they produce too small a quantity of some growth factor rather than none at all, and streptomycin makes them produce more. A reasonable hypothesis is that their mutation was to a rarely used codon and that streptomycin suppresses that codon, reading instead a more frequently utilized synonym—that they too are corrected by streptomycin through misreading, but the correction is "silent" in the sense that one cannot demonstrate actual amino acid substitution.

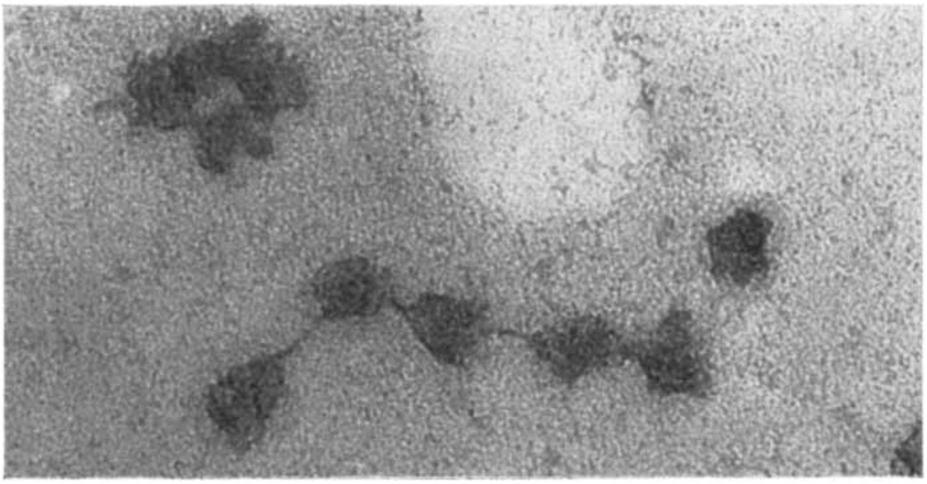
This is only a hypothesis, however; the leaky auxotrophs might suggest, on the contrary, that streptomycin always acts in living cells by somehow stimulating enzyme production—a process for which several explanations other than codon misreading can be imagined. To convince ourselves that the misreading obtained in cell-free preparations does indeed account for the suppression observed in living cells, we need unequivocal demonstrations of the occurrence of misreading in such cells. The most direct approach would be to isolate, purify and analyze an enzyme and demonstrate that in the presence of streptomycin one actually gets a mixture of molecules with slightly different amino acid compositions. Unfortunately, this seems to be a very laborious and difficult task. Streptomycin correction is of the order of less than 1 percent, and the few corrected molecules may be impossible to distinguish from impurities.

Fortunately there is another way in which misreading can be demonstrated unequivocally. That is to inquire directly whether the two well-known types of mutation are susceptible to streptomycin correction. One is the "nonsense" mutation, in which the affected triplet codes for no amino acid at all, and the protein corresponding to the mutated messenger is therefore missing. The mechanism of suppression of these mutations is well established and consists in making sense of the nonsense triplet, causing the protein to be formed [see "The Genetics of a Bacterial Virus," by R. S. Edgar and R. H. Epstein; SCIENTIFIC AMERICAN, February, 1965]. Since it has been demonstrated, particularly in bacterial viruses, that streptomycin corrects mutants harboring a well-known and easily detected nonsense mutation, it is clear that streptomycin corrects by misreading a nonsense triplet into a "sense" amino acid codon. In a "missense" mutation, on the other hand, the wrong amino acid is encoded, resulting in an altered or inactive enzyme. Here streptomycin suppression through misreading could insert either the correct amino acid or another one that permits some enzyme activity. A mutant both conditionally streptomycin-dependent and temperature-sensitive—one that ordinarily produces an altered enzyme that is stable at one temperature but not stable at a higher temperature, but that in the presence of streptomycin produces at least some stable enzyme—offers unequivocal evidence of amino acid substitution. We have isolated such mutants and we are studying them.

Streptomycin-induced translation errors can of course hurt the cell as well as help it, since they affect certain codons in certain ways whether or not those codons are mutated. We studied the effect of misreading on the synthesis of four enzymes in a conditionally streptomycin-dependent mutant in which the effect of the drug was enhanced by a second mutation. Increasing concentrations of streptomycin raised the level of the defective enzyme (OTC), but it also markedly reduced the level of the other three enzymes. We call this effect "oversuppression." It tends to flood a cell with faulty proteins.

Intuitively, misreading would seem to be the reason why streptomycin acts as an antibiotic, and there is very suggestive evidence that it is indeed the basis for an explanation of the aminoglycoside drugs' bactericidal effect. Bacteria resistant to the antibiotic effect of streptomycin are also resistant to its close relatives dihydrostreptomycin and bluensomycin, but they are killed by neomycin and kanamycin. The parallel to this is that in cell-free preparations in which streptomycin-resistant ribosomes are resistant to misreading induced by streptomycin and its close relatives they are nevertheless susceptible to misreading induced by neomycin and kanamycin, and neomycin-resistant mutants are susceptible to misreading induced by streptomycin. Although a flood of bad protein might well stop cell growth, however, its effect should be reversible. Special types of misreading or other effects would seem necessary to account fully for the killing of cells.

Apart from its pharmacological implications, our work with streptomycin adds a new dimension—the ribosomal dimension—to investigations into the mechanism of protein synthesis and provides the genetic tools with which to investigate it. Our findings also raise the broad question of the meaning of ambiguity in the genetic code. That ambiguity and the flexibility to which it gives rise may play an important role in the life of cells and in their evolution.



POLYRIBOSOMES from rabbit reticulocytes, the cells that make hemoglobin, are enlarged 370,000 diameters in this electron micrograph made by Henry S. Slayter of the Children's Cancer Research Foundation. They appear to be groups of ribosomes connected by strands of RNA, presumably the messenger RNA encoding the amino acid sequence of a protein.

MATHEMATICAL GAMES

The eerie mathematical art of Maurits C. Escher

by Martin Gardner

There is an obvious but superficial sense in which Op art (discussed in this department last July) can be called mathematical art. This aspect of Op is certainly not new. Hard-edged, rhythmic, decorative patterns are as ancient as art itself, and even the modern movement toward abstraction in painting began with the geometric forms of the cubists. When the French Dadaist painter Hans Arp tossed colored paper squares in the air and glued them where they fell, he linked the rectangles of cubism to the gobs of paint slung by the later "action" painters. In a broad sense even abstract expressionist art is mathematical, since randomness is a mathematical concept.

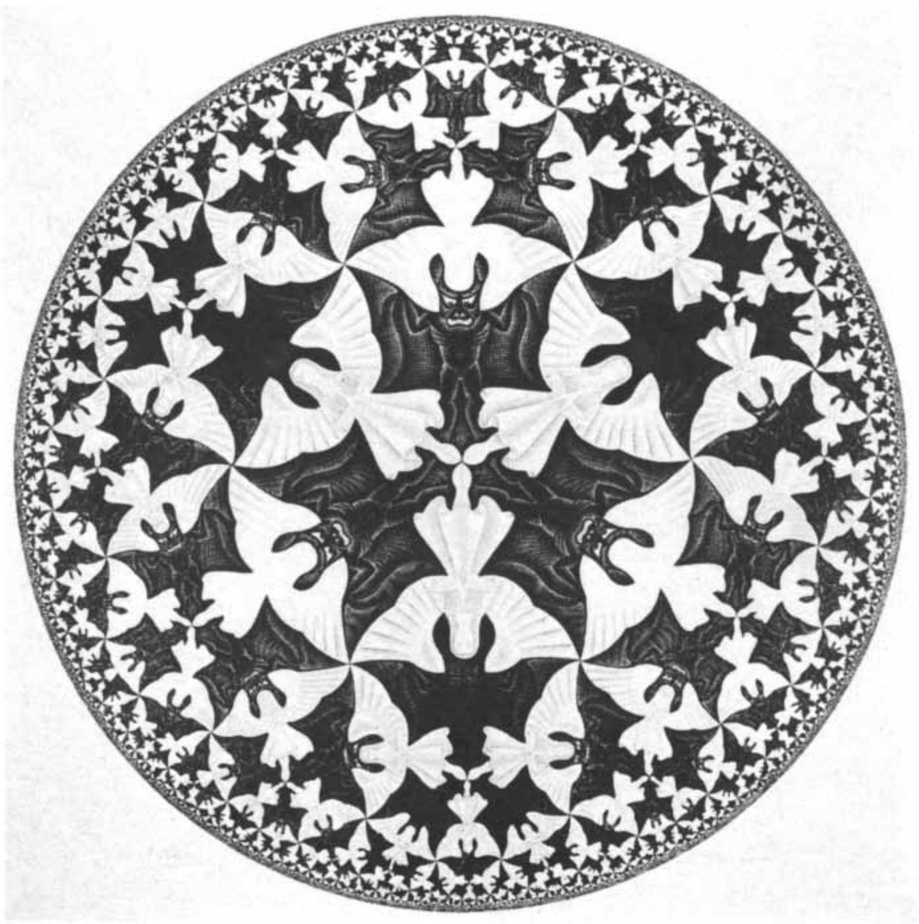
This, however, expands the term "mathematical art" until it becomes meaningless. There is another and more useful sense of the term that refers not to techniques and patterns but to a picture's subject matter. A representational artist who knows something about mathematics can build a composition around a mathematical theme in the same way that Renaissance painters did with religious themes or Russian painters do today with political themes. No living artist has been more successful with this type of "mathematical art" than Maurits C. Escher of the Netherlands.

"I often feel closer to mathematicians than to my fellow-artists," Escher has written, and he has been quoted as saying, "All my works are games. Serious games." His lithographs, woodcuts, wood engravings and mezzotints can be found hanging on the walls of mathematicians and scientists in all parts of the world. There is an eerie, surrealist aspect to some of his work, but his pictures are less the dreamlike fantasies of a Salvador Dali or a René Magritte than they are subtle philosophical and mathematical observations intended to evoke what the poet Howard Nemerov, writing about Escher, called the "mystery, absurdity, and sometimes terror" of the world. Many of his pictures concern mathematical structures that have been discussed in this department, but before we examine some of them a word or two about Escher himself.

He was born in Leeuwarden in Holland in 1898, and as a young man he studied at the School of Architecture and Ornamental Design in Haarlem. For 10 years he lived in Rome. After leaving Italy in 1934 he spent two years in Switzerland and five in Brussels, then settled in the Dutch town of Baarn, where he and his wife now live. Although he had a successful exhibit in 1954 at the Whyte Gallery in Washington, he is still much better known in Europe than he is here. A large collection of his work is owned by Cornelius Van Schaak Roosevelt of Washington, D.C., an engineer who is a grandson of President Theodore Roosevelt. It was through Roosevelt's generous cooperation, and with Escher's permission, that the pictures reproduced here were obtained.

Among crystallographers Escher is best known for his scores of ingenious tessellations of the plane. Designs in the Alhambra reveal how expert the Spanish Moors were in carving the plane into periodic repetitions of congruent shapes, but the Mohammedan religion forbade them to use the shapes of living things. By slicing the plane into jigsaw patterns of birds, fish, reptiles, mammals and human figures, Escher has been able to incorporate many of his tessellations into a variety of amusing, startling pictures.

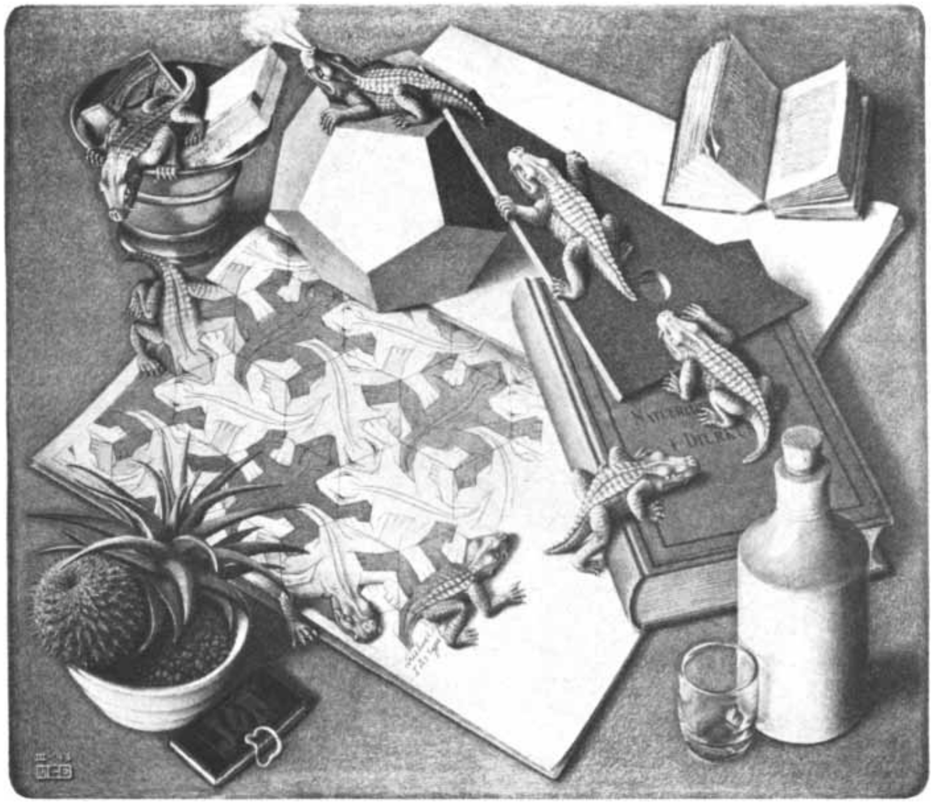
In "Reptiles," the lithograph shown at the top of the opposite page, a little monster crawls out of the hexagonal tiling to begin a brief cycle of three-space life that reaches its summit on the dodecahedron; then the reptile crawls back again into the lifeless plane. In "Day and Night," the woodcut at the bottom of the opposite page, the scenes at the left and the right are not only



"Heaven and Hell," woodcut (1960)

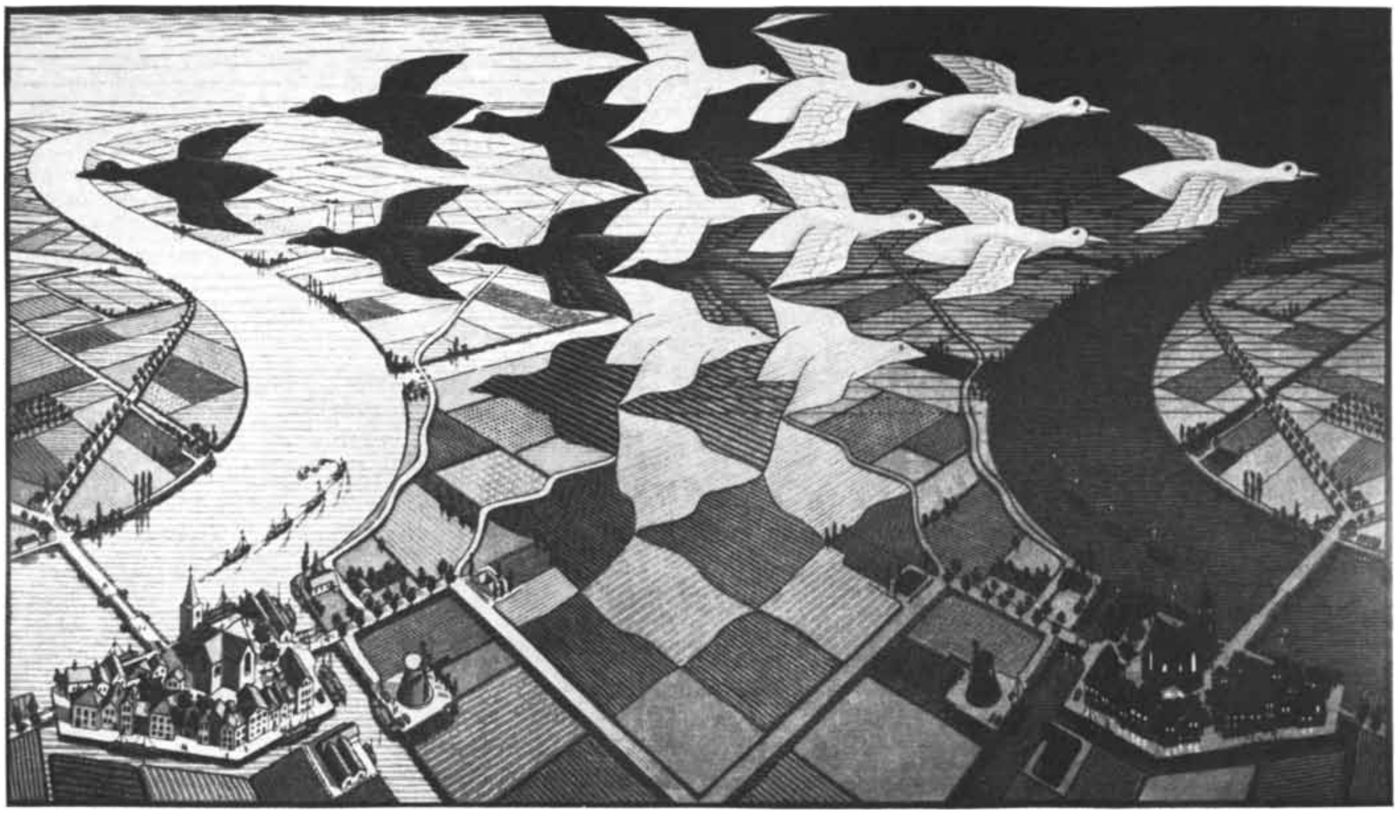
mirror images but also almost "negatives" of each other. As the eye moves up the center, rectangular fields flow into interlocking shapes of birds, the black birds flying into daylight, the white birds flying into night. In the circular woodcut "Heaven and Hell" [*opposite page*] angels and devils fit together, the similar shapes becoming smaller farther from the center and finally fading into an infinity of figures, too tiny to be seen, on the rim. Good, Escher may be telling us, is a necessary background for evil, and vice versa. This remarkable tessellation is based on a well-known Euclidean model, devised by Henri Poincaré, of the non-Euclidean hyperbolic plane; the interested reader will find it explained in H. S. M. Coxeter's *Introduction to Geometry* (Wiley, 1961), pages 282–290.

If the reader thinks that patterns of this kind are easy to invent, let him try it! "While drawing I sometimes feel as if I were a spiritualist medium," Escher has said, "controlled by the creatures I am conjuring up. It is as if they themselves decide on the shape in which they choose to appear.... The border line between two adjacent shapes having a double function, the act of tracing such a line is a complicated business. On either side of it, simultaneously, a recognizability takes shape. But the human eye and mind cannot be busy with two things at the same moment and so there must be a quick and continuous jumping from one side to the other. But this difficulty is perhaps the very moving-spring of my perseverance."



"Reptiles," lithograph (1943)

It would take a book to discuss all the ways in which Escher's fantastic tessellations illustrate aspects of symmetry, group theory and crystallographic laws. Indeed, such a book has been written by Caroline H. MacGillavry of the University of Amsterdam: *Symmetry Aspects of M. C. Escher's Periodic Drawings.* This book, published in Utrecht last year for the International



"Day and Night," woodcut (1938). From the Mickelson Gallery, Washington

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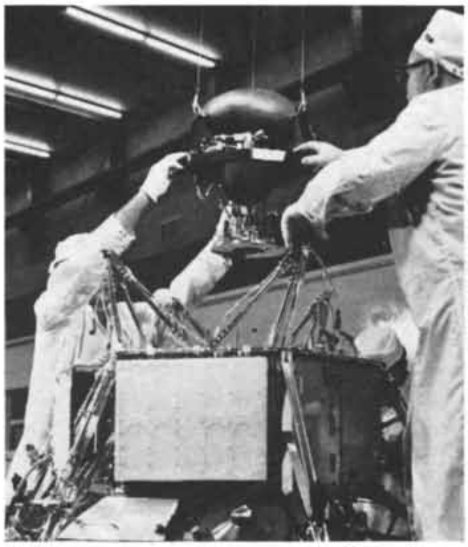
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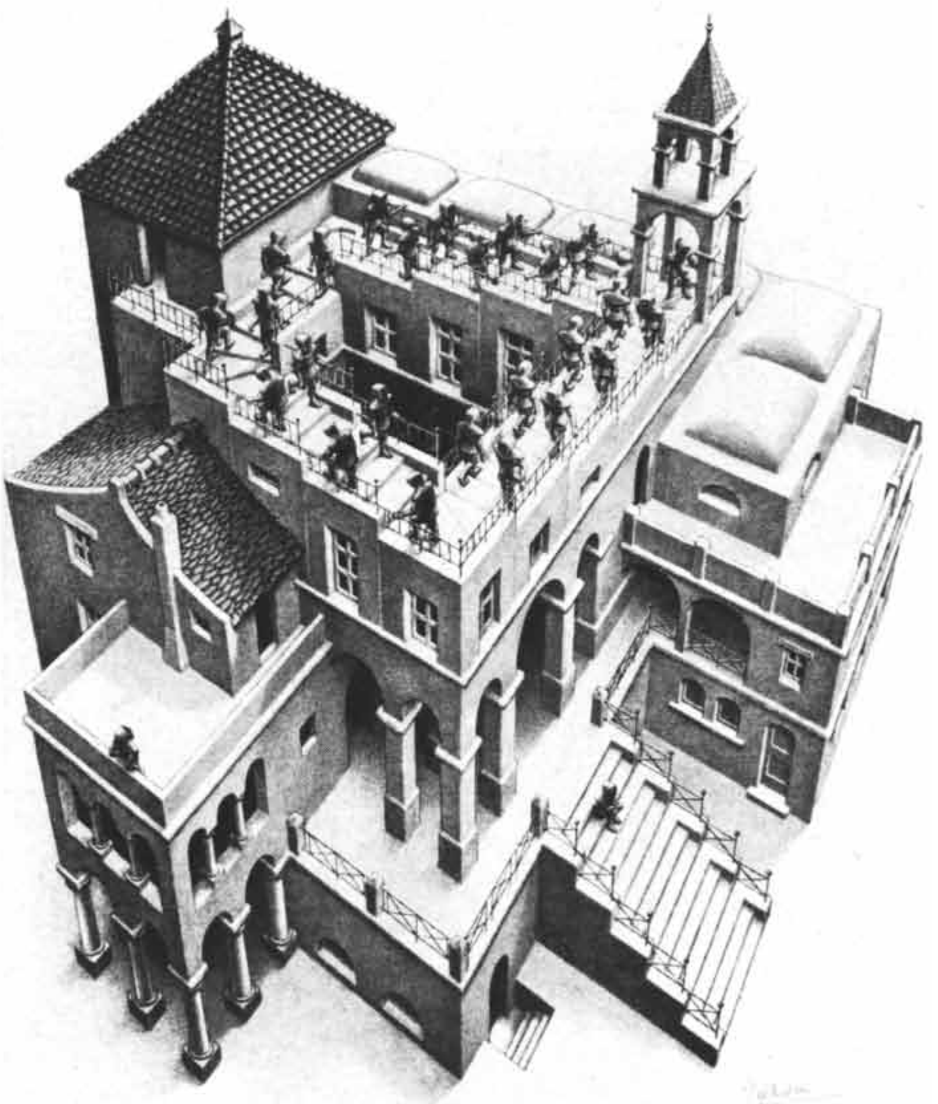
Union of Crystallography, reproduces 41 of Escher's tessellations, many in full color. Other reproductions have been published in this department (April, 1961), on the jacket of C. N. Yang's *Elementary Particles* and in Melvin Calvin's contribution to *Interstellar Communication,* edited by A. G. W. Cameron.

The picture below and the one on the next page illustrate another category of Escher's work, a play with the laws of perspective to produce what have been called "impossible figures." In the lithograph "Belvedere" observe the sketch of the cube on a sheet lying on the checked floor. The small circles mark two spots where one edge crosses another. In the skeletal model held by the seated boy, however, the crossings occur in a way that is not realizable in three-space. The belvedere itself is made up of impossible structures. The youth near the top of the ladder is outside the belvedere but the base of the ladder is inside. Perhaps the man in the dungeon has lost his mind trying to make sense of the contradictory structures in his world.

The lithograph "Ascending and Descending" derives from a perplexing impossible figure that first appeared in an

"Belvedere," lithograph (1958)



"Ascending and Descending," lithograph (1960)

article, "Impossible Objects: A Special Type of Visual Illusion," by L. S. Penrose, a British geneticist, and his son, mathematician Roger Penrose (*British Journal of Psychology*, February, 1958). The monks of an unknown sect are engaged in a daily ritual of perpetually marching around the impossible stairway on the roof of their monastery, the outside monks climbing, the inside monks descending. "Both directions," comments Escher, "though not without meaning, are equally useless. Two refractory individuals refuse to take part in this 'spiritual exercise.' They think they know better than their comrades, but sooner or later they will admit the error of their nonconformity."

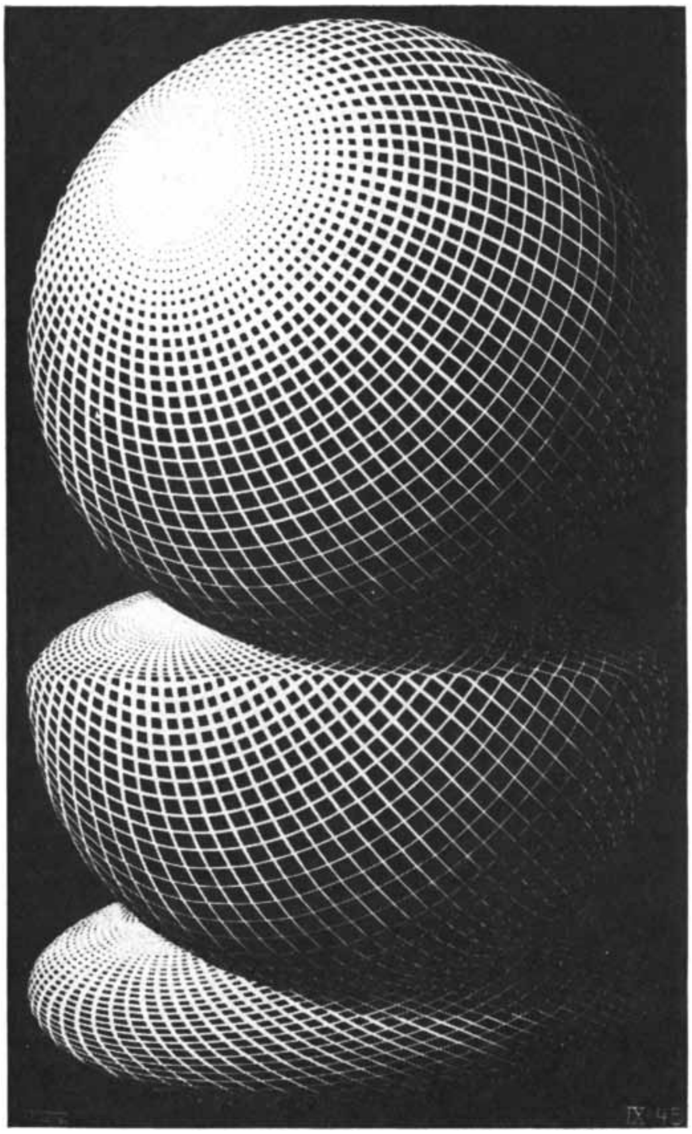
Many Escher pictures reflect an emotion of wonder toward the forms of regular and semiregular solids. "In the midst of our often chaotic society," Escher has written, "they symbolize in an unrivaled manner man's longing for harmony and order, but at the same time their perfection awes us with a sense of our own helplessness. Regular polyhedrons have an absolutely nonhuman character. They are not inventions of the human mind, for they existed as crystals in the earth's crust long before mankind appeared on the scene. And in regard to the spherical shape—is the universe not made up of spheres?"

The lithograph "Order and Chaos" [*bottom of page 118*] features the "small stellated dodecahedron," one of

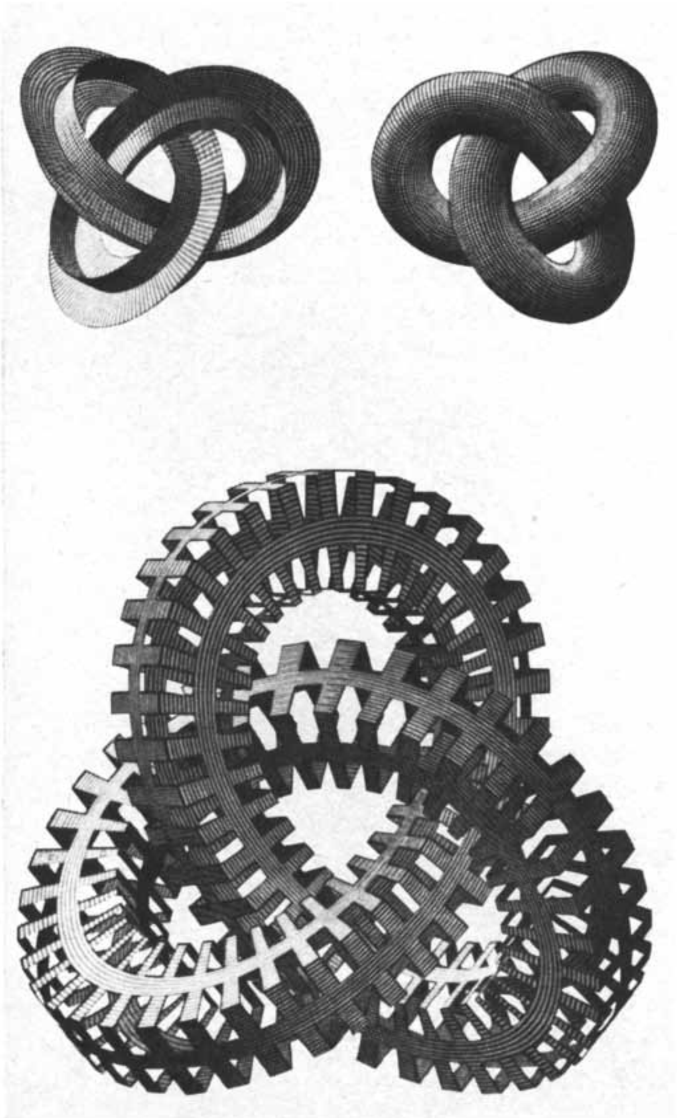
the four "Kepler-Poinsot polyhedrons" that, together with the five Platonic solids, make up the nine possible "regular polyhedrons." It was first discovered by Johannes Kepler, who called it "urchin" and drew a picture of it in his *Harmonices mundi* (*Harmony of the World*), a fantastic numerological work in which basic ratios found in music and the forms of regular polygons and polyhedrons are applied to astrology and cosmology. Like the Platonic solids, Kepler's urchin has faces that are equal regular polygons, and it has equal angles at its vertices, but its faces are not convex and they intersect one another. Imagine each of the 12 faces of the dodecahedron (as in the picture "Reptiles") extended until it becomes a pentagram, or five-pointed star. These 12 intersecting pentagrams form the small stellated dodecahedron. For centuries mathematicians refused to call the pentagram a "polygon" because its five edges intersect, and for similar reasons they refused to call a solid such as this a "polyhedron" because its faces intersect. It is amusing to learn that as late as the middle of the 19th century the Swiss mathematician Ludwig Schläfli, although he recognized some face-intersecting solids as being polyhedrons, refused to call this one a "genuine" polyhedron because its 12 faces, 12 vertices and 30 edges did not conform to Leonhard Euler's famous polyhedral formula, $F + V = E + 2$. (It *does* conform if it is reinterpreted as a solid with 60 triangular faces, 32 vertices and 90 edges, but in this interpretation it cannot be called "regular" because its faces are isosceles triangles.) In "Order and Chaos" the beautiful symmetry of this solid, its points projecting through the surface of an enclosing bubble, is thrown into contrast with an assortment of what Escher has described as "useless, cast-off and crumpled objects."

The small stellated dodecahedron is sometimes used as a shape for light fixtures. Has any manufacturer of Christmas tree ornaments, I wonder, ever sold it as a three-dimensional star to top a Christmas tree? A cardboard model is not difficult to make. H. M. Cundy and A. P. Rollett, in *Mathematical Models* (Oxford University Press, revised edition, 1961), advise one not to try to fold it from a net but to make a dodecahedron and then cement a five-sided pyramid to each face. Incidentally, every line segment on the skeleton of this solid is (as Kepler observed) in golden ratio to every line segment of next-larger length. The solid's polyhedral dual is the "great dodecahedron," formed by the intersection of 12 regular pentagons. For details about the Kepler-Poinsot star polyhedrons the reader is referred to the book by Cundy and Rollett and to Coxeter's *Regular Polytopes,* now a Macmillan paperback.

The lithograph "Hand with Reflecting



"Three Spheres," wood engraving (1945)



"Knots," woodcut (1965)

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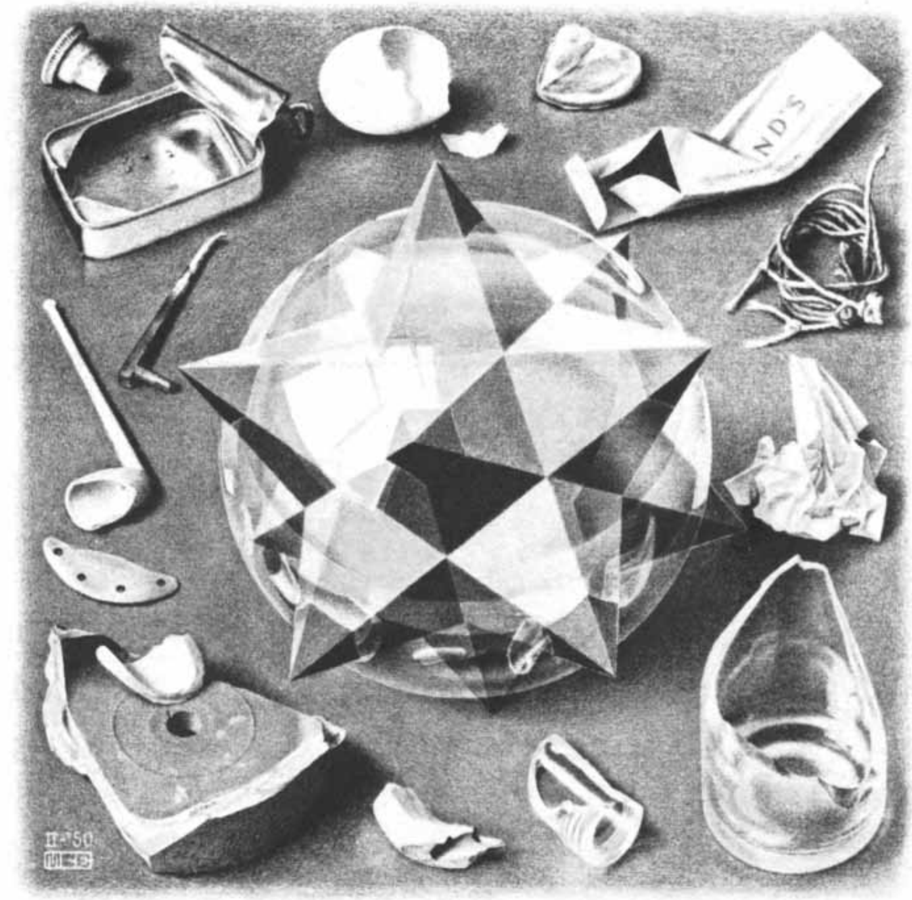
Globe" [*right*] exploits a reflecting property of a spherical mirror to dramatize what in philosophy is sometimes called the "egocentric predicament." All any person can possibly know about the world is derived from what enters his skull through various sense organs; there is a sense in which one never experiences anything except what lies within the circle of his own sensations and ideas. Out of this "phenomenology" he constructs what he believes to be the external world, including those other people who appear to have minds in egocentric predicaments like his own. Strictly speaking, however, there is no way he can prove that anything exists except himself and his shifting sensations and thoughts. Escher is seen staring at his own reflection in the sphere. The glass mirrors his surroundings, compressing them inside one perfect circle. No matter how he moves or twists his head, the point midway between his eyes remains exactly at the center of the circle. "He cannot get away from that central point," says Escher. "The ego remains immovably the focus of his world."

Escher's fascination with the playthings of topology is expressed in a number of his recent pictures. At the top of the woodcut "Knots" [*at right on page 116*] we see the two mirror-image forms of the trefoil knot. The knot at top left is made with two long flat strips that intersect at right angles. This double strip was given a twist before being joined to itself. Is it a single one-sided

"Hand with Reflecting Globe," (1935)



"Order and Chaos," lithograph (1950)

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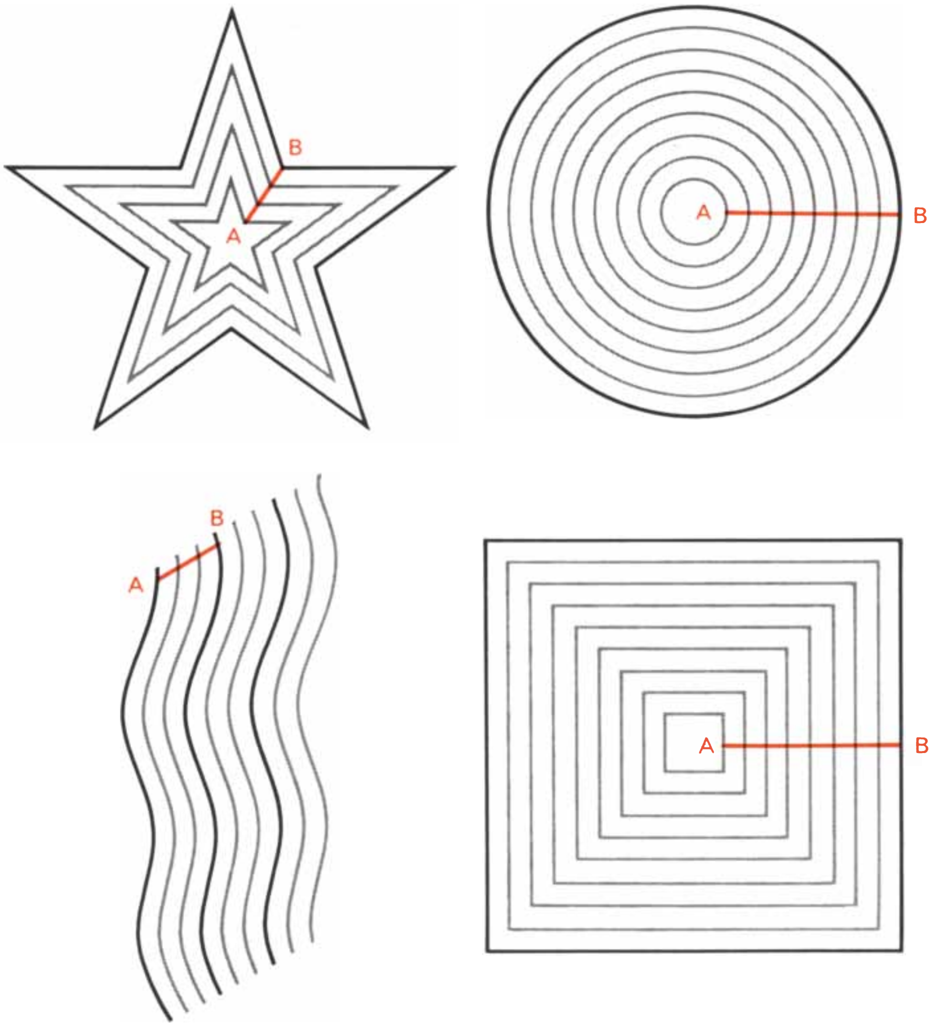
A Division of Lockheed Aircraft Corporation band that runs twice around the knot, intersecting itself, or does it consist of two distinct but intersecting Möbius bands? The large knot below the smaller two has the structure of a four-sided tube that has been given a quarter-twist so that an ant walking inside, on one of the central paths, would make four complete circuits through the knot before it returned to its starting point.

The wood engraving "Three Spheres" at the left on page 116, a copy of which is owned by New York's Museum of Modern Art, appears at first to be a sphere undergoing progressive topological squashing. Look more carefully, however, and you will see that it is something quite different. Can the reader guess what Escher, with great verisimilitude, is depicting here before his explanation is given next month?

Last month's problem was to determine which of the five "ESP" symbols cannot be drawn an aleph-one number of times on a sheet of paper, assuming ideal lines that do not overlap or intersect, and replicas that are similar although not necessarily the same size. Only the plus symbol is limited to aleph-null repetitions. The illustration below shows how each of the other four can be drawn an aleph-one number of times. In each case points on line segment *AB* form an aleph-one continuum. Clearly a set of nested or side-by-side figures can be drawn so that a different replica passes through each of these points, thus putting the continuum of points into one-to-one correspondence with a set of nonintersecting replicas. There is no comparable way to place replicas of the plus symbol so that they fit snugly against each other. The centers of any pair of crosses must be a finite distance apart (although this distance can be made as small as one pleases), forming a countable (aleph-null) set of points.

The problem is similar to one involving alphabet letters that can be found in Leo Zippin's *Uses of Infinity* (Random House, 1962), page 57. In general only figures topologically equivalent to a line segment or a simple closed curve can be replicated on a plane, without intersection, aleph-one times.



Proof for "ESP"-symbol problem

THE AMATEUR SCIENTIST

How to perform experiments with animal cells living in tissue culture

Conducted by C. L. Stong

The cells of many animal tissues can be kept alive for long periods outside the animal by means of the technique known as tissue culture. In some cases the original cells maintain themselves without dividing; in others they divide repeatedly. Essentially tissue culture consists in transferring cells from an animal to a glass vessel containing the appropriate nutrients at body temperature. One line of cells established in this way has been maintained for almost 20 years, long after the death of the animal from which they came. Such cells maintain their vitality and show no evidence of aging. Tissue culture thus offers insights into some intriguing questions. Do the cultured cells acquire a longevity they lack when they are part of an animal? Or is this longevity an intrinsic property of the cell, one that disappears when the cell functions as a member of the highly organized and complex cellular community that constitutes the intact animal?

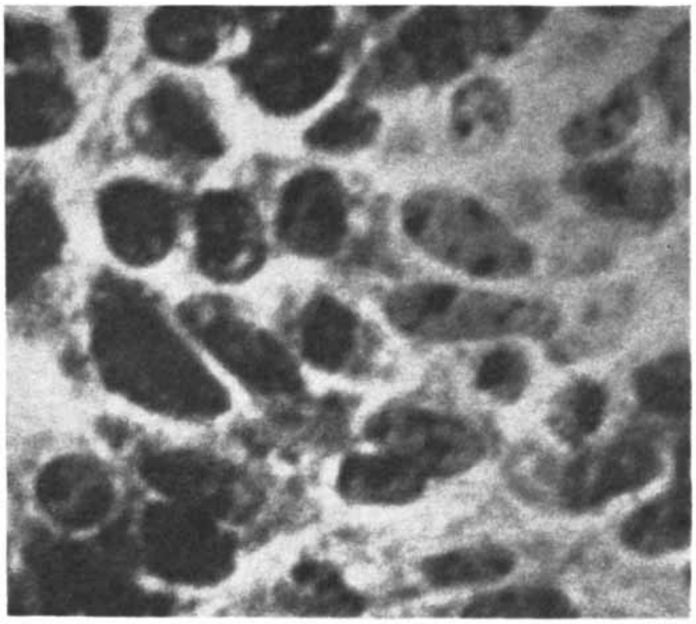
Until recent years experiments with tissue cultures were all but closed to amateurs. Mastery of the essential procedures required a long apprenticeship. The ingredients of the nutrient mixtures were difficult to obtain and even more difficult to compound. The procedure called for rigorous routines to prevent the infection of cultures by bacteria.

Today ready-made ways of solving such problems are at hand. Nutrient mediums can be bought inexpensively from distributors of biological supplies. Bacterial infections are controlled by antibiotics. Cultures of living cells can also be bought. With such materials Ted M. Fancolli, who attends the American River Junior College in Sacramento, Calif., has developed simplified methods of making tissue cultures. The methods require little more skill than growing bacteria on a plate of nutrient agar. In effect these procedures place in the amateur's hands a powerful tool for looking into such diverse matters as the structure and function of cells, the susceptibility of cells to various bacteria and viruses, the nutrition of cells and the effects of drugs and radiation on cells.

"Cell cultures," Fancolli writes, "have been grouped in three classes according to the origin of the cells and their behavior. Those established directly from animal tissue are known as primary cultures. Examples are cells from the kidneys of rhesus monkeys that are used in the production of poliomyelitis virus for both the Salk and the Sabin vaccines. Primary cultures can be established from almost any kind of tissue, but they must be prepared fresh each time they are used, necessitating a constant source of tissue.

"The cells of some primary cultures can be serially subcultivated. They are then known as cell strains and will usually persist through 40 or more generations before dying out. In form and structure, cell strains do not differ significantly from primary cultures.

"For reasons that remain obscure the cells of some strains continue to reproduce indefinitely. Such cultures are known as cell lines. The oldest culture of this type, called the *L* line, was established in 1947 by Wilton R. Earle



Cultured cells: epithelial class **(left),** ***fibroblastic class*** **(right)**

of the National Cancer Institute from tissue taken from a male mouse 100 days old. The oldest culture of malignant origin is the 'HeLa' cell line taken from a human cancer in 1952. It has since become one of the most extensively investigated cell lines. In contrast to primary cultures, cell lines reproduce indefinitely and contain an abnormal number of chromosomes. They grow much faster than cell strains.

"All cell cultures require the same growth factors and nutrients at approximately the same concentrations regardless of the animal from which the tissue is taken. This astonishing uniformity of metabolism is quite different from the requirements of bacteria and other microorganisms, which exhibit varied nutritional needs. Twenty-nine factors appear to be enough for supporting the growth of most cell cultures: 12 amino acids, eight vitamins, glutamine, dextrose or glucose, six inorganic salts and serum protein. Compared with what an animal needs in its diet, a cell culture requires a greater variety of amino acids but fewer vitamins in its diet. The fact that a single medium can be used to grow a wide variety of cell strains and lines enables the experimenter to maintain many different kinds of cell for study.

"Before setting up a tissue culture the beginner should learn the elements of standard bacteriological procedures as previously discussed in this department [March, 1958]. An autoclave is almost indispensable for sterilizing glassware, certain mediums and reagents. A large pressure cooker can serve as the autoclave. Materials placed in the autoclave will be thoroughly sterilized in 15 to 20 minutes at 121 degrees centigrade, the temperature of steam at a pressure of 15 pounds per square inch. Start timing the sterilization after the pressure of the autoclave reaches 15 pounds. When sterilizing apparatus in the autoclave, always loosen the screw caps of bottles so that steam can reach the inside. Cool the autoclave slowly, particularly after sterilizing fluids, to prevent the contents from boiling when returned to atmospheric pressure.

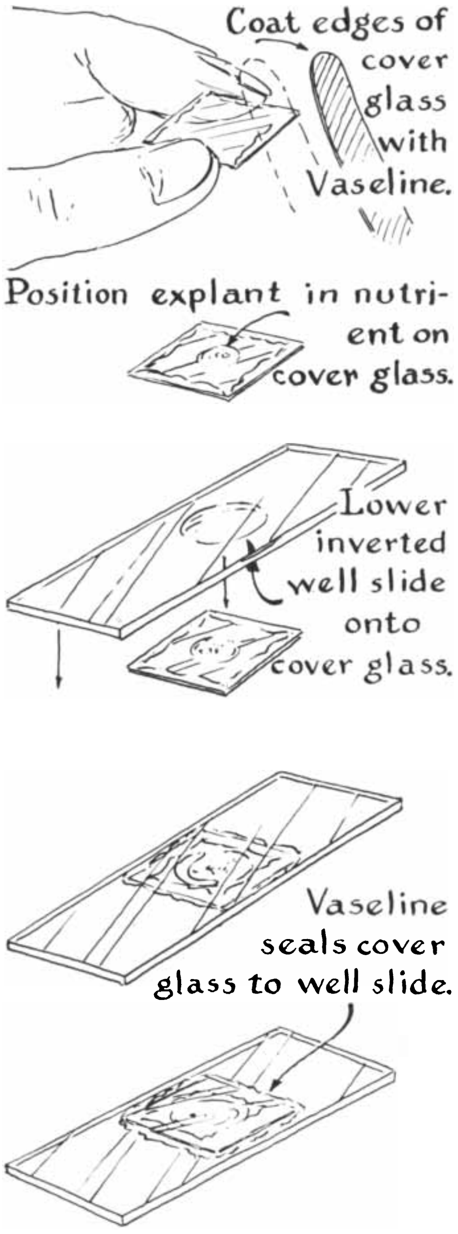
"Particles of dead bacteria, molds and yeasts suspended in sterilized fluids can be removed by filtering the material through either asbestos pads or unglazed porcelain. An inexpensive and convenient apparatus for filtering consists of a syringe of the Luer type fitted with a Swinny adapter that holds the asbestos filter. A syringe of this type can be procured from the Fisher Scientific Company, 633 Greenwich Street, New York, N.Y. 10014. The Swinny adapter is available from the Baltimore Biological Laboratories, 2201 Asquith Street, Baltimore, Md. 21218.

"All reagents must be of the highest available purity. Triple-distilled water should be used in all procedures. The experimenter should anticipate spending much of his time washing apparatus. All containers must be rinsed at least four times with tap water followed by a final rinse with triple-distilled water.

"For specimen materials beginners are urged to buy a starter cell culture. This material can be obtained from Difco Laboratories Inc., 920 Henry Street, Detroit, Mich. 48201, or from the Baltimore Biological Laboratories. Information on available cultures, prices and shipping will be sent on request. Alternatively, tissues and organs for culturing can be taken from an animal. This must be done under sterile operating conditions. If the animal must be killed, the method must be one—such as an overdose of chloroform—that does not introduce toxic agents into the animal's system.

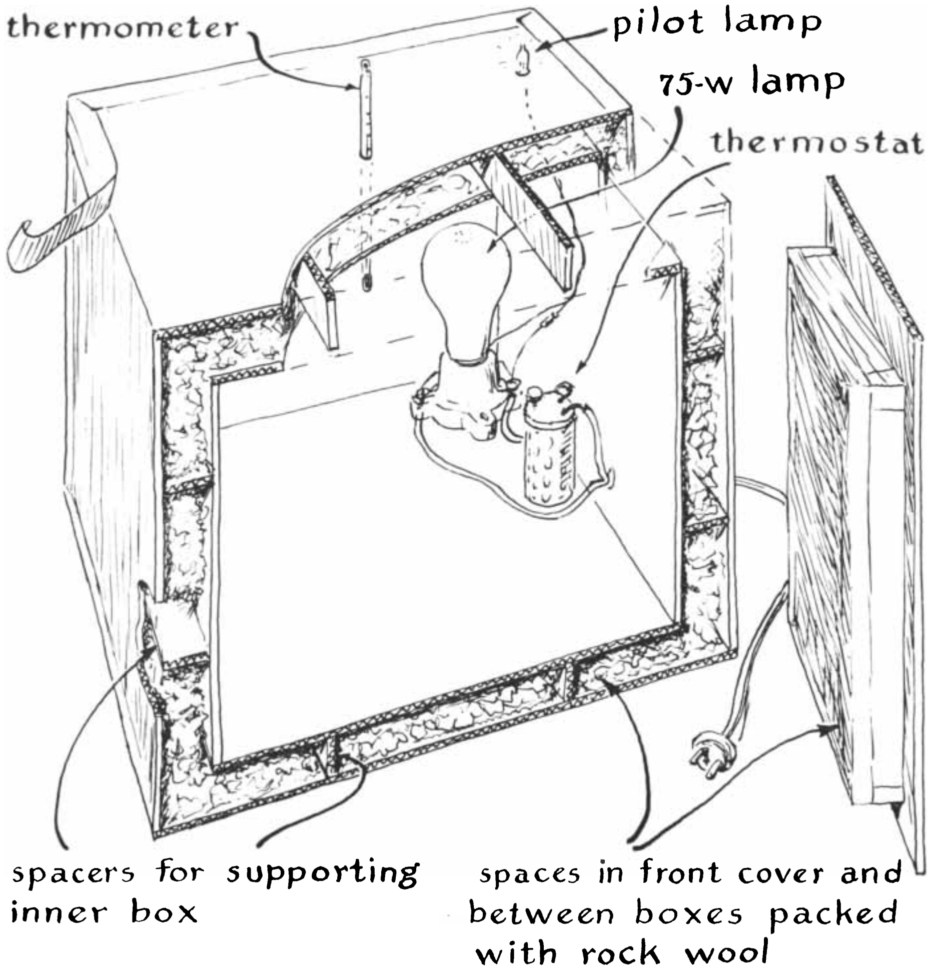
"The tissue specimen must be washed immediately in a sterile salt solution, a specially compounded mixture of salts, phosphates, carbonates and dextrose that maximizes tissue survival. The solution can be obtained from the Baltimore Biological Laboratories or from Difco Laboratories. I used TC-Hanks Balanced Salt Solution. (Reagents and mediums preceded by *TC* are products of Difco Laboratories.) All superfluous membranes or structures must be removed while the tissue specimen is immersed in the balanced salt solution. The remaining tissue is then washed in the balanced salt solution, placed in a sterile container such as a watch glass, minced into fragments about a cubic millimeter in size with scissors or a scalpel and stored in the balanced salt solution.

"The fragments can be cultivated in either of two ways. One is to keep them in a form called 'plasma clot' on microscope slides or in flasks or tubes. The other is to disperse them as separate cells for cultivation in a liquid medium in tubes or bottles, where they grow as a single layer of closely spaced cells that adhere to the glass walls of the container. The choice between these two procedures depends on the use for which the cultures are intended. The plasma clot is excellent for microscopic examination but poor for maintaining cultures, because nutrient can be made available to the growing tissue only a drop or two at a time. The nutrient must be replaced frequently. The monolayer type is widely used for perpetuating cultures, for investigating the interaction of cells and viruses and for studying cell lines.



Preparation of a "plasma clot"

"A plasma-clot culture is prepared by placing one drop of TC-Chicken Plasma in the center of a square of thin glass of the type used for covering microscope slides. To this drop is added one drop of TC-Embryo Extract $EE_{20}1$. (A numerical subscript indicates the percentage of extract or medium in the solution.) Mix the drops with a spatula and spread the fluid over an area about the size of a dime. Add two pieces of minced tissue to the center of the fluid. The specimens are now called explants. Each one should be about a millimeter square. Measure the size carefully. Explants larger than recommended cannot absorb adequate nourishment. Moreover, the initial size must be known



An incubator that can be built for tissue culture

so that the rate of subsequent growth can be determined.

"Cover the preparation and set it aside for about an hour, until it clots. An inverted microscope slide that contains a deep depression makes a convenient cover [*see illustration on preceding page*]. Seal the cover glass to the slide with a ring of yellow petroleum jelly. Incubate the preparation at approximately 37 degrees C. and observe the culture under a microscope every 24 hours. The growing tissue must be transferred to fresh nutrient every two or three days, a procedure known as 'patching.' Simply cut the old slide culture back to a one-millimeter square, transfer it to a freshly prepared cover glass and continue incubation.

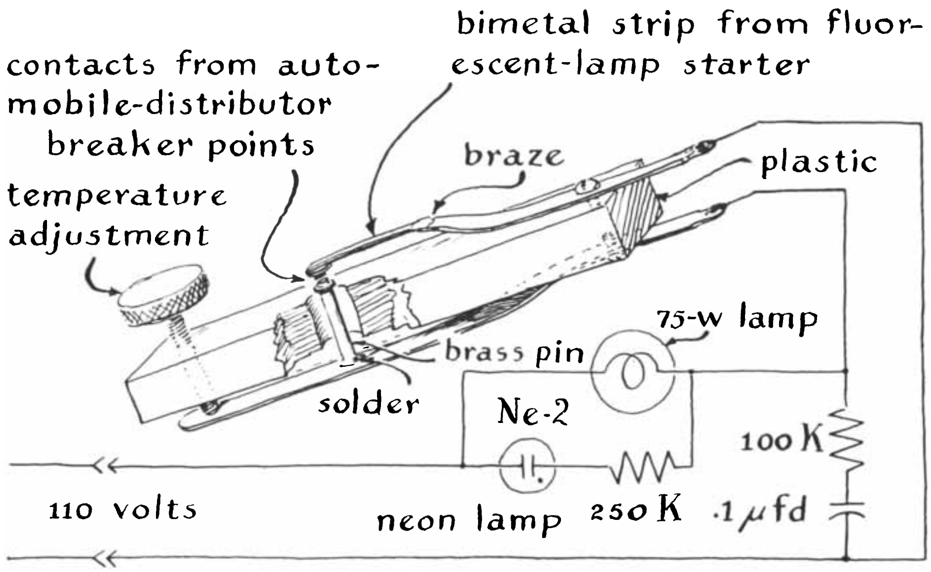
"I use a homemade incubator: a pair of nested cardboard boxes insulated with rock wool [*see illustration at left*]. Controlled heat is provided by a 75-watt lamp bulb regulated by a thermostat of the type used in aquarium tanks. Such thermostats are also available with a built-in heating unit at slightly higher cost. Alternatively, you can improvise your own from a bimetal strip salvaged from the starter switch of a fluorescent lamp [*see bottom illustration on this page*]. The temperature of the incubator should be maintained between 34 and 37 degrees C.

"Cultures of the monolayer type involve several additional operations. The cells grow as individuals. For this reason the term 'cell culture' seems more appropriate than 'tissue culture.' To disperse the cells the fragments of tissue are first placed in a flask containing a few glass beads, which serve as agitators when the flask is swirled, and a sterile saline solution that contains .25 percent trypsin. The trypsin dissolves the cement between the cells to produce a suspension. Diluted trypsin does not affect living cells and can be removed easily from the suspensions.

"To prepare the solution dissolve 25 milligrams of 1:250 trypsin (the number is part of the name and designates the activity of the preparation) in 10 milliliters of calcium-and-magnesium-free phosphate-buffered saline (CMF-PBS). Filter-sterilize this preparation through a sterile Swinny filter into half-ounce prescription bottles. Store five milliliters in each bottle.

"To prepare the CMF-PBS solution dissolve 800 milligrams of sodium chloride, 30 milligrams of potassium chloride, eight milligrams of sodium orthophosphate mono-H, two milligrams of orthophosphate di-H and 200 milligrams of dextrose in 100 milliliters of triple-distilled water. Do not autoclave this preparation but keep it frozen until you are ready to use it. For dispersing tissue cells thaw the solution, add five fragments of tissue of the same size as that used in the tissue-clot experiment, let the mixture stand for six hours at 4 degrees C. and then shake it vigorously to make a uniform suspension of cells.

"Now centrifuge the suspension at 800 revolutions per minute for five minutes. Pour off the solution gently. Add five milliliters of basic salt solution and again shake the container to resuspend the cells. Filter the suspension through



A thermocouple for use in the incubator

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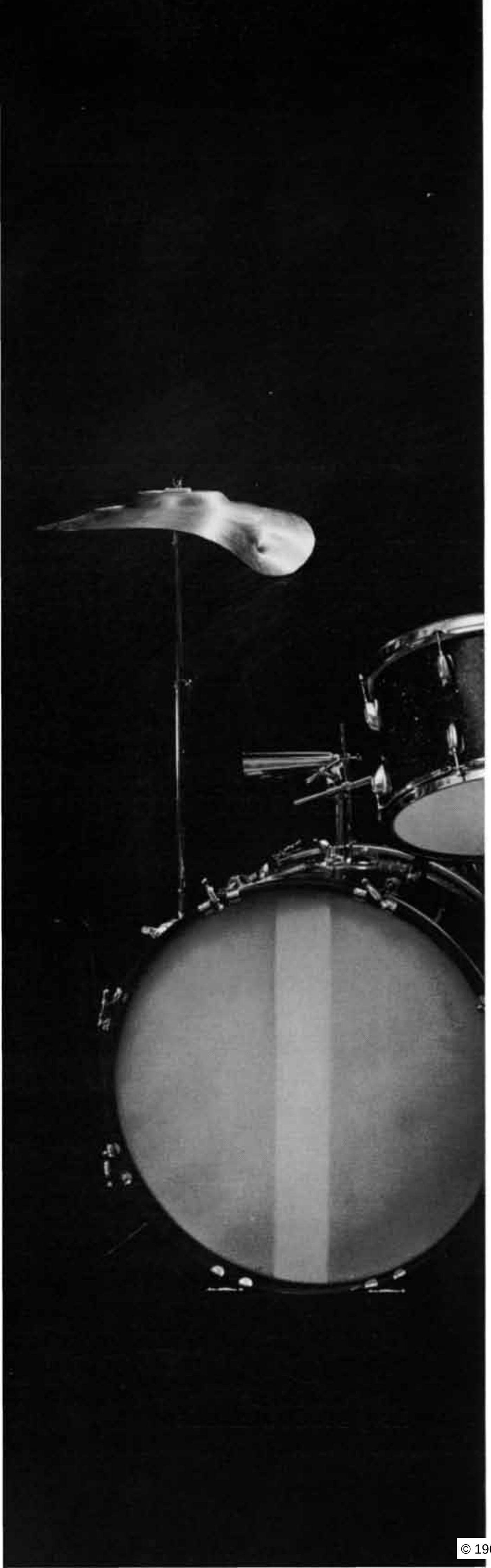


One of a series briefly describing GM's research in depth

Lead cymbals and hysteresis loops

Lead isn't exactly the cymbal maker's dream material. But then, not everyone wants a material that resonates, peals, or hums.

Lead isn't the engineer's dream material, either. It lacks strength and weighs too much.

A curious phenomenon being explored by GM Research physicists could give engineers what they've never had before: a material with the noise damping qualities of lead and the physical strength of steel. The phenomenon, called magnetomechanical damping, originates with the tendency of magnetic domains to line up when a ferromagnetic material is stretched or squeezed.

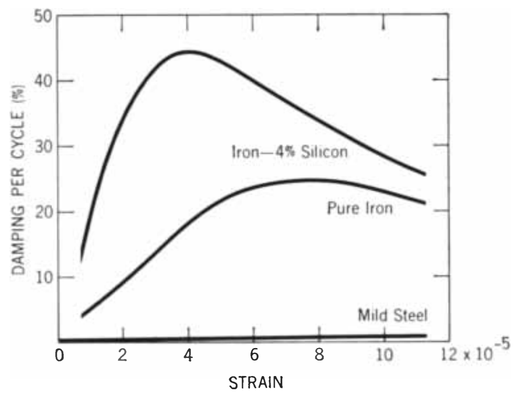
What happens, apparently, is that vibrations shuffle domain boundaries and cause a cyclic variation in the magnetization of the material; the material is cycled through a small magnetic hysteresis loop, and part of the vibrational energy is converted into heat.

What excites us now is our finding that some iron-silicon alloys with usable tensile strengths (e.g., 70,000 psi) can give very high damping. This damping occurs at strain values associated with audible vibrations, and it's relatively independent of frequency.

But we need to learn much more before we can tailor alloys for specific applications; for instance, how do magnetic domain walls interact with static and dynamic strain? What are the detailed effects of crystallographic orientation and of specific impurities?

Still, the spirit of science thrives on unanswered questions.

General Motors Research Laboratories
Warren, Michigan 48090



sterile gauze into a clean container and centrifuge it again at 800 r.p.m. for five minutes. The washed cells collected at the bottom of the centrifuge tube are ready, after resuspension in basic salt solution, for monolayer culturing [*see bottom illustration at right*]. Much of this work can be avoided, of course, by buying prepared starter cultures.

"Mediums for making monolayer cultures are available from Difco Laboratories or the Baltimore Biological Laboratories. I use Eagle's Basal Medium (also known as Eagle's HeLa Medium). It is currently priced at $2.50 per 100 milliliters. Glutamine must be added in the proportion of 30 milligrams per 100 milliliters of medium. Glutamine is unstable even at refrigerator temperatures; therefore it must be added as the medium is prepared for use. Make up the glutamine solution by dissolving 30 milligrams of reagent *L*-glutamine in two milliliters of triple-distilled water. Pass the solution through a Swinny filter into the container of medium. Reagent *L*-glutamine can be bought from Nutritional Biochemicals Inc., 21010 Miles Avenue, Cleveland, Ohio 44128.

"The medium must also contain serum—5 to 10 percent for maintaining a culture and 15 to 20 percent for encouraging growth. Serum provides growth factors that have not yet been identified. It also appears to encourage the attachment of cells to the glass walls. I use any of three serums: TC-Horse Serum, TC-Fetal Calf Serum or TC-Human Serum.

"To the medium thus completed antibiotics can be added for the control of bacterial infection. I use a combination of antibiotics that is effective against both gram-positive and gram-negative organisms. The combination consists of 100 units of sterile potassium penicillin *G* and 100 micrograms of dihydrostreptomycin sulfate per milliliter of medium. The antibiotics must be procured in the form of dry powders, without preservatives that might poison the cultures. A 500,000-unit vial of potassium penicillin *G* and a one-gram vial of dihydrostreptomycin constitute an adequate stock. The drugs can be obtained with the help of a cooperative physician.

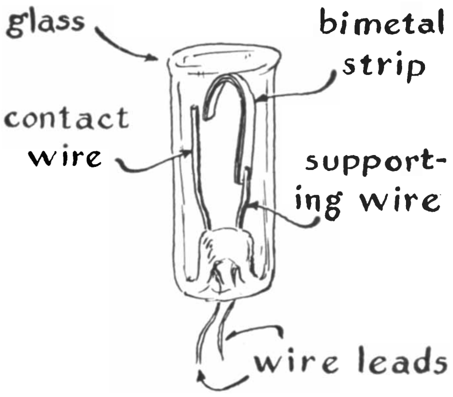
"To start a monolayer culture, plant a quarter-milliliter of the cell suspension and one milliliter of the prepared medium in a screw-cap tube about 16 millimeters in diameter and 150 millimeters long. Close the cap tightly and place the tube in the incubator at an angle of about 15 degrees, so that the contents wet most of the wall at the bottom. Within 24 to 36 hours a dense monolayer will form where the fluid wets the glass. I substituted ordinary half-ounce prescription bottles for the screw-cap tubes. Bottles of this type have one flat side. (A druggist let me have six dozen for four cents a bottle.) The bottle is laid on its flat side. The flat inner surface appears to encourage the growth of exceptionally massive cultures.

"The growing culture exhausts the nutrient in about four days. To replenish the spent medium pour off the fluid, refill the container with four milliliters of fresh medium and shake the solution gently until the monolayer disintegrates. Then asceptically transfer two milliliters of the fresh cell suspension to another bottle. This procedure is known as making a 'split.' You now have two cultures.

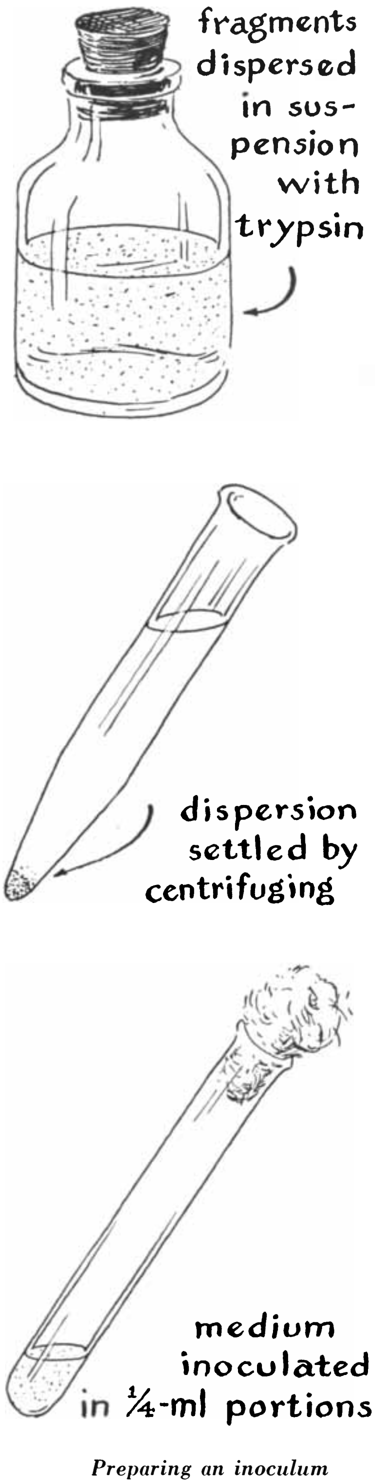
"The medium as supplied includes phenol red, an ingredient that serves to indicate the acidity or alkalinity of the fluid. The color of a fresh culture ranges from cerise to pink. As the cells metabolize, the solution gradually becomes acid, so that the color changes from pink to yellow. Alkalinity must then be restored by admitting air to the culture. This is done by loosening the cap of the bottle about a quarter-turn and retightening it.

"To stain monolayers for microscopic examination remove from a culture as much of the specimen as can be picked up with a sterilized wire loop approximately three millimeters in diameter [*see illustration on page 129*]. Transfer the cells to a clean microscope slide by pressing the loop on the glass. Wash the material gently with three changes of basic salt solution and then fix, or preserve, the cells by a drop of 10 percent formalin in .8 percent saline solution. Wash the material again to remove the formalin and let the specimen dry at room temperature. During the drying the cells become firmly attached to the glass; they can be stained by any of several preparations without becoming dislodged. Wright's stain is particularly easy to use. Flood the dried cells with two drops of a solution composed of .1 milligram of dry certified Wright's stain in 60 milliliters of acetone-free reagent methanol. Let the stain act for two minutes and then add four drops of water. Let the slide stand for five minutes. Rinse off the stain and dry the slide at room temperature.

"An alternative procedure is to stain the cells by basic fuchsin—.5 percent of the stain in a 20 percent solution of methanol in water. Let the preparation



Starter switch for incubator



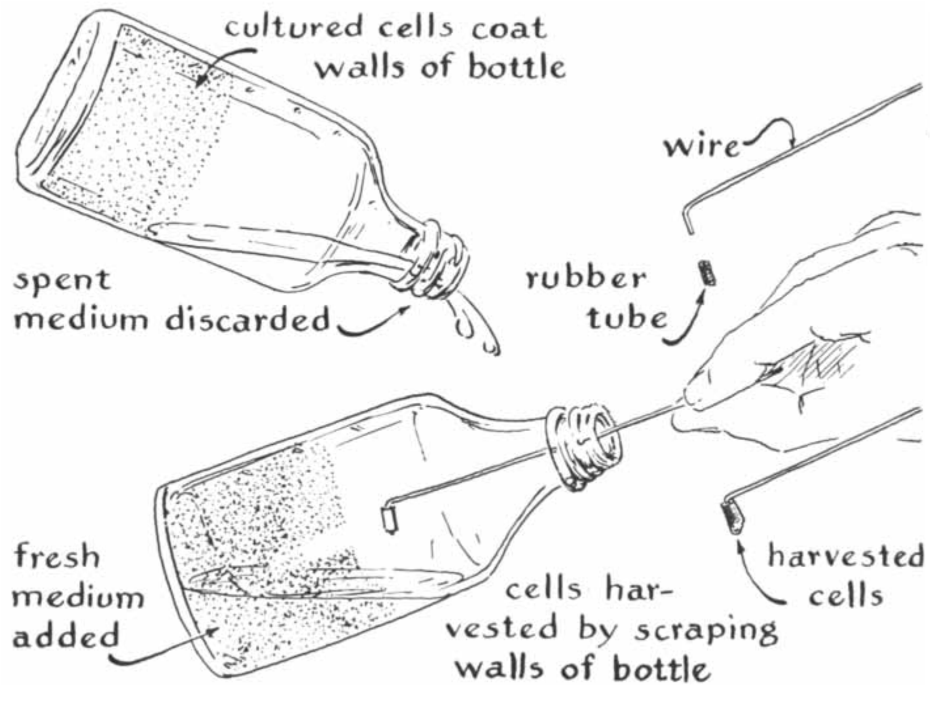
Preparing an inoculum

act on the cells for five minutes. Then rinse the cells in water or in a 50 percent solution of methanol in water. The diluted alcohol tends to produce slides of greater contrast between the cytoplasm and the nuclei than the water rinse does. On the other hand, the alcohol tends to bleach the dye. The slide must be watched carefully and the action stopped at maximum contrast by rinsing the preparation in water to prevent total destaining.

"As seen under the microscope monolayer cultures can be separated into two broad classes according to their appearance. Those that grow into long, spindly, loosely connected cells are called fibroblastic, because of their similarity to muscle fibroblasts. An example is the widely studied murine *L* cell line. Cells of the second class grow as closely joined polygonal shapes, called epithelial. The HeLa cell line is an example of this type, as are the great majority of other existing cultures [*see illustration on page 122*].

"Because active tissues require frequent changes of medium, biologists sought a method of maintaining cells for long intervals with minimum attention. This was found in the technique of 'agar slant' culture, in which a supply of nutrient is in effect stored in an agar substrate. To establish a culture of this kind prepare a solution of Eagle's Basal Medium of twice the strength used for monolayer cultures. Next make up a 3 percent solution of Noble agar ('Noble' indicates a purified grade of agar) or of ordinary agar washed five times in cold, triple-distilled water and then dried. Autoclave the solution and cool it. Mix equal volumes of the concentrated medium and agar solution, dispense the mixture in four-milliliter amounts in sterile test tubes and cool the tubes in an almost horizontal position so that the agar solidifies as a 'slant' that extends from the bottom of each tube almost to the top. When the agar has cooled, pipette .3 milliliter of Eagle's Basal Medium with 10 percent TC-Horse Serum into the tube. Store the tube upright in the refrigerator. Such slants are satisfactory for six months or more of use.

"In order to establish a tissue culture in the agar slant tubes, harvest cells from a young monolayer (two or three days old) and then wash them once with sterile basic salt solution. Separate the cells from the fluid by centrifuging. Gently pour the solution from the centrifuge tube without disturbing the cells that have settled to the bottom. Add half a milliliter of sterile basic salt solu-



Harvesting monolayer tissue culture

tion to the tube and agitate it to make a dense suspension of cells. Using a wire loop that has been sterilized by flame, transfer a loopful of the cell suspension to a prepared agar slant, touching the agar with the loop at several places. (Do not smear the inoculum by dragging the loop across the surface of the agar.) Cap the agar tube tightly and incubate it in an upright position at 37 degrees C. Colonies of cells will appear in about four days and will grow to a diameter of five to 10 millimeters within 10 days. The nutrient solution should be changed at least every three weeks. The culture will live for six weeks or longer. For this reason agar slants are well suited for keeping stock cultures of cell lines and cell strains.

"To establish pure cultures of bacteria one can take advantage of the fact that a single bacterium can give rise to a colony of descendants. A parallel exists in which tissue cultures are used for separating mixed viruses into pure viral strains. The technique is called plaquing. A single virus particle can infect a cell in a monolayer overlaid with agar. The infected cell produces more virus. Neighboring cells become infected and die. A plaque, or pock, appears at the site; it contains the pure viral strain. The procedure is useful, of course, only when the tissue cells are susceptible to infection by the virus under test.

"To prepare an agar overlay for investigating viruses make up the agar solution as for an agar slant, but to each 10 milliliters of the solution add .3 milliliter of a .1 percent autoclaved aqueous solution of 1:30,000 Neutral Red Certified. Then grow the selected cell line or strain on the flat side of a half-ounce prescription bottle, using two milliliters of Eagle's Basal Medium plus 20 percent TC-Horse Serum, until a dense monolayer has formed. This will take about three days.

"With the bottle resting on its flat side wash the monolayer once with sterile basic salt solution, taking care to keep the layer intact. To the bottle add two milliliters of sterile basic salt solution and a specimen of virus that has been suspended in .1 to .5 milliliter of sterile basic salt solution. Incubate the preparation for two hours. During this interval the virus will migrate into the tissue culture. Pour off the surplus fluid and gently flow the prepared agar, at a temperature of 40 to 45 degrees C., into the bottle so that it covers the monolayer. After the agar solidifies incubate the material with the bottle resting on its flat side. Within four days irregular patches of lighter-than-average color will be observed if a cell-destroying virus is present. Each plaque developed from a single virus particle can be cut out and propagated as a pure strain of virus.

"Additional experiments with tissue cultures will be described subsequently in this department. In the meantime I shall be pleased to correspond with amateurs who take up this fascinating hobby. My address is Ted M. Fancolli, 5117 Boyd Drive, Carmichael, Calif. 95608."

BOOKS

Knowledge v. wisdom in the relations between scientists and the government

by Kenneth E. Boulding

THE SCIENTIFIC ESTATE, by Don K. Price. The Belknap Press of Harvard University Press ($5.95).

This is an important book for two and a half reasons. The first is that the subject is important. The rise of science as a subculture, an organization, a body of knowledge and skill within human society—and the power that derives therefrom—is perhaps the most important single social phenomenon of the past 100 years. Accordingly the problem of the mutual interactions of science and political life, which is the subject of this book, has a pressing claim on our attention.

The second reason is that the author is an important man. The fact that he is dean of the Graduate School of Public Administration at Harvard University and that he has achieved this eminence without a Ph.D. is suggestive of his quality. He has been an associate director and vice-president of the Ford Foundation and before that had a distinguished career in government, both in the Bureau of the Budget, where he worked on the legislation that created the Atomic Energy Commission and the National Science Foundation, and in association with the Research and Development Board of the Department of Defense. He was a Rhodes scholar, an associate director of the Public Administration Clearing House and an adviser to at least three Presidents. He is a distinguished and influential member of what might be called the advice establishment, and he is therefore eminently qualified to express views on the subject matter of this work, with some confidence that a powerful ear is listening at the other end.

The half reason for regarding this as an important book is the book itself. It comes out of the wide experience of an able and reflective mind. It covers somewhat the same ground as the author's earlier work on the same subject (*Government and Science,* 1954) but digs into it more deeply. The style is a sound establishment style, steering a sober middle course between the arch and the turgid and never quite falling into either. It is a book that reflects on every page the solid training of the author as a political scientist, so that when he is dealing with governmental processes, he writes with a professional sureness of touch and avoids the errors (but also perhaps some of the insights) of the enthusiastic amateur.

The texture of the book is intricate, with a constant interweaving of themes rather than an orderly procession of argument. The major theme, which is implied in the title, is that science has become "something very close to an *establishment,* in the old and proper sense of that word: a set of institutions supported by tax funds, but largely on faith, and without direct responsibility to political control." The parallel is drawn with the religious establishment, and Price paraphrases Gibbon's cynical remarks about religion by saying that "all sciences are considered by their professors, as equally significant; by the politicians, as equally incomprehensible; and by the military, as equally expensive." In contrast to the "sacred" scientific establishment, government is secular, and inevitable tensions result. Nonetheless, a cheerful optimism pervades the book; this may not be the best of all possible worlds, but it seems to be the best that any reasonable person could think up. Consequently, although there may be tension between the secular world of politics and the new sanctity of science, there is no sense of crisis, no sense of any revolutionary uprising or religious war. The scientists are going to be good little Americans, loyal to the purposes of the tribe and disinclined to seek power.

Moving in harmonious counterpoint to this theme is another: There is a division of labor between science, which seeks truth, and politics, which is concerned with power, purpose and responsibility. "These deep differences between science and politics make possible the system of relative checks and balances in the unwritten constitution. Science can be the basis of an objective criticism of political power because it claims no power itself. Politics can afford to respect the independence of science because science does not attempt to dictate its purposes.... The more an institution or function is concerned with truth, the more it deserves freedom from political control...; the more an institution or function is concerned with the exercise of power, the more it should be controlled by the process of responsibility to elected authorities and ultimately to the electorate." One might interpret this a little unkindly as saying that science can be free as long as it is irrelevant, or if not irrelevant, subordinate to the purposes of power.

A third theme that goes along with the other two is that science (and also technology) cannot suggest purposes. If it does, the purposes, with the exception of "the abstract purpose of advancing truth and knowledge," will tend to be corrupting. Science, that is, should always be a means rather than an end. Price does not repeat the famous slogan (he quotes it in his earlier book) that "the scientist should be on tap, not on top," but clearly he thinks that the purposes of man in his societies are foreordained, that they are quite independent of any change in his view of the universe that science might produce, and that science should therefore be subordinate to these ultimate purposes.

A fourth theme that also runs through the book is that there are four estates of the realm, which Price describes as the scientific, the professional, the administrative and the political. Science manufactures pure truth, professionals apply it to particular and narrow purposes such as building a bridge or healing the sick, administrators comprise the structure necessary to carry out any purpose and politicians proclaim and promote the larger and ultimate purposes of the society. These estates, he recognizes, are not sharply distinguished but form a broad spectrum without clear lines of demarcation, and particular individuals may often perform roles in more than one estate. He does think of the estates, however, as constituting not merely a division of labor but also a separation of powers, and he postulates a kind of unwritten constitution—what John R. Commons would no doubt have called "working rules"—that allots the various roles, prevents too much overlap and keeps any one of the estates from dominating the others. He distinguishes four "defenses" of the various estates against possible challenges by the others: (1) the self-government of college and university departments, (2) the dependence of the professions on scientists for the basic knowledge they apply, (3) the dependence of politicians and administrators on both professionals and scientists for objective knowledge, or at least for protection from the criticism of being unscientific, and (4) the self-administration of membership in the particular discipline or profession, an arrangement so completely self-policing that the politician has no power to interfere with it.

These principles are further developed and illustrated in a number of case studies throughout the book. There is, for instance, a brief discussion of the problem of "command and control" in the military establishment, from which three further principles arise. The first is that the professional, and even the scientist in a somewhat professional role, must be active in the formulation of policy, because he alone possesses some basic information on which the policy must be founded. The second is that politicians and administrators must control key aspects of the technological system if they are to make responsible decisions. The third is the one I have already mentioned: checks and balances among the various estates. My personal view is that these fine principles have created a system with a built-in probability of almost total disaster, and that they will not look particularly impressive in the smoking ruins. One is reminded of the man who jumped off the Empire State Building and was heard to shout as he passed the 10th floor, "All right so far!"

Another case Price uses extensively is the curious history of this country's oceanography program, which seems to illustrate most of the problems that arise in the uneasy marriage of science and politics. Here he distinguishes what he calls three classic strategies: the first to take a problem out of politics altogether and set up machinery outside the normal structure of responsibility, the second "to insist that political authority act with the help of competent professional advisers" and the third "to demand that the professional advisers be publicly identified and held accountable for what they do." These three principles are illustrated at length by the various proposals and strategies in the oceanography program.

There are also some knowledgeable asides, for example on the way in which the atomic energy program, because of its peculiar organization, has been transformed from a program for the control of atomic energy to a program for its encouragement, quite contrary to the intention of its original designers. Throughout the book there are also some excellent bits of wisdom on the role of advice in the political system. Indeed, anyone who has ambitions either to give advice or to set up an organization for giving it should read this work very carefully.

Since the book is sensible, knowledgeable, respectable and wise it will no doubt seem curmudgeonly of me to award it only half a reason for being important. My reasons for withholding total praise stem partly from what seem to me some sins of commission in the fundamental principles that underlie the work and partly from some related sins of omission in dealing with the subject matter. My uneasiness with the underlying philosophy arises from a sense that the author does not really perceive the total social system as a process centrally concerned with information and knowledge and that hence he misses some of the real significance of the rise of science, both for the general social process and for the political institutions embedded in it. Perhaps this flows from the prejudices of the political scientist, who tends to see political institutions as being more dominant in the general social process than in fact they are. Even the most "responsible" political decisions are made in the light of the image of the world that the decision-maker possesses, and his image is largely created by the nature of the information system that surrounds him. If we are interested in the content of political decisions rather than in their form, we must see them as an integral part of a much larger structure in which information is collected and processed into images of the world. Science derives its political importance from the fact that it has become an increasingly significant part of the whole social process by which images of the world—including the images of political decision-maker—are created.

It is this insensitivity to the information content of political decisions that seems to me the gravest weakness of Price's analysis. Curiously nowhere in the book does he mention the traditional "fourth estate." This is all the more surprising in the light of the fact that he started out as a newspaperman. Perhaps long experience of whispering in the ears of the mighty has led him to forget the origin of a good deal of what is whispered. Indeed, the politician's image of the world is largely created by the particular methods of collecting and processing information that are practiced by the mass media. It seems rather odd to have a discussion of the new estates of the realm that pays no attention at all to the problem of mass media and public communication. We may not go all the way with Marshall McLuhan, who states boldly that the medium *is* the message and that presumably if we take care of the medium, the message will take care of itself, but it surely reveals a certain blindness to the real dynamics of the modern world to discuss the relation between science and politics without even mentioning the role of the mass media. The journalist does not even fit very well into Price's fourfold classification of estates. He is certainly not a scientist, barely a professional and clearly neither an administrator nor a politician.

What I cannot help regarding as a lack of perceptivity concerning the significance of information processes is similarly reflected in Price's attitude—one might almost say lack of attitude—toward the social sciences. The physical and biological sciences essentially deal with systems different from those familiar to the politician, who is concerned with social systems. The increase of knowledge in the physical and biological sciences, although it undoubtedly alters the characteristics of the social system, does not directly add to our knowledge of the social system itself. Therefore the sharp specialization of function among the politician, the administrator and the scientist that Price postulates is quite plausible—as long as we are dealing with the nonsocial sciences. The special skills and training of a physicist or biologist do not give him any particular claim to good political judgment, apart from the claim created by what is presumably a high general level of intelligence. In social systems the folk knowledge of the politician is likely to be superior to what is also the folk knowledge of the physicist.

When we come to the social sciences, however, we are in a quite different

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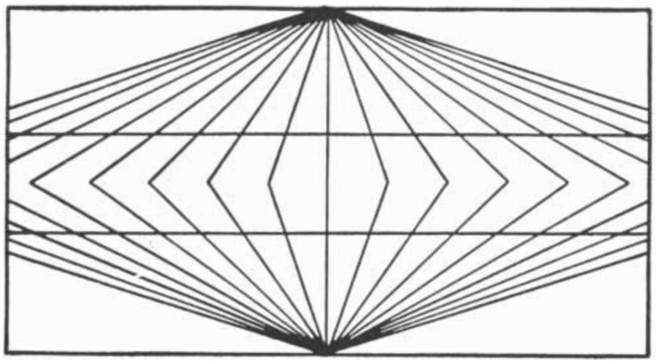

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world. The social scientist and the politician operate in the same system. The impact of the social sciences on the political system is of a different order of magnitude from the impact of the other sciences. Price gives no indication that he perceives this. He is hostile to the notion of science as "a unified and authoritative system of thought that pretends to explain all types of knowledge and to guide all types of actions," because "it becomes more a rationalization of a will to power than a valid intellectual discipline."

Scientific images, of course, are not the only true and valid form of knowledge. A great deal of the folk knowledge we gain in the ordinary affairs of life is perfectly true, or at least workable, and there is no theorem stating that the more developed and elaborate folk knowledge with which the politician generally works, which Price thinks of as "wisdom," should not also have a high probability of being true. Nevertheless, the rise of the social sciences cannot fail to have an enormous impact on our images of the social system, and even on our values and purposes. In this respect the neat distinction between truth and power, on which Price rests his entire philosophy, becomes hopelessly confused. One sees this already in economics, where we now have a social-scientific establishment in the form of a Council of Economic Advisers and a Joint Economic Committee. It is surprising that Price pays little attention to such matters. The fact that we have devised institutions for establishing formal communications between the economic-scientific community, the economic-professional community and the administrators and the politicians (to use Price's own categories) has effected a silent but nonetheless fundamental revolution in the prevailing image of the economy and even in the values and purposes of economic policy. The other social sciences have not yet achieved this degree of membership in the establishment. The Department of State, for instance, is still operated on folk knowledge and is deeply hostile to the social sciences. How long we can tolerate the absurd expense and insecurity of an international system run by "wisdom" remains to be seen.

I am not suggesting, of course, that the knowledge of the social sciences will replace political wisdom or remove the necessity for democratic institutions. What is the best choice in any particular political situation cannot be determined by operations research, simply because of the complexity of the system in which decision-makers operate. Furthermore, the politician who is a representative has to be sensitive to a great variety of pressures and interests; his decisions always involve the resolution of conflict rather than simple maximization and cannot be reduced to mere information processes. At this point Price is undoubtedly right in saying that there are elements in "power" that are not wholly subsumed under "truth." Nevertheless, truth, in the old Quaker phrase, speaks to power. The nature of the decisions of the powerful is enormously affected by the nature of the truth they perceive, and particularly the nature of the truth about social systems. Moreover, the values by which we make choices are themselves affected by the processes of arriving at truth. The purposes of politics are not foreordained but are the result of an epistemological process. It is perhaps the failure to realize this that blinds Price to the impact of the social sciences.

His sins of omission arise even more fundamentally, perhaps, from what one suspects is a deep hostility to the scientific revolution, which he sees as threatening the traditional purposes to which he has made a deep personal commitment. He is a nationalist, not a humanist. Whenever he says "we" or "our," it refers to only about 7 percent of the human race, or at best to a single stream of human history. Price is a man of the 18th century, not of the 20th and still less of the 21st. He is therefore incapable of appreciating the nature and depth of the crisis we face. He is a wise man, and this is a wise book. Unfortunately he is likely to take this last remark as a compliment.

Short Reviews

MICHAEL FARADAY, by L. Pearce Williams. Basic Books, Inc. ($12.50). Next year is the centenary of Faraday's death. During that period of giant steps in physics (Faraday himself, it is worth remarking, disliked the name "physics"; he preferred "natural philosophy") very few men have made contributions to the discipline comparable to his own. It is a tiny, select company, of which Maxwell, Rutherford and Einstein are members. Many books have been written about Faraday's work but only a single full-scale biography: a Victorian-style two-volumer published in 1870 by Henry Bence-Jones, then secretary of the Royal Institution. This is an invaluable source, replete with letters, journal excerpts and similar material, but it has shortcomings. Bence-Jones often edited the documents he reproduced; moreover, his descriptions of Faraday's experiments and theories fall short. It was, in any case, time for a modern assessment of the man and his work, and this is what Pearce Williams has undertaken to provide after several years of painstaking study of all available unpublished materials as well as published ones. We are fortunate in having in Faraday's diaries and in the celebrated *Experimental Researches* a marvelously meticulous account of his labors (both the failures and the successes), and Williams not only has explained and interpreted them well but also, by affording a view of contemporary scientific thinking, has admirably clarified our understanding of the development of Faraday's ideas—now in opposition to the theories of others, now in consonance with them, now overturning them, now building on them. The nature of a sequence of profound discoveries has rarely been so ably presented.

Faraday is conventionally characterized as a brilliant experimenter who, in spite of his ignorance of mathematics, ingeniously foiled nature in her reluctance to disclose how things work. This, however, is an empty notion based on a misunderstanding of experiment in general and Faraday's style in particular. Anyone who has carefully read even a few of his papers can see, and Williams convincingly demonstrates, that Faraday was at all times guided by a theme, by a coherent set of theories. He knew what he was looking for, how to recognize it when he found it, how to adapt his assumptions to failure or to the unexpected. He was wonderfully persistent in following clues, even stubborn in pursuing apparent will-o'-the-wisps. It was the stubbornness of a firm, shaped mind, and he was always ready to change his direction before getting lost in the forest. The theory of atoms that had been put forward by Roger Boscovich—that atoms were point sources of force rather than tiny material particles—gained Faraday's commitment early in his career; thereafter the point atoms played a continuing and important part in the evolution of his ideas. In addition to discarding Dalton's atoms he rejected such established concepts as the fluid theory of electricity and action at a distance, thus arriving at his comprehensive vision of a universe ruled by a web of physical lines of force that determines the complex phenomena of light, electromagnetism, gravitation and even chemistry. In an epilogue Williams presents a hitherto unpublished letter from Maxwell to Faraday expressing admira-

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tion for the hypothesis of lines of force and stating his belief that it had opened up a "new road" toward the understanding of electricity. This was the road Maxwell himself greatly extended, leading to the establishment of electromagnetic field theory.

Williams has written a superior biography, yet it falls short of being absolutely first-class. It is prolix and in its scientific elucidations (although these are by far the best part of the work) unnecessarily repetitious. Often a long quotation that is perfectly clear is followed by a paraphrase. The forays into philosophy are not impressive. A rather loose hodgepodge of arguments is intended to relate Faraday's metaphysics of nature—his abiding conviction that forces are inherently identical and convertible—to his religious opinions and to the German-inspired natural philosophy of Coleridge and his circle.

As for the portrayal of Faraday's personal life, the book offers little that is better than stilted and trite. Apart from his prodigious powers as an investigator, Faraday was an interesting and complex personality, not the "man of simplicity" he has often been called. Outwardly he was much the Victorian: virtuous, pious, didactic, moralizing, ever improving himself and striving to improve others. But there was more. He was intensely ambitious, jealous, suspicious. For years he suffered from violent headaches, and he had extended periods of breakdown. He had an observant eye; this is demonstrated by his travel journals. Williams quotes from them but too sparingly. Altogether he makes Faraday a tintype. One ventures to suggest that the author spent too many hours in the archives of the Royal Institution, else how explain such a passage as this: "Faraday's domestic life was completely satisfactory to him. His work absorbed him; his wife provided a calm and warmth that allowed him to relax and stretch his mental legs in comfort and tranquillity.... The serenity and calm which marked both Faraday's countenance and his work were the results of this domestic harmony."

In spite of these defects and the occasional professorial style, this is a valuable and definitive memoir.

100 Great Problems of Elementary Mathematics, by Heinrich Dörrie. Dover Publications, Inc. ($2). Famous Problems of Mathematics, by Heinrich Tietze. Graylock Press ($10). The renowned problems of mathematics never lose their luster or their fascination. Some are very old; some are ridiculously simple to state but immensely difficult, if not impossible, to solve; some seem highly artificial unless one can place them in the context of mathematical interests at the time they arose and can recognize them as arising in the evolution of mathematical ideas as naturally as the dinosaurs or the great apes arose in the evolution of biological organisms. The various species of problem seize our imagination not only because of their content but also because they represent that highest quality of intellect also expressed in other great works of science and art.

Dörrie's book, first published in German in 1932 under the title *Triumph der Mathematik: Hundert berühmte Probleme aus zwei Jahrtausenden mathematischer Kultur,* appears here in an English translation by David Antin. It covers 100 of the most illustrious problems of elementary mathematics, briefly sketching their history and working out solutions; not infrequently more than one solution is given, representing the efforts of different mathematicians to deal with the same problem in a fresher, simpler, more convincing or more elegant way. Archimedes' cattle problem is here, as are Newton's problem of the fields and cows, Berwick's classic logical joke of the seven 7's, the Bernoulli-Euler problems of the misaddressed letters (someone writes n letters and writes the corresponding addresses on n envelopes; how many different ways are there of putting all the letters in the wrong envelopes?), Buffon's needle (which in its fall computes pi), Lucas' query about the married couples, Gauss's fundamental theorem of algebra, the tangency proof of Apollonius (to draw a circle that is tangent to three given circles), the ancient tasks of duplicating the cube and trisecting the angle, Alhazen's billiard problem (on a circular billiard table there are two balls; in what manner must one be struck in order for it to strike the other after rebounding from the cushions?), Mascheroni's compass problem (to prove that any construction that can be carried out with a compass and straightedge can be carried out with a compass alone), Steiner's straightedge problem (to prove that every construction that can be executed with compass and straightedge can be executed with a straightedge alone in the event that within the picture plane there is also given a fixed circle) and sundry pretty set pieces in extremes such as: How must a sailboat tack with a north wind in order to get north as quickly as possible? What is the maximum number of days a comet can remain within the earth's orbit? (With the use of a formula by Gauss one can calculate that the time is 78 days.) Dörrie asserts that only the theorems of elementary mathematics are needed to solve the great majority of his selections. It would be more accurate to say that only a skilled mathematician would be able to find the solutions by elementary methods.

Tietze's volume, also for the first time made available in English, has for many years delighted and instructed a large company of readers. He discusses in much greater detail than Dörrie some 14 major problem areas and provides for each abundant historical data, supplementary notes and useful bibliographies. Included are engrossing problems of prime numbers and prime twins, the age-old question of squaring the circle (solved when Ferdinand Lindemann showed it to be unsolvable), the construction of the regular polygon of 17 sides (achieved by Gauss at the age of 18), the celebrated four-color-map problem (first proposed in 1850 by Francis Guthrie, a student of mathematics at Edinburgh, and still unsolved), the profound work of Georg Cantor in bringing order to infinity, and perhaps the most spectacular, notorious and intriguing of all mathematical queries: Fermat's last problem—ridiculously easy to state, almost insurmountably difficult to prove. Tietze's book has many illustrations, some in color.

Sherlock Holmes used to speak of a hard exercise in deduction as a "three-pipe problem." There is enough in these delightful books to keep a man smoking through 100 hogsheads of tobacco.

ISLAMIC ARCHITECTURE AND ITS DECORATION, by Derek Hill and Oleg Grabar. The University of Chicago Press ($17.50). Derek Hill is a painter who during a period of nine years photographed a large number of monuments of Islamic architecture in Turkey, Persia, Afghanistan and Soviet Central Asia. This book reproduces some 500 of the photographs, all but a few of which are in black and white. His primary interest is in the decorative features of the architecture, the manner in which the builders brought life to blank walls in contrast to what he calls the "slab-cake buildings" that grow daily in every city, austerely (or perhaps unimaginatively) devoid of decoration or elaboration of any kind. In his scholarly introduction to the plates Oleg Grabar, an art historian at the University of

Michigan, describes the physical and historical setting of the places and times covered and the various techniques—carved stone, decorated brickwork, stucco, mosaic faïence and colored tiles—the designers and craftsmen used. Basically, he informs us, there were five central themes of ornament. The rarest were human and animal features. A second decorative theme is architectural, although in Islamic art a considerable number of elements that had originally had a structural meaning—such as columns, pilasters, bases and, most common of all, the so-called *muqarnas*, which appeared first on the upper part of minarets and were later spread to almost every figure in between—were transformed into purely decorative devices and as such played a part in vast ornamental compositions. Geometry was a third theme of ornamentation, prolific in extent and variety and exhibiting amazing inventiveness in the use of rectangles, squares, diamonds, net patterns and star patterns. (It is worth noting that the study of the Central Asian ornaments has shown that almost all the geometric designs can be made with ruler and compass.) A fourth theme of decoration was writing, which carried passages from the Koran, eulogies to builders, triumphant inscriptions and the like. The last of the themes consisted of reproductions and modifications of flowers, leaves and so on. Photographs of such monuments as the tomb of the Samanids in Bukhara, the Gur-i Amir of Samarkand (which includes the tomb of Tamerlane), the mosque of Bibi Khanum, the congregational mosque Isfahan (the masterpiece of the architecture of the Great Seljuqs in Iran) and various structures of Seljuq Anatolia are sometimes fascinating and beautiful. Too often, however, the photographs are amateurish and faulty in composition and in the display of the very features with which Hill is concerned. To show the intricate decorative schemes to the best effect more skill was required on the part of the photographer and more generosity, as well as imagination, in layout on the part of the publisher. In spite of these serious faults, this is a book of considerable interest for Orientalists, medievalists and anyone concerned with architecture and decorative art.

THE NEXT GENERATION, by Donald N. Michael. Vintage Books ($1.65). In 1963 Donald Michael, a social psychologist, prepared a report for the Federal Government on the foreseeable, or at least reasonably prophesiable, conditions over the next 20 years that need to be considered in planning youth-development programs. This book is based on the report. In a fairly brief compass Michael discusses such topics as the economy, technological developments, marriage, sex and the family, education, work, leisure and the values that are likely to determine planning for the period up to Orwell's dismal year. Michael is a fluent writer. He has cast his net so as to gather opinions from a variety of specialists in subjects ranging from cybernetics and automation to juvenile delinquency and disarmament. The book has a businesslike crispness and flatness not uncharacteristic of reports one must make to the Government if one hopes they will be read (and perhaps even acted on) by decision-making officials and politicians. He is overly impressed by cyberneticists and their like, and he shies away from a serious analysis of the stereotyping effects of American culture. Although this is not an exciting book, the author makes several sound points and shows himself to be an enlightening scholar.

EMBODIMENTS OF MIND, by Warren S. McCulloch. The M.I.T. Press ($12.50). A selection from the writings of Warren Sturgis McCulloch, a physician, philosopher, teacher, mathematician and poet who has gained a reputation in neurophysiology for his attempts to establish logical models and mechanical analogues of the working of the human brain. His best-known paper, written in collaboration with Walter H. Pitts, is "A Logical Calculus of the Ideas Immanent in Nervous Activity," which has been cited as having first put forward certain similarities between the brain and a computer. He has written numerous papers that are notable for, among other things, their provocative titles: "What Is a Number, that a Man May Know It, and a Man, that He May Know a Number?" "Why the Mind Is in the Head," "Where Is Fancy Bred?" and so on. It is characteristic of McCulloch that his titles promise more than his discourse yields, that he is by turns teasing, provocative, oracular, stimulating, oblique and inconclusive. After one has read a number of his papers one is likely to be uneasily uncertain of exactly what he said or exactly what he means.

ELECTRICAL CORONAS: THEIR BASIC PHYSICAL MECHANISMS, by Leonard B. Loeb. University of California Press ($14). A systematic survey of corona research based on the work of Loeb and his group, who have worked in the field intensively since 1936, and on the studies of others. Although coronas, as Loeb says in his preface, are a relatively inconspicuous form of electrical discharge, these "seemingly unimpressive phenomena" are of great value in industry and, more important, their study aids the understanding of electrical breakdown in gases.

Notes

The Crystalline State, Volume I: A General Survey, by Sir Lawrence Bragg. Cornell University Press ($8). The Crystalline State, Volume II: The Optical Principles of the Diffraction of X-Rays, by R. W. James. Cornell University Press ($12.50). These two books, forming a treatise first published some years ago in Britain, are now reissued in this country. The treatise is regarded as a classic of its kind.

The Therapeutic Nightmare, by Morton Mintz. Houghton Mifflin Company ($6.95). An able, courageous journalistic account of the delinquencies and abuses of the U.S. Food and Drug Administration, the American Medical Association, pharmaceutical manufacturers and others who are primarily responsible for "the irrational and massive use of prescription drugs which they knew to be either worthless, injurious or even lethal."

The Eightfold Way, edited by Murray Gell-Mann and Yuval Ne'eman. W. A. Benjamin, Inc. ($9). A collection of research papers dealing with the classification of strongly interacting particles according to the "eightfold way" symmetry put forward by Gell-Mann and Ne'eman.

Humidity and Moisture: Measurement and Control in Science and Industry, Volume I. Edited by Arnold Wexler. Reinhold Publishing Corporation ($30). This first volume of what is to be a four-volume work representing the expanded proceedings of a symposium on the subject held in Washington deals with the principles and methods of measuring humidity and gases. The editor of this volume is Robert E. Ruskin.

Submarine Geology and Geophysics, edited by W. F. Whittard and R. Bradshaw. Butterworth, Inc. ($21). The 1965 Colston symposium held at the University of Bristol, with papers on submarine studies of oceanic regions throughout the world.

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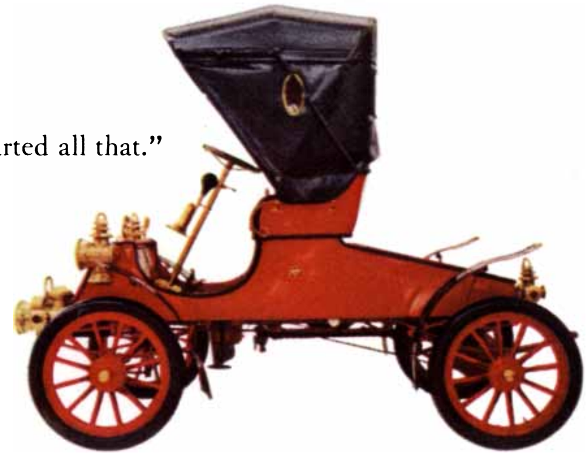

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